CHAPTER 7: DEMISE OF THE DAMS: THE CONSTRUCTION, DESTRUCTION, AND LEGACY OF LATE CENOZOIC VOLCANISM IN THE WESTERN GRAND CANYON

> *"We have no difficulty as we float along, and I am able to observe the wonderful phenomena connected with this flood of lava. The canyon was doubtless filled to a height of 1,200 to 1,500 feet, perhaps by more than one flood. This would dam the water back, and in cutting through this great lava bed, a new channel has been formed, sometimes on one side, sometimes on the other . . . .*
>
> *What a conflict of water and fire there must have been here! Just imagine a river of molten rock running down a river of melted snow. What a seething and boiling of waters, what clouds of steam rolled into the heavens!"*
>
> *John Wesley Powell, August 25, 1869*

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INTRODUCTION

Volcanic episodes have occurred periodically throughout the history of the Grand Canyon (e.g. Garber, this volume; Bennett, this volume). During certain phases of the tectonic evolution of the Grand Canyon, uplift of the Colorado Plateau lead to an extensional tectonic environment that thinned the Earth's crust facilitating transport of magmatic material to the Earth's surface, often along fault zones that acted as conduits for the basaltic magma generated in the mantle below (see Bennett, this volume for discussion of regional tectonics). There are three volcanic fields on the western Grand Canyon: the Grand Wash, Shivwits Plateau, and Uinkaret Plateau, from west to east, respectively. The youngest of these, the Uinkaret Plateau, was active during the Pleistocene (Crow et al., 2008; Dalrymple and Hamblin, 1998; Hamblin, 1994). The Uinkaret volcanic field is located between the Toroweap and Hurricane faults (river mile 178 and 191, respectively) (see Elliott, this volume for discussion of faults in the western Grand Canyon). The Grand Canyon is the southern boundary of the Uinkaret volcanic field with volcanism extending to the north for about 80 km (Hamblin, 1994). The Uinkaret volcanic field has produced more than 150 individual lava flows that originated or flowed into the western Grand Canyon building 13 major lava dams (Hamblin, 1994). The inner gorge of the Grand Canyon is estimated to have been filled with a minimum of 22 km^3 of lava with dams hundred of meters tall and several that were more than 100 km in length (Hamblin, 2003).

This paper presents the four styles of lava dams, the change in lava dam morphology during the four periods of lava dam construction, and the extent and effect of lava dam lakes within the Grand Canyon as well as the proposed theories for the destruction of the lava dams. Finally, this paper will examine the constraints that lava dams place on erosional capacity of the Colorado River, and how this affects the time scale needed to form the Grand Canyon.

CONSTRUCTION OF THE LAVA DAMS

Eruption of low viscosity, effusive basaltic lava in the Uinkaret volcanic field lead to the formation of lava dams in the Grand Canyon (Crow et al., 2008; Hamblin, 1994, 2003). These eruptions were centered in the Grand Canyon, on the Esplanade Platform, or on the margins of the Uinkaret Plateau (Crow et al., 2008; Dalrymple and Hamblin, 1998; Hamblin, 1994, 2003). A typical lava eruption on the Uinkaret Plateau is approximately 15 m thick (Hamblin, 1994). Unlike an eruption on a plateau where the basaltic lava can spread and thin as it flows, the canyon contained the lava flow, channeling the flow down the inner gorge resulting in flows thickened to >45 m for an eruptive volume similar to ones that produced a 15 m thick plateau flow (Hamblin, 1994). The majority of lava flows were erupted above the river gorge and cascaded into the inner gorge (Crow et al., 2008; Hamblin, 1994). However, regardless of the eruption site, once in the inner gorge the upriver end of the lava flow immediately interacted with the water in the canyon. This is observed in elliptical and pillow structures (Hamblin, 1994, 2003). Pillow structures are rounded lava mounds that form when lava is erupted underwater and the surface of the lava that is contact with the water quenches, making a glassy rind that is then inflated from lava continuing to erupt, much like the inflation of a balloon (i.e., pillow lavas at mid ocean ridges, on the flanks of Hawaii, etc.). The elliptical features are hypothesized as forming as an interaction between the lava and water similar to the pillow lavas (Hamblin, 1994). In this case, the water would overflow the dam penetrating cracks in the crust cooling the lava rapidly resulting in the elliptical structures. Some of the lava would flow upstream from the dam. Lava that flowed upstream into the lake that was forming behind the dam would create hydroexplosive tephra that would accumulate like a tephra delta into the lava dam lake, forming bedding that would prograde upstream (Hamblin, 2003). Most of the lava from the eruption would flow downstream into what had effectively become a dry valley.

In the dry valley, the lava would cool similarly to the Hawaiian basalts flows or flood basalts. The top of the flow would cool rapidly forming an a’a’ crust what is characterized by a rough, broken surface. This quench margin insulates the main body of the lava flow allowing it to cool more slowly. The main body of the flow is divided into three portions: the upper colonnade, the entablature and the lower colonnade (Figure 7.1). The upper and lower colonnades have straight, regular polygonal columns while the entablature has more irregular columns that are often curved and skewed. Although several theories for the formation for columnar jointing exist (Hsui, 1982; Kantha, 1981) the most widely accepted mechanism is the contraction of the flow during cooling (Long and Wood, 1986; Lyle, 2000; Spry, 1962; Tomkeieff, 1940). The flow cools from the outside (top and bottom) toward the center. As the top and bottom cool, tensional stresses form joints. These joints propagate along the cooling front, perpendicular to the cooling surfaces (i.e., from the top down and from the bottom up) forming polygonal, 4- to 7- sided columns, although 5- or 6- sided are the most common. The entablature is also formed from columnar joints but these joints propagate irregularly often displaying curved surfaces. Proposed mechanisms for entablature formation are deformation of a ductile flow center (Tomkeieff, 1940), or water infiltration along the joints formed in the colonnade resulting in rapid cooling of the entablature (Long and Wood, 1986).

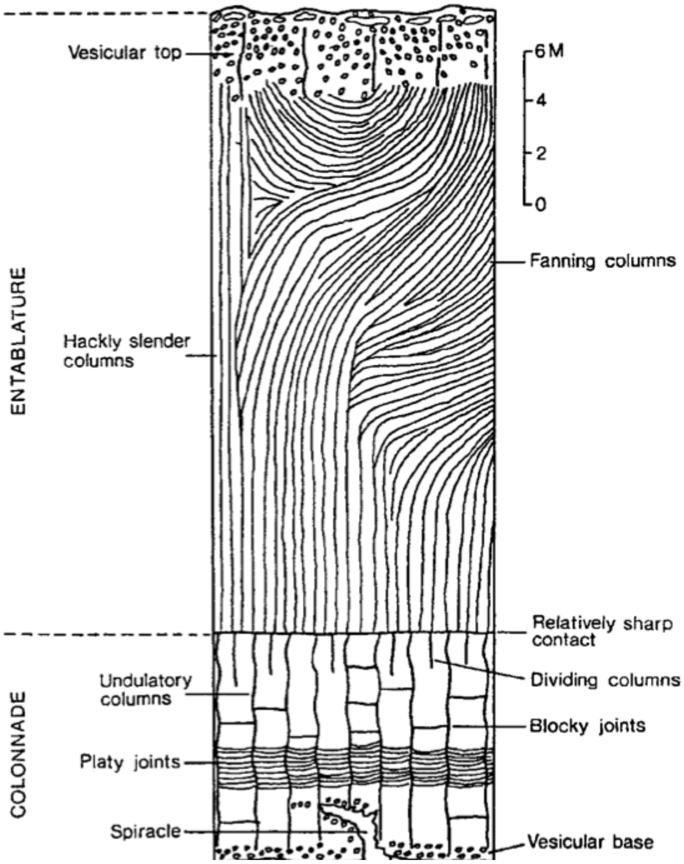

Figure 7.1 The internal structure of a basalt flow. This basalt flow is modeled after the Yakima Basalt Subgroup of the Columbia River flood basalt. The upper colonnade is labeled as the "Vesicular top". Modified from (Lyle, 2000).

Lava Dam Morphology

The simplest lava dam is constructed of single thin lava flow (Figure 7.2 A). These thin flow dams are 45 to 180 meters thick and up to >135 km in length (Hamblin, 1994). These lava flows constructed lava dams within a few weeks based on the modern examples of lava flows in Hawaii and Iceland (Hamblin, 2003).

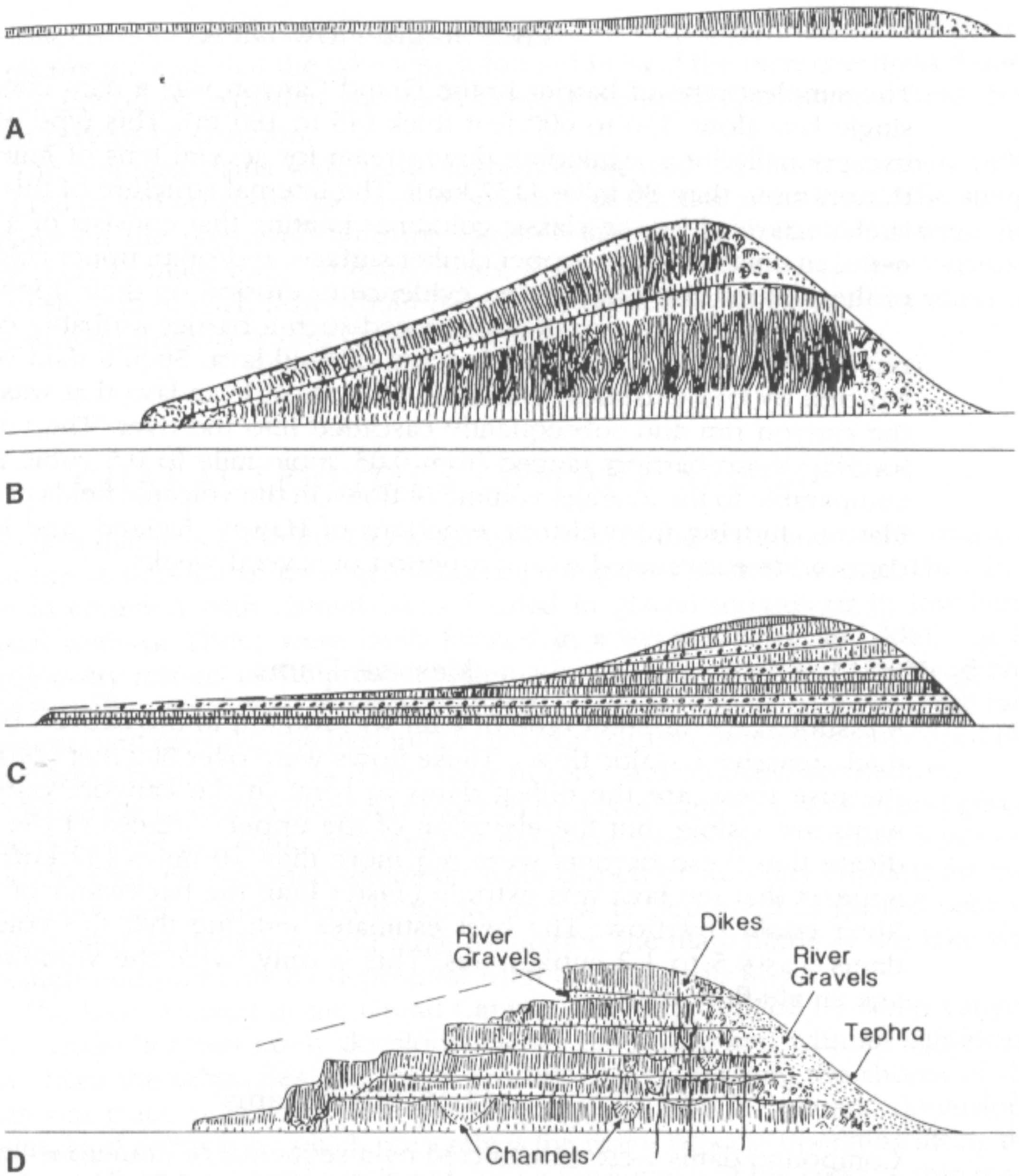

Figure 7.2 The morphology of the four types of lava dams: A) single thin flow dam, B) massive dam, C) compound dam, and D) complex dam. From (Hamblin, 2003).

Massive dams are constructed of abnormally thick lava flows (Figure 7.2 B). A single massive flow is >240 m in thickness (Hamblin, 1994). These flows are shorter than the thin single flows not exceeding 40 km in length. Massive dams often lack erosional surfaces between flows indicating that these flows were extruded faster than the backwater of the Colorado River could overflow the dams (Hamblin, 2003). Massive dams were typically extruded in the canyon rather than cascading into the inner gorge (Crow et al., 2008; Dalrymple and Hamblin, 1998; Hamblin, 1994).

Compound dams were formed from numerous thin lava flows (Figure 7.2 C). Individual flows were commonly 3-9 m thick (Hamblin, 1994). The rapid succession of numerous flows constructed dams that were 90-270 m thick. The stacking of individual thin flows lacking erosional surfaces between flows indicate that there were multiple eruption events over a short time period as the river could rapidly overflow single <10 m dam leading to erosion of the dam prior to the successive eruption (Hamblin, 2003).

Complex dams were constructed from multiple lava flows 60-150 m thick (Figure 7.2 D). The total height of these dams were 180-240 m thick with lengths less than 20 km (Hamblin, 1994). These dams were similar to single flow dams but the upper colonnades of the flows in the complex dams are often eroded by localized deep river channels. These channels are commonly filled with river sediment and ash from younger flows (Hamblin, 2003). Additionally, major flow units in complex dams are frequently separated by lenses of river gravel and sand, and in some cases ash beds corresponding to younger flows (Crow et al., 2008; Hamblin, 1994). These erosional features with the presence of interbedded river gravels indicate that the lake behind the dam overflowed and the lava flows were eroded to some extent between eruption periods (Crow et al., 2008; Hamblin, 1994).

Four Periods of Lava Dam Construction in the Late Cenozoic

In the Pleistocene there were 4 distinct periods of volcanism that resulted in lava dam construction in the Grand Canyon. The earliest volcanism was focused in the southern end of the Uinkaret Plateau with volcanism migrating generally northwest over time. Relative ages of the lava flows were determined by juxtaposition (Hamblin, 1994) (Figure 7.3). These relationships can be difficult to determine in the field due to the limited remnants of the lava dams. Initial ages determined by $^{40}K/^{40}Ar$ dating of the lavas resulted in ages that both corroborated and conflicted with this proposed stratigraphy (Dalrymple and Hamblin, 1998; Hamblin, 2003). The ages of the lavas have been refined by $^{40}Ar/^{39}Ar$ and cosmogenic ^{3}He dating (Crow et al., 2008). The ages determined by $^{40}Ar/^{39}Ar$ dating are more tightly constrained than the $^{40}K/^{40}Ar$ ages and in some cases the $^{40}Ar/^{39}Ar$ ages are significantly younger, as much as half of the previously determined $^{40}K/^{40}Ar$ age. The $^{40}Ar/^{39}Ar$ and cosmogenic ^{3}He ages are better correlated with the proposed relative ages determined by juxtaposition (Figure 7.3) (Crow et al., 2008). The four periods of volcanism reported below are reported in ages determined by $^{40}Ar/^{39}Ar$ and cosmogenic ^{3}He dating.

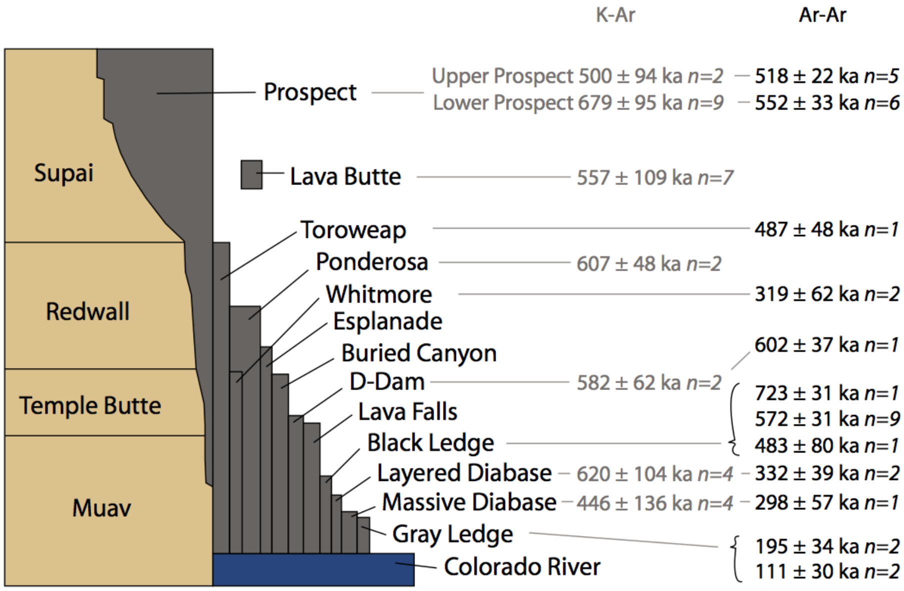

Figure 7.3 The ages of lava dams determined by juxtaposition (left) (Hamblin, 1994), ^{40}K/^{40}Ar dating (center) (Dalrymple and Hamblin, 1998), and ^{40}Ar/^{39}Ar dating (right) (Crow et al., 2008). From (Crow et al., 2008).

The oldest, furthest south, and most voluminous volcanic period spanned 725-475 Ma. The lava dams formed during this period were the Prospect dam, the D dam, the Toroweap dam, the Ponderosa dam, the Lava Butte dam, and Buried Canyon flow (Crow et al., 2008). The volcanism during this period was focused along the Toroweap fault (river mile 179) within the inner gorge of the Grand Canyon with additional volcanism on both the north and south rims of the canyon (orange, Figure 7.4) (Crow et al., 2008; Dalrymple and Hamblin, 1998; Hamblin, 1994). Dikes within the inner gorge are correlated to the Prospect dam indicating that volcanism, most likely in the form of cinder cones, occurred within the inner gorge (Crow et al., 2008; Hamblin, 1994). For eruptions in the inner gorge, the entirety of the flow was contained within the canyon leading to large lava flow volumes. The Prospect dam was a complex dam constructed from 3-4 major 120 m thick flows (Hamblin, 1994). The Toroweap and Buried Canyon dams are also complex dams (Hamblin, 1994, 2003). The Ponderosa Dam was constructed from a single massive flow 300 m thick (Hamblin, 1994). There were also examples of single thin flow dams constructed during this period such as the Lava Butte dam (Crow et al., 2008; Hamblin, 1994, 2003).

The second period of volcanism occurred from 400-275 Ma (green, Figure 7.4) (Crow et al., 2008). The volcanism during this period moved north out of the inner gorge of the canyon and west to the Hurricane fault. The largest dam constructed during this period was the Whitmore dam (Crow et al., 2008; Hamblin, 1994). The lava that formed the Whitmore dam was erupted along the Hurricane fault on the north rim of the Canyon in the Uinkaret volcanic field and on the Esplanade platform (Crow et al., 2008; Dalrymple and Hamblin, 1998; Hamblin, 1994). The lava cascaded into Whitmore canyon and was then channeled into the Grand Canyon (Hamblin, 1994). The Whitmore dam is a complex dam constructed of numerous thin lava flows that are interbedded with river gravels (Hamblin, 1994). The top of the Whitmore dam was approximately 215 m high, the same height as the Glen Canyon Dam (Hamblin, 1994, 2003). $^{40}Ar/^{39}Ar$ dating indicates that the Massive and Layered Diabase flows were both part of the Whitmore flows (Crow et al., 2008; Dalrymple and Hamblin, 1998; Hamblin, 1994).

The two youngest periods of volcanism were initially identified as one flow, the Grey Ledge flow (Crow et al., 2008; Dalrymple and Hamblin, 1998; Hamblin, 1994). $^{40}Ar/^{39}Ar$ and cosmogenic ^{3}He dating indicates that there were two periods of volcanism that constructed two separate dams. The Lower and Upper Grey Ledge remnants have ages of approximately 200 ka and 100 ka, respectively (Crow et al., 2008). The flow originally mapped as Black Ledge is the same age as Upper Grey Ledge and is likely from the same source (Crow et al., 2008; Dalrymple and Hamblin, 1998; Hamblin, 1994). The volcanic sources that produced these two periods of dams are more difficult to tease out than the two older periods that are centered along major faults. There are lava flows on the north rim of the canyon near Vulcan's Throne and Vulcan's Footrest (Toroweap Fault) of a similar age as the Lower Grey Ledge flows but whether they entered the canyon remains unclear (Crow et al., 2008). The younger Upper Grey Ledge flows are hypothesized as originating from cinder cones on the north rim of the canyon (between river mile 182-185) (Crow et al., 2008).

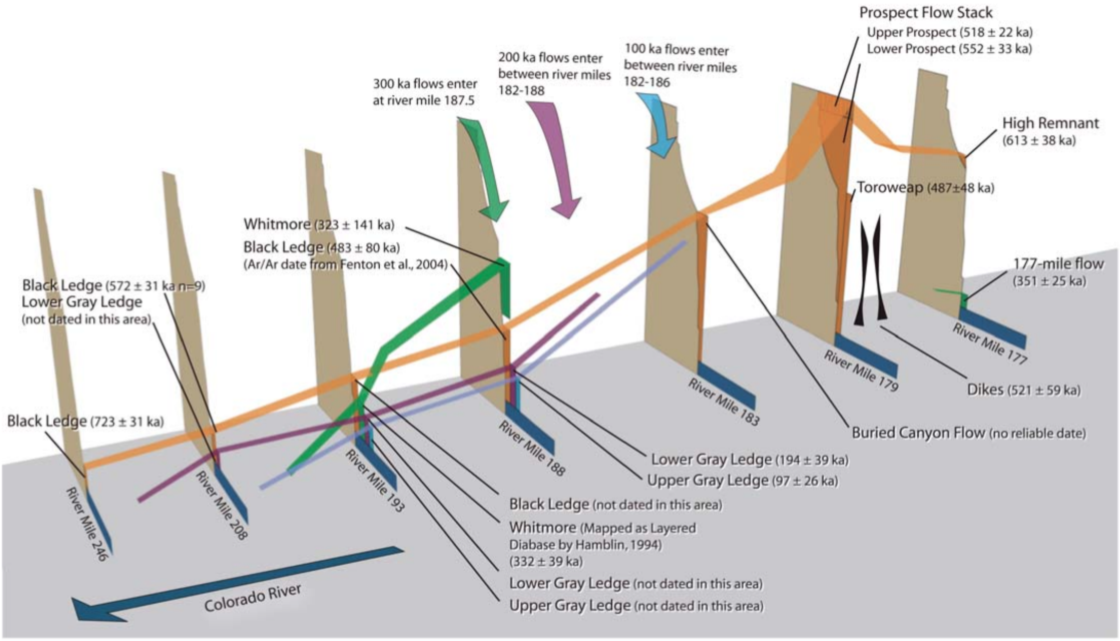

Figure 7.4 The location of lava entrance into the canyon and extent of flows for the four periods of lava dam construction. Orange is the oldest flow corresponding to the Prospect dam and other flows from the first period of volcanism. Green corresponds to the Whitmore dam and the purple and blue corresponds to the lower and upper grey ledge dams, respectively. The Toroweap fault is along river mile 179 and the Hurricane fault is along river mile 188. From Crow et al. (2008).

THE EXTENT AND DEMISE OF LAVA DAM LAKES

The lakes that formed behind the lava dams were geologically unusual: they occupied a deep canyon in contrast to the natural lakes that formed in low-lying coastal areas and glacial terrains. These lakes were formed instantaneously on a geological time scale with the largest lakes taking a few tens of years to fill (Hamblin, 2003). The lake that formed behind Prospect dam could have been the longest and deepest lava dam lake. Based on the height of the remnants of Prospect dam, Prospect Lake may have filled the Grand Canyon to the Esplanade Platform. By extending the lake height back along the Colorado River, the upper reaches of Prospect Lake would have extended past what is now Moab, Utah (Hamblin, 2003). Once the lake filled, it would overflow the dam resulting in a waterfall at the head of the lava dam. This would create a knick point at the end of the lava dam that would erode away the dam as it migrated upstream. For the larger dams, this nick point created a waterfall that may have been hundreds of meters tall and hundreds of meters wide (Figure 7.5 A). Dam shortening could lead to catastrophic failure since the water pressure behind the dam remained constant while the dam was weakening due to reduction in the dam length. A catastrophic failure resulted in a surge of water that flushed out the accumulated sediments in the lake behind the lava dam leaving little record of these lakes (Fenton et al., 2004; Fenton et al., 2006; Hamblin, 1994). There is some evidence for such catastrophic failures of dams from outburst flood deposits perched 200 m above the Colorado River (Fenton et al., 2004). These outburst flood deposits are characterized by the presence of basalt cobbles and boulders, some reaching >10 m along their b-axis (Fenton et al., 2004). There are confirmed outburst deposits for the Prospect, Toroweap, and Whitmore dams (Fenton et al., 2004).

Crow et al. (2008) propose that although some dams did fail catastrophically, many of the dams may have been compromised by weak layers of interbedded tephra and cinder deposits or the presence of fractures and lava tubes. In these cases, the dam was a compromised dam or a “leaky” dam, and water would have had a method of penetrating the lava dam without requiring an outburst flood (Figure 7.5 B, C). Additionally, ^{14}C and amino acid geochronology of possible lacustrine deposits thought to be lava dam lake deposits in Lee’s Ferry, Marble Canyon, Lava Valley, Elves’ Chasm and Lower Havasu Creek have been shown to be spring fed pools indicating that lava dam lakes and the corresponding outburst flood were likely less frequent and significant than originally thought (Kaufman et al., 2002).

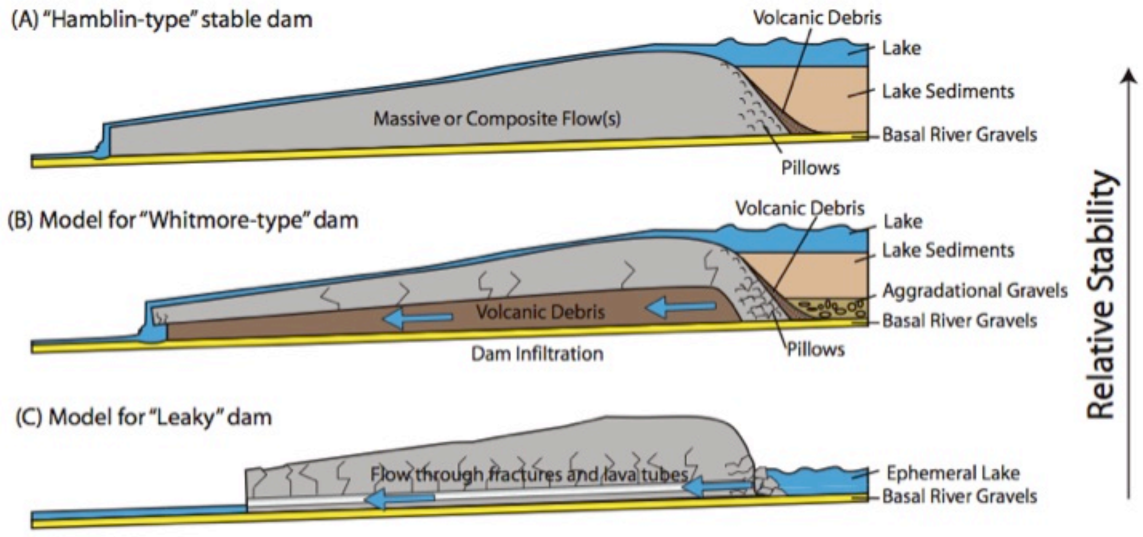

Figure 7.5 Proposed erosional process that lead to dam destruction. A) The upstream migration of a nick point that would lead to shortening of the dam resulting in outburst floods (Hamblin, 1994). Mechanism for weakening the lava dams from B) underlying volcanic debris and C) fractures and lava tubes within the dam (Crow et al., 2008). Modified from Crow et al. (2008).

CONSTRAINTS ON THE FORMATION OF THE GRAND CANYON

Rates of Incision

The profiles of the lava dams extend to the current level of the Colorado River indicating that river has been down cut to its current depth since the emplacement of the lava dams began at 725 ka (Figure 7.3). The Colorado River has cut down through the lava and as the hardness of basalt and sandstone are similar, the rate at which the Colorado River cut through the lava flows can serve as an estimate for the minimum time needed for the Colorado River to incise the Colorado Plateau. The minimum total height of Pleistocene lava dams was over 3 km, several times the depth of the Grand Canyon (Figure 7.6) (Hamblin, 1994). The juxtaposition of younger lava dams inside the remnants of old flows indicate that each flow was significantly eroded before the emplacement of the next dam (Figure 7.3) (Hamblin, 1994). Assuming that the total height of the lava dams took the entire 725 ka, although it likely proceeded faster, the Colorado has a minimum incision rate of 5 m/ka. This means that the time need to incise the Grand Canyon to its current depth is <220 ka, markedly less time than other theories suggest (see Longinotti, this volume for discussion).

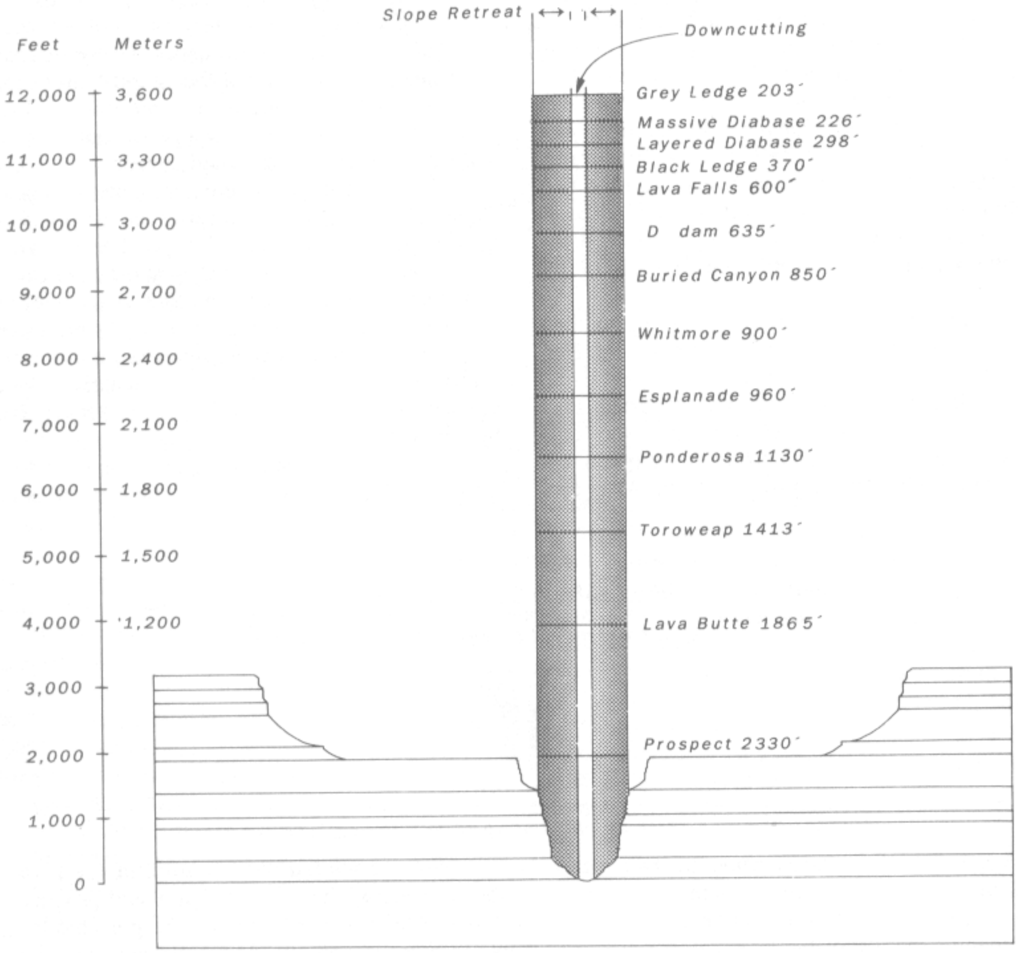

Figure 7.6 The total height of the lava dams eroded in comparison to the depth of the Grand Canyon. From Hamblin, (1994).

Rates of Slope Retreat

The preservation of lava dams within the canyon walls demonstrates that the profile of the Grand Canyon has not significantly changed for more than 725 ka. The slope retreat of the river balances with the rate of down cutting. Since the base of the canyon has remained constant since the emplacement of the lava dams (as indicated above) then the profile of the Grand Canyon is in a state of quasiequilibrium for the past 1 Ma. Figure 7.7 shows the amount of slope retreat accomplished by the erosion of all the lava dams. From figures 7.6 and 7.7 it is seen that the erosional capacity of the Colorado River in the Grand Canyon is significant. However, the profile of the Grand Canyon has remained constant through these massive erosion events indicating that the Grand Canyon is in a state of quasiequilibrium. When this quasiequilibrium is perturbed, i.e., the formation of a lava dam, the river erodes the lava dam rapidly until the state of quasiequilibrium is regained.

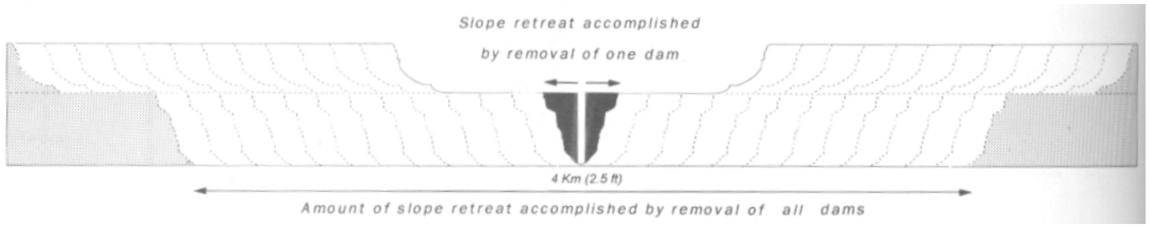

Figure 7.7 The total width of slope retreat achieved by the removal of all the Pleistocene lava dams. From Hamblin (1994).

LAVA DAMS AND THE MODERN GRAND CANYON

Rapid erosion of large volumes of lava from the Grand Canyon along with the lack of evolution of the canyon profile indicate that the Grand Canyon was not produced by a slow and steady incising Colorado River. Rather deep incision and major slope retreat is initiated by perturbations to the quasiequilibrium state such as the construction of a lava dam or tectonic uplift of the Colorado Plateau. This argues that the perturbation from the Glen Canyon Dam is ephemeral. The Grand Canyon is in a state of quasiequilibrium and evolution away from the current canyon profile requires a major perturbation.

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