

CHAPTER 4: HISTORY OF COLORADO RIVER INCISION AND FORMATION OF THE GRAND CANYON

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INTRODUCTION

Throughout the Cenozoic Era, the southwestern United States has been very tectonically active (Chapter 3) which has resulted in a diverse network of rivers that have responded differently to these tectonic changes. The formation of a drainage system can be explained by four principal mechanisms: antecedence, superimposition, piracy, and overflow (Douglass et al., 2009). An antecedent river erodes downward into uplifting bedrock and predates tectonic activity, while a superimposed river erodes into buried, post-tectonic strata. Piracy (or capture) occurs either when a river changes its course to the course of another stream, or when headward erosion of a stream cuts across a drainage divide and captures the stream on the other side of the topographic divide. The fourth mechanism, overflow, results from spillover of a river that has ponded into a lake. An active tectonic history disrupts drainage basins, with some rivers maintaining their course through antecedence, and others re-organizing through piracy and overflow, or developing a new, superimposed drainage. The Colorado River has been extensively studied, and yet it remains unclear which mechanism primarily influenced its formation. Beginning with Powell (1875) who proposed an antecedent river and Walcott (1890) who suggested a superimposed river, the formation and path of the Colorado River have been debated up to the present, and alternately all four mechanisms of river formation have been proposed for the Colorado River. The formation of the Grand Canyon is unmistakably linked to the evolution of the Colorado River and cannot be understood without uncovering the history of the Colorado River. The southwestern United States has been extensively studied for over a century, yet the origin and evolution of the Grand Canyon is still debated. Studies have used a variety of techniques to explore the history of the Colorado River and timing of canyon incision, which has led to conflicting interpretations of the age and evolution of the Grand Canyon.

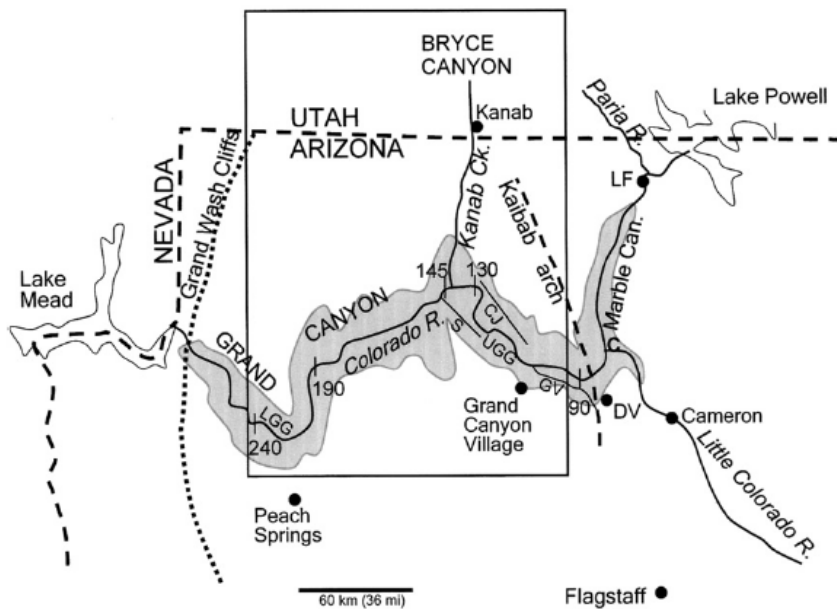


Figure 4.1 The Grand Canyon (shaded in grey) in the northwestern corner of Arizona from Hill and Ranney (2008). The abrupt western edge occurs along the Grand Wash Cliffs. The proposed Laramide proto-Grand Canyon of Hill and Ranney (2008) is contained within the rectangle. LF=Lees Ferry, C=Confluence, DV=Desert View, GV=Grandview monoclone, CJ=Crazy Jug monoclone, S=Supai monoclone, UGG=Upper Granite Gorge, LGG=Lower Granite Gorge.

MODERN COLORADO RIVER: 6 MA TO PRESENT

The current Colorado River integrates a very large drainage network that extends into seven states and travels ~2300 km before entering the Gulf of California. The river cuts down through horizontal Paleozoic strata (Chapter 2) and into basement rocks (Chapter 1). In the western part of the canyon the flat-lying beds are interrupted by the north-trending Hurricane and Toroweap faults (Chapter 5), while the eastern part of the canyon is disrupted by the Kaibab arch (or upwarp). The river exits the western edge of the Grand Canyon at the Grand Wash Cliffs, which is the abrupt fault-bounded transition between the Colorado Plateau and the Grand Wash Trough (Fig 4.1).

The general consensus is that the current Colorado River course has existed for the last 5 or 6 Myr. Colorado River sediment first appeared in the Grand Wash Trough after 6 Ma (Spencer et al., 2001) and reached the Salton Trough at ~5.3 Ma (Dorsey et al., 2007). No significant volume of river sediment with clear Colorado Plateau provenance was deposited in the Muddy Creek Formation of the Grand Wash Trough. The Muddy Creek Formation was deposited from ca. 11 to 6 Ma and is composed of locally derived alluvial-fan and lacustrine deposits (Pederson, 2008). The youngest member of the formation is the Hualapai Limestone with an age of ~6 Ma (Spencer et al., 2001). No sediment suggestive of a large river system is found in the formation. This lack of river sediment has given rise to the “Muddy Creek problem” (e.g. Pederson, 2008). There is no geologic evidence for a pre-6 Ma Colorado River system flowing from the western Grand Canyon into the Grand Wash Trough (Fig 4.2), nor is there evidence for the river running an alternate route. If an ancient Colorado River of significant size did exist and was incising the Grand Canyon prior to 6 Ma, it was not recorded in the sedimentary deposits where the river most likely would have terminated. This has given rise to the belief by many that no Colorado River incision occurred pre-6 Ma and that the entire ~1500 m deep Grand Canyon was formed in the past 5 to 6 Myr (e.g. Faulds et al., 2001; Lucchitta et al., 2001; Spencer and Pearthree, 2001).

Since the fully integrated modern Colorado River does not appear to have shifted to its current course until ca. 6 Ma, some change must have occurred to alter the river network. Prior to the late Miocene it is theorized that the Colorado River was divided into two opposite flowing drainages: an upper, eastern Colorado River and a lower, western Colorado River that were separated by a drainage divide at the approximate location of the Kaibab arch. Integration of the two separate drainage networks ca. 6 Ma created the modern Colorado River system. Multiple methods of integration have been proposed: capture of streams on the Colorado Plateau by headward erosion of the western Colorado River (Lucchitta et al., 2001), lake spillover across the Kaibab arch (Meek and Douglass, 2001; Spencer and Pearthree, 2001), or a karst-aquifer connecting the eastern and western Colorado Rivers under the Kaibab arch that collapsed and incised downward (Hill et al., 2008).

Some studies suggest that integration of the modern Colorado River led to rapid incision of the Colorado Plateau and formation of the entire Grand Canyon (Faulds et al., 2001a; Lucchitta et al., 2001; Spencer and Pearthree, 2001). The current rate of incision is too slow to have carved the entire Grand Canyon in the last 6 Myr (Pederson et al., 2002; Polyak et al., 2008; Karlstrom et al., 2008), thus either the incision was initially higher and has decreased towards the present, or some component of incision occurred prior to 6 Ma.

ANCESTRAL COLORADO RIVER AND EVIDENCE FOR A PRECURSOR CANYON : THE PRE-6 MA MIOCENE

The history of the pre-6 Ma Colorado River west of the Grand Canyon remains controversial. It is generally agreed that in the early Miocene drainage flow in the southwestern United States reversed

from a northeastern to a southwestern direction. The change in flow direction occurred in response to Basin and Range crustal extension, which lowered the elevation in the south and west. Prior to extension there existed highlands to the southwest and drainage flowed northeastward onto the Colorado Plateau (Young, 2001). Reversal of flow may have occurred as early as the Oligocene (Hill and Ranney, 2008), or at the latest ~15.3 Ma based on fanglomerates containing a 15.3 Ma ash-flow tuff that accumulated in the basin to the west of the Grand Wash Cliffs (Faulds et al., 2001b),

A regional reversal of flow is recorded in the geologic record, though the course of the Colorado River during the majority of the Miocene remains unclear. Colorado River sediment does not appear in the Grand Wash Trough region until after deposition of the Hualapai Limestone at ca. 6 Ma (Spencer et al., 2001). In addition, an alternate river route to the northwest can be ruled out by a composition of river deposits that is clearly different from the sediment carried by the Colorado River (Pederson, 2008). One hypothesized history proposes that a much smaller ancestral Colorado River dissipated in the central-western Grand Canyon and infiltrated the Paleozoic limestones which dominate in this region (Pederson, 2008). A second theory also suggests a smaller, ancestral drainage system that cut headward from the Grand Wash Cliffs after initiation of Basin and Range extension (Young, 2008; Fig 4.2). A smaller ancient river system may not have had a large sediment load. Currently the majority of discharge is supplied by the Rocky Mountains. A smaller, ancestral drainage system may have had a small fraction of the current run-off. Additionally, the majority of exposed rock in the lower part of the Colorado River basin is carbonate-rich, and therefore during Muddy Creek time the drainage system would have discharged a high concentration of dissolved calcium carbonate into the Grand Wash Trough and minimal siliciclastic sediment. Young (2008) also suggests a large lake may have extended up into the region where the western Grand Canyon was incising. If such a lake existed, the river sediment would have been deposited in a delta upstream of the Grand Wash Trough deposits.

A controversial study performed by Polyak and colleagues (2008) used speleothems to estimate the historic water table of the Grand Canyon. Speleothems are mineral deposits that form in caves near the water table. Incision rates can be derived from the age of these formations if it is assumed that the declining groundwater table is equivalent to river incision rates. The study yielded an age range of 17 to 0.8 Myr and supports the existence of a pre-6 Ma Grand Canyon. Comments on this study argue that unjustifiable assumptions were made and anomalous data points were used that can be interpreted differently (Pederson et al., 2008; Pearthree et al., 2008).

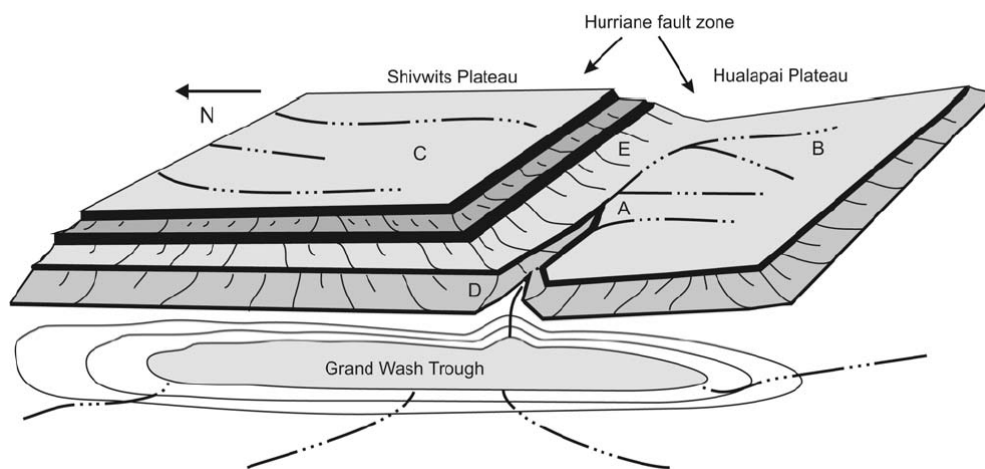


Figure 4.2
Diagram of the Muddy Creek Problem from Young (2008) and proposed method of initial canyon incision. (A and D) Incision of the Hualapai Plateau. (B) Headward erosion. (E) Erosion of the Shivwits Plateau. (C) Interior drainage.

EVIDENCE FOR A LARAMIDE PROTO-GRAND CANYON

Recent research has emerged supporting the existence of a proto-Grand Canyon during Laramide time (Hill and Ranney, 2008; Flowers et al., 2008). Hill and Ranney (2008) examine two separate sets of river gravels located on plateaus north and south of the Grand Canyon. The gravels found south of the Colorado River are derived from a source to the south of the Grand Canyon. A controversial age of late Paleocene to middle Eocene is currently assigned to these southern rim gravels. Deposition of the northern rim gravels is believed to have begun in the Oligocene, and the sediment is derived from the Canaan Peak Formation of southern Utah. The Hill and Ranney study proposes that none of the southern rim gravels exist north of the Colorado River, nor does the northern rim gravels cross the Grand Canyon and exist to the south. This suggests a proto-canyon had to be present at the time of rim gravel deposition, preventing the transport of gravels from both north to south and south to north (Fig 4.1).

A recent (U-Th)/He thermochronometric study also found evidence for a proto-Grand Canyon. Apatite (U-Th)/He thermochronometry is a method of dating that is based on the production of He through the decay of U, Th, and Sm within mineral grains in the rock (Farley, 2000). He only accumulates at temperatures < 70°C, which is the temperature range of rocks in the uppermost 3 km of crust. The He date signifies the time at which the mineral grain cooled past its closure temperature. If an older Grand Canyon did not exist, the He date of apatite grains at the bottom of the Canyon would be much younger than the apatite grains ~1500 m higher on the rim of the canyon. This history is not recorded in the apatite grains. Instead, the dates at the bottom of the canyon and on the above Kaibab surface are similar, suggesting rocks at the bottom of the canyon and on the rim have similar thermal histories. A proto-Grand Canyon incised in the early Tertiary is necessary to explain the similar thermal histories (Fig 4.3).

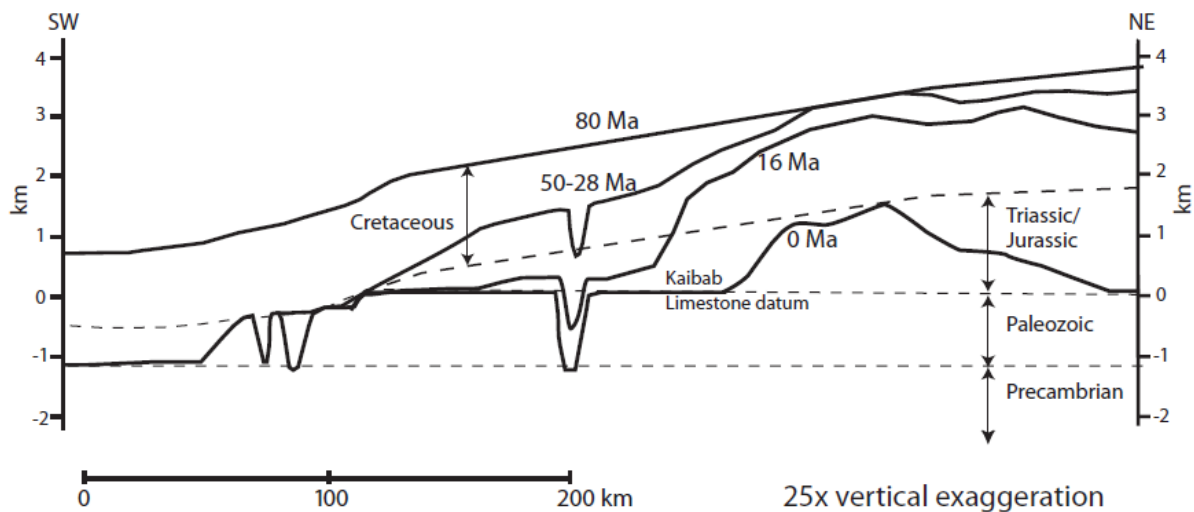


Figure 4.3 Proposed canyon formation from Flowers et al. (2008). Dashed lines separate rocks of different age.

THE "CALIFORNIA RIVER" AND EXISTENCE OF A PRE-LARAMIDE PALEOCANYON

Wernicke (2011) further explores the He data published by Flowers and collaborators (2008) and argues that the rim and gorge samples existed at different temperatures prior to 80 Ma, and that the thermal histories converge after 70 Ma (Fig 4.4). This suggests a paleocanyon formed between 70 and 80 Ma. A three-phase paleohydrologic history of the southwestern United States is proposed in this

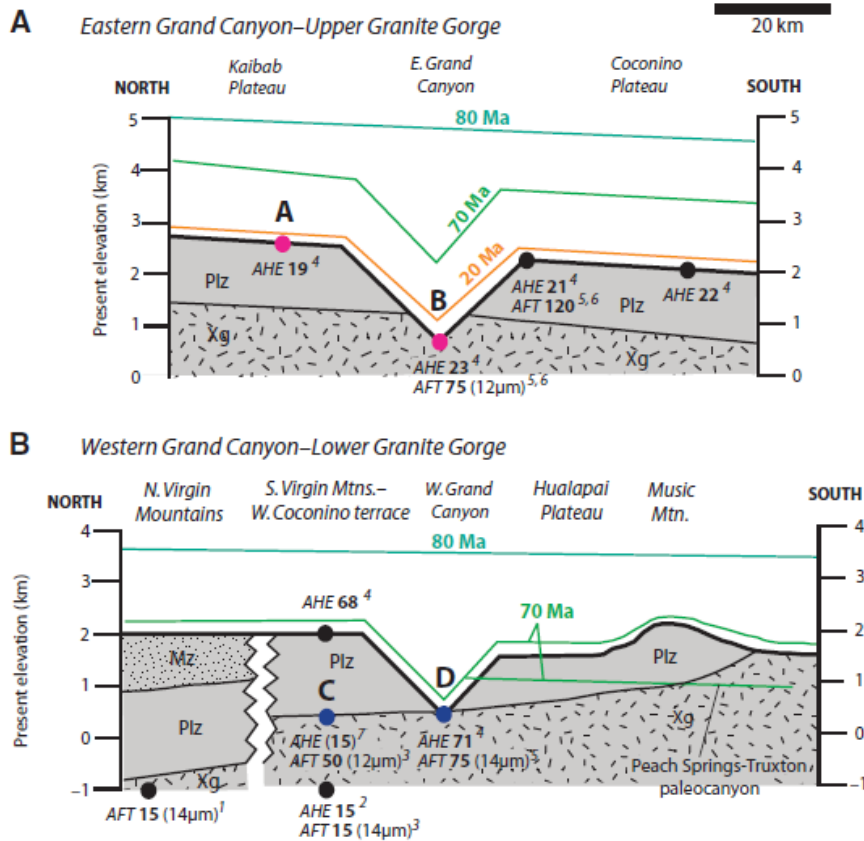


Figure 4.4 Cross sections of thermochronological data from Wernicke (2011). (A) Rim and gorge samples (dots) and the position of the current erosion surface, along with the inferred surface at 20, 70, and 80 Ma. AHE – (U-Th)/He apatite age; AFT – fission-track apatite age. (B) Same as A for western Grand Canyon. Superscript numbers denote sources of data: 1—Quigley et al. (2010); 2—Reiners et al. (2000); 3—Fitzgerald et al. (1991, 2009); 4—Flowers et al. (2008); 5—Kelley et al. (2001); 6—Dumitru et al. (1994); 7—age inferred from structural position between the surface and the base of the partial annealing zone for apatite fission tracks (Fitzgerald et al., 1991; Reiners et al., 2000).

study. The initial paleocanyon was incised by an east-flowing river with headwaters in California, referred to as the “California River.” This phase of incision is hypothesized to have occurred ca. 80-70 Ma. During Laramide deformation sediment with an Arizona provenance was deposited in the region, indicating a second paleoriver existed, which Wernicke calls the “Arizona River.” This second paleoriver was ultimately disrupted by Basin and Range extension. The third and final hydrologic phase occurred post-6 Ma with integration of the modern Colorado River and completion of the Grand Canyon incision.

A second study also proposes the existence of a Paleogene California River (Davis et al., 2010). During the early Paleogene, paleoflow in Arizona and southern Utah appeared to be to the north-northeast. The study dates detrital zircons in samples collected in the Colton Formation located in northeastern Utah, as well as samples collected in the McCoy Mountains Formation found in southwestern Arizona. Zircon ages from the two sets of samples are a statistical match. This finding suggests a Cordilleran arc existed in the Mojave and was the primary source of the Colton and McCoy deposits. The study argues that it seems likely a large river system existed and carried the sediment from the southern California source into Arizona and Utah.

UNDERSTANDING THE GRAND CANYON

Debate continues over the evolution of the Grand Canyon. It remains unclear which mechanism formed the Grand Canyon and how the modern river became an integrated, throughflowing drainage system. However the canyon was formed, it is clear that the Grand Canyon experienced a unique history of incision. The Colorado Plateau has remained a solid block, preserving a thick layer of largely

undisturbed horizontal sediment. At its western edge the plateau abruptly transitions to a down-dropped extensional region. Without this exceptional set of circumstances that led to the formation of the Grand Canyon, this 1500 m deep gorge would not exist today.

The Grand Canyon has astounded and mystified scientists for over a century. Considerable research has explored the timing of Colorado River incision and formation of the Grand Canyon, and instead of revealing a simple history of canyon formation, this extensive research has led to many, contrasting interpretations. While the evolution of the Grand Canyon currently remains unknown, it is clear that the canyon experienced a complex history of incision. I find the (U-Th)/He data persuasive evidence that a proto-Grand Canyon existed prior to integration of the modern Colorado River at ca. 6 Ma. It is possible that the majority of canyon incision occurred prior to deposition of the Muddy Creek Formation, and a more recent component of incision could have occurred post-6 Ma, cutting the Grand Canyon to its current depth. This debate, however, is by no means resolved. Future research is needed to further explore the potential for a proto-Grand Canyon and to better constrain timing of Colorado River incision.

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