Theories on the age of the Grand Canyon

Wilson Salls

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Abstract

The Grand Canyon is possibly the most iconic of the U.S.'s natural treasures, yet the nature of its origin remains a mystery. Fervent controversy plagues discussions of its age. Dozens if not hundreds of studies have been conducted since the late 19th Century on formation of the canyon and the intrinsically tied paleohydrology of the southwest, particularly the Colorado Plateau. Uplift of the Colorado Plateau by the Laramide Orogeny has unquestionably been one of the largest factors impacting Grand Canyon formation, creating the base level change necessary for such a canyon to be carved. Yet, various studies provide evidence for seemingly conflicting ages and explanations of carving.

Most fundamentally, debate originated around whether river carving can be described by antecedence, in which the river pre-dates landscape warping, or superposition, in which the newly warped landscape determines the path of the river. Later studies indicated that the Colorado River as we know it today is unlikely to have been responsible for most of the Grand Canyon's incision—rather, two or more separate drainages became connected in order to form today's hydrologic system. Currently, debate still hinges on whether the canyon is "young" or "ancient." Dating of basalts within the canyon seem to provide solid evidence that a majority of incision occurred since 5 Ma or less, yet speleothem dating and apatite grain cooling histories suggest an age as old as 70 Ma. This study summarizes relevant literature since 1875, providing a sense of the enormous variety of theories throughout that time.

Introduction and Background

At a roughly a mile deep and nearly two hundred long, the Grand Canyon dwarfs its albeit impressive surroundings. Because of this, it may be hard to imagine that this relatively diminutive landscape inevitably holds the key to the Canyon's formation. Yet the geologic history of the area is so complex that, after well over a century of devoted, intensive, and often controversial research, there is by no means consensus on how or when the Canyon formed. In attempting to dissect the history of the Grand Canyon, one must first look at the history of the Colorado River running through it; and in order to understand that, an in depth comprehension of the surrounding region and indeed the greater American Southwest is in order. Needless to say, given the scale of time and space across which climate, faulting, folding, extension, volcanism, and other tectonic forces vary, the history of the Grand Canyon is incredibly complex.

<u>Laramide Orogeny</u>

An intrinsic piece of the Grand Canyon's geologic history is the Laramide Orogeny. This mountain building event was active 30-70 Ma (Mega annum, or million years), during which time it uplifted, among other provinces, the Colorado Plateau. In order for the

Grand Canyon to have been formed, one thing is certain: there must have been a *base level change* in the regional hydrology—that is, the level to which water drains, either the ocean or an internal lake, lowered relative to the basin's headwaters. It is generally accepted that, by uplifting the Colorado Plateau in which the Grand Canyon is carved, the Laramide Orogeny caused this base level change.

Early Theories

Some of the earliest debate on the formation of the Grand Canyon revolved around whether its carving occurred before or after Laramide uplifting. John Powell, an early geologist and explorer, posited that the Colorado River was *antecedent*, meaning it already existed at the time uplift began—that its erosive power paced the uplift of the Colorado Plateau (Powell 1875). In his treatise, he states, "The river preserved its level, but the mountains were lifted up, as the saw revolves on a fixed pivot, while the log through which it cuts is moved along." Though the sediments had already been deposited, he hypothesized, the river predated uplift and warping of those sediments and more or less maintained its course during that tectonic activity. Soon after, Dutton (1882) agreed that the river was antecedent, hypothesizing that it reached its present course by the end of the Eocene Period (34 Ma).

In contrast, Emmons (1897) proposed the Colorado River was *superposed*—that it became established after tectonic uplift had occurred, only then incising the Colorado Plateau. He agreed with Powell that the Uinta Arch through which the Green River—the main tributary of the Colorado River above the Grand Canyon—cuts was uplifted at the end of the Cretaceous Period (~65 Ma), coinciding with the Laramide Orogeny. The two also agreed that lakes occupied the lowlands on both sides of the Uinta Mountains during the Tertiary Period (65-2.5 Ma), and that 8,000 feet of sediment eroded from those mountains was deposited in the lakes. Emmons argued that any river flowing through the area would have ceased to exist after being inundated beneath a lake, and furthermore filled with such a large volume of sediment. This would also seemingly preclude any river existing after the lakes receded from being influenced by the original river, much less be the same river. Though Emmons doesn't provide an explicit timeframe on the carving of the river, he implies that it must have occurred after recession of the lakes, presumably near the end of Tertiary time (as late as 3 Ma). Despite the flaw in Powell's logic, after over a century and myriad scientific inquiries, essentially the same fundamental debate remains.

Integration of Discreet Drainages

<u>Top-down</u>

Since the early explorers, a consensus was nearly reached on a third theory. Several studies suggested that the Grand Canyon did not form as the drainage of a single river as first thought, but rather as two separate drainages that later became connected. Blackwelder (1934) first noted that the Rocky Mountains were lower than their current elevation until late Tertiary time, suggesting that the region would have received less orographic rainfall. This likely would have precluded the existence of a river as big as the

Colorado. Instead, he hypothesized, the area was characterized by a series of internally drained lakes. When further uplift of the Rockies occurred during or after Pliocene time, increased precipitation would have caused these lakes to overflow into other basins southward toward the Gulf of California, eventually creating an integrated drainage. Longwell (1946) agreed that this could be the case, suggesting that volcanic flows may have diverted then-northward flowing drainage to the west in a way that resembles the modern path of the Colorado River.

<u>Bottom-up</u>
Lucchitta (1972) hypothesized that the Colorado Plateau laid low relative to the westward Basin and Range Province until between 18 and 10 Ma, when faulting occurred to uplift it. Prior to this time, drainage was to the north, and no Colorado River existed. When the Gulf of California opened around 5.4 Ma, drainage into that basin ultimately carved the lower Colorado River by headward erosion. At this time, a separate, internally drained basin existed beyond the Kaibab upwarp (McKee et al. 1967), a significant drainage divide cutting across the rim of the canyon marked by the large bend of the Colorado River just upriver of Phantom Ranch. At some point no later than 3.3 Ma, Lucchitta stated, the ancestral lower Colorado River cut headwardly into and through the Kaibab upwarp, integrating the drainage beyond into a singular through-flowing river emptying into the Gulf of California—essentially the modern Colorado River as we know it today.

<u>Groundwater Erosion</u>
Essentially, most theories of how disparate drainages became integrated fit into either the lake spillover model or headward erosion model, or some combination of the two. However, Pederson (2008) suggests that integration may not have originated from surface flow dynamics, but rather from groundwater. "Groundwater sapping" and spring discharge may have induced erosion between the two (or more) drainages, possibly being aided by a karst environment, ultimately causing the collapse of drainage divides and allowing integration.

Paleohydrology – Flow Reversal
As mentioned above, a reversal of drainage in the Grand Canyon region from northeast to southwest relating to Laramide uplift of the Colorado Plateau is generally accepted (Longwell 1946, Lucchitta 1972, Young 2008). Drainage in paleocanyons currently connected to the Colorado River is believed to have been to the northeast, as well (Potochnik 2001), and some theories suggest that an ancient river flowing through the Grand Canyon itself flowed southwest to northeast, the opposite of today (Young 2008, Flowers 2008, Wernicke 2011). The timing of this reversal is uncertain, but is constrained as no later than late Oligocene through Miocene (~23 Ma?) extension disconnected drainage to the south and west (Young 2008).

Age of the Modern Colorado River

In any event, there is strong evidence that the Colorado River did not reach its modern through-flowing state until, at earliest, 6 Ma. Muddy Creek Formation sediments in the Grand Wash Trough at the lower end of the Grand Canyon (see Figure 1), dated 13-6 Ma, contain only lacustrine and alluvial fan deposits of local origin, showing no evidence of a river as large as the modern Colorado such as the rounded pebbles found today. This concept—known as the "Muddy Creek Problem" in reference to the issue it presents with theories of an ancient Grand Canyon—constrains the modern Colorado River's age to younger than 6 Ma (Longwell 1936, Longwell 1946, Lucchitta 1972).

Evidence for a similar age of the modern Colorado River exists in river gravel deposits just below the mouth of the Grand Canyon. These gravels lie atop the Hualapai Limestone, the upper member of the Muddy Creek Formation dated at 6 Ma, and below the 4.4 Ma Sandy Point basalt (Howard and Bohannon 2001). Thus, the modern Colorado River must have initiated at some point during this timeframe.

Furthermore, the first sediments of modern Colorado River provenance originating from the Rocky Mountains appeared in the Gulf of California at 5.3 Ma (Dorsey et al. 2007). These sandstones consist of "well-rounded quartz with hematite coatings, syntaxial quartz overgrowths, and distinctive chert and metavolcanic lithic fragments," and area starkly distinguishable as deposits from a large river. They are directly underlain by mudstone with late Miocene fossils, placing another constraint on the earliest through-flowing Colorado River.

However, Wernicke (2011) argues that, while these facts rule out a modern, through-flowing Colorado River prior to 6 Ma, they do *not* preclude the carving of the Grand Canyon occurring prior to that.

Complicated evidence that could either support or refute this notion was found in the form of "rim gravels" (see Figure 1). These coarse deposits characteristic of a river environment line some highlands above the canyon and underlie a late Miocene basalt flow dated at ~7-14 Ma, and were assumed to be not much older than that flow (McKee and McKee 1972). Originally, the presence of these rim gravels at high elevation was thought to confirm the existence of the Colorado River at roughly the same level, implying that incision of the canyon had not yet occurred at that time.

In revisiting the mysterious rim gravels, Elston and Young (1991) came to a different conclusion. They noted that undated—but assumed pre-Pleistocene (>2 Ma)—gravel deposits within the lower canyon appeared similar to the rim gravels and quite possibly were of the same origin and age. If in fact contemporaneous with the rim gravels, these canyon deposits would confirm that the canyon had been cut to near its present depth by late-Miocene time. Pointing to the more arid conditions and frequent flash flooding during the Miocene and Pliocene, the authors asserted that the time period was characterized by regional fluvial aggradation and debris accumulation within canyons that would clog flow. This theory agrees with several features characteristic of flow ponding from the same time period, namely the Bidahochi Formation (see Figure 1) deposited by a large lake of the same name in the Little Colorado River Basin and the Muddy Creek Formation itself. A Grand Canyon blocked by debris during Miocene and Pliocene time could explain the presence of high-elevation rim gravels, and of the low-flow regime draining from the canyon responsible for the Muddy Creek Formation.

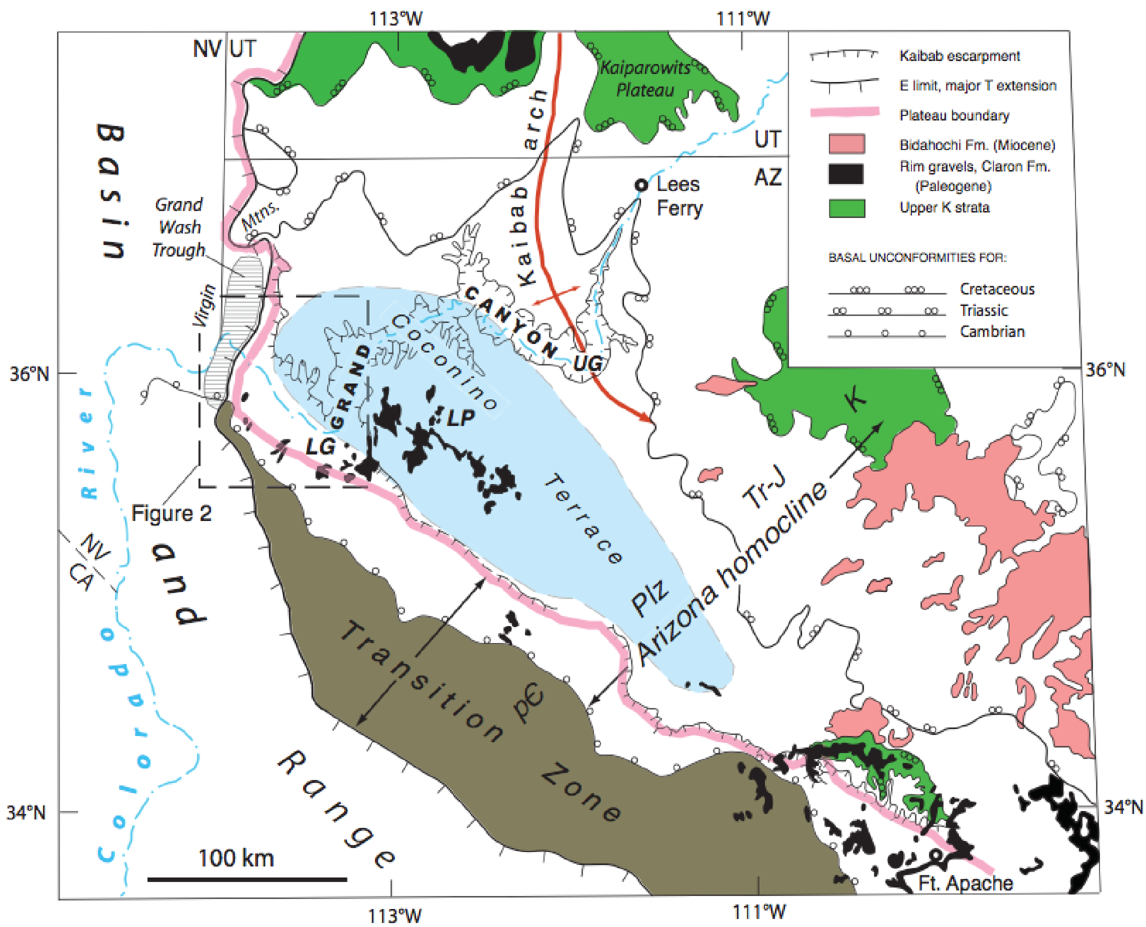


Figure 1. *From Wernicke (2011): "Tectonic map showing selected geographical and geological features discussed in text. Geology of Colorado Plateau and Transition Zone is generalized with late Cenozoic volcanic units removed. Boundary of Coconino terrace (light-blue area), based on regional elevation of the top of the Kaibab Formation at 1600 ± 200 m, is based on contour map of Hunt (1969). LG—Lower Granite Gorge of Grand Canyon; LP—Long Point area; UG—Upper Granite Gorge; p C—Proterozoic crystalline and overlying Proterozoic stratified rocks; Plz—Paleozoic strata; Tr-J—Triassic and Jurassic strata; K—Cretaceous strata." Note in particular Grand Wash Trough, Rim Gravels, and Bidahochi Formation.*

Young or Ancient Canyon?

Today, most scientists studying the Grand Canyon's history fall into one of two basic categories: those who believe the canyon was formed in the last few million years, and those who believe it is substantially older.

<u>Young Canyon</u>

By dating basalts that had flowed into the canyon at a time when it was nearly as deep as today, Hamblin (1994) estimated that most incision occurred between 6 and 1.2 Ma. A more recent study found that termination of carving was even more recent, with significant cutting still occurring through basalt flows until 723 Ka or even sooner (Karlstrom et al. 2007). Since the theory behind superposition of these flows over an already carved canyon is fairly fundamentally sound, much of the scientific community appears to put a good deal of stock in these ages (Karlstrom et al. 2008).

<u>Ancient Canyon</u>

Using U-series and $^{40}Ar/^{39}Ar$ dating, Pederson et al. (2002) found that incision rates over the past 6 Ma, if relatively constant, have not been adequate to explain all Grand Canyon carving. This suggests either that these rates were once faster, or that substantial carving occurred prior to 6 Ma.

In a study that attracted a great deal of attention from the science and popular communities alike, Polyak et al. (2008) used U-Pb dating on speleothems thought to have formed at or near the water table, inferring groundwater drop due to incision and finding that the western Grand Canyon appeared to have been slowly carved since 17 Ma (Figure 2). In contrast, they observed much faster incision rates in the eastern Grand Canyon, agreeing with the 5-6 Ma dates assumed for drainage integration. However, Karlstrom et al. (2008) derived different conclusions from the same data, considering other factors such as differential fault rate to generate estimates of only 3-4 Ma for commencement of canyon incision.

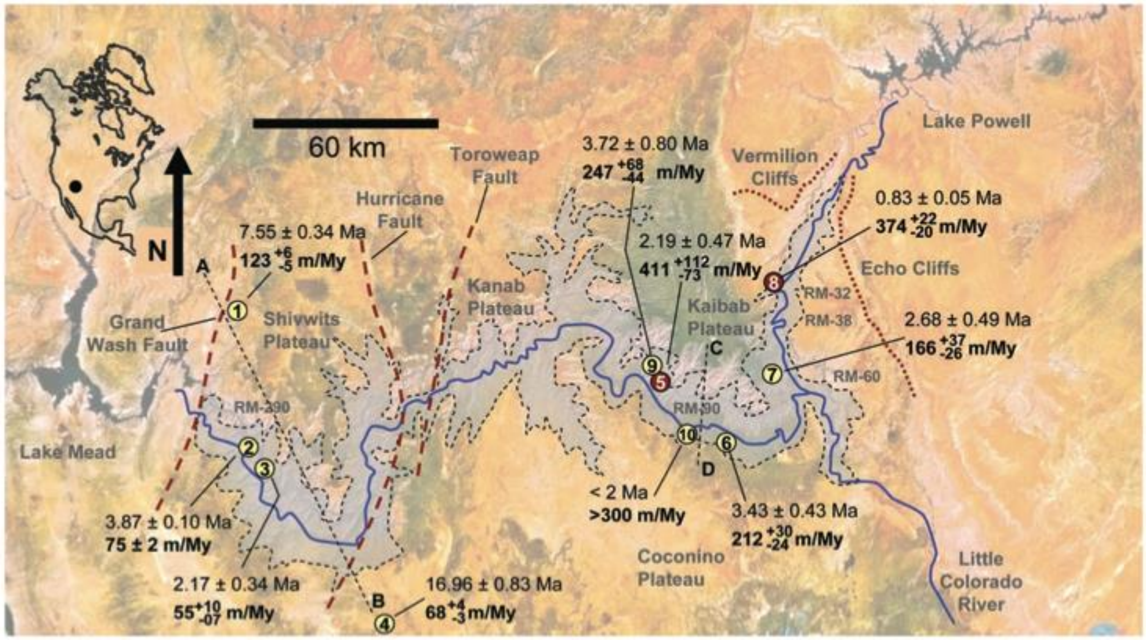
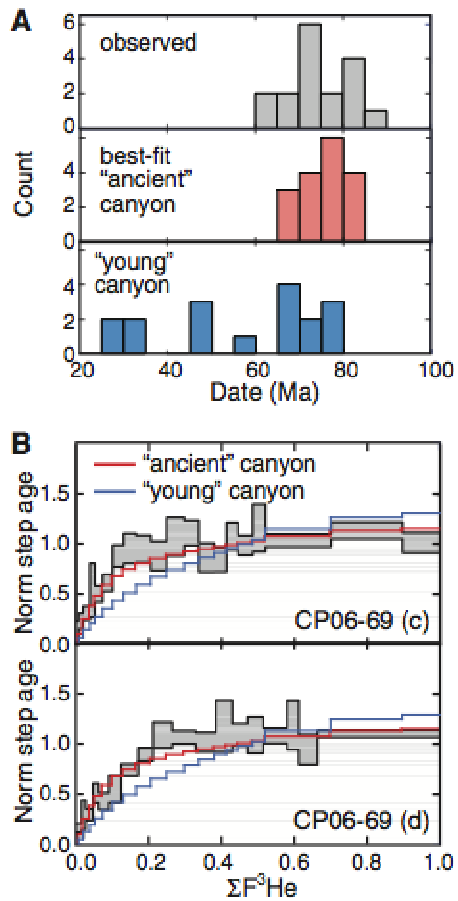


Figure 2. *From Polyak et al. 2008: "Map showing locations and U-Pb ages of cave mammillary samples and their apparent incision rates. Site numbers (in circles) are those referred to in Table 1 and the text [not included here]; those in brown circles represent surface-exposed mammillary calcite. Washout satellite image was taken from the NASA World Wind Web site, with darker regions representing higher elevations. Gray area is the canyon corridor. Two cross sections, A-B and C-D (fig. S3 [not included here]), show generalized pertinent stratigraphy. RM denotes the river-mile location. Incision rate errors assume d234U initial values = 3100‰ for sites 1, 2, 4, 6, and 9; see Fig. 3C [not included here] for expanded uncertainties for these sites."*

In another, more recent high profile study, Flowers and Farley (2012) used $^{4}He/^{3}He$ and U-Th cooling histories of apatite grains to determine when canyon incision occurred (Figure 3). They agreed with Polyak et al. (2008) that eastern carving was more recent and rapid than in the west, but—in one of the oldest models proposed—estimated that the western canyon was carved before 70 Ma. They interpret their results is in agreement with the notion of independent eastern and western carving and of flow reversal (Wernicke 2011).



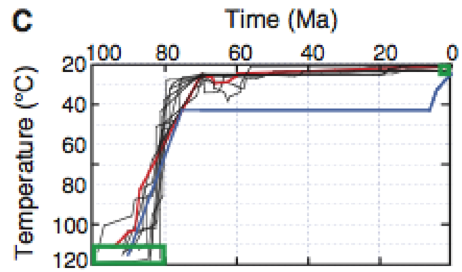


Fig. 3. Results for the western Grand Canyon. **(A)** Distribution of measured AHe dates for multiple replicates of four samples (upper panel) compared with AHe dates predicted by the best-fit thermal history from the inverse modeling suggesting an "ancient" Late Cretaceous canyon [middle histogram, using the red cooling path in (C)], and those predicted by the conventional "young" post–6 Ma canyon model [bottom histogram, using the blue path in (C)]. **(B)** Normalized ^{4}He/^{3}He step age plots for two apatites from CP06-69. Red and blue curves are profiles predicted by the best-fit and young canyon thermal histories in (C), respectively. **(C)** Thermal histories that satisfy the bulk AHe data in (A) (G = 0.3) and the two normalized step age profiles in (B) (G = 0.32). The red line denotes best-fit thermal history. The blue line shows conventional post–6 Ma incision history based on (*4*) as described in (*30*) and yields a substantially poorer fit to the AHe data and ^{4}He/^{3}He spectra in (A) and (B) (G < 0.06). Green boxes are thermal history constraints.

From Flowers and Farley (2012).

Conclusion

Despite nearly a century-and-a-half of relatively continuous addition to the body of literature and knowledge, a consensus on how and when the Grand Canyon formed eludes us. There seems to be some agreement, at least, that the Colorado River and Grand Canyon reached their modern, through-flowing state roughly 5-6 Ma. Yet, in many cases, a given theory of canyon age and formation is stated as being at odds with existing theories. It might be noted that the language used by some authors in those cases seems stronger than is due—these different theories often seem reconcilable and don't necessarily preclude each other. For example, the canyon may have some portions carved nearly 100 Ma and others within the last few million years after drainage integration. Semantics—how we define "the Grand Canyon," for instance—may play a part, as well.

In any event, given the flurry of new dating techniques in the last decade, it seems likely that new insights will arise as these are expanded upon, improved, and complemented by new innovations. Until then, one of the most well known icons of American heritage remains shrouded in mystery.

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