

TECTONIC AND LANDSCAPE EVOLUTION OF THE COLORADO PLATEAU

Chad Trexler

Abstract

The Colorado Plateau is a large, structurally intact, high elevation, tectonically enigmatic province that makes up a large part of the North American southwest. Approximately 90% of the Plateau is drained by the Colorado River and its tributaries, and evolution of the Plateau as a province is critical to understanding the formation of the Grand Canyon over the past 100 million years (Ma). Multiple, sometimes contradictory datasets have been used to argue for several versions of the history of the Colorado River Basin: that the Colorado River, more or less as we know it today, is responsible for carving the Grand Canyon over the last 6 Ma; that an ancestral, eastward-flowing 'California River' carved a portion of the canyon as long ago as ~70 Ma; or one of many variations and combinations of the two hypotheses. Though the debate is far from settled, most recent research suggests that some segments of the canyon conform to the 'old canyon' hypothesis, while others appear to be much younger; this has led to a new flurry of research attempting to provide a mechanism that could produce what is recorded in the geologic record. The dramatic geologic events recorded by the Colorado Plateau and the Grand Canyon provide context for the scale of human modifications to the Colorado River basin over the past half century.

Geologic History of the Colorado Plateau

The Colorado Plateau, located in the heart of the American Southwest, is a large (~500,000 km²) geographic province bounded by the Rocky Mountains in Colorado and Wyoming to the east and north, the Basin & Range in Utah and Nevada to the west, and the Mogollon Rim in Arizona and Rio Grande Rift in New Mexico to the south [FIG]. The Colorado Plateau is home to more than 25 National Park units, including Grand Canyon National Park and others that protect and regulate much of the Colorado River's route across the Plateau. The Colorado River and its tributaries, including the Green, San Juan, and Little Colorado, drain approximately 90% of the Colorado Plateau [Kiver & Harris, 1999]. The provinces that delineate the plateau margins are defined by the tectonic processes that created them, and are often significantly faulted and folded. The Plateau itself is 1000 m or more above sea level, where the Paleozoic sedimentary rocks it is composed of were deposited. Despite this dramatic tectonic context, the Colorado Plateau has largely remained internally intact, and despite its significant uplift lacks the significant

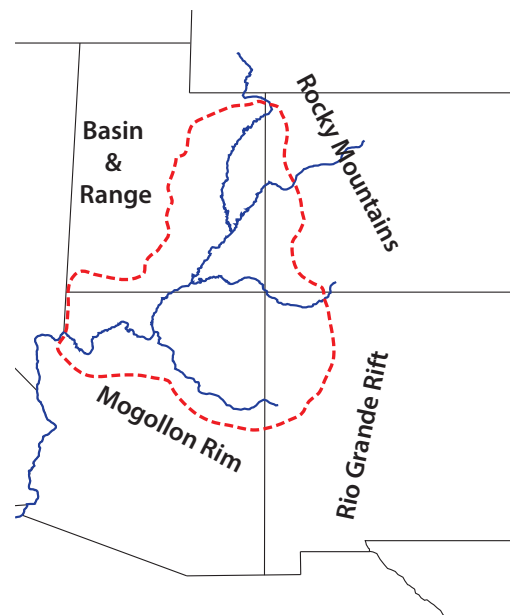


Figure 1. Map showing the extent of the Colorado Plateau (red dashed line), and the tectonic provinces that define its borders. State boundaries in black; Colorado River and major tributaries in blue.

deformation of the regions surrounding it. The tectonic history of the Colorado Plateau has driven the evolution of the Colorado River over the past 70 million years, including the incision of the canyons and landscapes we have today.

Stratigraphy

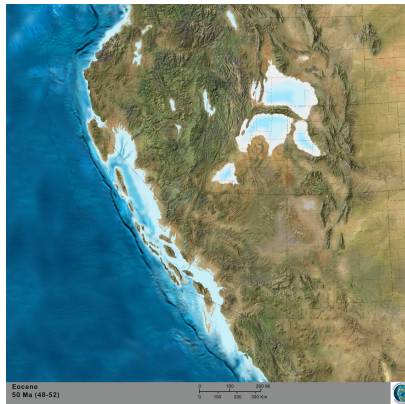
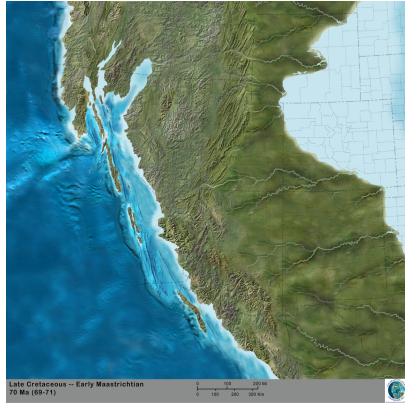
Though several significant unconformities -- gaps in the geologic record -- exist, the stratigraphy of the Colorado Plateau records the history of the Colorado Plateau beginning in the Proterozoic era (the Vishnu Schist, at the bottom of the Grand Canyon, ~1.8 billion years old) and continues through the Paleozoic, the Mesozoic and into the early Cenozoic era (the Claron Formation, Bryce Canyon National Park, ~60 million years old). Most of the sedimentary rocks deposited during this span of time (limestones, sandstones, and shales) are of a shallow marine or coastal terrestrial origin. For much of the Paleozoic, these were likely deposited on passive continental margin along western North America similar to the modern eastern seaboard.

Tectonics

At the beginning of the Mesozoic era (~265 million years ago), the breakup of the Pangea supercontinent began, separating eastern North America from northwestern Africa and ultimately leading to the initiation of a subduction zone along western North America. During the early Cretaceous period (~140 Ma), the Colorado Plateau was once again in a shallow marine/coastal terrestrial depositional setting, this time in the Cretaceous Interior Seaway (figure 2).

At around ~70 million years ago (Ma), subduction of the downgoing Farallon plate beneath western North America shallowed dramatically, causing the deformation belt to migrate eastward [Coney & Reynolds, 1977]. Known as the Laramide orogeny, this event caused widespread uplift, faulting, and folding throughout what is now the interior west of North America, and formed the modern Rocky Mountains. Though the Colorado Plateau is contained within the region deformed by the Laramide, it remained largely intact.

At ~40 Ma, the subduction angle of the Farallon slab is thought to have steepened again, causing the compressional deformation responsible for thrust faulting and folding to migrate westward toward the North American coast and bringing an end to Laramide deformation [Coney & Reynolds, 1977]. As a result of the westward retreat of compression, regions of extensional tectonics began to form surrounding the Plateau. In the Rio Grande Rift, a narrow region of modest (10-50% of its initial width) extension southeast of the Plateau, extension initiated at ~32 Ma and continues today [Aldrich et al., 1986]. The Basin and Range province, which borders the Plateau to the west and southwest, is over 100 km wide and exhibits much more significant extension (over 100% of its initial width) than the Rio Grande Rift, and initiated later, perhaps around 17 Ma [Hamilton, 1987]. Though seemingly surrounded by extensional regions, the Colorado Plateau once again escaped significant internal deformation. The Colorado River exits the western end of the Grand Canyon at the Grand Wash Cliffs, which represents the eastern margin of Basin & Range extension and the western limit of the Colorado Plateau [Faulds et al., 2005].



Uplift of the Colorado Plateau

The mechanism for the uplift of the Colorado Plateau remains enigmatic. Proposed mechanisms for uplift include isostatic response to Laramide-age compression and crustal thickening; lithospheric attenuation during Laramide low angle subduction; increased heat flux due to post-Laramide extension and crustal thinning; and more buoyant crust due to mantle upwelling beneath the Plateau. Some mechanisms are mutually exclusive (for example, isostatic response to thickening and heat flux due to thinning), while others are potentially complementary [Flowers, 2010].

One reason that this problem is difficult to solve is that there is currently no reliable method for deciphering the paleoelevation of continents, and constraining the elevation history of the plateau is critical in determining the uplift mechanism, as many mechanisms rely on processes with specific temporal requirements. Methods as diverse as using paleobotany as a proxy for elevation, and even basalt flow vesicle size as a proxy for atmospheric pressure and thus elevation, have been attempted; however, these results are widely debated and often contradictory. Additionally, it is possible (even likely) that the Plateau did not uplift uniformly either spatially or temporally, which has the potential to confound paleoelevation results from different locations on the Plateau.

The Colorado River Through Time

The timing of incision of the Grand Canyon is also subject to an ongoing and often lively debate. As with attempts to understand of the Colorado Plateau, a variety of techniques have been applied to constrain the timing of incision, which has led to diverse, often conflicting results about the evolution of the Grand Canyon. The debate has largely been divided into two camps – one supporting a young canyon, formed in its entirety over the past 6 Ma; the other advocating a much older canyon, existing in some form or another for the past 60 Ma or more.

The Modern River

It is widely agreed upon that the Colorado River has

Figure 2. Paleogeographic maps of the Colorado Plateau. From top to bottom: 80 Ma, 50 Ma; 15 Ma; and present day. Note the uplift of the Rocky Mountains during the Laramide (panel 2) and the opening of the Gulf of California between 15 Ma and present day. From Blakey (2013)

existed in its current state for at least the ~5.3 Ma. Sediment traceable to the Colorado River first appears in the Grand Wash Trough after 6 Ma, and appears in the Salton trough at approximately ~5.3 Ma. Prior to this time, these basins appear to only have received locally derived sediment. Additionally, volume estimates for the amount of sediment filling the extensional basin in the Gulf of California ($2.2\text{-}3.4 \times 10^5 \text{ km}^3$) are roughly equivalent to the volume of rock that was likely eroded from the Colorado River catchment over the past 5-6 Ma ($2.5\text{-}3.1 \times 10^5 \text{ km}^3$; projected backwards in time using early 20th century discharge rates) [Dorsey, 2010]. The modern Colorado River has not established an equilibrium profile through the Grand Canyon – gradients are higher within the canyon than either up or downstream [Cook et al., 2009] – lending credence to the idea that the river connected to its modern base level recently enough that it has not had sufficient time to equilibrate. It has been argued that integration of the modern Colorado River led to rapid incision of the entire Grand Canyon over the last 6 Ma [e.g., Spencer & Pearthree, 2001; Sears, 2013], and late Quaternary incision rates are high enough (as high as 60-180 mm/y) to carve the Canyon; however, it is unclear whether it is reasonable to project these rates back to 6 Ma [Wernicke, 2011].

The Pre-5.3 Ma River

Though its timing is debated, evidence from multiple sources suggests that the direction of flow of the Colorado River reversed, from northeastward to southwestward, some time between ~60 Ma and ~15 Ma. Proposed mechanisms for the reversal in flow direction of this proto-Colorado River (sometimes dubbed the ‘California River’) include Laramide uplift of the distal end of the drainage [Wernicke, 2011] Basin & Range-related extension and dissection resulting in lower elevations in the southwest [Young, 2011]. Some models of the drainage evolution also include an intermediate ‘Arizona River,’ which replaces the California River when the drainage direction reverses, and is interrupted by the Basin and Range extension that ultimately connects the Colorado River to the Gulf of California [Wernicke, 2011]. The size of these paleorivers is hotly debated, and no consensus yet exists.

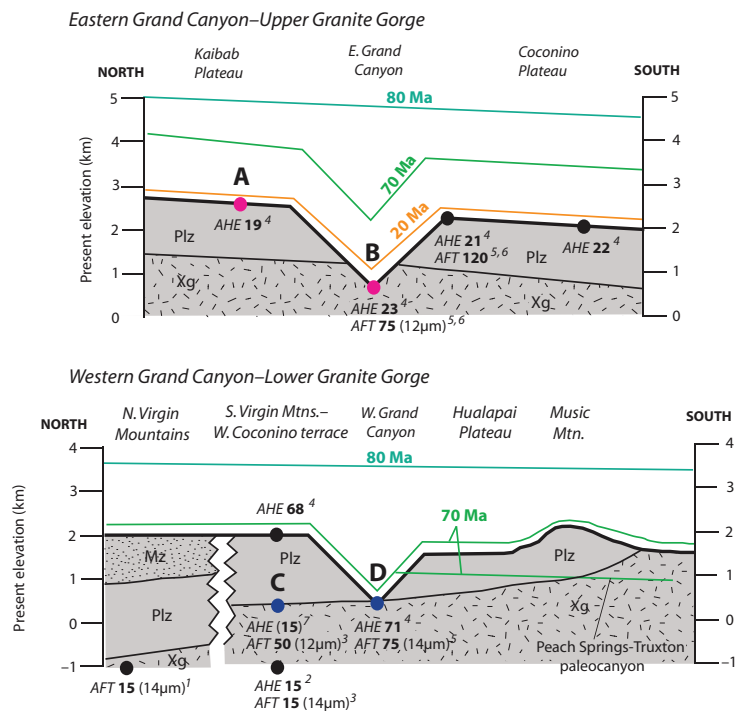


Figure 3. Schematic cross sections across the Grand Canyon, showing paleoelevations (green lines) based on thermochronometric data. From Wernicke (2011).

The Proto-Grand Canyon

Recent studies of rock exhumation rates within the Grand Canyon suggest that portions of the Grand Canyon have existed in some form or another since at least ~70 Ma [Flowers et al., 2008; Wernicke, 2011]. U-Th/He closure temperatures in apatite grains give similar ages for both the bottom of the modern Canyon and the Kaibab plateau, suggesting that both have similar thermal histories most easily explained by an early Tertiary proto-Canyon [Farley, 2000]. Work by Wernicke (2011) takes this result further by using several thermochronometric methods to constrain the location of the paleotopography through time at multiple locations along the Canyon, convincingly arguing that a canyon of some form existed by ~70 Ma (figure 3).

Although some segments of the modern canyon appear to have existed since ~70 Ma, other portions of the Grand Canyon have been dated using the same techniques as forming around 5-6 Ma [Karlstrom et al., 2014]. The authors of this study argue that this suggests the modern Grand Canyon formed by connecting together several preexisting canyon segments at ~5-6 Ma.

Ongoing Problems & Continuing Debate

Though there is an increasing consensus that there is some truth to the stories originally pitched by both the young canyon and old canyon advocates, many questions remain to be answered. These include the size of the river as it evolved over the past 70 m.y., with some studies suggesting a small river (primarily due to the lack of evidence for a large river) and other suggesting a more substantial river system, with a drainage area as large or larger than the modern Colorado. Additionally, the location of the river through time is difficult to constrain, particularly in the models arguing for 6 Ma canyon formation. If, as Karlstrom et al. [2014] argue, the modern Colorado formed by connecting several discrete preexisting segments of canyon, then there should be evidence outside the canyon for the rivers that existed pre-6 Ma. The authors argue convincingly

the modern canyon could not have been throughgoing and attempt to provide routes for their paleorivers that explain the evolution seen; however, these paleorivers are not well documented outside the canyon.

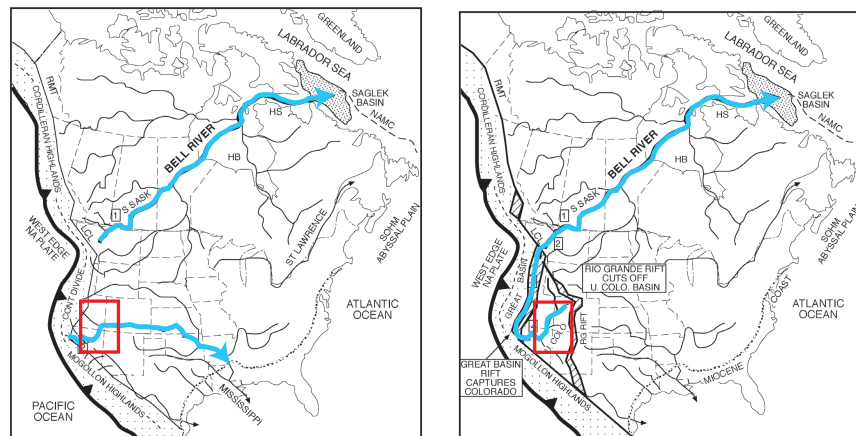


Figure 4. Paleogeography of N. America in the Paleocene (left) and Miocene (right), highlighting the connection between a proto-Colorado River and the Canadian Bell River (blue lines) draining northward into the Labrador Sea. Colorado Plateau identified by red box. Modified from Sears (2013).

One of the most significant obstacles in the debate over the size, location, and flow direction of the Colorado River over the past 70 Ma is the issue of sediment flux. As discussed above, the flux of sediment through the Colorado River drainage over the past 6 Ma is well constrained and consistent with the amount of sediment deposited in the Gulf of California and Salton Trough during the same time interval [Dorsey, 2010]. However, the Colorado Plateau has seen erosion of much larger volumes of sediment than can be accounted for over the past 6 Ma. If major drainages such as the proposed Arizona River existed, then it is expected that (much like the modern Colorado) they would have carried substantial amounts of sediment from the central Plateau and deposited them at the toe of the river. Multiple studies have argued that the Arizona River or its equivalent drained into a terminal basin for at least some period of time [Faulds et al., 2008; Wernicke, 2011]; the extensive lacustrine deposits expected in a terminal basin do exist, but only extend back to the middle Miocene (~15 Ma) [Faulds et al., 2008].

A recent publication has proposed a creative solution to this problem: the Arizona/proto-Colorado River flowed westward across the Colorado Plateau, turned north in the Lake Mead region, and traveled northeastward along the margin of the Great Basin to connect to the Miocene ‘Bell River’ of Canada, which drained northeast into the Labrador Sea [Sears, 2013]. This drainage would ultimately have been segmented and dammed by continuing Basin and Range extension, leading to the formation of lacustrine deposits in the Grand Wash region until ~6 Ma, when the Colorado drainage was rerouted to the Gulf of California. Though seemingly far-fetched, this solution ties together multiple different proposed elements of the ancestral Colorado drainage, and is consistent with flow directions and timing of river segments [e.g., Wernicke, 2011]. Though it has yet to be substantiated, it provides a new hypothesis to be tested in the ongoing saga of the evolving Colorado River.

Conclusions: A Geologic Context for Human Impact on the Colorado River

The history of the Colorado Plateau and the evolution of the Colorado River Basin highlight the immense scale of changes that can occur over relatively short periods of geologic time.

For all its vastness, the modern Colorado River is likely a short-lived feature, subject to dramatic and relatively rapid changes. This serves to put the scale of human modifications to the Colorado River over the past 50 years into perspective. While the changes we’ve

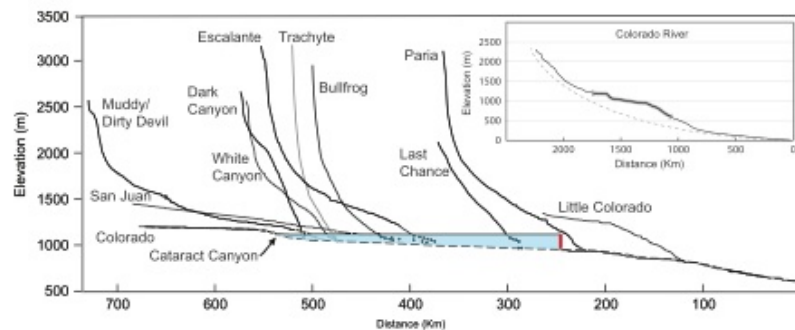


Figure 5. Elevation profiles of the Colorado River and major tributaries in the middle elevations of the drainage. Glen Canyon dam denoted in red, with the extent of Lake Powell shown in blue. Inset: Full Colorado River profile, with extent of main figure in bold. Modified from Cook et al. (2009).

made in the past half century may not be long-lived features in geologic time, they also have occurred on a scale comparable to other significant changes in the drainage in the past 5-10 million years [Cook et al., 2009]. By creating Lake Mead and Lake Powell, the artificial base levels and sediment traps we have imposed within the Colorado River Basin are potentially as significant to the current drainage as the capture of the Colorado River by the Gulf of California at 5.3 Ma, or the dissection of the northward-draining Arizona River by Basin and Range extension at 15 Ma. It is impossible to know how long in geologic time the results of our modifications will be apparent. Even so, it is important to recognize the scale of our modifications to the modern drainage and the amount of time required for similar changes by geologic processes.

References

- Bennett, S., 2012, The tectonic evolution of the Colorado Plateau and Grand Canyon region: *Ecogeomorphology of the Grand Canyon 2012*.
- Cook, K. L., Whipple, K. X., Heimsath, A. M., and Hanks, T. C., 2009, Rapid incision of the Colorado River in Glen Canyon - insights from channel profiles, local incision rates, and modeling of lithologic controls: *Earth Surface Processes and Landforms*, p. n/a-n/a.
- Darling, A. L., Karlstrom, K. E., Granger, D. E., Aslan, A., Kirby, E., Ouimet, W. B., Lazear, G. D., Coblenz, D. D., and Cole, R. D., 2012, New incision rates along the Colorado River system based on cosmogenic burial dating of terraces: Implications for regional controls on Quaternary incision: *Geosphere*, v. 8, no. 5, p. 1020-1041.
- Dickinson, W. R., 2012, Rejection of the lake spillover model for initial incision of the Grand Canyon, and discussion of alternatives: *Geosphere*.
- Dorsey, R. J., 2010, Sedimentation and crustal recycling along an active oblique-rift margin: Salton Trough and northern Gulf of California: *Geology*, v. 38, no. 5, p. 443-446.
- Faulds, J. E., Howard, K. A., and Duebendorfer, E. M., 2008, Cenozoic evolution of the abrupt Colorado Plateau-Basin and Range boundary, northwest Arizona: A tale of three basins, immense lacustrine-evaporite deposits, and the nascent Colorado River: *Geological Society of America Field Guide 11*, p. 119-151
- Faulds, J. E., Wallace, M. A., Gonzalez, L. A., and Heizler, M. T., 2000, Depositional Environment and Paleogeographic Implications of the Late Miocene Hualapai Limestone, Northwestern Arizona and Southern Nevada.
- Flowers, R. M., 2010, The enigmatic rise of the Colorado Plateau: *Geology*, v. 38, no. 7, p. 671-672.
- Flowers, R. M., and Farley, K. A., 2012, Apatite $4\text{He}/3\text{He}$ and $(\text{U-Th})/\text{He}$ evidence for an ancient Grand Canyon: *Science*, v. 338, no. 6114, p. 1616-1619.
- Flowers, R. M., Shuster, D. L., Wernicke, B. P., and Farley, K. A., 2007, Radiation damage control on apatite $(\text{U-Th})/\text{He}$ dates from the Grand Canyon region, Colorado Plateau: *Geology*, v. 35, no. 5, p. 447.
- Flowers, R. M., Wernicke, B. P., and Farley, K. A., 2008, Unroofing, incision, and uplift history of the southwestern Colorado Plateau from apatite $(\text{U-Th})/\text{He}$

- thermochronometry: *Geological Society of America Bulletin*, v. 120, no. 5-6, p. 571-587.
- Hamilton, W., 1987, Crustal extension in the Basin and Range Province, southwestern United States: *Geological Society, London, Special Publications*, v. 28, p. 155-176.
- Hill, C. A., and Ranney, W. D., 2008, A proposed Laramide proto-Grand Canyon: *Geomorphology*, v. 102, no. 3-4, p. 482-495.
- Huntington, K. W., Wernicke, B. P., and Eiler, J. M., 2010, Influence of climate change and uplift on Colorado Plateau paleotemperatures from carbonate clumped isotope thermometry: *Tectonics*, v. 29, no. 3.
- Ingersoll, R. V., Grove, M., Jacobson, C. E., Kimbrough, D. L., and Hoyt, J. F., 2013, Detrital zircons indicate no drainage link between southern California rivers and the Colorado Plateau from mid-Cretaceous through Pliocene: *Geology*.
- Karlstrom, K. E., Beard, L. S., House, K., Young, R. A., Aslan, A., Billingsley, G., and Pederson, J., 2012, Introduction: CRevolution 2: Origin and Evolution of the Colorado River System II: *Geosphere*, v. 8, no. 6, p. 1170-1176.
- Karlstrom, K. E., Lee, J. P., Kelley, S. A., Crow, R. S., Crossey, L. J., Young, R. A., Lazear, G., Beard, L. S., Ricketts, J. W., Fox, M., and Shuster, D. L., 2014, Formation of the Grand Canyon 5 to 6 million years ago through integration of older palaeocanyons: *Nature Geoscience*, v. 7, no. 3, p. 239-244.
- Kiver, E. P., and Harris, D. V., 1999, *Geology of U.S. Parklands*, 5th ed., Wiley, 395 p.:
- Sears, J. W., 2013, Late Oligocene–early Miocene Grand Canyon: A Canadian connection?: *GSA Today*, p. 4-10.
- Spencer, J. E., and Pearthree, P. A., 2001, Headward erosion versus closed-basin spillover as alternative causes of Neogene capture of the ancestral Colorado River by the Gulf of California, Grand Canyon, AZ, Grand Canyon Association, *Colorado River Origin and Evolution*.
- Wernicke, B., 2011, The California River and its role in carving Grand Canyon: *Geological Society of America Bulletin*, v. 123, no. 7-8, p. 1288-1316.