

How Rivers Get Across Mountains: Transverse Drainages

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Although mountains represent a barrier to the flow of liquid water across our planet and an Earth of impenetrable mountains would have produced a very different geography, many rivers do cross mountain ranges. These transverse drainages cross mountains through one of four general mechanisms: *antecedence*—the river maintains its course during mountain building (orogeny); *superimposition*—a river erodes across buried bedrock atop erodible sediment or sedimentary rock, providing a route across what later becomes an exhumed mountain range; *piracy or capture*—where a steeper gradient path captures a lower gradient drainage across a low relief interfluvium; and *overflow*—a basin fills with sediment and water, ultimately breaching the lowest sill to create a new river. This article reviews research that aids in identifying the mechanism responsible for a transverse drainage, notes a major misconception about the power of headward eroding streams that has dogged scholarship, and examines the transverse drainage at the Grand Canyon in Arizona. *Key Words*: *antecedence, overflow, piracy, superimposition, transverse drainage.*

尽管山岳对于横越地球的水流带来阻碍，且若地球充满无法穿越的山岳的话将会产生非常不同的地理，但诸多河流的确横跨了山脉。这些横断水系透过四个普遍的机制之一穿越山脉：前行——河流在山岳形成时（造山运动）维持其河道；叠加——河流侵蚀越过在可侵蚀的沉积物或沉积岩上被深埋的基岩，提供越过日后成为崛起山脉之路径；袭夺或捕集——其中一个更为陡峭的倾斜路径捕集了横越低地势起伏的河间地块的较低倾斜度之水系；以及溢流——一个充满沉积与水的流域最终破坏了最低的岩床，创造了新的河流。本文回顾协助指认造成横断水系的机制之研究，指明长期纠缠学术界的有关向源侵蚀河流力量的重大错误概念，并检视亚利桑那州大峡谷中的横断水系。关键词：前行，溢流，袭夺，叠加，横断水系。

Aunque las montañas representan una barrera contra el flujo del agua líquida a través del planeta y una Tierra de montañas impenetrables habría producido una geografía muy diferente, la verdad es que muchos ríos se abren camino a través de cadenas montañosas. Estos sistemas de avenamiento transversal logran cruzar las montañas por medio de uno de cuatro mecanismos generales: *antecedencia*—el río conserva su curso durante el proceso de construcción de las montañas (orogenia); *superposición*—un río erosiona al través de la roca madre sepultada sobre un sedimento erosionable o de roca sedimentaria, generando una ruta a través de lo que luego se convertirá en una cadena montañosa exhumada; *piratería* o *captura*—donde una trayectoria de gradiente más pronunciado captura un gradiente de avenamiento más bajo a través de un interfluvio de bajo relieve; y *desborde*—una cuenca se llena con sedimento y agua, rompiendo en últimas la estructura inferior para crear un nuevo río. Este artículo revisa la investigación que ayuda a identificar el mecanismo responsable de un avenamiento transversal, hace notar una concepción equivocada acerca del poder erosivo contracorriente que ha sido persistente en la erudición, y examina el avenamiento transversal del Gran Cañón en Arizona. *Palabras clave*: *antecedencia, desborde, piratería, superposición, avenamiento transversal.*

A new or young hydrogeomorphic landscape is commonly perceived to have a few likely origins. The new or young landscape is either exposed by deglaciation, altered by volcanism or mass wasting processes, or has previously been hydrologically isolated by active tectonics. In North

America the characteristics of young landscapes often mark the boundaries between major physiographic regions (e.g., Powell 1896; Fenneman 1931, 1938; Hunt 1967; Graf 1987). Often overlooked in this general physiographic perspective of landscapes are a suite of processes that result in new

hydrogeomorphic systems via transverse drainage development (Douglass and Schmeckle 2007). Transverse drainages are river pathways counterintuitive to the perception that rivers commonly originate in mountain ranges rather than pass completely through them. Ultimately, a transverse drainage connects two or more landscapes by cutting through a mountain range. This article explores specific processes that result in transverse drainages; we then review modeling and criteria to identify the process. Finally, we conclude with a case study highlighting the most visited transverse drainage in the world, the Colorado River at Grand Canyon.

Transverse Drainage Mechanisms

Prior scholarship includes four mechanisms to explain the origin of transverse drainages: antecedence, superimposition, overflow, and piracy or capture (Figure 1). These mechanisms are evoked in isolation (e.g., Stokes and Mather 2003; House et al. 2005) or in combination (e.g., Harvey and Wells 1987; Alvarez 1999; Mayer et al. 2003).

The *antecedence* hypothesis requires that a river existed prior to orogeny that then incises through uplifting mountains. Thus, antecedent streams commonly occur in regions of active tectonism and volcanism. Evidence must exist indicating that the river predates the mountain range. Examples of antecedence include the Columbia River gorge through the Cascade Range (Douglass et al. 2009), drainages exiting the Himalaya (e.g., Wager 1937; Searle and Treloar 1993; Lang and Huntington 2014), drainages of the Umbria–Marchean Apennines (Alvarez 1999), streams exiting the High Atlas Mountains of Morocco (Stokes et al. 2008), rivers of northern Peloponnesus in Greece (Zelididis 2000), the Hsiukuluan River of eastern Taiwan (Lundberg and Dorsey 1990), and the Santa Ana River in Southern California (Dudley 1936).

The *superimposition* hypothesis posits that mountainous terrain was once buried by unconsolidated or easily erodible material, with the river flowing atop this cover mass. With an increase in stream power, the river first erodes the cover mass and then exhumes the underlying bedrock. Geomorphologists support superimposition when a river crosses a resistant rock layer multiple times or a river flows long distances against the slope of an exhumed bedrock plain or has barbed drainages. The Susquehanna River and others in the northeastern

United States (e.g., W. M. Davis 1909; Johnson 1931a, 1931b), the drainages of the Umbria–Marchean Apennines (Alvarez 1999; Mayer et al. 2003), the Aguas and Feos Rivers of southeastern Spain (Harvey and Wells 1987), streams of the Zagros Mountains of Iran (Oberlander 1965), and the Colorado River across the Marble Platform in Arizona (Babenroth and Strahler 1945) exemplify superimposed drainages.

The *overflow* (or spillover) hypothesis posits that a basin fills with sediment and water. When the water and sediment reach the lowest elevation interfluvium, an overflow occurs into an adjacent region. The overflow model has been applied to the lower Colorado River, downstream of the Grand Canyon (House et al. 2005; House, Pearthree, and Perkins 2008); the Mojave River (Meek 1989; Reheis, Miller, and Redwine 2007; Reheis and Redwine 2008); the Salt River of Arizona (Larson et al. 2010; Larson et al. 2014); the Ebro River in Spain (Arche, Evans, and Clavell 2010); the Hutuo River in China (Ren et al. 2014); the Kashmir Valley (Ganjoo 2014); Rio Mimbres and Rio Grande Rivers of the Rio Grande Rift (Mack, Love, and Seager 1997); the Amargosa River (Morrison 1991; Menges and Anderson 2005); and elsewhere.

The *stream piracy* (capture) hypothesis requires a stream to divert its course to flow down a new drainage path that is steeper. Douglass and Schmeckle (2007) modeled four possible processes that result in piracy (capture): headward erosion, channel aggradation, sapping, and lateral erosion. Locations where piracy has recently been discussed include the Rio Almanzora crossing the Sierra Almagro in Spain (Stokes and Mather 2003), in California's coastal range (Garcia and Stokes 2003; Garcia 2006), the Cahabón River in Guatemala (Brocard et al. 2012), the Osip-cheon River in Korea (Lee et al. 2011), and the Apennines of central Italy (Mayer et al. 2003).

Results of Investigating Biases

Some transverse drainage scholarship contains bias favoring the idea that headward erosion of streams commonly results in stream piracy or capture. In reality, headward erosion is a slow process, even in the softest sediments (Douglass and Schmeckle 2007). Meek (2009) argued that piracy (via headward erosion) is likely where mass movement processes are active on the topographic barrier separating rivers, similar to explanations of the San Lorenzo River and Pancho Creek, California (Garcia and Stokes 2003).

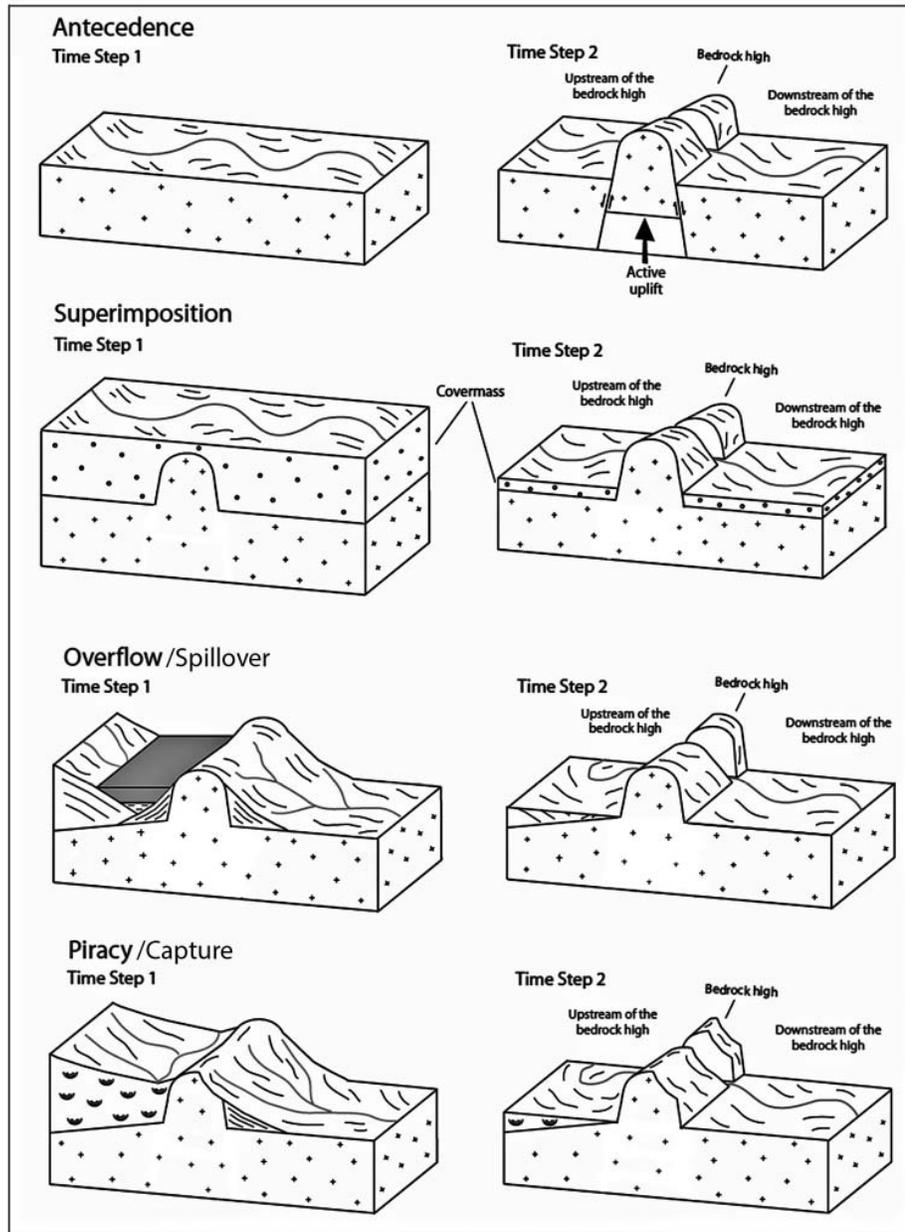


Figure 1. Transverse drainage mechanisms of antecedence, superimposition, overflow and piracy (capture). Modified from Douglass et al. (2009); used with permission.

Both modeling (Douglass and Schmeckle 2007) and field observations (e.g., Figure 2) reveal that piracy can occur through channel aggradation, sapping undermining the interfluvium, or stream lateral erosion removing the topographic barrier—referred to as drainage diversion (Bishop 1995). The lower gradient stream commonly ends up diverting from the top down, into the steeper gradient channel and forming an elbow of capture.

Because piracy or capture via headward erosion has become the prevailing conceptual view for many, Meek (2002) investigated the intellectual upbringing of earth scientists through the treatment of transverse drainage processes in textbooks. The only textbook found discussing overflow was W. M. Davis and Snyder (1898). In 2002, of the nine randomly sampled introductory physical geology texts, eight presented piracy and five antecedence and superimposition. Of the

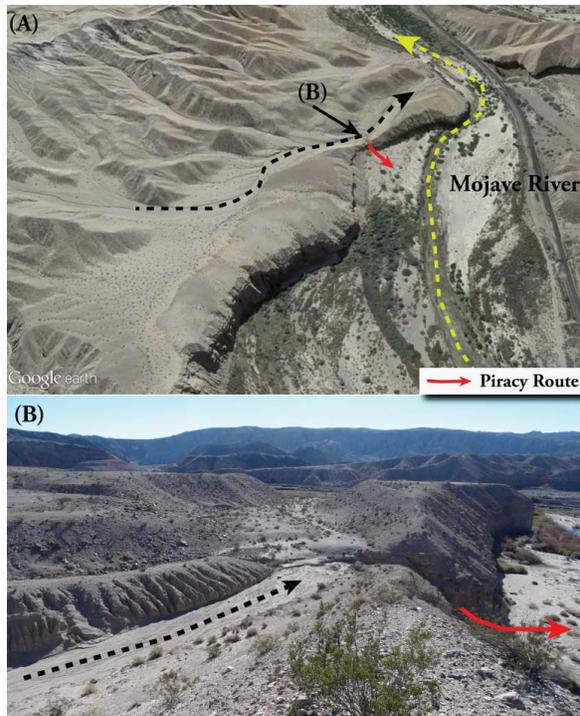


Figure 2. Piracy or capture via drainage diversion (Bishop 1995) occurring near the Mojave River, California, as a result of lateral stream erosion removing the topographic barrier between the streams, 35.03592° N, and 116.37257° W. (A) Oblique Google Earth view of a pirated drainage in development. (B) A photograph at the piracy apex taken by Norman Meek in winter of 2015. (Color figure available online.)

nine introductory physical geography textbooks sampled, only three discussed piracy, antecedence, and superposition. All five geomorphology texts sampled presented piracy, and only four discussed antecedence and superposition. In addition, several textbooks confuse headward erosion with knickpoint recession, leading to the mistaken belief that stream piracy can be caused by vigorous growth of a “precocious gully”—an issue of muddled thinking recognized more than forty-five years ago (Hunt 1969). Thus, it is not surprising that bias is engrained. We agree with Hunt (1969) and Bishop (1995) that piracy is overutilized in academia and comparatively rare in reality.

Criteria to Identify Transverse Drainages and Reduce Bias

Following physical modeling experiments (Douglass and Schmeckle 2007) and field investigations across the southwestern United States, Douglass et al.

(2009) developed a “decision tree” of criteria to determine the mechanism responsible for a transverse drainage (Figure 3). To show its applicability, we provide an example, the Salt River of south central Arizona. The Salt River forms a bedrock canyon that connects the Tonto basin with the lower Verde River basin and Higley and Paradise basins near Phoenix, Arizona.

Figure 3 plots evidence from the Salt River where Douglass et al. (2009) determined that overflow was likely responsible for this transverse drainage. The process begins by investigating whether the drainage is older or younger than the mountain(s) it crosses. Recent studies (Larson et al. 2010; Larson et al. 2014) and a recent dissertation (Larson 2013) revealed that the Salt River significantly postdates the age of the Mazatzal Mountains the river now crosses. Larson et al. (2010) also identified a new, topographically higher river terrace that contains sedimentary evidence indicating a shifting provenance of the Salt River through time, from local to more distant sources. This shifting provenance represents establishment of the transverse drainage and adjustment of the upstream Tonto basin in response to integration. Earlier, Laney and Hahn (1986) recorded subsurface evidence in deposits under eastern metropolitan Phoenix for the sudden arrival of ancestral Salt River gravels. Larson et al. (2010) concluded that this terrace, the existence of a Pliocene lake in the Tonto basin (Peirce 1984), and the striking similarities to the sedimentologic sequences along the lower Colorado (House et al. 2005; House, Pearthree, and Perkins 2008) support an overflow origin. Despite this evidence, headward erosion was again used to explain the bedrock canyon passages in the Gila River drainage—of which the Salt River is a tributary.

Bedrock canyon passages (BCP) form where headward erosion from a lowstanding basin breaches the bedrock divide forming a barrier separating the basin from a highstanding basin, commonly leading to sediment aggradation on the lowstanding basin floor and to dissection of the highstanding basin floor. A bedrock canyon passage might also logically arise from erosion downward into bedrock from the level of a sediment ramp transiting the barrier range. (Dickinson 2015, 7)

Unfortunately, the discussion of the Salt River in Dickinson’s manuscript did not reference the most recent work or the physical models of Douglass and Schmeckle (2007). Discussions on the terraces along the Salt did not include the new, higher terrace and

Criteria to distinguish between the four transverse drainage mechanisms

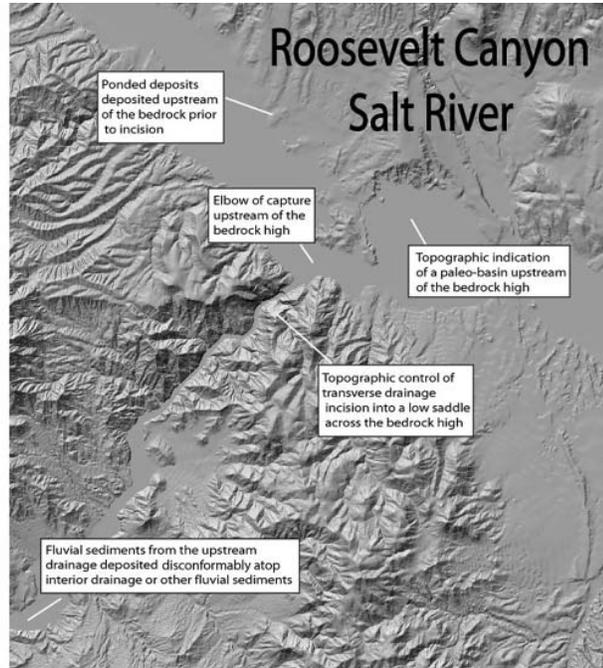
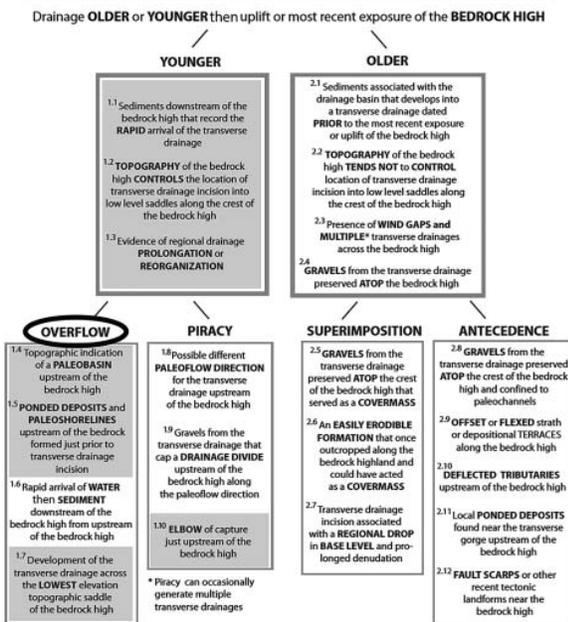


Figure 3. Using the criteria to determine the mechanism responsible for Roosevelt Canyon on the Salt River, Arizona.

did not discuss the criteria-based decision tree or conclusions of Douglass et al. (2009). Out of the three transverse mechanisms suggested by Dickinson in the Gila River drainage, two involved headward erosion of some form (bedrock canyon passages and alluviated gaps), and the last (spillover ramp passages) was discredited by using an argument frequently used to reject overflow:

But no instances of that behavior have been detected within the Gila River drainage. Nor is there any expectation in the arid to semiarid environment of the Gila River that the surface of any lake occupying a basin of interior drainage ever rose to the level required to overtop a barrier range and initiate the erosion of a bedrock canyon by an outlet stream. (Dickinson 2015, 7)

The misconception invoked is that present-day elevation of lacustrine sediments in a former lake basin indicates the elevation of a paleo-lake surface. In the case of the Salt River, it is likely that adjustment to integration and subsequent erosion of prior lake sediments in the Tonto basin has been ongoing for hundreds of thousands of years, based on cosmogenic nuclide dating of postintegration terraces downstream (Larson et al. forthcoming). In addition, periods of cooler and wetter climatic (pluvial) conditions in the southwestern United States have been well documented throughout

the Pleistocene. Thus, the perception that this region has always been too arid for water to accumulate in a basin and spill over is an unsupported assessment of these transverse systems. Further research will likely investigate linkages between transverse drainage development and paleoclimatic variability.

Grand Canyon

The Grand Canyon is the most visited transverse drainage in the world, as more than 4 million visitors entered Grand Canyon National Park each of the past twenty years to view where the Colorado River cuts through the Kaibab Plateau (Figure 4). One of the longest academic debates in earth science concerns the origin of the Grand Canyon of the Colorado River, which began with the hypothesis of lake overflow (Newberry 1861, 1862). After hiking to the Colorado River in the western Grand Canyon, Newberry documented the existence of lake clays now called the Bidahochi formation along the Little Colorado River. He proposed lake overflow to explain the formation of the Grand Canyon, an idea later elaborated (Blackelder 1934; Gross et al. 2001; Meek and Douglass 2001; Spencer, Smith, and Dowling 2008; Douglass et al. 2009).

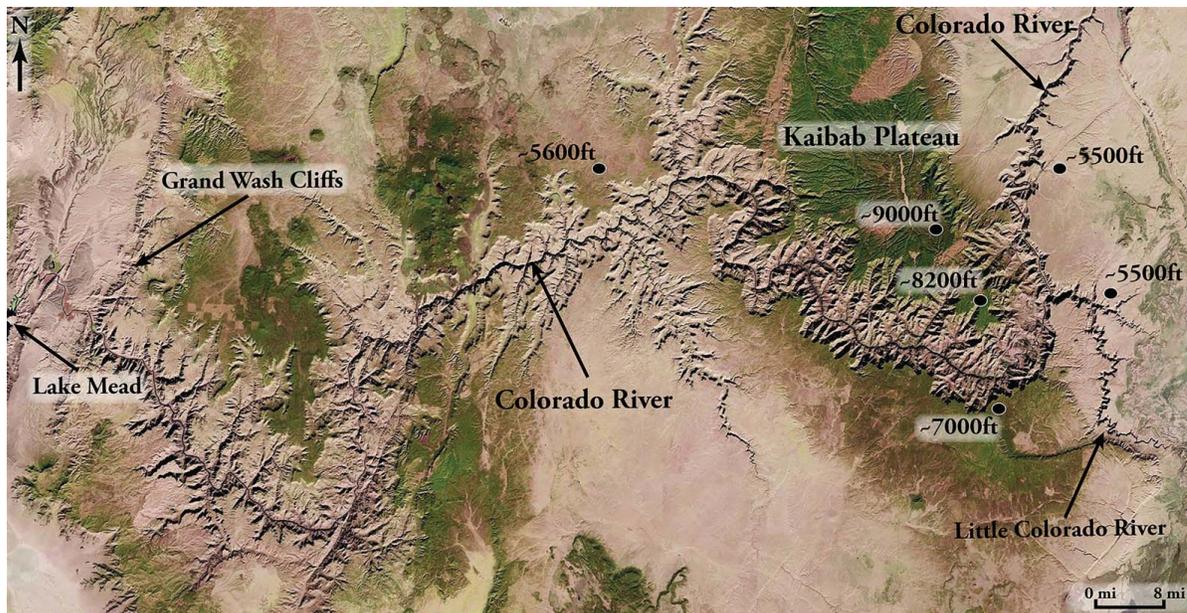


Figure 4. 2013 Landsat 8 mosaic of the Grand Canyon, Arizona. At Grand Canyon the Colorado River becomes a transverse drainage as it crosses the uplifted range of the Kaibab Plateau and exits the Grand Canyon at the Grand Wash Cliffs. *Source:* Modified mosaic from U.S. Geological Survey, http://landsat.usgs.gov/images/gallery/317_L.jpg. (Color figure available online.)

To evaluate Newberry's idea, lake overflow can be ruled out if the river's course is older than the mountains it crosses, and this is not the case. The Kaibab Plateau uplifted during the Laramide Orogeny between ~ 60 and 40 million years ago (Ma; Yonkee and Weil 2015)—whereas the Colorado River reached its exit from the Grand Canyon at ~ 5 –6 Ma (Roskowski et al. 2010; Spencer et al. 2013; Pearthree and House 2014) and brought in sediment characteristic of the Colorado River to the lower Colorado River basin (Kimbrough et al. 2015).

An age for the Grand Canyon younger than ~ 6 Ma is consistent with a basic geomorphic understanding of the behavior of rivers (Karlstrom et al. 2008; Darling and Whipple 2015) and with the paleogeography and stratigraphy of the area (Young and Crow 2014). Thus, modern proponents of a Grand Canyon older than 6 Ma (Polyak, Hill, and Asmerom 2008; Wernicke 2011; Sears 2013), including those still supporting Powell's (1875) preference for antecedence, must grapple with overwhelming evidence for a youthful age for the Colorado River's course through the Laramide uplifted Kaibab Plateau.

A younger age for the river also rules out superimposition as considered by Dutton (1882), because an ancestral Colorado could not have flowed on top of slowly eroding Mesozoic layers that were upwarped more than 35 Ma before the canyon was born. The

broad curve of the Colorado River to the south might involve some superimposition from an erosional scarp retreating in a circular fashion off the Kaibab Plateau (Strahler 1948; Lucchitta 1984; Douglass 1999)—it is important to note that in our own physical modeling tests we could not replicate what we see at the Grand Canyon using superimposition in this way.

A young age for the Colorado River could be explained by stream piracy first discussed by McKee et al. (1967) and expanded on using groundwater sapping (Hunt 1969; Hill and Polyak 2014; Crossey et al. 2015). No evidence exists, however, to explain how a singular stream could extend 322 km (Spencer and Pearthree 2001) in 6 Ma across the Colorado Plateau as postulated by Crossey et al. (2015)—when insight reveals headward erosion to be slow and relatively ineffective in most situations (Bishop 1995; Douglass and Schmeeckle 2007; Meek 2009). Proponents of headward erosion must present clear geomorphic evidence that a stream working from the Colorado Plateau's rim could erode headward, through the plateau, at a rate averaging ~ 54 mm per year. Most rates reported in literature are much lower. Despite the lack of evidence supporting headward erosion-driven piracy, recent work still argues against overflow (Dickinson 2012) and once again suggests a headward eroding stream piracy or capture model (Pelletier 2010).

The strengths of the lake overflow model are that (1) it has explained the evidence for numerous transverse drainages on the lower Colorado River downstream of the Grand Canyon; (2) the age of existing river sediments from Colorado and Wyoming to the Salton Trough are consistent with a Colorado River extending downstream over time via ponding and overflow; and (3) it would seem to require extraordinary conditions to explain one transverse drainage through a convoluted and poorly constrained form of piracy, where elsewhere along the river the overflow mechanism clearly explains the pathway's transverse drainage (House, Pearthree, and Perkins 2008; Roskowsky et al. 2010; Spencer et al. 2013; Pearthree and House 2014).

In the end, this debate will continue and we agree with the perspective that "it is exciting to realize that such a well-known landform like the Grand Canyon still holds an element of mystery" (Dexter 2010, 47).

Conclusion

This article recognizes the importance of mountains and their interaction with river systems. Recent advances in geomorphic and physical geographic theory provide a set of tools and conceptual models by which future geographers and geomorphologists can adjudicate between the different processes that result in rivers crossing mountains resulting in transverse drainages. We hope that this work opens doors for a new generation of research to help resolve ongoing debates over famous landscapes in the world, such as the Grand Canyon.

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