CRevolution 2: Origin and Evolution of the
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Karst piracy: A mechanism for integrating the Colorado River across the Kaibab uplift, Grand Canyon, Arizona, USA

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ABSTRACT

Age, isotopic, and detrital zircon data on the Hualapai Limestone Member and Muddy Creek Formation (western United States) constrain the time of the first arrival of the Colorado River on the west side of the Grand Canyon to ca. 6–5 Ma. We propose a karst piracy mechanism, along with a 17–6 Ma western paleo–Grand Canyon, as an alternative explanation for how the Colorado River became integrated across the Kaibab uplift and for the progressive upsection decrease in $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values of the Hualapai Limestone Member. An earlier Laramide paleocanyon, along which this western paleocanyon followed, can also perhaps explain why no clastic delta exists in the Grand Wash trough.

Karst piracy is a type of stream piracy where a subterranean drainage connection is made under a topographic divide. The process of karst piracy proceeds through five main stages: (1) establishment of a gradient across a topographic divide due to headward erosion into the low side of the divide, (2) leakage in soluble rock along the steepest gradient, (3) expansion of the leakage route into a cave passage that is able to carry a significant volume of water under the divide, (4) stoping and collapse of rock above the underground river, eventually forming a narrow gorge, and (5) widening of the gorge into a canyon. A karst piracy model is proposed here for the Kaibab uplift area that takes into account the structure and hydrology of that area. Other examples of karst piracy operating around the world support our proposition for integrating the Colorado River across the Kaibab uplift in the Grand Canyon.

INTRODUCTION

Past Work

How did the Colorado River cross the Kaibab uplift? Why does the river run nearly south for hundreds of miles, then for no obvious reason turn abruptly southwest to west in the Desert View area of Grand Canyon (Blackwelder, 1934; Fig. 1)? These are questions that have perplexed geologists since John Wesley Powell's first river trip in 1869.

Babenroth and Strahler (1945) were the first to try and explain how the river may have crossed the Kaibab uplift: it had coursed around the south-plunging nose of the Kaibab upwarp, with scarp retreat being downdip to the south in soft Moenkopi and Chinle shales. Strahler (1948, p. 536) elaborated on the weakness of this model: "…some reason must be shown why the river commenced to cut vertically downward into Paleozoic strata instead of continuing to shift south, downdip, as the Mesozoic beds were progressively stripped away." Strahler's

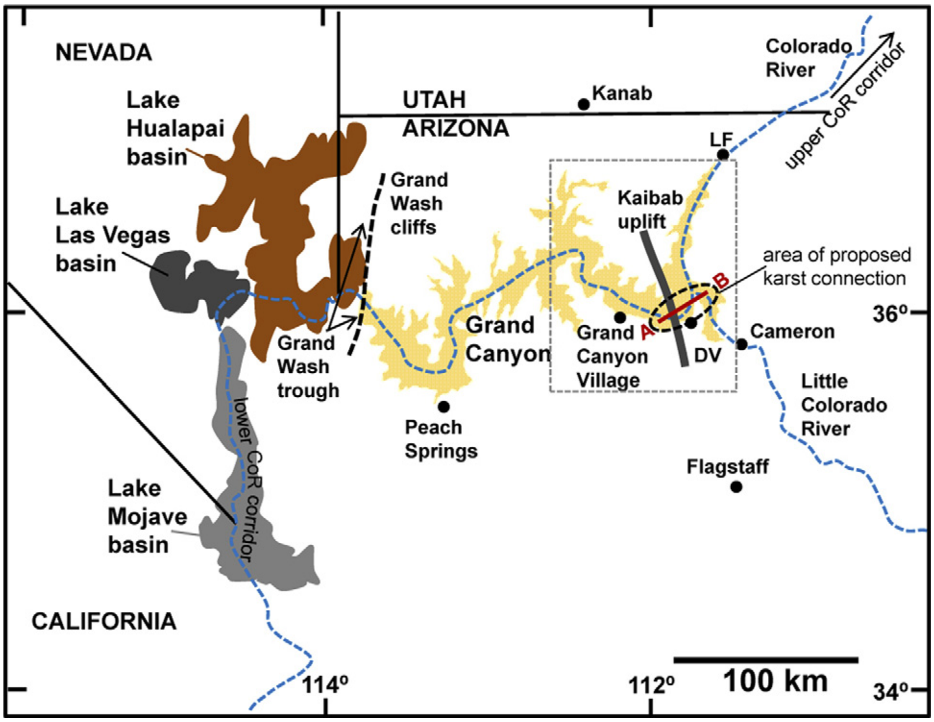

Figure 1. Location map showing pertinent geographic features and those mentioned in the text. LF—Lees Ferry, DV—Desert View, CoR—Colorado River. The Hualapai, Las Vegas, and Lake Mojave basins are from Spencer et al. (2008). The Hualapai Limestone Member and the Bouse Formation in Figure 8 were deposited in the Lake Hualapai basin and Lake Mojave basin, respectively, shown in this figure. Cross-section A–B is also in Figure 4.

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(1948) objection is especially true in the case of the very resistant Kaibab Limestone, which has formed the caprock of the Grand Canyon area for many millions of years. According to Dickinson (2013), when encountering nonresistant rock, extensive lowlands are developed across fold crests, but when they encounter resistant strata they migrate laterally down the plunge of the fold until forced to incise downward into harder rock. In this case, what factors would have forced incision into the very resistant Kaibab Limestone, and in what time frame would a Mesozoic scarp still have been present to facilitate the forcing?

Lucchitta (1975, 1984, 1989), in a variation of the Babenroth and Strahler (1945) model, invoked a Miocene Colorado River crossing the nose of the Kaibab uplift along an arcuate strike valley carved in Mesozoic rock and continuing northwestward on the west side of the uplift and into the ancestral Virgin River drainage basin. A number of problems exist with this model. Where is the evidence for Colorado River-type gravels along the west side of the Kaibab uplift or anywhere on the plateaus north of the Grand Canyon? To where did Lucchitta's (1975, 1984, 1989) supposed Miocene-age ancestral Colorado River flow? Not into the Muddy Creek Formation in the Great Basin (Pederson, 2008). Furthermore, according to the thermochronologic unroofing model of Lee et al. (2013, fig. 9D therein), by the early Miocene (18 Ma) there was no Mesozoic rock in the immediate area of the future Grand Canyon across the Kaibab uplift (river miles ~80–90).

Blackwelder (1934) originally suggested a lake spillover hypothesis for the upper Colorado River corridor (Fig. 1), where the Colorado River had overflowed a number of lake basins by breaching topographic barriers. Blackwelder's (1934) regional idea of lake overflow was revived by Meek and Douglass (2001) and Scarborough (2001) and specifically applied to the carving of the Grand Canyon. Meek and Douglass (2001) proposed that a large lake had spilled westward across the Kaibab uplift ca. 6 Ma, thus initiating rapid incision of the canyon. The many arguments against this model were summed up by Dickinson (2011, 2013), who concluded from various lines of evidence that lake spillover is not a viable model.

Hunt (1956) proposed yet another mechanism for crossing the Kaibab uplift, i.e., stream piracy, where headward erosion cuts into, and finally across, a topographic divide. However, even Hunt (1956, p. 85) was suspicious of this mechanism's validity: "It would indeed have been a unique and precocious gully that cut headward more than 100 miles across the Grand Canyon section to capture streams east of the Kaibab upwarp." Hunt's concern was echoed by Spencer and Pearthree (2001), who argued against this mechanism based on characteristic rates of headward erosion in arid climates, and by Pelletier (2010), who calculated that a pre–6 Ma basin west of the Kaibab uplift, such as proposed by Young (2008), would only have been able to headward erode as far as the mid-Grand Canyon and never reach the Kaibab uplift.

Wernicke (2011) proposed a further mechanism that invoked a California River that incised much of the Grand Canyon to near its present depth in the latest Cretaceous, including the incision of the Kaibab uplift section. However, the geological and thermochronological data of Karlstrom et al. (2014) for integration of the 6–5 Ma Colorado River through a more recent (25–5 Ma) route across the Kaibab uplift, in addition to the traditional so-called Muddy Creek constraint on the first arrival of Colorado River sediment to the Grand Wash trough at 6–5 Ma (Lucchitta, 2011), seriously challenges Wernicke's early (ca. 70 Ma) time frame for crossing the uplift.

We propose integrating the Colorado River under the Kaibab uplift via karst piracy. Karst piracy is a subtype of stream piracy where streams are pirated under a topographic divide along a soluble rock horizon such as limestone. On a small scale, karst piracy can be thought of as a diversion; for example, the diversion of water from an upper-level cave to a lower-level cave with a different outlet. However, here we use the term to describe karst processes that rearrange surface drainage on a grand scale.

All of these Kaibab uplift-crossing models remain speculative, including the karst piracy model we propose, because it is very difficult to confirm a model where the route may now be obscured or eroded away.

Terminology

Two terms in the literature have been confused with karst piracy. Hunt (1974) used the term "piping" to describe subterranean water diverted into the Grand Wash from the Hualapai Plateau. However, in karst terminology, piping refers to the settling of soil or loose debris into an underground void, not to cave passages that take water from one area to another (Ford and Williams, 1989; Palmer, 2007a). Groundwater sapping was the term used by Pederson (2001) to describe a mechanism for breaching a topographic divide, but this term appears to be synonymous with stream piracy and is not the mechanism of karst piracy described in this paper. The term karst connection, used in Hill et al. (2008), is not quite the same as karst piracy; karst connection refers to the condition of subterranean water hydrologically connecting one side of a topographic divide with the other side, whereas karst piracy refers to the mechanism by which this connection is achieved.

Longwell (1928, 1946) concluded, from his geologic and fossil observations of the Muddy Creek Formation in the Grand Wash trough (Fig. 1), that no Colorado River gravels had reached the west side of the Grand Canyon until after the deposition of the Hualapai Limestone Member. This young (late Miocene to Pleistocene) age for a Grand Canyon carved by the Colorado River became referred to as the Muddy Creek problem, because it was deduced that Longwell's (1928, 1946) observations disallowed a canyon older than this. New data have further constrained when and how the Colorado River first traversed the canyon, so now the problem is sometimes referred to as the Muddy Creek constraint (Lucchitta, 2011). In this paper, by "Muddy Creek," we specifically mean Muddy Creek Formation deposits within the Grand Wash trough area. These rocks were originally assigned to the Muddy Creek Formation in Virgin Valley (Stock, 1921), but later renamed "rocks of the Grand Wash trough" by Bohannon (1984) because they were somewhat older than, and deposited in a separate basin from, the defined Muddy Creek.

Names that refer to canyons existing prior to the present-day Grand Canyon of the Colorado River have changed significantly since they were first proposed, thus causing confusion in terminology among researchers. We use the terms paleocanyon, paleo–Grand Canyon, and paleo–Little Colorado River (or paleo–Colorado or San Juan rivers) when referring to geomorphologic features that existed *prior* to the modern Grand Canyon system. However, when quoting earlier papers we use the old names (and new names) to establish historicity. We also use the term Kaibab uplift instead of Kaibab arch or upwarp, except when quoting a historic article.

Motivation and Purpose

This paper proposes that karst piracy was the connection mechanism of integrating the Colorado River across the Kaibab uplift in the Grand Canyon. A karst connection model for the Grand Canyon was first proposed in Hill et al. (2006, 2008); the concept of karst piracy was introduced in Hill et al. (2012). However, this paper is not just a review or update of those earlier papers, but an attempt to explain how the process of karst piracy might have worked in a real-world case, the Grand Canyon, something that has not been done, even in publications such as *Journal of Caves and Karst* or in the two most influential karst books, *Karst Hydrogeology and Geomorphology* (Ford and Williams,

2007) and *Cave Geology* (Palmer, 2007a). Thus our paper breaks new ground in that it describes a mechanism for the development of landforms like the Grand Canyon that have not previously been considered as having been caused by, or related to, karst.

The importance of karst piracy to this *Geosphere* themed volume is that it not only offers an alternative way for the Colorado River to have crossed the Kaibab uplift, but it also offers an explanation for the age and isotopic data of the Hualapai Limestone Member and Muddy Creek and Bouse Formations west and southwest of the Grand Canyon. It also relates to a major controversy among Grand Canyon researchers, i.e., whether a westward-flowing Colorado River first transected the Grand Canyon area ca. 6 Ma, the consensus of geologists in the past, or was the canyon incised down to almost its present depth ca. 80–70 Ma by an eastward-flowing river, as according to the thermochronologic models of Flowers et al. (2008), Wernicke (2011), and Flowers and Farley (2012). The karst piracy model supports a 6–5 Ma age for the integration of the Colorado River from Colorado, through a Grand Canyon along the same route as today, and then to the Gulf of California. The main purpose of this paper is to propose a new conceptual mechanism for the geomorphic evolution of the Grand Canyon that addresses a number of important questions that still remain from the past two decades of Grand Canyon research.

REGIONAL PERSPECTIVE

Geologic Model with Respect to Karst Piracy

On the basis of geomorphic evidence such as barbed tributaries along Marble Canyon (Ranney, 1998), a young and narrow Marble Canyon located only 2.8 km from the Chuar basin, and the affinity between fossil fish in the Snake River and latest Miocene (upper) part of the Bidahochi Formation (Spencer et al., 2008), it was proposed in Hill et al. (2008), Hill and Ranney (2008), and Hill et al. (2011) that a paleo–Little Colorado River had flowed north from a series of ephemeral lakes (collectively called Hopi Lake; Dallegge et al., 2003) into an interior lake (the proposed Glen Lake of Hill et al., 2006) in southern Utah at least by 16 Ma until ca. 6 Ma (Fig. 2). The paleo–Little Colorado River was diverted ca. 6 Ma into a series of sinkholes in the area where the confluence of the Colorado River and Little Colorado River exists today. This downward diversion of progressively more Little Colorado River water into the Confluence sinkhole complex could have caused the rapid headward incision of Little Colorado River Canyon, thus

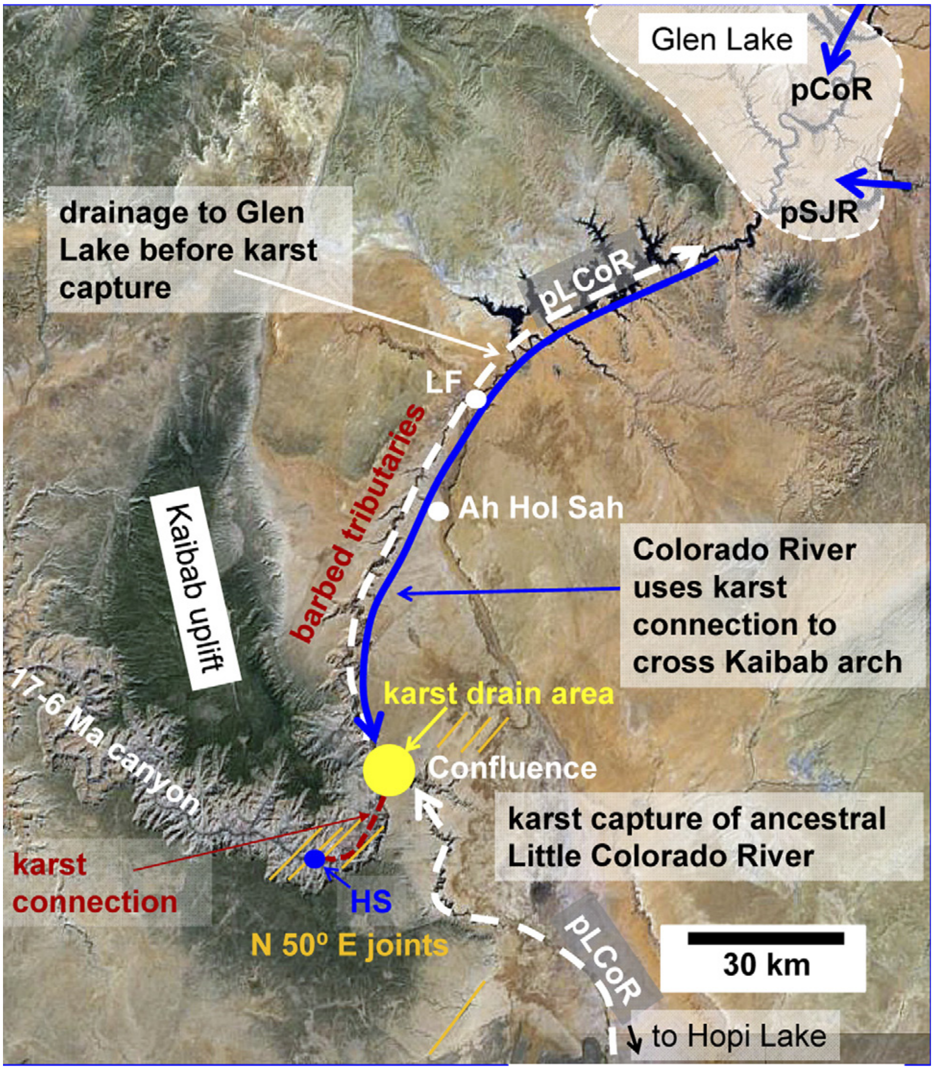

Figure 2. A schematic diagram over a Landsat image showing the geomorphology of the eastern Grand Canyon ca. 6–5 Ma as proposed in Hill et al. (2008) and Hill and Ranney (2008). The paleo–Little Colorado River was flowing north up Marble Canyon to the interior Glen Lake, with the barbed tributaries of Marble Canyon being interpreted as evidence of this once, north-flowing paleo–Little Colorado River. The paleo–Colorado River was flowing south into Glen Lake, and the paleo–San Juan River was flowing west into Glen Lake. The very narrow Marble Canyon was interpreted in Hill et al. (2008) to be a young river channel caused by headward erosion from the confluence of the Colorado and Little Colorado rivers up to Glen Lake after Little Colorado River water became completely captured by the confluence sinkholes. The white dashed arrow denotes the flow of the paleo–Little Colorado River before a karst connection; the blue solid arrow denotes the flow of the Colorado River after a karst connection. The route of the proposed karst connection is outlined by a red dashed line. The parallel yellow lines are N50E joints, which correspond to joint trends in the southern part of the Marble Plateau (Sutphin and Wenrich, 1988) and can be seen on the Landsat image. The final connection with Glen Lake ca. 6–5.5 Ma allowed the Colorado and San Juan rivers to flow south through Marble Canyon, down the sinkholes at the confluence of the Colorado and Little Colorado rivers, and under the Kaibab uplift, to exit on the west side of the uplift at Hance Spring. The Colorado River then flowed through Grand Canyon to the Grand Wash trough, and from there south to the Gulf of California. LF—Lees Ferry, HS—Hance Spring, pCoR—paleo–Colorado River, pSJR—paleo–San Juan River, pLCoR—paleo–Little Colorado River; “paleo” denotes these rivers before the modern Grand Canyon system was established. After ca. 6 Ma, the Little Colorado River flowed into the Colorado River. Ah Hol Sah is the sinkhole shown in Figure 5.

possibly initiating the ca. 6 Ma fluvial stage of the Bidahochi Formation (Dallegge et al., 2003) and possibly terminating the Neogene Crooked Ridge paleoriver system prior to canyon incision at 6–5 Ma (Hereford et al., 2013).

The model of Hill et al. (2008) and Hill and Ranney (2008) proposes that, once the paleo–Little Colorado became completely siphoned underground at the confluence of the Colorado and Little Colorado rivers, headward erosion also proceeded north from the confluence along the course of what is now Marble Canyon to make a final connection with Glen Lake ca. 6–5 Ma (Fig. 2). Thus, according to this geomorphic model, it was a karst piracy mechanism that actually *caused* Marble Canyon to form where it did 6–5 Ma, an age for Marble Canyon first proposed in Hill et al. (2008) and later supported by the thermochronological and geological work of Karlstrom et al. (2014). Once a final connection was made, the paleo–Colorado River, which flowed south into Glen Lake from Colorado (Fig. 2), was free to continue southward along the course of Marble Canyon to the confluence of the Colorado and Little Colorado rivers, where it then followed a subterranean route under the Kaibab uplift. After ca. 5 Ma, collapse of the karst piracy route into a narrow canyon and its subsequent deepening and widening over the past few million years created the current Desert View section of the Grand Canyon.

Types of Caves and Karst Processes

Before we discuss the process of karst piracy, we describe how this type of cave differs from other types of caves present in the Grand Canyon region. All caves are not alike; they form by different processes and under different sets of conditions. Therefore, this explanatory discussion of caves is meant to educate readers not familiar with karst so that the different types of Grand Canyon caves will not be confused with each other.

There are two main categories of present-day caves in the Grand Canyon: those formed under unconfined hydrologic conditions in the vadose zone and those formed in the phreatic zone mostly under confined hydrologic conditions (Huntoon, 1970, 2000a, 2000b; Hill and Polyak, 2010). Caves formed under unconfined hydrologic conditions above the phreatic zone are simple drains in the vadose (unsaturated) zone where water recharges on the Kaibab Plateau and moves gravitationally down along faults or master joints to form free-surface streams. Usually (but not always) they discharge from the base of the Muav Limestone and above the Bright Angel aquiclude. These are the great North Rim caves such as Roaring Springs and Thunder River that have waterfalls cascading from their entrances.

Caves formed under confined hydrologic conditions are those that formerly developed (or are developing) in the phreatic (saturated) zone below relatively impermeable caprock. The majority of the Grand Canyon confined caves are found in the Mooney Falls Member of the Redwall Limestone, with sandstones of the Supai Group forming the impermeable cap. The phreatically developed caves in the Grand Canyon happen to be hypogenic, although this is not true of most confined caves in the world. Hypogenic means that the source of solutional aggressiveness to dissolve caves is from depth rather than from surface infiltration (Palmer, 2007a; Hill and Polyak, 2010).

The mechanism of karst piracy is unrelated to both of these cave types. Karst piracy involves the development of large cave passages that transport large volumes of water under a topographic divide, and it also involves the connecting of two areas of different elevation and potentiometric surface on each side of the divide. In the final stages of this process, the former presence of karst piracy caves is difficult to document because of their being obliterated by headward erosion, stoping, collapse, and canyon deepening and widening along the former karst piracy route. Therefore, there may be no direct proof that these caves once existed, as is the case for the Kaibab uplift and the Grand Canyon. However, there is indirect evidence on the western, Grand Wash trough side of the Grand Canyon that possibly supports the mechanism of karst piracy.

APPLICABLE DATA

Age Data

The age constraint of when the Colorado River first arrived in the Grand Wash trough involves the ^{40}Ar/^{39}Ar dating of volcanic rocks located within the Hualapai Limestone Member and Bouse Formation. Spencer et al. (2001) reported a date of 5.97 ± 0.07 Ma for a tuff near the top of the Hualapai Limestone Member, and Sarna-Wojcicki et al. (2011) and Spencer et al. (2013) reported a date of 4.9 Ma for a volcanic ash bed in the Bouse Formation of Colorado River derivation; both dates imply that the first arrival of Colorado River water in the lower Colorado River corridor may have occurred at that time. However, Dorsey et al. (2007, 2011) favored a date of 5.3 Ma for when the Colorado River first reached the Gulf of California. Thus it seems likely that the first arrival of the Colorado River into the Grand Wash trough occurred sometime between ca. 6 and 5 Ma.

In Polyak et al. (2008), the age limits of paleo-water tables within the Grand Canyon were defined from U-Pb ages on mammillary calcite within caves and in surface exposures; lower than expected Miocene water tables in the western Grand Canyon are consistent with a pre–Colorado River, Miocene (17–6 Ma) western paleo–Grand Canyon, as well as with the similar western canyon proposed by Young (2008). The water-table data (Polyak et al., 2008) support a karst piracy model because a karst piracy mechanism would be difficult to propose without a fluvial system incising into the west side of the Kaibab uplift.

Isotopic Data

The δ^{18}O values and ^{87}Sr/^{86}Sr ratios reported for the Hualapai Limestone Member and Bouse carbonates place constraints on the sources of water and sediment delivered to the Hualapai and lower Colorado River corridor basins (Roskowski et al., 2010; Lopez Pearce et al., 2011; Spencer et al., 2011; Fig. 1). Combined, the data support a nonmarine origin for the Hualapai Limestone Member and for most of the Bouse carbonates.

Lopez Pearce et al. (2011) reported a gradual upsection decrease of δ^{18}O values in the Hualapai Limestone Member and attributed this trend to increasing freshwater and higher elevation recharge over time; they reported a similar trend for carbon isotopes. Roskowski et al. (2010) and Lopez Pearce et al. (2011) reported a gradual upsection decrease of ^{87}Sr/^{86}Sr ratios in the Hualapai Limestone Member, from 0.7195 to 0.7137, and from 0.7195 to 0.7120, respectively. In comparison to these high strontium ratios for the Hualapai Limestone Member, Spencer et al. (2011) reported ^{87}Sr/^{86}Sr ratios for Bouse carbonates (0.7102–0.7114) that are only slightly higher than normal Colorado River values (0.7103–0.7108). In comparison to both of these value sets, Crossey et al. (2006, 2009, 2011) reported ^{87}Sr/^{86}Sr ratios of 0.709987–0.734234 (n = 11) for hypogene spring water and travertines within the Grand Canyon.

Detrital Zircon Data

Detrital zircon data on the Hualapai Limestone Member and Muddy Creek Formation in the Grand Wash trough have been offered as a constraint on the source of zircon crystals at the mouth of the canyon; the constraint being that no detrital zircon from Colorado entered the Grand Wash trough until the Colorado River arrived ca. 6–5 Ma (Lopez Pearce et al., 2011). These three Grand Wash trough samples, two collected at the same site at South Cove and one at Pearce

Ferry, show a spectra of two peaks ca. 1.4 and ca. 1.7 Ga, implying that no detrital zircon input came from the nearby Colorado Plateau; otherwise, the samples should also contain Paleozoic peaks. Dickinson et al. (2012) reported detrital zircon results on the arkosic gravels of the Late Cretaceous to middle Eocene Music Mountain Formation (Young, 1999), collected from Long Point and Peach Springs Canyon, that have very similar Precambrian peaks (ca. 1.45 and ca. 1.75 Ga), but that also have Jurassic peaks ca. 170 Ma. In addition, Tillquist et al. (2012) reported Middle Jurassic (ca. 163–160 Ma) ages for rhyolite volcanic clasts from the Music Mountain Formation near Long Point. The Jurassic and Precambrian detrital zircon peaks perhaps imply a provenance from the Laramide Mogollon Highlands that formerly bordered the southern and southwestern margin of the Colorado Plateau (Bilodeau, 1986).

KARST PIRACY: A THEORETICAL MODEL OF HOW IT WORKS

In this section we present a theoretical five-stage model intended to illustrate the general principles of how the process of karst piracy works (Fig. 3). This model is not meant to be a specific portrayal of karst piracy under the Kaibab uplift, but roughly illustrates some of its geomorphic features: an uplift that water goes under (or through) from east to west down the hydraulic gradient, headward erosion from the west, a soluble limestone unit overlain by confining beds, and a canyon that eventually forms from this evolutionary process. In the next section we present a more realistic model of karst piracy for the Grand Canyon based on what is known about the structure, stratigraphy, and karst hydrology of the Kaibab uplift area.

Stage A

Stage A of Figure 3 shows the hydrologic set up before karst piracy begins. In stage A, two rivers are shown, one on the east parallel to the uplift, and a second headward eroding into the uplift from the west. Limestone extends completely under the uplift and is the soluble unit that will undergo karstification once it begins. The east recharge side is much higher than the west discharge side, so a steep hydraulic gradient is created between them.

Stage B

Stage B represents the period of hydraulic control of Palmer (2007a), where flow contributed by a surface stream loses only part of its water to an underlying water-filled conduit. This condition is usually limited to small underground flow routes that have not yet reached cave size. If there is enough water to keep the conduit completely filled throughout the year, the amount of flow at this stage depends only on the physical characteristics of the conduit (length, diameter, sinuosity, roughness). In stage B most of the water discharging from the outlet spring is probably provided by autogenic recharge rather than allogenic recharge, that is, from water falling on the karst area (curved arrows, Figs. 3A, 3B, 3C), rather than from the input of river water.

During stage B the conduit opens sufficiently to allow leakage from one side of the uplift to the other. Only when undersaturated water is able to flow all the way through from sink to spring is it possible for the conduit to grow. Secondary permeability along fractures helps solve the problem of water being able to stay unsaturated, so as to allow the entire flow path

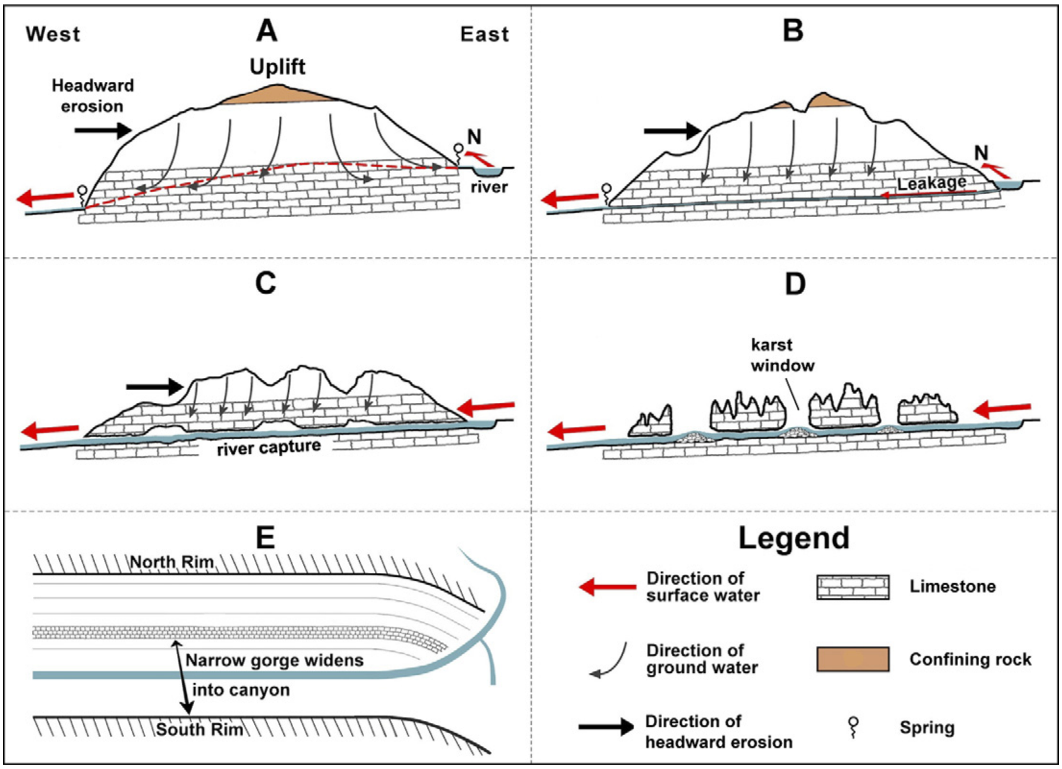

Figure 3. Five stages of theoretical model for a karst connection under an uplift via a karst piracy mechanism. (A) Before karst piracy begins a steep hydraulic gradient must be created between the east and west sides of the uplift, and a high-permeability rock unit must be able to transport water under the uplift. Headward erosion into the uplift proceeds initially by the process of stream piracy. (B) Leakage occurs under the uplift and discharge is at a spring or series of springs on its west side. The conduit is still too small to carry gravels under the uplift. At this stage spring discharge is mostly from autogenic recharge (slightly curved arrows) rather than from allogenic leakage of river water. (C) The river on the east side is now completely captured and diverted underground. The substantial volume and/or increase of undersaturated water enlarges the cave passage, so that the river flows freely under the uplift. (D) Unroofing occurs by spring sapping, upward stoping, ceiling collapse, and the addition of more undersaturated water through karst windows. This process eventually forms a narrow gorge. At this stage, sediment and/or detrital zircon is transported by the river across the uplift. (E) The narrow gorge widens and deepens into a canyon. Stages A–D are shown in cross section; stage E is shown in map view.

to dissolve simultaneously. Evolving from leakage to a free-flowing stream, the flow path can grow somewhat uniformly over its entire length, but nevertheless fastest at the upstream end where undersaturated river water is recharging the system.

Stage C

As the cave conduit enlarges via undersaturated water moving under the uplift, progressively more flow becomes diverted from the river until all of its water is captured. Because this undersaturated river water readily dissolves more limestone, the karst piracy cave passage becomes larger until a cave stream flows freely under the uplift. The discharge for this water can be from one large spring on the west side of the uplift, as shown in Figure 3C, or a series of smaller springs at slightly different elevations as headward erosion progressively incises eastward and downward into the west side of the uplift.

Stage D

Stage D in Figure 3 represents the unroofing phase of stoping, collapse, and headward erosion. Upward stoping by collapse is self-accelerating because as collapse occurs, the partial blockage and diversion of water around it causes further collapse, the result being large holes working their way up to the surface along the trend of the underground channel. Also, spring sapping (where a spring emerges at the head of a valley and the overlying rock is quickly undermined by solution and collapse) is another likely mechanism that facilitates unroofing. During unroofing, sections of the underground river still flow through the old karst piracy cave passage, while other sections become exposed to the surface. Finally, collapse is complete along the former underground river and a narrow gorge forms.

Stage E

The final stage of evolution is where the narrow gorge widens into a canyon, and where continuing river erosion cuts down into older rock. Figure 3E shows this stage, but with the configuration of the Grand Canyon, Marble Canyon, Little Colorado River, and Colorado River routes in mind.

KARST PIRACY IN GRAND CANYON: A MODEL OF HOW IT MAY HAVE WORKED

We apply the concept of karst piracy as presented herein to a geologic cross section across the Kaibab uplift (A–B; Fig. 1). Note how the application of the model, as shown in Figure 4, differs from the theoretical model of Figure 3. The Redwall Limestone along the Kaibab uplift is offset by two splays of the Butte fault. The proposed discharge spring (Hance Spring) is in the area of Hance Rapids (now at Precambrian level); just before 6 Ma it would have been at the level of the Redwall Limestone. In contrast to the theoretical model presented here, recharge on the east is not from a river at the same elevation as the Redwall Limestone (as shown in Fig. 3), but from a paleo–Little Colorado River being pirated down a sinkhole complex in the Colorado and Little Colorado rivers confluence area of the Marble Plateau (Fig. 4).

Presented here are the five stages of karst piracy as applied to crossing under the Kaibab uplift so as to effect a karst connection. Approximate time spans are given for the last four of these stages; stage A is not given a time designation because it encompasses the entire history of the Kaibab uplift (ca. 80–70 Ma) until the time when karst piracy began (ca. 8–6 Ma).

Stage A

Stage A shows the hydrologic set up before karst piracy began (Fig. 4). As in our regional geomorphic evolution scenario (Fig. 2), we have the paleo–Little Colorado River heading north toward Utah and Glen Lake, and headward erosion into the Kaibab uplift from the west by the 17–6 Ma western Grand Canyon of Polyak et al. (2008). The difference in elevation between

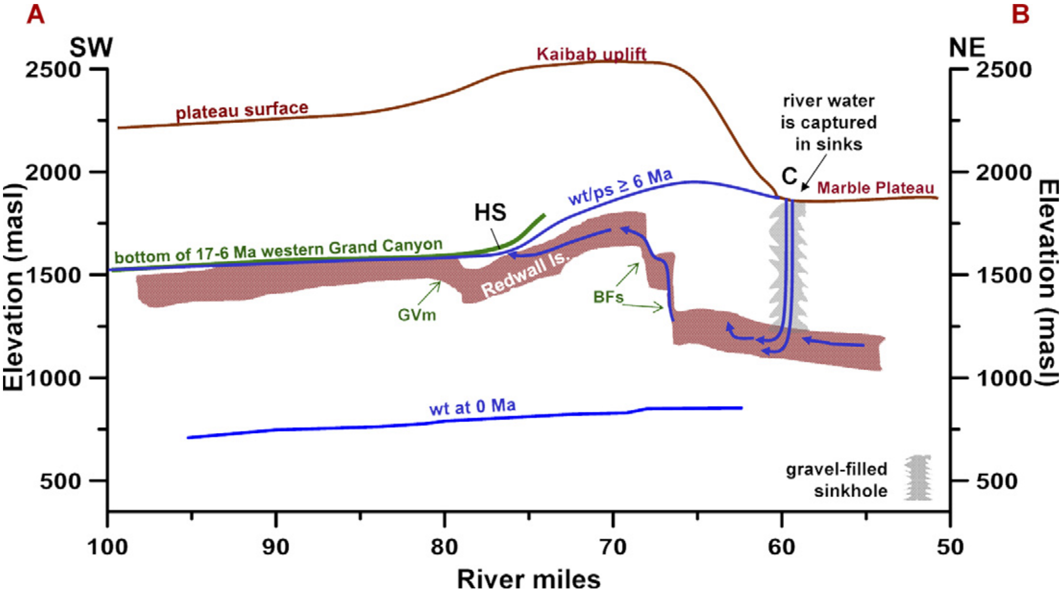

Figure 4. A model of how water could have crossed under the Kaibab uplift from the Marble Plateau on the east side of the Kaibab uplift to the Hance Rapids area on the west side of the uplift. The elevation difference between the top of the Redwall Limestone of the two sides is ~356 m and the proposed distance between recharge and discharge is ~22 km, or an overall gradient of 0.0166. The sinkhole shown at the confluence of the Colorado and Little Colorado rivers was not a 600-m-deep pit; it was a collapse sinkhole filled with rubble, as is the case today for the large Ah Hol Sah sinkhole on the Marble Plateau (Fig. 5). The combined thickness of the Redwall-Muav aquifer in the region of the Kaibab uplift is ~180–195 m. BFs—Butte fault splays; GVm—Grandview monocline, synclinal axis; HS—Hance Spring; masl—meters above sea level; wt/ps = water table/potentiometric surface (water-table data of Polyak et al., 2008). This diagram is based on the geology of Huntoon et al. (1996). The present-day dips of the Redwall Limestone along monoclines, and displacements along the two southern branches of the Butte fault, were also considered when making this diagram. This diagram roughly follows the northeast-southwest–trending cross-section A–B in Figure 1. Vertical exaggeration = 19.85.

the two sides of the Kaibab uplift could have been as much as 365 m, thus creating a steep hydraulic gradient between them (Hill et al., 2008; Fig. 4). The Redwall Limestone extends completely under the uplift and is the soluble unit that undergoes karstification. The most likely transmissive horizon is the Mooney Falls Member of the Redwall Limestone because it contains a zone of Mississippian paleokarst breccia (Hill and Polyak, 2010). This paleokarst zone of high permeability could have facilitated the movement of water under the uplift because a completely low-permeability limestone would have inhibited the initiation of flow.

Another factor enabling transmission of water through the Redwall Limestone could have been fractures and/or joints. Limestone may have low primary permeability, but secondary permeability can be orders of magnitude greater. There are two main fracture trends in the Redwall Limestone; both are Mississippian in age and formed prior to the deposition of the Supai Group. The first fracture trend strikes, on average, ~N50°–60°E, and the second strikes ~N40°–50°W (the F1 and F2 joint trends of Roller, 1987, 1989, respectively, measured on the Hualapai Plateau). Solutioning is widespread along the F1 trend, and many modern-day Grand Canyon caves have developed along this N50°–60°E trend (Hill and Ranney, 2008). These two joint trends were delineated by Sutphin and Wenrich (1988) in the Kaibab uplift–southern Marble Plateau area by an alignment of breccia pipe structures. The F1 joint trend in this area may explain the ~N50°E direction that the Colorado River takes from Basalt Canyon to Hance Rapids (Fig. 2); the interpretation is that today's Colorado River may follow the original joint-controlled subterranean traverse of karst piracy under the Kaibab uplift.

Stage B, ca. 8–7 Ma

The Polyak et al. (2008) 17–6 Ma western paleo–Grand Canyon reached, and began incising into, the west side of the Kaibab uplift ca. 8–7 Ma, so that water began leaking from its eastern side to its western side. Secondary permeability along N50°E fractures in the Redwall Limestone could have helped this leakage water remain unsaturated so that dissolution could proceed relatively uniformly over its length. Autogenic water recharging on the Kaibab uplift would have descended to the permeable paleokarst horizon, thus further recharging the groundwater system.

In a real-world scenario, such as described, there would have been the complicating effect of structure. Small underground flow routes of stage B would have developed along fractures parallel to the two splays of the Butte fault and up along the eastward-dipping beds of the East Kaibab monocline. The Redwall Limestone in these two Butte fault blocks is offset along the karst piracy route (Fig. 4), and fracture connections between adjacent blocks could have allowed water to follow carbonate rock all the way under the uplift. Because the combined Redwall-Muav aquifer in the Kaibab uplift area is ~180–195 m thick, such a carbonate-rock connection seems likely. The vertical exaggeration of Figure 4 makes this proposed path look difficult, but it is not unusual for karst water to flow through complex structural settings, especially up along faults and related fractures when the hydraulic head difference between two sides of an area is large (Palmer, 2007a).

The sinkhole shown in Figure 4 at the confluence of the Colorado and Little Colorado rivers is also not unrealistic. It has its modern-day analog on the Marble Plateau (Ah Hol Sah sinkhole; Fig. 5), where recharge is also from the Kaibab Limestone surface down to the Redwall aquifer. The Colorado and Little Colorado rivers confluence sinkhole, like the karst connection route, would have developed slowly, starting with narrow fissures and then enlarging to a maximum size over many thousands of years. Water probably filled the original fissure route (stage B), but as the sinkhole enlarged, collapsed, and filled with breccia over time, the actual water level would have varied depending on the amount of recharge and diameter of the hole. Because our proposed Colorado and Little Colorado rivers confluence sinkhole bottoms out in the cavernous Redwall Limestone (Fig. 4), much or most of sinkhole growth would have been upward because of stoping from below, as is the case today for the Ah Hol Sah sinkhole on the Marble Plateau (Figs. 2 and 5).

Sediment carrying detrital zircons probably could not have been transported under the Kaibab uplift during stage B because the connection route was still too tight. In addition, the transition from stages A to B to C took a long time to develop (probably a few million years; Table 1). Thus, karst piracy under the uplift would not have been abrupt, as would have been the case for the rapid spillover of a lake.

Stage C, ca. 7–6 Ma

During stage C the paleo–Little Colorado River was completely captured and water could have begun flowing through cave passages under the Kaibab uplift. However, even in this free-flow situation, the pathway was probably still too convoluted to allow a gravelly bedload to pass, so only water and fine-grained clastics could make it all the way under the uplift. Such a feat would have had to wait until collapse along the karst connection route brought the entire cave stream down toward base level, with a river able to carry gravel-size sediment from one side of the uplift to the other side. Once the karst system became fully integrated under the uplift, any stored sediment would have been flushed down the system. The transport of gravels under the Kaibab uplift probably did not occur until very late into stage C and during stage D.

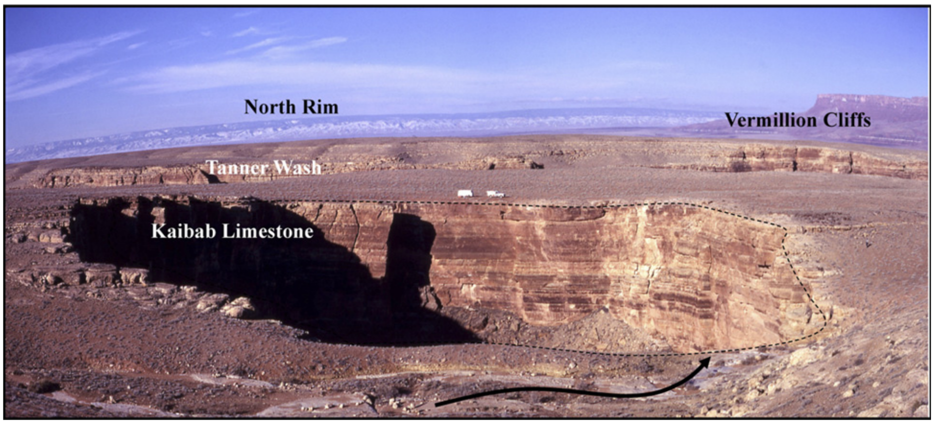

Figure 5. Ah Hol Sah sinkhole on the northern Marble Platueau. The sinkhole is 150 m in diameter (note vehicles for scale), 40 m deep down to its rubble bottom, and is actively collapsing into the Redwall karst aquifer hundreds of meters below. A small wash (foreground) now drains into the sinkhole (arrow). The water probably discharges from the Redwall Limestone along the Fence Spring complex on the east side of the Colorado River. This photo shows that sinkholes, such as our proposed 6 Ma Colorado and Little Colorado rivers confluence sinkhole, can form on the Marble Plateau and be a mechanism for diverting water down to the Redwall-Muav aquifer. Photo by Bob Buecher.

TABLE 1. PROPOSED TIMELINE OF EVENTS FROM THE LATE CRETACEOUS TO THE PRESENT AS THEY RELATE TO KARST PIRACY

Date (Ma)	EVENT
ca. 80–70	The Laramide paleo–Grand Canyon of Hill and Ranney (2008) incised due to the upwarping of the southwestern Colorado Plateau and Kaibab uplift (Kelley and Karlstrom, 2012; Tindall et al., 2010). This canyon had two segments that joined in the Kanab Point area: (1) a deeper western section that formed off the uplifting Hualapai Plateau, and (2) a shallower eastern section that formed off the west side of the Kaibab uplift. The western section incised into the upper Paleozoic clastic units of the Colorado Plateau and this clastic material was transported northward into Utah. This Laramide paleo–Grand Canyon established the route that the later 17–6 Ma western paleo–Grand Canyon and 6–0 Ma Colorado River canyon followed.
ca. 70–60	A period of aggradation on both the Hualapai and Coconino plateaus; Music Mountain Formation gravels were carried northward to partly fill the Laramide paleocanyons (Young, 1999; Hill and Ranney, 2008; Karlstrom et al., 2014).
ca. 60–20	Drainage in this Laramide paleocanyon continued to flow northward and transport upper Paleozoic clastics into southern Utah.
ca. 20–17	The Basin and Range began to downdrop along the Grand Wash fault; probable time of a regional drainage reversal from north to south and then westward to the Grand Wash trough.
ca. 17–6	(1) The 17–6 Ma western Grand Canyon paleoriver (of Polyak et al., 2008) flowed into the Grand Wash trough due to Basin and Range downfaulting. (2) Headward erosion proceeded up this paleo-western canyon toward, and then into, the Kaibab uplift (stage A of Fig. 3). (3) As this western basin expanded, a progressive increase of freshwater from higher altitudes caused a gradual decrease in oxygen and Sr/Sr isotopic values of the Hualapai Limestone Member. (4) Since this 17–6 Ma western paleoriver follows the route of the Laramide paleo–Grand Canyon, along which a major amount of upper Paleozoic clastic material had already been transported to Utah, detritus from the Colorado Plateau was minimal and there was no clastic delta in the Grand Wash trough.
ca. 8–7	(1) The 17–6 Ma western paleo–Grand Canyon headward eroded into the west side of the Kaibab uplift and down to Redwall Limestone level. This initiated stage B karst piracy leakage under the uplift. (2) Probably very little sediment/detrital zircon and paleo–Little Colorado River water made it across the Kaibab uplift, but a small amount of leakage water could have contributed to a decrease in Sr/Sr values of the Hualapai Limestone Member.
ca. 7–6	(1) Once karst piracy stage C was reached and the paleo–Little Colorado was completely captured, headward erosion proceeded northward from the confluence of the Colorado and Little Colorado rivers, up what is now the course of Marble Canyon toward Glen Lake. This erosion caused the formation of a young (6–5 Ma), narrow, Marble Canyon.
ca. 6–5	(1) Headward erosion reached the Glen Lake of Hill et al. (2006, 2008), and a final connection was made. Once this lake basin was breached, a large volume of Colorado River water flowed south down Marble Canyon, into sinkholes at the confluence of the Colorado and Little Colorado rivers, and then westward under the Kaibab uplift, to arrive in the Grand Wash trough in the time frame of 6–5 Ma. (2) The increase of water volume during stage D facilitated unroofing and collapse along the former karst piracy route. (3) By this time, the Colorado River flowed all the way from Colorado to the Gulf of California and was responsible for the low Sr/Sr Colorado River water values of the Bouse Formation.
ca. 5–Present	(1) The Colorado River was the major eroding agent carving the Grand Canyon; the two older canyons excavated much less material. (2) During stage E, the widening and deepening of the canyon by the Colorado River obliterated the old karst piracy route under the Kaibab uplift.

A good modern analog for stage C is the River Danube–Aach spring system of the Swabian Alb, Germany (Fig. 6). The Danube River, which flows eastward toward the Black Sea, is captured in the western Alb by the Danube sink (Donauversickerung), periodically leading to a complete loss of water in the upper Danube (Hötzl, 1996). The disappearing Danube water has been shown by dye-tracer analysis to exit from the Aach spring (Aachtopf); from there it flows to the River Rhine and North Sea. The Danube water in its karst transit makes a 90° turn from east to south and travels 11.7 km underground from recharge to discharge. In comparison, the proposed Grand Canyon karst route would be about twice as long (22 km). Aach Spring, the largest spring in Germany, is 175 m lower in elevation than the Danube sink complex and has an average discharge of 8590 L/s and a velocity of 195 m/h. Flow time through this karst system is normally 2 days; such rapid transit is explainable by flow through cave conduits. The massive carbonate rock sequence, along which water flows, acts as one hydraulically connected karst aquifer, even though it is disrupted by five major faults between recharge in the Danube Valley and discharge at Aach Spring. The Danube-Aach karst is Holocene in age (Hötzl, 1996), and therefore dissection, collapse, and headward erosion of this system have not yet matured (i.e., it is still in the early stage C period and has not yet proceeded to stage D).

Stage D, ca. 6–5 Ma

Stage D is the unroofing phase of stoping and collapse. The collapse areas where the surface is reached are called karst windows because they allow undersaturated water to enter the underground system (Fig. 3D). Undersaturated Colorado River water and karst-window water together would have accelerated the stage D unroofing process. Stage D in the Grand Canyon is equivalent to the time when Hill et al.'s (2008) proposed final connection with Glen Lake was made, ca. 5.5 Ma (or after the ca. 6 Ma earliest river constraint) (Fig. 2). It is also the time when the Colorado River began flowing through the entire Grand Canyon, from its west side to its east side and all the way to the Gulf of California. This stage of river transect occurred after the final deposition of the Hualapai Limestone Member of the Muddy Creek Formation in the Grand Wash trough. During this stage, Colorado River water was derived from the entire upper Colorado River and Little Colorado River watersheds, and it flowed through the Grand Canyon carrying Colorado Rocky Mountain detrital zircon to the Grand Wash trough and into the early Pliocene Bouse and Imperial Formations southwest of the Grand Canyon.

A good modern analog of stage D is the Chongquing karst of south China (Fig. 7), where cave unroofing (collapse and lateral roof retreat) has been shown to be a large-scale geomorphic process in the creation of narrow gorges (Klimchouk, 2006). In the south China karst, huge depressions called tiankengs (karst windows), as deep and wide as 670 m, have collapsed into river cave passages (Palmer, 2007b). The age of the Chongquing karst system, which is today only partly unroofed, is late Pliocene to Pleistocene (Zhu and Chen, 2005). The distance from sink to spring is 12 km for the Chongquing karst (compared to 22 km for the proposed Grand Canyon karst route), not counting the sinuosity of the known cave (A. Palmer, 2013, written commun.).

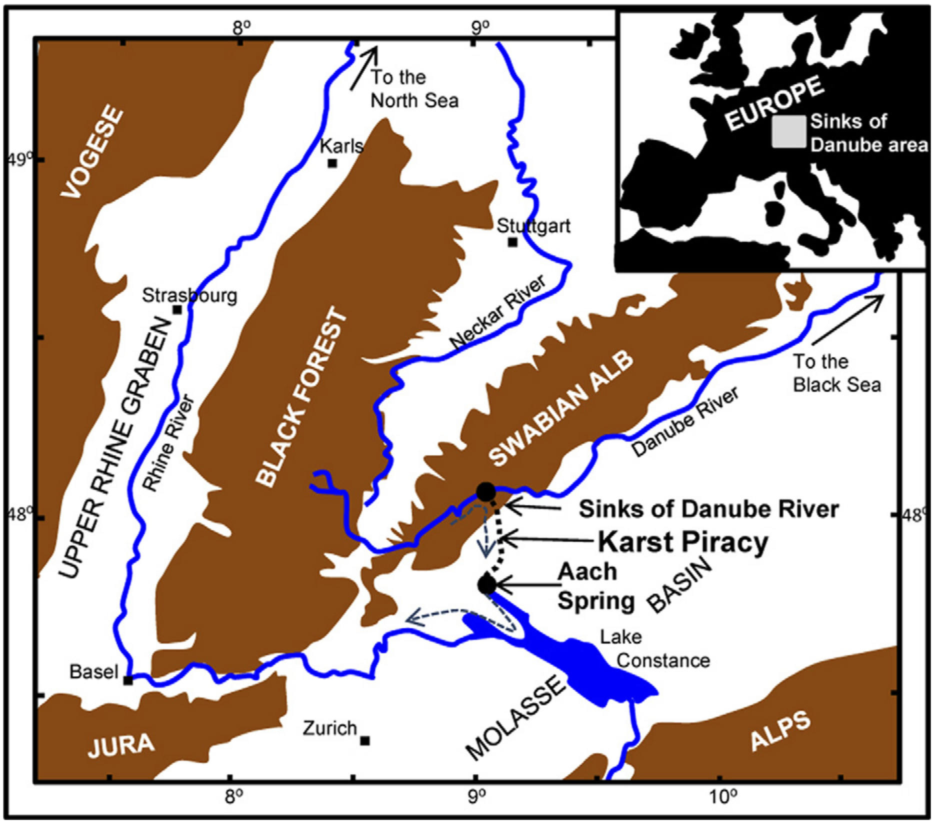

Figure 6. The River Danube–Aach spring system of the Swabian Alb, Germany. Karst piracy diverts water in the Danube from flowing to the Black Sea; instead, it finally ends up in the North Sea (after Hötzl, 1996). The proposed distance for the Grand Canyon karst system is about twice as long (22 km) as for the Danube-Aach system (11.7 km). However, the gradient of the Danube-Aach diversion is somewhat less than that proposed for a Grand Canyon connection route. According to Palmer (1991), the time required to allow rapid dissolution along an entire flow path is proportional to gradient (head/length) over length (or i/L in units of cm^{-1}). The i/L for the Danube-Aach system = 1.3 × 10^{-8} cm^{-1}, and that proposed for the Grand Canyon is ~7.7 × 10^{-9} cm^{-1}. Using the i/L charts of Palmer (1991), it would have required only about twice as long to produce a rapidly forming solution conduit under the Kaibab uplift than at Danube-Aach.

Stage E, ca. 5 Ma–Present

The final stage of karst piracy evolution is where the newly formed narrow gorge widens into a canyon, or in the case of the Grand Canyon, the section of canyon we see today from Desert View (Fig. 3, stage E). Today the bottom of the canyon in this area is far below the level of the Redwall Limestone. The caves seen in the Redwall Limestone high above the canyon when taking a river trip through the Desert View bend area are *not* karst piracy caves, nor are they related *to* this process or evidence *of* this process. They are confined hypogene caves that have been dissected by the widening of the main canyon and by headward propagation of its tributaries. Today, no section of a former karst piracy cave remains because it has been obliterated and superseded by a widening Grand Canyon. From the age constraints described here, stage D probably happened between ca. 6 and 5 Ma. Thus, there have been ~5 m.y. during stage E for the widening and deepening of the Grand Canyon in the Desert View area.

MIOCENE (17–6 Ma) WESTERN GRAND CANYON

Based on uranium-lead (U-Pb) dates of water table-type speleothems in Grand Canyon hypogene caves, a Miocene (17–6 Ma) paleocanyon west of the Kaibab uplift was proposed (Polyak et al., 2008). Young (2008) also proposed a similar Miocene precursor subbasin canyon of more than 13,000 km^2 that was restricted to the plateaus west of the uplift. Pelletier (2010) performed a numerical modeling study on the late Cenozoic geomorphic evolution of the canyon and concluded that there could have been a western Grand Canyon prior to Colorado River integration formed by headward erosion starting at the Grand Wash fault ca. 16.5 Ma. Pelletier's (2010) results are also consistent with speleothem records of water-table lowering in the western Grand Canyon (Hill et al., 2001; Polyak et al., 2008) and with the Miocene paleogeography of the region as interpreted by Young (2008).

We here explain how the concept of a 17–6 Ma western paleo–Grand Canyon fits both with a karst piracy model and with the isotopic and detrital zircon data on the Hualapai Limestone Member and Muddy Creek Formation. Refer to Table 1 for the proposed sequence of events that relates to this 17–6 Ma canyon and to how karst piracy fits into this time frame.

A western Grand Canyon headward-eroding eastward into the Kaibab uplift would be necessary for karst piracy under the Kaibab uplift because it is essential that there be an elevation difference between the recharge and discharge sides of a topographic divide, so that a strong hydraulic gradient exists between the two sides (Fig. 3, stage A). Hill et al. (2008) argued that headward erosion of a western paleo–Grand Canyon (their protowestern Grand Canyon) had to incise down to Redwall Limestone level before the setup could have been right for water to discharge on the west side of the Kaibab uplift; they also suggested that the most logical place for headward incision to have occurred was along the synclinal axis of the Laramide-age Grandview monocline (Fig. 8), which was filled with soft Moenkopi and Chinle Triassic rock.

This idea of a Miocene western paleo–Grand Canyon being necessary for karst piracy brings us back to Hunt's (1956, p. 85) objection to a Grand Canyon created by a stream piracy mechanism: i.e., it does not seem possible that a small stream would have been able to erode headward and capture streams east of the Kaibab upwarp. Spencer and Pearthree (2001) argued that headward erosion could not have made it to the Kaibab uplift from the Grand Wash in a Miocene time frame. In addition, Pelletier's (2010) modeling results (the second of his two models, based on Young's [2008] paleocanyon dimensions) suggest that a western Grand Canyon eroding headward from the Grand Wash fault at 16.5 Ma could have only reached a position east of the Shivwits Plateau by 6 Ma. If all of these arguments are correct, then it is necessary to invoke either a larger 17–6 Ma drainage basin than proposed by Pelletier (2010), or an even earlier paleocanyon in order for headward erosion to have proceeded eastward as far as the Kaibab uplift in a Miocene time frame.

Figure 7. South China karst, showing a line of collapse and unroofing along an underground river occupying a former karst piracy cave. (A) Xiaozhai Tiankeng is the biggest collapse in the area, averaging 600 m deep from the near the rim (upper left). The cave entrance is >100 m high. (B) A gorge upstream from A, where entrenchment is taking place by way of headward erosion, collapse, and diversion. The total relief in this photo is ~200 m from the bottom of the deep part shown in the foreground up to the surface that is in mist. The top of the photo is actually the bottom of a broad mature valley into which the gorge has been entrenched. We propose that, for the Grand Canyon, a karst gorge produced in this manner could have subsequently widened into a canyon by downward and sideward erosion. Photos by Alexander Klimchouk, used with permission.

In Hill and Ranney (2008; their section 5.1.2, p. 488) such an earlier Laramide paleocanyon that had formed along the Hurricane monocline was proposed, but it then veered N60°E to Kanab Point and then east to the west side of the Kaibab uplift (Fig. 8). Karlstrom et al. (2014) proposed a 70–50 Ma Hurricane fault segment paleocanyon, almost identical in time and place to the Hill and Ranney (2008) Laramide paleocanyon, except that it jogs only slightly to the northeast before heading northward along the Toroweap monocline into Utah. The basic idea in Hill and Ranney (2008) is that a Laramide paleo–Grand Canyon first incised west of the uplift due to upwarping; the Polyak et al. (2008) 17–6 Ma western Grand Canyon later followed this earlier paleocanyon, thus being able to erode headward eastward all the way to the west side of the uplift; and finally from ca. 6 Ma to the present, due to a ca. 6 Ma karst connection under the uplift, the Colorado River followed this combined Late Cretaceous–Miocene western canyon system and carved the modern Grand Canyon (Table 1).

Such a combined three-canyon system model can also help explain the classic question, Why is there no clastic delta, or large amounts of clastics from the nearby Colorado Plateau, at the mouth of the Grand Canyon if any earlier canyon system had existed? In Hill and Ranney (2008, p. 493) an attempt to answer this question invoked a Laramide paleo–Grand Canyon: "A canyon headward-eroding eastward from the Grand Wash Cliffs would have intersected a preexistent Laramide proto-Grand Canyon [meaning a Laramide paleo–Grand Canyon]… Erosion of upper Paleozoic clastic units (Toroweap, Coconino, Supai) along this paleocanyon (meaning the later 17–6 Ma western paleo–Grand Canyon of Polyak et al. [2008]) would have been *minimal* because these units had *already* been incised by a proto–Grand Canyon earlier in time; hence, very little clastic sediment would have been supplied to the Muddy Creek Formation."

In other words, the absence of a clastic delta at the mouth of the canyon may be because a Laramide paleo–Grand Canyon drainage system had previously incised into the upper Paleozoic clastic units of the central Grand Canyon and had transported this material into southern Utah during a time when the drainage pattern on the southwestern Colorado Plateau was northward; that is, before the time of a regional drainage reversal. When a drainage reversal happened is not agreed on, but most likely it was brought about by the onset of the Basin and Range episode, which was strongly underway by 17 Ma (Blakey and Ranney, 2008).

ISOTOPIC AND DETRITAL ZIRCON DATA RELATED TO A KARST PIRACY MODEL

Upsection Decrease in $\delta^{18}O$ Values and $^{287}Sr/^{286}Sr$ Ratios of the Hualapai Limestone Member

The gradual upsection decrease of oxygen and strontium isotopic values in the Hualapai Limestone Member, as reported by Roskowski et al. (2010) and Lopez Pearce et al. (2011), can be explained by a headward-expanding Mio-

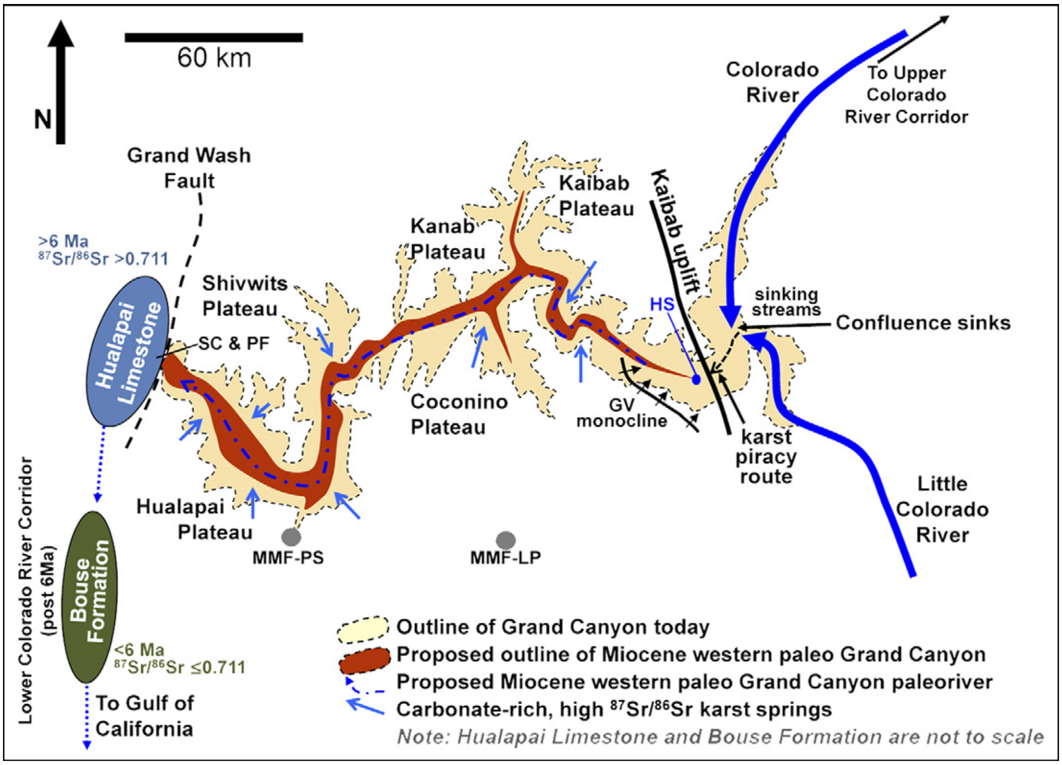

Figure 8. Model of the Polyak et al. (2008) Miocene (17–6 Ma) western paleo–Grand Canyon incising into the west side of the Kaibab uplift along the synclinal axis of the Grandview monocline. Carbonate-rich springs discharging from the Redwall karst aquifer (blue arrows) supplied high ^{87}Sr/^{86}Sr water to a small paleoriver occupying the Miocene western paleocanyon. This paleoriver fed Lake Hualapai with high-carbonate, high ^{87}Sr/^{86}Sr water, from which the Hualapai Limestone Member precipitated. A karst piracy model explains the different ^{87}Sr/^{86}Sr ratios of the Hualapai Limestone Member and the Bouse Formation. Before ca. 6 Ma and a karst connection, high ^{87}Sr/^{86}Sr karst-spring water flowed westward along this 17–6 Ma paleocanyon and into Lake Hualapai, thus accounting for its high ^{87}Sr/^{86}Sr values. After a karst connection, the Colorado River supplied low ^{87}Sr/^{86}Sr water to the Bouse Formation. The Hualapai Limestone Member in this figure was deposited in the Lake Hualapai basin of Figure 1, and the Bouse Formation in this figure was deposited in the Lake Mojave basin of Figure 1. KP—Kanab Point; MMF—Music Mountain Formation; GV—Grandview monocline; HS—Hance Spring; MMF-LP—site where Long Point Music Mountain Formation zircons were collected; MMF-PS—site where Peach Springs Music Mountain zircons were collected; SC—South Cove; PF—Pearce Ferry sites where Grand Wash trough zircons were collected.

cene (17–6 Ma) western Grand Canyon drainage in combination with a karst piracy mechanism. The first, western canyon expansion is the most important in the time frame of 12–8 Ma, before any water traversed under the Kaibab uplift; the second became more prominent in the time frame of 8–6 Ma (the beginning of subterranean water leakage; stage B to C; Fig. 3). As the 17–6 Ma Grand Canyon drainage basin west of the Kaibab uplift expanded over time, freshwater recharge would have derived from a progressively larger area and higher elevations, thereby causing the Hualapai Limestone Member to gradually decrease in its isotopic values upsection. In addition, as more water leaked under the uplift via karst piracy into this western basin ca. 8–6 Ma, it would have provided a progressive increase in low ^{87}Sr/^{86}Sr Colorado River water to the Hualapai Limestone Member.

^{87}Sr/^{86}Sr Ratios of the Hualapai Limestone Member Compared to the Bouse Formation

The Bouse Formation, which was deposited in Pliocene (after 6 Ma) Lake Mohave just south of Miocene (12–6 Ma) Lake Hualapai (Figs. 1 and 8), has much lower ^{87}Sr/^{86}Sr ratios than the Hualapai Limestone Member. Spencer et al. (2008, p. 381) made the comment that "The apparent disappearance of high ^{87}Sr/^{86}Sr values associated with lake Hualapai during the time lake Mohave was being filled also remains unexplained." We believe that this mystery can be explained from a karst piracy perspective related to a 17–6 Ma western paleo–Grand Canyon.

We have previously discussed the karst hydrology of the Grand Canyon in Hill and Polyak (2010). Essentially, hypogenic water rose from the Precambrian basement (as proposed by Crossey et al., 2006, 2009), and it was this high ^{87}Sr/^{86}Sr water mixing with epigenic water that created the acidity responsible for dissolving the confined caves in the Redwall Limestone. As the western Grand Canyon drainage of Polyak et al. (2008) extended eastward, it progressively dissected more of the Redwall Limestone, causing discharge of this high ^{87}Sr/^{86}Sr Redwall karst water at springs all along this paleocanyon. By ca. 12 Ma, when dissection reached to the level of the Redwall karst aquifer, flow of this high ^{87}Sr/^{86}Sr water down this western paleocanyon contributed significantly to the filling of Miocene Lake Hualapai (Fig. 8). Therefore, the 12–6 Ma Hualapai Limestone Member, which was deposited *before* a karst connection was complete under the Kaibab uplift ca. 6 Ma, has high ^{87}Sr/^{86}Sr ratios that reflect its high ^{87}Sr/^{86}Sr, karst-spring water source.

This situation changed *after* the karst piracy mechanism became operative under the Kaibab uplift. Once low ^{87}Sr/^{86}Sr Colorado River water began crossing under the uplift and inundating the hydrologic system of the western Grand Canyon, it swamped the effect of the high ^{87}Sr/^{86}Sr karst-spring water that had formerly fed Lake Hualapai. After 6 Ma, the Colorado River not only flowed through the Grand Canyon, but it also flowed south, filling the Bouse lakes along the lower Colorado River corridor with low ^{87}Sr/^{86}Sr Colorado River water (Fig. 8). Therefore, the Bouse Formation deposited within Lake Mojave just south of the Hualapai Limestone Member has only slightly higher strontium values than Colorado River water (Spencer et al., 2011).

Detrital Zircon Data

The detrital zircon constraints imposed by the work of Lopez Pearce et al. (2011) on the Hualapai Limestone Member seemingly negate Wernicke's (2011) model of an earlier Grand Canyon crossing the Kaibab uplift ca. 80–70 Ma (Karlstrom et al., 2011). Lopez Pearce et al.'s (2011) three samples collected from the Hualapai Limestone Member and Muddy Creek Formation at South Cove and Pearce Ferry also seemingly negate any river supplying sediment through a canyon eroding into the Colorado Plateau to the east, because these samples lack detrital zircon spectra typical of late Paleozoic rock (but not of early Paleozoic rock). However, to us these seem like premature conclusions based on only three samples (with the two South Cove samples being collected at the same site, one above the other). Also, the lack of Jurassic detrital zircon in these three samples may suggest a provenance from a Proterozoic source terrain to the south rather than from the Music Mountain Formation on the Colorado Plateau. Before a negative verdict on any western canyon existing prior to 6–5 Ma is pronounced, a more robust detrital zircon sampling program seems necessary.

Specifically, with regard to our karst piracy model, we interpret that detrital zircon from a Colorado River source could have not made it under the Kaibab uplift until after a connection had been firmly established during karst piracy stage D at 6–5 Ma (Fig. 3). However, once the Colorado River flowed freely under the uplift, Colorado Rocky Mountain gravels and detrital zircons could have been transported by the Colorado River to the west side of the Grand Canyon and then down the lower Colorado River corridor. Thus, Rocky Mountain and Colorado Plateau detrital zircon signatures can be found today in post-Hualapai (Bouse and Imperial Formations) sediments all the way to the Gulf of California (Dorsey et al., 2007, 2011; Kimbrough et al., 2011).

HUNT'S "OUTRAGEOUS PIPING HYPOTHESIS"

Hunt (1974) was the first to propose a karst connection for the Grand Canyon, calling it "an outrageous hypothesis." However, it was not a karst connection across the Kaibab uplift; it was a karst connection in the western Grand Canyon, between the Hualapai Plateau and the Grand Wash trough. Specifically, Hunt (1974) proposed that a lake had once ponded in the Peach Springs Canyon region, and piping into cavernous limestone caused this lake water to escape via caverns to the Grand Wash. This carbonate-rich cave water discharged in springs that filled Lake Hualapai, from which the Hualapai Limestone Member precipitated. Pederson (2008, p. 8–9) invoked Hunt's "forgotten idea," calling it "the infiltration and dissipation hypothesis" and citing the now-dissected karst system exposed in the walls of the western Grand Canyon as possible evidence for Hunt's model. If Hunt's piping is taken to mean karst piracy, then this process could have operated in the western Grand Canyon as well as under the Kaibab uplift, as we have proposed in this paper.

It is possible that movement along the Grand Wash fault ca. 16 Ma could have set up the right gradient conditions necessary for the karst piracy mechanism. However, a model as envisioned by Pederson (2008, p. 9), where water infiltrated through the "now-dissected karst system exposed in the western limestone," does not explain the caves in the western Grand Canyon or along the Grand Wash Cliffs. The caves along the Grand Wash Cliffs (e.g., Site 1 of Polyak et al., 2008) or along the Colorado River in the western Grand Canyon (e.g., Bat Cave) are hypogene phreatically developed caves, as evidenced by the mammillary speleothems and replacement gypsum in them (Hill and Polyak, 2010). These caves were never part of a dissected cave system, and they were not originally drains to the Grand Wash. They formed like Carlsbad Cavern and Lechuguilla Cave in the Guadalupe Mountains of New Mexico, where speleogenesis was due to the point-source input of hypogenic acids that dissolve caves unconnected to each other (Hill, 1990). However, if a karst piracy mechanism once operated in the westernmost Grand Canyon, it would have obliterated any traces of former karst piracy cave passages, and it would have also exposed the phreatically developed caves like Bat Cave along its former course (as we have proposed for the Kaibab uplift).

Another problem with a karst piracy mechanism for the westernmost Grand Canyon is that a barrier like the Kaibab uplift has never been defined or proposed for this area. However, it is possible that the interpretation of Karlstrom et al. (2014) of a 6–5 Ma westernmost Grand Canyon may require such a barrier.

CONCLUSIONS

A karst piracy model offers a viable way for the Colorado River to have crossed under the Kaibab uplift ca. 6 Ma. The comparison of the Grand Canyon to other river systems of the world where karst piracy is known to occur, offers strong support for karst piracy under the uplift.

Karst piracy was not an abrupt process, but probably took a few million years to happen once the necessary geomorphic conditions were achieved.

Karst piracy, in conjunction with a headward-eroding, 17–6 Ma western paleo–Grand Canyon, can explain the gradual upsection decrease in the $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values of the Hualapai Limestone Member. With drainage-basin expansion of the headward eroding western paleocanyon system, more freshwater from progressively higher elevations would have reached the Hualapai Limestone Member in the Grand Wash trough, thus producing the isotopic decrease.

Oxygen and strontium isotope data on the Hualapai Limestone Member favor a slow and relatively gradual change of groundwater chemistry for the water depositing the limestone, and do not support a lake spillover model. The distinct values of the Hualapai Limestone Member should not have freshened gradually upsection if there was a sudden and relatively catastrophic spillover of the Colorado River ca. 6 Ma.

While the $^{87}Sr/^{86}Sr$ data are not uniquely supportive of a karst piracy model, they appear to favor it. A stream piracy mechanism slowly eroding headward into the Kaibab uplift could explain the data, but it seems like such a connection would have produced a rapid release of water from the east side of the uplift. The gradual change of $^{87}Sr/^{86}Sr$ in the Hualapai Limestone Member seems best explained by the gradual (over a few million years) process of karst piracy under the Kaibab uplift.

A karst piracy model can explain the high $^{87}Sr/^{86}Sr$ ratios in the Hualapai Limestone Member, in comparison to the low $^{87}Sr/^{86}Sr$ ratios of the Bouse Formation, located just south of the Hualapai Limestone Member. Before a karst connection ca. 6 Ma, Lake Hualapai was partly supplied by high $^{87}Sr/^{86}Sr$ karst spring water issuing from the Redwall Limestone along a 17–6 Ma paleocanyon west of the Kaibab uplift. After a karst connection ca. 6 Ma, when the Colorado River made its way across the entire Grand Canyon, the Colorado supplied river water to Lake Mohave, resulting in the Bouse Formation having lower $^{87}Sr/^{86}Sr$ values.

No Colorado River sediments carrying a Colorado Plateau detrital zircon signature arrived in the lower Colorado River corridor from the Colorado Rockies until after ca. 6 Ma, when a karst connection enabled the Colorado River to breach the Kaibab uplift.

While the process of karst piracy possibly began a few million years prior to 6 Ma, a karst connection under the Kaibab uplift happened ca. 6–5 Ma, and probably not much earlier. Therefore, the karst piracy model differs from the eastern Grand Canyon model of Flowers et al. (2008) or Wernicke (2011), where water flowing east across the Kaibab uplift carved a much older (ca. 80–70 Ma) Grand Canyon down to almost its present depth.

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