A Miocene river in northern Arizona and its implications for the Colorado River and Grand Canyon

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ABSTRACT

The southwesterly course of the pre–late Miocene Crooked Ridge River can be traced continuously for 48 km and discontinuously for 91 km in northern Arizona. It is visible today in inverted relief. Pebbles in the river gravel came from at least as far northeast as the San Juan Mountains. The river valley was carved out of easily eroded Jurassic and Cretaceous rocks, whose debris overloaded the river with abundant detritus, possibly steepening the gradient. After the river became inactive, the regional drainage network was rearranged twice, and the Four Corners region was lowered by erosion 1–2 km. The river provides constraints on the history of the Colorado River and Grand Canyon; its continuation into lakes in Arizona or Utah is unlikely, as is integration of the Colorado River through Grand Canyon by lake spillover. The downstream course of the river was probably across the Kaibab Arch in a valley roughly coincident with the present eastern Grand Canyon.

INTRODUCTION

A turning point in the long history of thought about the origin and age of the Colorado River and Grand Canyon came in the mid-1960s and 1970s when McKee et al. (1967) and Lucchitta (1975, 1989) proposed a polyphase history in which an old upper river flowing on the Colorado Plateau was captured by a young lower river that extended itself by headward erosion from the just-opened Gulf of California (Durham and Allison, 1960). This model implied a post-5–6 Ma age for the integrated Colorado River and the Grand Canyon.

Recent work mostly accepts a complex history, but some rejects a young age or the concept of integration through headward erosion. Data from Crooked Ridge River provide constraints on several of the new proposals, including (1) that an ancestral river flowed into or out of "Hopi Lake" in a north or northwesterly direction (see below); (2) that an ancestral river flowed northward along the present course of Marble and Glen Canyons; and (3) that the Colorado River was integrated through Grand Canyon by the spillover of Hopi Lake.

Scattered exposures of gravel in northern Arizona have long been known (e.g., Cooley et al., 1969; Hunt, 1969; R. Hereford, 1975, personal commun.), but integration of these observations into a coherent drainage system only became possible with the advent of detailed topographic maps, and especially satellite and digital elevation model (DEM) data. Such images presented here are composites of Landsat and shaded-relief DEM data with 10–30 m resolution and 2× vertical exaggeration, obtained from the U.S. Geological Survey Eros Data Center's seamless server.

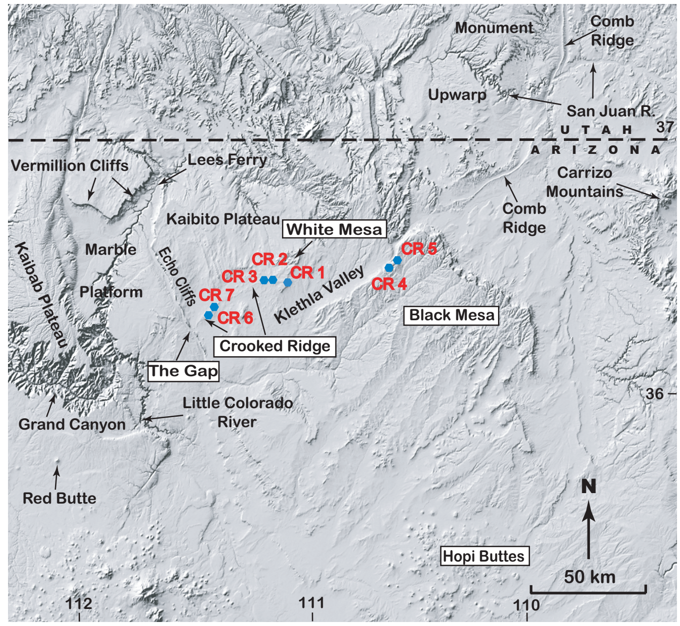

Figure 1. Digital elevation model image showing geographic features of the Kaibito Plateau–Black Mesa region in Arizona near Crooked Ridge. Blue dots show sample localities; red labels are sample numbers.

PHYSICAL CHARACTERISTICS OF CROOKED RIDGE

Crooked Ridge extends continuously across the Kaibito Plateau of northern Arizona from the eastern edge of White Mesa to The Gap, a large wind gap carved into the Jurassic Navajo Sandstone at the Echo Cliffs (Figs. 1 and 2). The ridge is 48 km long in a straight line, and 55 km long along its trace. An isolated remnant of river deposits with distinctive clasts similar to those on Crooked Ridge occurs near the northwest corner of Black Mesa, ~43 km from the nearest exposures on White Mesa and approximately on the same gradient and trend (Figs. 1 and DR1[1]). The river course can thus be traced for 91 km.

The sinuous Crooked Ridge is an example of inverted relief that came about because deposits in the floodplain of an ancient river were protected by a cap of massive 1–2 m pedogenic Stage V calcrete, whereas the rest of the valley was not so protected and has been preferentially lowered by erosion (Figs. 3 and 4).

Remnants of the river deposits now occur on about a quarter of the ridge's length westward from White Mesa and about a third of the length eastward from The Gap (Figs. 1, 2, and DR1). The intervening part has either fragmentary river deposits or none. The capped parts of the ridge rise as much as 110 m above the adjacent landscape, whereas the eroded bedrock parts are as much as 50–80 m above it. On satellite images, the preserved river deposits are as much as ~1000 m wide, though generally less.

GSA Today, v. 21, no. 10, doi: 10.1130/G119A.1

[1]GSA supplemental data item 2011320, Tables DR1–DR3 and Figures DR1 and DR2, is available online at www.geosociety.org/pubs/ft2011.htm. You can also request a copy from *GSA Today,* P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

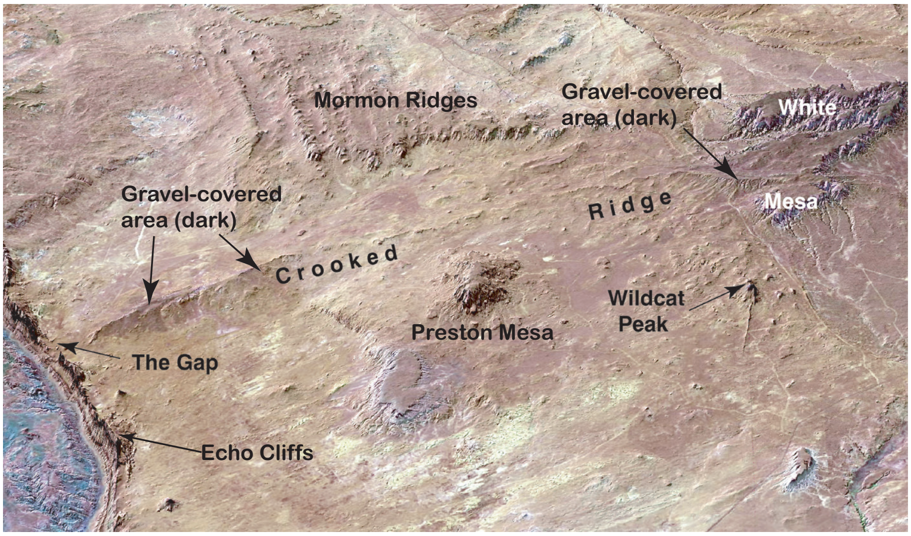

Figure 2. Oblique view of Kaibito Plateau with Crooked Ridge in center, looking north. Approximate straight-line length along the ridge from east edge of White Mesa to The Gap is 48 km. North side of old river valley is clearly visible. Wildcat Peak is a monchiquite intrusive probably 8–6 Ma. No monchiquite clasts were found in the gravel, even though the peak is less than 13 km from Crooked Ridge.

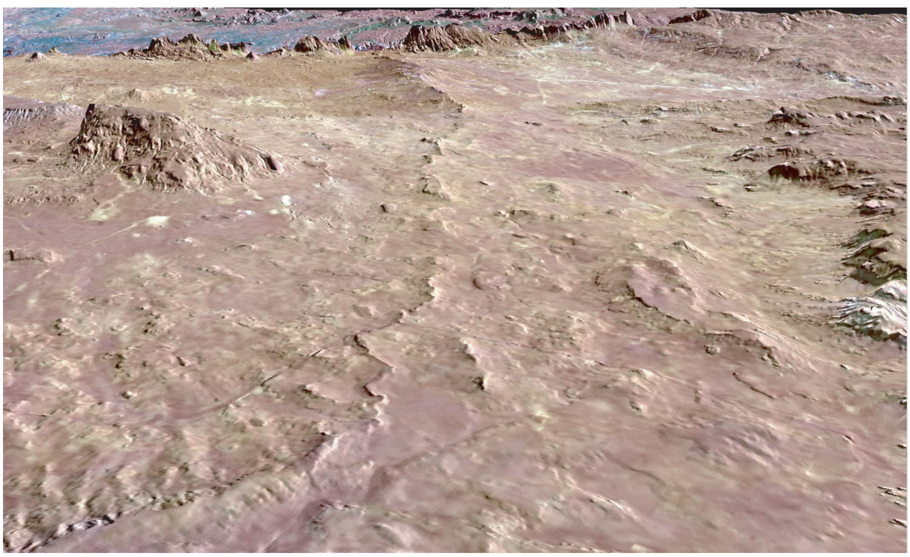

Figure 3. Oblique view looking SW along Crooked Ridge to The Gap 48 km away in a straight line. Ridge follows course of the ancient river in inverted relief. Wider parts of ridge in foreground and at far end are mantled with river deposits; parts in between are primarily bedrock.

Figure 4. Exposure of fluvial sediments on Crooked Ridge, 9 km northeast of The Gap. The exposure consists primarily of sand, with subordinate mud and clay. Gravel is common near top, also within light-colored calcrete cap. Channeling is common.

Along most of the Kaibito Plateau reach, the bedrock for the Crooked Ridge valley is the relatively weak upper part of the Navajo Sandstone and the easily eroded Carmel Formation at the base of the San Rafael Group. These rocks allowed formation of a wide river valley. Evidence for this is visible on satellite images, where the north edge of the old valley is marked by a south-facing 150 m scarp that parallels the trend of Crooked Ridge and truncates the south-southeast–trending Mormon Ridges (Figs. 2 and 3).

The ill-defined south edge of the valley probably is along the northern end of bedrock prominences such as Preston Mesa (Fig. 2) and the southern part of White Mesa. This alignment parallels both Crooked Ridge and the northern edge of the valley. If this alignment is taken as the south edge, the valley may have been as much as 5–10 km wide across most of the Kaibito Plateau.

At The Gap (Figs. 1 and 2), the valley crosses the Echo Cliffs ridge, formed by the resistant Navajo Sandstone upturned along the Echo Cliffs monocline. This defile is visible today in cross section. The present rim-to-rim width of the gap is 3.4 km and its depth is 290 m, as measured on satellite images and topographic maps.

STRUCTURAL AND STRATIGRAPHIC FEATURES

Between Black Mesa and White Mesa, the ancient drainage crosses Klethla Valley at a low angle. This is a strike valley along the south continuation of the Tsegi–Comb Ridge system of monoclinal flexures, a part of a major structural trend that continues northward for ~250 km along Comb Ridge and separates the Monument upwarp to the northwest from structurally low areas to the southeast (Figs. 1, 5, and DR2 [see footnote 1]).

On Kaibito Plateau, Crooked Ridge crosses several down-to-the-east monoclinal flexures (Fig. DR2). West of Echo Cliffs, the Kaibab Plateau is a north- and south-plunging dome (Fig. 1) bounded on the east by the East Kaibab monocline, which also has down-to-the-east displacement. The Colorado River forms a great bend that follows the strike of the strata around the south-plunging part of the dome. The effect of the various monoclines is to expose strata successively lower in the section toward the west.

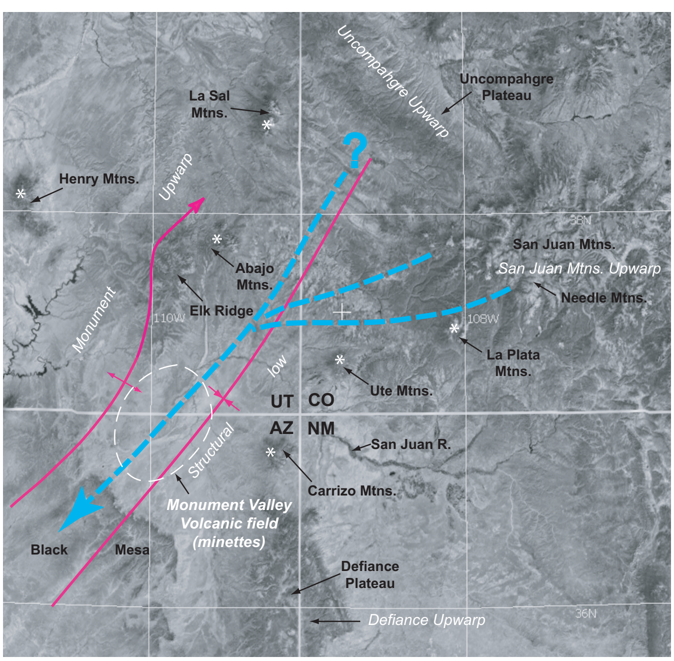

Figure 5. Thick dashed blue lines indicate inferred approximate courses of Crooked Ridge River and possible tributaries. Magenta anticline and syncline symbols denote structurally high and low areas, respectively. Thin dashed white line bounds Monument Valley minette volcanic field. White asterisks mark laccolithic mountains with hypabyssal porphyry exposed. White lettering denotes geologic features; black lettering, geographic features.

The remnant of fluvial deposits on Black Mesa rests on the Wepo Formation in the middle of the Upper Cretaceous Mesaverde Group. The ancient valley sides are not preserved here but must have been composed of Upper Cretaceous rocks above the Mesaverde Group, perhaps correlating with the Wahweap Formation of the Kaiparowits Plateau ~110 km northwest in southern Utah. This unit probably also formed the valley floor and sides northeast of Black Mesa toward the San Juan Mountains.

The sides of the old valley between Black Mesa and White Mesa, now occupied by Klethla Valley, were in the Mesaverde Group and the underlying Mancos Shale and Dakota Sandstone of Cretaceous age as well as the Morrison Formation and Entrada Sandstone of Jurassic age.

White Mesa is capped today by the Entrada Sandstone and thin remnants of the Cretaceous Dakota Formation (F. Peterson, 2010, personal commun.). The reach between White Mesa and The Gap is rimmed by the upper part of the Jurassic Navajo Sandstone and the Carmel Formation, capped locally by small remnants of Entrada. In Crooked Ridge time, Jurassic and Cretaceous rocks most likely rimmed all these parts of the valley.

The abundance of easily eroded rocks along the river course likely influenced the character of the river.

LITHOLOGIC CHARACTERISTICS AND PROVENANCE OF TRANSPORTED MATERIAL

A minimum of 20 m of fluvial material is exposed on Crooked Ridge. Good exposures show that the bulk of the deposits consist of sand containing stringers and interbeds of gravel, mud, and clay. Gravel is more abundant near the top of several exposures. Channeling at <1 to ~10 m scale is common (Fig. 4), as is cross bedding that shows a southwest flow direction (noted by us and by Hunt, 1969). The sand is weakly indurated, fine- to medium-grained but locally medium- to coarse-grained, and subrounded to subangular. A small percentage of grains are fine, very well rounded, and frosted, and were probably derived from Mesozoic eolianites. The scarcity of eolian sand suggests that the Oligocene Chuska erg of Cather et al. (2008) either was never present in the area traversed by Crooked Ridge River or was eroded by the time the river was active.

Composition, sampling methods, sampling locations, and inferred sources of gravel are shown in Tables DR1 and DR2 (see footnote 1). Clasts are considered distinctive or non-distinctive according to the level of confidence in assessing provenance; both locally derived and far-traveled or exotic clasts are present. Most locally derived clasts are quartz sandstones from the upper Mesozoic formations that formed the valley sides on the Kaibito Plateau, Black Mesa, and upstream from Black Mesa (Harshbarger et al., 1958; Page and Repenning, 1958; Cooley et al., 1969). Also common are petrified wood and fossiliferous limy sandstone, both derived from upper Mesozoic formations. Typically, these clasts are subangular to subrounded; maximum size generally is ~30 cm, but a few boulders, which probably rolled in from the valley sides, reach 100 cm in diameter. Exotic clasts are subrounded to rounded, mostly 1–3 cm in diameter, but reach 10 cm.

Exotic clasts include many types of volcanic, hypabyssal, plutonic, and metamorphic lithologies; petrographic characteristics link them with specific sources northeast of Crooked Ridge and

Black Mesa at least as far as the San Juan Mountains (Table DR2). Minettes came from the late Oligocene to early Miocene dikes and diatremes of the Navajo volcanic field, most likely from the Monument Valley section (Laughlin et al., 1986, and references therein) (Fig. 5). Clasts of granite, pegmatite, and perthitic microcline also probably came from intrusions in Monument Valley, where these lithologies are especially common as xenoliths.

The intermediate porphyries are strikingly similar to rocks reported in laccolithic centers of the Colorado Plateau, including the Abajo, Carrizo, Henry, La Plata, La Sal, and Ute Mountains (Friedman and Huffman, 1998, and references therein). The emplacement depth of these Laramide and middle Tertiary intrusions is uncertain, but probably <2400 m below the surface at the time of intrusion. Erosion of Upper Cretaceous and possibly early Tertiary strata unroofed these distinctive porphyries in the Crooked Ridge River drainage basin and fed pebbles into the river.

All the distinctive clasts of metamorphic rocks can be matched with Proterozoic rocks mapped in the Needle Mountains (Fig. 5), where today they crop out at elevations as high as 4000 m. The quartz metaconglomerate and metawacke are comparable with some of the lithologies in the Vallecito Conglomerate and the Irving Formation, and the fine quartzofeldspathic gneiss matches the Twilight Gneiss (Larson and Cross, 1956; Barker, 1969).

Felsic lava flows, welded tuffs, andesites, latites, and hydrothermal mineral deposits are widespread and abundant in the Oligocene San Juan volcanic field (Lipman et al., 1978). The distinctive clasts of these lithologies, as well as most if not all the non-distinctive clasts of the same type, are likely to have come from this region.

The pebbles of crystal tuff and altered rhyolite and andesite are not likely to be reworked from older gravel deposits because the former are friable and the latter are soft. Pebbles of rhyolitic vitrophyre are not likely to be reworked from the Chinle and Morrison Formations because they are glassy and not devitrified as are those from the Mesozoic formations (Cadigan, 1972; Thordarson et al., 1972; Dodge, 1973). Notably absent from the samples collected at Crooked Ridge and Black Mesa are clasts of limestone similar to the Kaibab Formation on the Kaibab Plateau, red sandstone similar to that of Triassic rocks on the Colorado Plateau, and monchiquite, a volcanic rock common in the Hopi Buttes to the south (Fig. 1) and also present at Wildcat Peak, not far south of Crooked Ridge on the Kaibito Plateau (Fig. 2).

AGE OF CROOKED RIDGE

We only have indirect methods for estimating the age of Crooked Ridge River. One is that the course of the river has no relation to the present drainage network. Instead, two distinct episodes of drainage arrangement have occurred since Crooked Ridge River time. The first of these is the development of Klethla Valley (Fig. 1), which cuts across the course of the ancient river. Klethla Valley is broad and mature and typical of many such valleys on the Colorado Plateau. This valley in turn is being beheaded by immature drainages of the canyon-cutting cycle that are tributary to the Colorado and San Juan Rivers. These two major rearrangements of the drainage network since Crooked Ridge time require an indeterminate but substantial time interval.

Another indirect method involves Wildcat Peak (Fig. 2), a monchiquite intrusive that is part of the Tuba volcanic field (Akers et al., 1971). Wildcat Peak has not been dated, but volcanic rocks of this composition have been dated in the Hopi Buttes at 6–8.5 Ma (Damon and Spencer, 2001), suggesting a similar age for this intrusive. No monchiquite clasts have been found in the gravel even though Wildcat Peak is <13 km from Crooked Ridge, toward which tributary streams near Wildcat Peak presumably flowed. Therefore, we infer that the river became inactive before the intrusive was emplaced or unroofed in the late Miocene.

Finally, removal of 1–2 km of strata from the area of the laccolithic intrusives since they were first unroofed (see below), must have taken a substantial time. Such deep erosion is in agreement with results obtained by other techniques (e.g., Pederson et al., 2011).

On the basis of these considerations, we infer that the Crooked Ridge River was active in mid-Miocene (and perhaps earlier?) time, in keeping with Hunt's (1969) suggestions concerning the age of paleodrainages in the region. The river became inactive in the late Miocene.

LONGITUDINAL PROFILE OF THE RIVER

The farthest east and highest exposure of river deposits is on Black Mesa at 2240 m; the farthest west and lowest near The Gap is at ~1700 m. Over the 91 km that Crooked Ridge River can be traced from Black Mesa to The Gap, the river deposits drop 530 m, giving an average present-day gradient of 5.8 m/km. The gradient of individual reaches varies considerably (Fig. DR1), probably reflecting differences in the rocks into which the valley was carved, structural features such as monoclines, and constrictions such as The Gap in the river's path. The relatively high gradient can plausibly be ascribed to overloading by sediment derived from the easily eroded Jurassic and Cretaceous rocks that formed the valley sides upstream from The Gap. Internal structures of the river sediments suggest a braided stream and support this interpretation.

An alternative explanation for the steep gradient of the deposits is post-depositional tilting of the channel due to crustal warping such as a "bull's-eye" of isostatic unloading to the north (Lazear et al., 2011; Pederson et al., 2011) or mantle dynamics (Robert et al., 2011; Moucha et al., 2009). However, the inferred bull's-eye is in the Canyonlands country north to northwest of Crooked Ridge River, so the river's course is essentially tangential to the uplift contours and should be little affected by this unloading.

The mantle-dynamics studies suggest northeast tilting for nearly all the Miocene and southwest tilting since then. Therefore, the river would have been tilted first northeast and then southwest. It is currently not possible to evaluate the net effect of these tilting events on the gradient of Crooked Ridge River.

The erosional history of the Colorado Plateau in the eastern Grand Canyon region shows a wave of erosion starting in the southwest and progressing northeast with time, mostly through cliff retreat at 4–8 km/Ma (Lucchitta, 1975; Holm, 2001; Lucchitta and Jeanne, 2001). This erosion would cause northeast tilting of the region because of isostatic uplift and may have decreased the original gradient of the nearby Crooked Ridge River.

In conclusion, the steep gradient of the river deposits is plausibly explained by overloading, although tectonic adjustments can neither be proved nor ruled out at this time.

COMPARISON WITH OTHER RIVERS

It is useful to compare the characteristics of Crooked Ridge River with those of other present-day overloaded streams with similar configurations in order to estimate the gradient and possible discharge of the ancient river. Two such streams are a reach of the Animas River upstream from Durango and the San Juan River upstream from Pagosa Springs, both in southwest Colorado. Data for these streams and for Crooked Ridge River are in Table DR3 (see footnote 1).

The comparison suggests that a steep gradient for the overloaded Crooked Ridge River is not unreasonable, and that (together with the exotic clasts) the ancient river was not a minor local wash, but a river of regional extent whose discharge was at least comparable to those of today's Animas and upper San Juan Rivers.

EROSIONAL LOWERING

The relative scarcity of porphyry clasts in Crooked Ridge gravel contrasts markedly with their abundance in even the oldest terraces of the Colorado River. We infer that the laccolithic intrusives were less exposed when the Crooked Ridge River was active than they are today and that some were not exposed at all (Eckel et al., 1949). Today, a few of these rocks are exposed at altitudes as high as 4000 m, and many are at 3000–3500 m; in Crooked Ridge River time, only the highest would have been exposed. Hence, the scarcity of these clasts in the gravel suggests a topographic surface in the 3500+ m range. Today, the region in southwest Colorado and southeast Utah near the intrusives is at 1500–2000 m, suggesting that 1–2 km of strata has been removed since Crooked Ridge River time.

PERMISSIBLE AND IMPERMISSIBLE PALEODRAINAGES

The middle Miocene to lowermost Pliocene(?) Bidahochi Formation figures prominently in hypotheses on the history and integration of the Colorado River on the Colorado Plateau. The formation was deposited in Bidahochi basin, roughly centered in the Hopi Buttes (Fig. 1). The origin of the formation is controversial. Spencer et al. (2008) proposed that it was deposited in a deep "Hopi Lake" large enough to potentially extend into southern Utah. The postulated lake was the sump of a large drainage system that crossed the Colorado Plateau and headed in the Snake River basin, as inferred from fossil fish of Snake River affinities and adapted to swift-flowing rivers. The lake would eventually have spilled over into a drainage along the present Grand Canyon, initiating a top-down cascade of spillovers that integrated the Colorado River in its present course through Grand Canyon and the lower Colorado region (e.g., Meek and Douglass, 2001; Scarborough, 2001).

Others (e.g., Dallegge et al., 2001; Dickinson, 2011) propose that the formation was deposited not in a deep lake, but rather in shallow and ephemeral ones that at times probably were playas and were filled by fluvial aggradation.

Crooked Ridge River provides useful constraints on the Bidahochi Formation issue. The southwesterly course of the river from the San Juan Mountains to the Kaibab upwarp makes it impossible for rivers such as an ancestral Colorado to flow southward or southeastward from western Colorado or eastern Utah into "Hopi Lake" or, conversely northward or northwestward from "Hopi Lake" (Fig. 6).

It is difficult to reconcile the existence of a large lake near (let alone across) the well-established Crooked Ridge River, which presumably had a developed drainage network and had cut down to a lower elevation than the lake. It is also difficult to envision a sudden, catastrophic, and canyon-forming spillover of the lake in an area where the valley of the Crooked Ridge River already existed. Even had the spillover taken place, the resulting flow would have been along the course of Crooked Ridge River, not through western Grand Canyon.

As the current evaluations of tilting are speculative, we use the 1700 m altitude of Crooked Ridge River sediments near The Gap as a preliminary constraint on possible continuations of Crooked Ridge River downstream, where no deposits are preserved (Fig. 6).

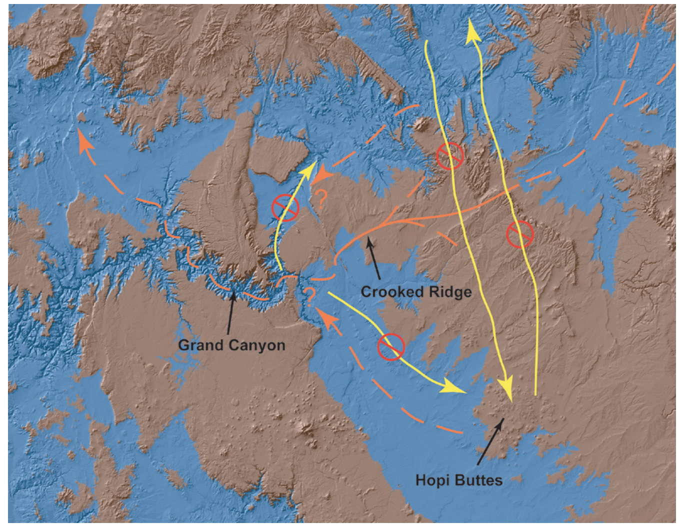

Figure 6. Digital elevation model image showing elevations above (brown) and below (blue) 1700 m, the elevation of Crooked Ridge gravel at The Gap. Brown areas are excluded from possible continuation of river; blue areas are permissible continuations assuming no gradient for the river (boundary condition). Hopi Buttes are mostly excluded. Headwaters of Little Colorado River (off image) are excluded. Orange lines are permissible river courses; yellow lines, impermissible. Orange lines with query denote possible ancestral Colorado and Little Colorado Rivers.

Accordingly, the Bidahochi basin is part of the excluded terrain, because the base of the Bidahochi Formation is at ~1750 m (Love, 1989; Cather et al., 2008). Thus, it is unlikely that the Crooked Ridge River would have filled the hypothetical Hopi Lake even in the absence of a gradient.

Figure 6 also shows that the only possible continuation beyond The Gap is southward along the alignment of the Echo Cliffs, then westward to near the present-day confluence of the Colorado and Little Colorado Rivers. From this point, the river could flow either north along the alignment of the present Marble Canyon, or west along the alignment of the present eastern Grand Canyon.

If the ancient river flowed north, possibly to a hypothetical and undocumented "Glen Lake" (Hill and Ranney, 2008), its current average gradient would place it at an elevation of 920 m at Lees Ferry, which is below even the present Colorado River elevation there. If the gradient had been only 3 m/km, the river would have been ~350 m above present river grade in the Miocene. However, the present river grade is much lower than it was in Crooked Ridge time because the Colorado was ~200 m higher just 525–600 ka ago (Lucchitta, unpub. field data, 1998; Lucchitta et al., 2000, 2001), giving an incision rate of 380–330 m/Ma. So even at 1 Ma the Colorado River grade would have been at that of the Crooked Ridge River or higher. The incision is the product of vigorous post–5 Ma downcutting by the Colorado River. Projecting the rate over this interval would bring the river elevation at Lees Ferry to 1600–1900 m above present river grade, or ~1 km above the elevation of the Crooked Ridge River at The Gap. Neither distant nor more local warping is likely to overcome such a topographic disparity.

We conclude that the Crooked Ridge River was unlikely to flow northward from the area of The Gap. On the other hand, our data do not preclude an ancient river such as the ancestral Colorado River flowing southwestward along approximately its present course but at a higher elevation, to join the Crooked Ridge River in the area of the present-day confluence of the Little Colorado River.

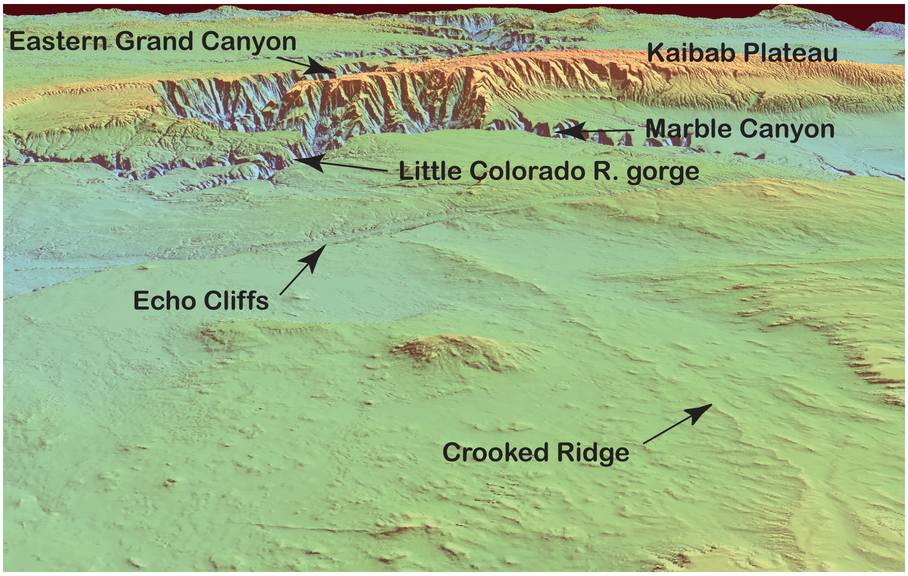

Figure 7. Oblique view to SW along Crooked Ridge (foreground) heading for eastern Grand Canyon (background).

A course westward is possible along the alignment of the present eastern Grand Canyon (Figs. 6 and 7). This potential route was proposed long ago by Babenroth and Strahler (1945) and Lucchitta (1975, 1989) and, more recently, by Scarborough (2001) and Flowers et al. (2008). The greater width and complexity of the Grand Canyon here supports an older age than for other parts of the canyon. Most likely, the old course was in a broad valley that followed the curving strike of strata around the south-plunging part of the Kaibab arch. Valley rims were in Mesozoic rocks and the floor was incised some hundreds of meters below the top of the Kaibab Limestone.

Regarding the continuation of the Crooked Ridge River beyond the Kaibab Plateau, a course along western Grand Canyon and the Lake Mead area is precluded by widespread and well documented Miocene interior-basin deposits at the mouth of the Grand Canyon (Longwell, 1936; Lucchitta, 1966, 1967, 1972, 1989). We offer instead the speculation that the river flowed northwestward (Fig. 6) to near St. George, Utah, then generally northward along the east flank of the Sevier orogenic belt, eventually reaching the Snake River basin. This would allow fish of Snake River affinities (Spencer et al., 2008) to reach the Colorado Plateau area near Crooked Ridge River.

CONCLUSIONS

1. Crooked Ridge River was a substantial stream of northern Arizona that headed at least as far northeast as the San Juan Mountains of Colorado. The age of the river is poorly constrained. In keeping with Hunt (1969) and our findings, we think it was of middle Miocene age, and possibly older. The river probably became inactive in late Miocene time.
2. The clasts of the river are not reworked from some older river because several of the clast lithologies would not survive recycling.
3. Channel characteristics and gradient compare favorably with two substantial present-day rivers in the region.
4. The ancient river bore no relation to the present-day drainage network. On the contrary, two entirely different drainage configurations have developed since Crooked Ridge River time.
5. The southwesterly course of the river from the San Juan Mountains to the Kaibab upwarp makes it impossible for other rivers such as an ancestral Colorado to flow across the Crooked Ridge River into or away from northeast Arizona and lakes such as Hopi Lake, nor could it empty into these lakes.
6. The Crooked Ridge River could not flow northward along the present course of Marble Canyon.
7. A southwest- or south-flowing river (ancestral Colorado?), topographically much higher than the present river, could have joined Crooked Ridge River somewhere near the present mouth of the Little Colorado River.
8. A westward continuation of the river(s) along the alignment of the present eastern Grand Canyon around the Kaibab arch is possible and our favored alternative.
9. It is unlikely that a lake spillover would have integrated the Colorado River through the western Grand Canyon because an older and well developed river system was already in place that did not flow through the western Grand Canyon into the upper Lake Mead area.
10. Since the river became inactive, the Four Corners region has been lowered erosionally by 1–2 km.

ACKNOWLEDGMENTS

We thank Fred Peterson and Marith Reheis for their helpful reviews, and Trent Hare for indispensable help with the graphics.

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Manuscript received 23 Feb. 2011; accepted 20 July 2011. ✷

~ This paper is dedicated to the memory of Charlie Hunt, Chester Longwell, and Eddie McKee—On whose shoulders we stand. ~