Re-evaluation of exotic gravel and inverted topography at Crooked Ridge, northern Arizona: Relicts of an ancient river of regional extent

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ABSTRACT

An ancient drainage, named Crooked Ridge river, is unique on the Colorado Plateau in extent, physiography, and preservation of its alluvium. This river is important for deciphering the generally obscure evolution of rivers in this region. The ancient course of the river is well preserved in inverted relief and in a large valley for a distance of several tens of kilometers on the Kaibito Plateau–White Mesa areas of northern Arizona. The prominent landform ends ~45 km downstream from White Mesa at a remarkable wind gap carved in the Echo Cliffs.

The Crooked Ridge river alluvium contains clasts of all lithologies exposed upstream from the Kaibito Plateau to the San Juan Mountains in Colorado, so we agree with earlier workers that Crooked Ridge river was a regional river that originated in these mountains.

The age of Crooked Ridge river cannot be determined in a satisfactory manner. The alluvium now present in the channel is the last deposit of the river before it died, but it says nothing about when it was born and lived. Previous research attempted to date this alluvium, mostly indirectly by applying a sanidine age obtained ~50 km downstream from White Mesa at a remarkable wind gap carved in the Echo Cliffs.

INTRODUCTION

The development of Cenozoic drainage on the Colorado Plateau has long been a subject of interest and debate. Active research continues to the present day, in part because drainage development included, at some stage, the formation of the Grand Canyon. Data on which to base paleodrainage reconstructions are few, largely owing to the deep erosion that has affected the plateau in late Cenozoic time.

Seen in this context, a paleoriver that is exposed for tens of kilometers in the Kaibito Plateau and Black Mesa of northern Arizona stands out as the best, and indeed the only, paleoriver that is exposed so well, for such a distance, and in so large a valley on the Colorado Plateau. We name this paleoriver Crooked Ridge river.

One part of the paleoriver’s valley has long been known because it forms a conspicuous wind gap in the impressive Echo Cliffs (Figs. 1 and 2). Because of this, geologists such as M.E. Cooley (Cooley et al., 1969) and C.B. Hunt (1969) visited the area near the wind gap (Figs. 1 and 2) and found far-traveled exotic gravel that led them to conclude that the river originated in the San Juan Mountains of SW Colorado (Fig. 3). Hunt suggested that the river was an ancestral San Juan River (Fig. 3), but the actual course and nature of the river remained obscure until satellite images, combined with digital elevation models (DEM), became available. These images revealed in a spectacular manner the course of the river in inverted relief, as shown by a sinuous ridge known to the Dineh residents of...
the area (in translation) as Crooked Ridge (Figs. 2 and 3; also see Lucchitta et al., 2013).

Impressed by these new data, R.F. Holm, B.K. Lucchitta, and Ivo Lucchitta, who had long been interested in the possibility of an ancient and far-reaching river here, undertook to investigate the unique sinuous landform (Crooked Ridge river; Lucchitta et al., 2011, 2013). Simultaneously, Billsley et al. (2012) noted the presence of old gravels on Crooked Ridge, but they did not report far-traveled exotic lithologies.

In 2016, Hereford et al. (2016) obtained an age of ca. 2 Ma for the alluvium now present in the channel, mostly indirectly by applying a sandstone age obtained from Blue Point, 50 km away, and directly from six sandstone grains (but no zircon grains) from the alluvium, and only four sandstone grains with a small age spread. They concluded that Crooked Ridge river was a small river of local significance that only existed ca. 2 Ma. This age, if valid, may determine when the river was captured by the San Juan River and died, but it says nothing about when it was born and lived. Their hypothesis was that Crooked Ridge river obtained its exotic clasts by locally reworking an older piedmont that presumably extended from the San Juan Mountains into northeast Arizona and northwest New Mexico. Furthermore, they inferred that the Crooked Ridge river was only one of several drainages of equal significance on the Kaibito Plateau. These authors also concluded that alluvial deposits on White Mesa are the significant stratigraphic unit, so the name Alluvium of Crooked Ridge should be dropped in favor of Alluvium of White Mesa.

We believe that the Crooked Ridge river is important in the context of the regional alluvial history of the southern Colorado Plateau and the Grand Canyon, and so we analyzed the issues that are the subject of debate. In our analysis, we reviewed and compared some of our previously published data with pertinent information compiled from published literature. The issues are: (1) Were the exotic clasts in the Crooked Ridge river gravel derived from corresponding bedrock sources by direct fluvial transport, or were they reworked locally from previous piedmont deposits? (2) Was Crooked Ridge river of regional significance, or was it merely a local stream? (3) Was Crooked Ridge river’s valley large or small? (4) What is the age of Crooked Ridge river? (5) Which alluvium best represents the alluvial history of the region—that of Crooked Ridge river, or the Alluvium of White Mesa? (6) Did Crooked Ridge river cross the Kaibab upwarp and, if so, when? The answers to these questions are important and relevant to the numerous topical conferences, field trips, and Geological Society of America (GSA) special sessions held in recent years on the Cenozoic history of the southern Colorado Plateau and Grand Canyon.

The results of the compilations and analyses showed that the Crooked Ridge river: (1) was a river of regional extent and importance that was headed in the San Juan Mountains of Colorado, (2) probably came into existence when these mountains were formed, and thus was of Miocene or Oligocene age, (3) flowed in a substantial valley, (4) died when it was beheaded by the developing San Juan River, and (5) crossed the Kaibab Plateau approximately in the alignment of the eastern Grand Canyon and continued from there in a northwestern direction to an unknown destination.
The idea of an Oligocene piedmont that stretched downslope over 200 km from the San Juan Mountains to the Chuska Sandstone was introduced by Cather et al. (2003, p. 397, 404); the San Juan volcanic field was considered to be the principal source of the Chuska Sandstone. The piedmont idea was sustained by Cather et al. (2008, their figure 14, p. 28) in connection with the origin of the Chuska erg. However, Dickinson et al. (2010, p. 128) discounted the piedmont by showing that all the strata in the San Juan Mountains (Fig. 3) piled from published literature sources as evidence that the Oligocene piedmont of Cather et al. (2003) never existed in northeastern Arizona or northwest New Mexico. Our conclusion is that the exotic gravel on Crooked Ridge arrived on the Kaibito Plateau from the San Juan Mountains and downstream sources by direct fluvial transport in the channel of Crooked Ridge river; the idea of local recycling is rejected.

Exotic clasts include many types of volcanic, hypabyssal, plutonic, metamorphic, and hydrothermal lithologies. Percentages of these lithologies in controlled statistical and in grab samples confirm they represent significant percentages in the Crooked Ridge river deposit (Table 1). These lithologies represent all rock types found along the course of Crooked Ridge river between White Mesa and the San Juan Mountains (Fig. 3).

# EXOTIC PEBBLES AT CROOKED RIDGE

The gravel deposits contain clasts derived both locally and distally. Most locally derived clasts are sandstones from Jurassic and Cretaceous formations on the valley sides; these clasts will be discussed below.

The exotic clasts (excluding quartzite and chert) comprise 22%, 15%, and 32.7% respectively, for each of the three columns in Table 1. Given the large contribution of clasts from local valley walls, these percentages are not “rare,” as described by Hereford et al. (2016).

## Lithologies of Exotic Clasts

The lithologies of the exotic clasts that are diagnostic of specific sources include the following:

1. **minette**: dikes and diatremes in the Navajo volcanic field of northeast Arizona and northwest New Mexico; ca. 28–19 Ma;
2. **monchiquite**: Wildcat Peak on the Kaibito Plateau; 19.5 Ma;
3. **intermediate porphyry**: laccolith complexes of the Colorado Plateau; ca. 85–60 Ma and ca. 29–20 Ma;
4. **felsic volcanics**: rhyolite tuff, welded tuff, silicic volcanic rocks, and vitrophyre of the San Juan volcanic field; ca. 29–23 Ma;
5. **intermediate volcanics**: andesite and latite of the San Juan volcanic field; ca. 35–23 Ma;
6. **metawacke, metaconglomerate, granite, and gneiss**: Proterozoic basement rocks from the San Juan Mountains (Fig. 3); 1800–1400 Ma;
7. **hydrothermal**: argillitic-altered rhyolite, propyritic-altered andesite, and earthy hematite with calcite veins, all from the San Juan volcanic field; 35–23 Ma.

## Clast Size and Rounding

Clast size as large as 20 cm indicates transport by a moderately vigorous stream, and rounded to subrounded shapes are consistent
with long-distance transport. In contrast, blocks of locally derived sandstone are large and angular, indicating little or no fluvial transport.

**Are the Exotic Clasts Recycled from a Regional Piedmont, Or Did They Arrive at Crooked Ridge River By Direct Fluvial Delivery?**

Hereford et al. (2016) proposed that the exotic clasts in Crooked Ridge river alluvium were derived by reworking of a preexisting piedmont deposit. However, no remnants of such a piedmont are exposed or even known in northeast Arizona or northwest New Mexico. The only possible piedmont deposit that has been discussed is the Chuska Sandstone, exposed exclusively on the Chuska Mountains of northwest New Mexico; this interpretation has been proposed by Cather in several publications.

In a 2003 paper, Cather et al. proposed that:
1. Piedmont deposits extended downslope from the San Juan Mountains to the Chuska Mountains ca. 35 to >25 Ma;
2. Sources of the piedmont deposits included the volcanic Conejos Formation of the San Juan Mountains, dated at ca. 35–31 Ma; and
3. The upper piedmont facies of the Deza Member (lower member of the Chuska Sandstone) and the Narbona Pass Member (upper member) contained similar provenance indicators and shared the same source regions. According to these authors, most plagioclase grains in the Narbona Pass Member are Na-rich (<An30; Fig. 4).

However, Lipman (1975) documented that (1) the Conejos Formation is dominated by andesite and low-silica rhyodacite; (2) plagioclase is the only feldspar phenocryst in these lithologies; and (3) the plagioclase is An55–45 (Fig. 5).

On the basis of these petrographic data (Fig. 5), the conclusion is that the material in the Chuska Sandstone could not be derived from the Conejos Formation of the San Juan Mountains.

In 2008, Cather et al. (2008) indicated that outcrops in the San Juan Mountains and the Chuska Mountains are 200+ km apart, and that no remnants of the piedmont exist between the two outcrop locations. In spite of this, these authors proposed that piedmont deposits that were prograded from southwestern Colorado are now represented by the Deza Member of the Chuska Sandstone (Fig. 6).

Lucchitta et al. (2013) and Dickinson et al. (2010) presented the following data (Fig. 7):
1. Gravel deposits in the Crooked Ridge river alluvium contain abundant pebbles and cobbles of lithologies characteristic of:
   - a) the San Juan Mountains: volcanic, plutonic, and metamorphic rocks;
(b) Colorado Plateau diatremes: minettes; and (c) Colorado Plateau laccoliths: intermediate porphyries.

(2) Similar lithologies occur on Black Mesa.

(3) Lithic clasts in the Deza Member of the Chuska Sandstone are instead mostly sand and silt size, have low abundances, and have a limited variety of lithologies. These data show that the lithic clasts in the Deza Member differ from those in the Crooked Ridge river alluvium in grain size, abundance, and composition (Fig. 7), which is inconsistent with stratigraphic, lithologic, or genetic connections between the Deza Member and Crooked Ridge river material.

In 2010, Dickinson et al. (2010) showed that:

(1) Ages of zircon grains in the Narbona Pass Member of the Chuska Sandstone indicate derivation from Precambrian sources in central Arizona:
   (a) Yavapai (1800–1700 Ma),
   (b) Mazatzal (1700–1600 Ma), and
   (c) anorogenic plutons (1450–1400 Ma).

(2) The sandstone petrography shows that the Deza and Narbona Pass Members are identical in principal components and probably had similar sources, so no material in the Chuska Sandstone was derived from the San Juan Mountains (Fig. 8).

However, the zircons of Proterozoic age could have been derived from basement rocks exposed in the Needle Mountain area of the San Juan Mountains, as is the case with clasts of that age in the Crooked Ridge river alluvium, so this by itself is not unequivocal evidence against derivation of at least some Chuska material from the San Juan Mountains, as pointed out by Dickinson et al. (2010).

In view of the collective evidence discussed above, the trend has been to discount derivation of any Chuska material from the San Juan Mountains and also to discount the existence of a piedmont derived from those mountains. In Figure 9, arrows are numbered and color-coded to publications. The arrows show inferred direction of sediment transport from presumed sources in the San Juan Mountains (right side) and central Arizona (left side).

It is clear that the more recent publications consider the material of the Chuska Sandstone as being derived from the southwest, not the northeast, as shown in Figure 9.

Finally, the channels described by Hereford et al. (2016) on White Mesa contain no exotic clasts; only the Crooked Ridge river channel (their channel 3) contains them. This implies that channels lacking exotic clasts were tributaries to the Crooked Ridge river and that deposits containing exotic clasts were not available to these tributaries, whereas the Crooked Ridge river, the master stream that flowed through the same region as the tributaries, was able to access and carry such clasts, implying a different source for them. This difference in sediment sources would be extremely unlikely if a regional piedmont deposit containing the exotic clasts were present then in the region. The only reasonable interpretation is that the exotic clasts were incorporated into the Crooked Ridge river alluvium by direct fluvial transport from sources to the northeast, as interpreted by Cooley et al. (1969), Hunt (1969), and Lucchitta et al. (2013).

The data presented above show that no piedmont that contained material derived from the San Juan Mountains is exposed or known in the region of interest. Only the Chuska Sandstone, which was once thought to be, in part, a piedmont deposit derived from the San Juan Mountains might have been a source for the exotic gravels, but this...
interpretation is contradicted by petrographic and other data, so it cannot be held. One might argue that an ancient piedmont once existed in the region but has been entirely removed by erosion. This, however, is contradicted by the absence of exotic clasts in the White Mesa tributaries, and in any case forces an important conclusion on an unprovable supposition that lacks evidence.

It is worth noting here that the present-day San Juan Mountains, which are very high, in no place are bordered by a piedmont; instead, they are the source of all the major rivers of the region.

In summary, there are no data to support the notion that the exotic clasts in the Crooked Ridge river alluvium were derived by reworking of a pre-existing piedmont deposit. Instead, the evidence is that the exotic clasts were emplaced through normal fluvial transport by a river originating in the San Juan Mountains. This interpretation, which is the simplest one, has been generally embraced by geologists (cited above) working on the problem.

### CROOKED RIDGE RIVER: REGIONAL OR LOCAL?

Several lines of evidence show that Crooked Ridge river was the master stream of the region:

1. No other stream in the region contains exotic, far-traveled clasts or detrital zircons (see below). Other streams with channels (narrower than that of Crooked Ridge river) exposed on White Mesa contain no exotic clasts and were thus tributaries to Crooked Ridge river.
2. No paleostream comparable to Crooked Ridge river is preserved in the region or, indeed, in the Colorado Plateau.
3. Crooked Ridge river was able to cut across the strike ridges once present along the monoclinic flexure at the east edge of White Mesa, whereas tributary streams in that area could not and were confined to strike valleys. (This flexure is at the southernmost end of a complex of northeast-trending, down-to-the-east monoclinal folds associated with the east side of the Monument Valley upwarp; it drops the Entrada Sandstone from ~2000 m elevation at the southeast edge of White Mesa to less than 1750 m at the foot of the nearby northwest-facing scarp of Black Mesa.)
4. Crooked Ridge river was able to cut across the resistant scarp made by the Navajo Sandstone at the Echo Cliffs. The resulting wind gap is the only one present along the 100 km length of the Echo Cliffs (Fig. 2), which shows that other comparable drainages were not present in the area of the Kaibito Plateau. One smaller gap ~5 km south of the Crooked Ridge river gap is thought by Billingsley (personal commun., 2018) to have been made by Crooked Ridge river recrossing the Echo Cliffs to a junction with Moenkopi Wash ~20 km to the southeast. Billingsley also saw lag gravel along the postulated course of this stream but did not report whether exotic clasts are present.

We consider this interpretation unlikely because: (1) The sill of the small gap is too high for the projected elevation of Crooked Ridge river at that location using measured gradients. (2) The cross-sectional area of the small gap is much smaller than that of the Crooked Ridge river gap. (3) It is unlikely that Crooked Ridge river, having once crossed the resistant barrier of the Navajo Sandstone, would then double back, crossing it.

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**Figure 7. Comparison of lithic clasts in the Deza Member with those in the alluvium of Crooked Ridge river.**

**Figure 8. Sandstone petrography of the Deza and Narbona Pass Members.**

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**Table:**

| Clast Size | Deza Member Count | Crooked Ridge Count |
|-----------|-----------------|-------------------|
| 10-105 mm | 68              | 12                |
| 10-83 mm  | 15              | 12                |
| sand      | 30              | 0                 |
| 15-83 mm  | 20              | 12                |

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**Data from Dickinson et al., 2010**

**Figure 7.**

- **Percent of 68 Grab Samples. Clast size: 10-105 mm**
  - Quartzite: 68
  - Chert: 12
  - Granite: 4.5
  - Bull quartz, Pegmatite: 6
  - Quartz metaconglomerate: 1.5

- **Deza Member**
  - Quartz: 50
  - Chert: 20
  - Porphyry: 10

- **Crooked Ridge**
  - Quartzite: 70
  - Chert: 30
  - Porphyry: 0

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**Figure 8.**

- **Deza Member**
  - Quartz: 60
  - Chert: 40

- **Crooked Ridge**
  - Quartz: 40
  - Chert: 60

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**Deza Member**

- ** Coyote**
  - Microgranular clastic, Metavolcanic Volcanic
  - Clast size: sand

- **Crooked Ridge**
  - Quartzite, Chert, Gravel: 1.5
  - Rhyolite, Vitrophyre: 8

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**Figure 8. Sandstone petrography of the Deza and Narbona Pass Members.**

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**Lucchitta and Holm | Re-evaluation and significance of Crooked Ridge river of northern Arizona**
again instead of following the strike valley in the easily eroded Chinle Formation. Instead, we propose that the smaller gap was made by a tributary to Crooked Ridge river. Light would be shed on this issue by careful examination of the lag gravels reported by Billingsley. In any case, either interpretation is consistent with the arguments made here.

### SIZE OF CROOKED RIDGE RIVER PALEOVALLEY

The Crooked Ridge river paleovalley had a considerable width and depth. The width cannot be determined with accuracy because of the erosion that has occurred since the Crooked Ridge river ceased to function, but it can be estimated through several criteria.

#### Width

The wind gap, which is carved through the resistant Navajo Sandstone, gives a minimum value because it was a constriction in the valley and has not been eroded significantly since Crooked Ridge river was active. The gap is ~3.3 km wide at the top and 1.8 km at the base.

The scarp that truncates the Mormon Ridges at their south end (Fig. 2) is quite straight and little embayed, suggesting that it has been eroded relatively little. This scarp is 7–8 km from the Crooked Ridge river ridge; assuming 20% erosional retreat, the original valley side would have been 5.5–6 km away from the thalweg. This reach is wide because it was eroded in the poorly resistant Carmel Formation, which overlies the Navajo Sandstone.

The terrain surrounding the valley of Crooked Ridge river would have had an elevation of ~2400 m, comparable to the present-day altitude of the Defiance Plateau, and thus a source of considerable runoff.

#### Depth

The depth of the paleovalley can be reconstructed with some accuracy because large angular blocks of sandstone rolled down the sides of the paleovalley, indicating what strata were exposed on the valley sides. Many of the blocks are of the Dakota Sandstone, ~270 m above the Crooked Ridge river thalweg (Fig. 10).

Abundant oysters in the Crooked Ridge river deposits were derived from the upper Dakota Sandstone and lower Mancos Shale, an estimated 300–330 m above the thalweg. Unprotected Mancos shale erodes quickly, so it is likely that it was protected by a cap of Mesaverde Sandstone in river time.

The large angular blocks also include feldspathic and micaceous sandstone like that of the Mesaverde Group. This would make the valley sides 720 m high (Fig. 10). By comparison, today’s scarp on the west side of Black Mesa is ~300 m high, and the Vermilion Cliffs are ~600 m high.

The terrain surrounding the valley of Crooked Ridge river alluvium would have had an elevation of ~2400 m, comparable to the present-day altitude of the Defiance Plateau, and thus a source of considerable runoff.

### AGE OF CROOKED RIDGE RIVER AND PROVENANCE OF ITS ALLUVIUM

Hereford et al. (2016, p. 16) proposed that Crooked Ridge river is “...no older than ca. 25 Ma...” on the basis of detrital zircon ages from the Crooked Ridge river alluvium, and ca. 2 Ma on the basis of a tuff interbedded with alluvium at Blue Point on the Moenkopi Plateau (Fig. 3), together with a few grains of detrital sandine from the Crooked Ridge river alluvium. These authors presented an impressive array of analytical age data, but the significant issue is the age as determined from sanidine. We examine these data here.

#### Blue Point Tuff

According to Hereford et al. (2016), the lithologic characteristics of the Blue Point alluvium...
“resemble” those of the alluvium of White Mesa, and these are the grounds on which the Blue Point alluvium was interpreted as part of the White Mesa alluvium. The age of the tuff interbedded with the Blue Point alluvium on Moenkopi Plateau (Fig. 3) was then given as a primary evidence for the age of the White Mesa (and Crooked Ridge river) alluvium. In fact, the exact 1.993 ± 0.002 Ma age of the Blue Point tuff is shown as being the age of the White Mesa alluvium, and the large numbers of Blue Point dates were then used to give this age a very high relative probability, while not taking into account the very low probability given by the four grains actually measured from the White Mesa alluvium (Hereford et al., 2016, their figure 13, field A). However,

1) Blue Point is more than 50 km as the crow flies from Crooked Ridge and White Mesa, with which there is no known or documentable geologic connection;

2) the Blue Point alluvium contains none of the exotic clasts that are so characteristic of Crooked Ridge river alluvium and of that part of the alluvium on White Mesa that is part of the Crooked Ridge river channel; and

3) the tuff at Blue Point is a distinct 15-cm-thick layer in that stratigraphic sequence, whereas material of that age is only present as a very few grains of detrital sanidine in the Crooked Ridge river/White Mesa alluvium. This difference is strange for air-fall tuff material that should be similarly preserved in two alluvial localities separated by 50 km, but this was not addressed by Hereford et al. (2016).

The data do not support correlation of the Blue Point alluvium with the alluvium of Crooked Ridge river and White Mesa, so Blue Point cannot legitimately be used to date Crooked Ridge river material.

**Zircon and Sanidine Geochronology**

Most of the data discussed here are best seen in figure 13 of Hereford et al. (2016). The detrital zircon ages correlate nicely with the lithologies of Crooked Ridge river exotic clasts, confirming derivation of not only the Crooked Ridge river clasts but also of the finer-grained alluvium from upstream sources. However, the youngest zircon is a single grain ca. 16 Ma (field B). There are no younger zircons, even though one would expect ca. 2 Ma zircons to be present because both zircon and sanidine should have fallen together from an ash cloud. This is troubling.

Sanidine ages again reflect well the ages of rocks exposed upstream, particularly the 32–27 Ma ages of rocks from the San Juan volcanic field (fields C and D). The peaks shown at ca. 2 Ma in field B are based on only six samples collected at Crooked Ridge and at the Highway Quarry; of these samples, only four are closely clustered. The prominent orange peak shown in field A is from Blue Point, which we discount for the reasons detailed above. What is then left are four ages clustering around 2 Ma that were actually collected from the Crooked Ridge river alluvium; these ages have a very low relative probability.

The extreme scarcity of ca. 2 Ma sanidine grains is troubling because one would expect that the ash falling out from an ash cloud would blanket the Crooked Ridge river valley and eventually get washed into the river alluvium. This is especially true because the presently exposed Crooked Ridge river alluvium is the last material deposited by the river before it ceased to function, so extensive reworking that might have removed the sanidine is unlikely.

**Significance of the Analytical Ages**

The presently exposed alluvium of Crooked Ridge river along Crooked Ridge and White Mesa is the last alluvium deposited by the river. This is well documented by the massive calcrite layer so well exposed at the western end of Crooked Ridge (Lucchitta et al., 2013). Calcrite does not form in active alluvial channels. Furthermore, no Crooked Ridge river alluvium younger than that presently exposed along the course of the paleoriver is known. The inescapable conclusion is that the 2 Ma age, if valid, gives a maximum age for the death of Crooked Ridge river, but it says nothing about the river’s origin and life.

Could the river have existed long before 2 Ma? We do not know, and maybe never will have convincing field and analytical evidence to say one way or the other. Karl Karlstrom (2018, personal commun.) rejected the concept of a pre-2 Ma existence for Crooked Ridge river as an unsupported hypothesis. This is correct, but the hypothesis that no Crooked Ridge river existed before 2 Ma is also unsupported and unrealistic. Not accepting any pre–2 Ma existence of Crooked Ridge river means reducing the entire history of the river and its substantial valley to a restricted interval in time, ca. 2 Ma.

We can use indirect evidence and inductive reasoning to help with the problem of when Crooked Ridge river might have been born:

1) The valley and wind gap of Crooked Ridge river at 2 Ma were deep and wide, and would have required some considerable time to be carved down from the original surface on which the river flowed.

2) Crooked Ridge river came into being in an area (northern Arizona and southwest Colorado) where no major mountains or streams existed before; this could only happen if a new and major source of water came into...
existence. The only such source is the volcanic San Juan Mountains, which were born in the latest Eocene and continued developing into the Miocene. Even today, these mountains remain high and are the source of all major rivers in the region. When the San Juan volcanic field was born, the first volcanic constructs were central-peak andesitic stratovolcanoes (Lipman, 1975; Lipman et al., 1970, 1978; Lipman and McIntosh, 2008), which were built on a platform of Cretaceous rocks and probably reached elevations of 5–7 km on the basis of present-day geology and topography, as observed by Lucchitta.

Such mountains would have been excellent rock and runoff makers and would have had a major impact on the weather and hydrology of the region, creating rivers that did not exist before. These rivers include the Colorado, Rio Grande, San Juan, and Crooked Ridge rivers. The causal relation between mountains and rivers implies that Crooked Ridge river would have come into being approximately when the San Juan Mountains did, probably in Oligocene time.

(3) Crooked Ridge river was beheaded by the San Juan River, which did not exist in its present configuration when Crooked Ridge river came into being. The San Juan River extended itself eastward across the Monument Upwarp by headward erosion from the Colorado River, capturing and beheading older streams such as Crooked Ridge river that drained the south flank of the San Juan Mountains. This could only happen if the Colorado River were the oldest and most deeply entrenched river of the region, giving its tributaries a high erosive power. This is consonant with the Colorado’s draining the northern and oldest part of the San Juan volcanic field. If valid, this hypothesis would place the birth of the Colorado River in the early part of the Oligocene Epoch.

On the basis of these arguments, we conclude that the birth of Crooked Ridge river occurred long before 2 Ma, and possibly as early as Oligocene time.

**CROOKED RIDGE RIVER ALLUVIUM OR ALLUVIUM OF WHITE MESA?**

The alluvium exposed on White Mesa is relatively extensive but was deposited in large part by streams that transported no exotic clasts and so were local tributaries to Crooked Ridge river. These streams probably were localized by strike valleys that formed along the east-dipping monoclinal flexure that drops the Entrada Sandstone from White Mesa to the bottom of the Black Mesa scarp to the east. In contrast, Crooked Ridge river cut across these strike valleys.

The significant alluvium in the region is that of Crooked Ridge river, which was the principal stream and the one of regional significance; the alluvium on White Mesa is of secondary importance. Assigning the name “White Mesa Alluvium” to both the alluvium of Crooked Ridge river and the alluvium on White Mesa, as proposed by Hereford et al. (2016), emphasizes interesting but relatively unimportant deposits at the expense of deposits that are critical to the alluvial history of the region. We therefore recommend the continued use of the term “Crooked Ridge River Alluvium.”

**CONTINUATION OF CROOKED RIDGE RIVER WEST OF THE GAP**

The absence of direct field evidence for the westward continuation of Crooked Ridge river has given rise to a variety of proposals. As mentioned above, G.H. Billingsley (2018, personal commun.) proposed that Crooked Ridge river recrossed the Echo Cliffs a short distance south of The Gap and then continued in a south-southeast direction to a junction with Moenkopi Wash and then to a confluence with the Little Colorado River (Fig. 3).

Hereford et al. (2016) proposed instead that Crooked Ridge river continued southward along the strike valley at the foot of the Echo Cliffs to a junction with Moenkopi Wash. Lucchitta et al. (2013) identified a shorter route to the Little Colorado River (and Colorado River?) by excluding as a boundary condition any terrain currently above the 1700 m elevation of Crooked Ridge river alluvium at its westernmost (and farthest downstream) exposure. The area of Big Canyon (Fig. 3) is a potential candidate for this Crooked Ridge river course, which would bring the river to a junction with the Little Colorado River not far from the present confluence of the Little Colorado and Colorado Rivers.

The difference between these proposals is not important to the history of drainage development. Important questions are: (1) What rivers were present on the east side of the Kaibab Plateau? (2) How and when did these rivers continue downstream from the plateau?

Whether the Colorado River was present east of the Kaibab Plateau in Crooked Ridge river time is critical for unraveling the drainage history of the Colorado Plateau. If the Colorado River were present, then it, the Little Colorado River, and Crooked Ridge river combined to form an ancestral river that crossed the Kaibab Plateau roughly along the alignment of the eastern Grand Canyon, as proposed on geologic grounds by Babenroth and Strahler (1945), Lucchitta (1975, 1989), and Scarborough (2001). More recently, Flowers and Farley (2012, 2013), Flowers et al. (2008), Lee et al. (2013), and Karlstrom et al. (2017) confirmed the earlier results using apatite thermochronology.

Three rivers should be considered in this analysis: Little Colorado, Crooked Ridge river, and the Colorado River.

**Little Colorado River**

The history of the Little Colorado River was extensively discussed by Karlstrom et al. (2017). Today’s Little Colorado River is a subsequent river that at least in part flows in a northwest-trending strike valley at the foot of scarps developed in Mesozoic strata that regionally dip northeast (see for example Hunt, 1956; Lucchitta, 1990, figure 4). The dip is away from the Mogollon Highlands of Sevier to Laramide age in central Arizona, which used to form the high mountainous south rim to what is now the Colorado Plateau.

The Mogollon Highlands were a topographically high terrain that produced consequent rivers flowing northeast down the topographic slope,
depositing the so-called Rim Gravels in the process (Cooley and Davidson, 1963; Young and Hartman, 2014). According to some, the rivers continued onto the Colorado Plateau far to the north of the Mogollon Highlands (Cooley and Davidson, 1963; Potochnik, 2001; Cather, 2004; Davis et al., 2010; Dickinson et al., 2012). However, an analysis based on apatite thermochronology indicated that the topographic development of the region was dominated by the northeast retreat of scarps developed in the Miocene section (Karlstrom et al., 2017, especially their figure 10), in keeping with the results of Lucchitta (1975), Lucchitta and Jeanne (2001), and Holm (2001). These scarps were associated with strike valleys that controlled drainage (Lucchitta, 1990, figure 4).

Before the Mogollon Highlands were rifted down by basin-and-range faulting, the subsequent drainage(s) at the foot of the Mogollon Slope was abundantly supplied with water and probably was substantially greater than the present Little Colorado River. This ceased to be the case after the Miocene rifting, when the high ground most productive of precipitation was separated from the Colorado Plateau along the Mogollon Rim.

Crooked Ridge River

As discussed here and in Lucchitta et al. (2013), Crooked Ridge river was a substantial river that flowed in a major valley, was probably of considerable age, and was slightly longer from source to the confluence on the east side of the Kaibab Plateau than the present-day Little Colorado River. As such, it was a major component of the river that then crossed the upwarp and continued northwest from there.

Colorado River

In his comprehensive analysis of the Colorado River, Hunt (1969) described a complex history that started in the Oligocene and featured a northern and earlier branch of the river as well as a younger southern branch, both originating in the Rocky Mountains of Colorado. Hunt also postulated extensive ponding of these rivers, and the eventual overflow of the resulting lakes. Because of the ponding, for which there is no evidence, but which was invoked because of “complications” downstream, the ancestral Colorado River would have reached the area of the Kaibab Plateau by late Miocene time, although a middle Miocene arrival was not discounted (Hunt, 1969, p. 110).

Aslan et al. (2011) stated that the Colorado River (or its tributary the Gunnison) flowed onto the Colorado Plateau in the area of southwest Colorado ca. 11 Ma, on the basis of gravel deposits exposed on Grand Mesa (near Grand Junction, Colorado) and elsewhere.

Karlstrom et al. (2014) use apatite fission-track (AFT) thermochronology to conclude that Marble Canyon of the Colorado River (Fig. 3) started being incised to its present depth only after 6 Ma, so no Colorado River could have been present in that area at that elevation before that date.

The hypothesis by Hunt (1969) and Karlstrom et al. (2017) that the Colorado River did not reach the east side of the Kaibab Plateau until late Miocene time presents the problem of what happened to the river during the 5+ m.y. that separate the time when it was flowing in its upstream reaches and the time when Marble Canyon (Fig. 3) was carved. If the river was ponded somewhere for a time that long, there should be evidence of lacustrine deposits, perhaps even extensive ones, but there is none. Furthermore, it does not seem likely that a substantial and probably high-discharge river system emptied into lakes for that long without spilling over. Another problem is the disposal of the enormous amount of debris produced by erosion of kilometers of Mesozoic strata: Would the paleo–Little Colorado River have been sufficient by itself to achieve the transport? Would not rivers also need to be active in northern Arizona, southern Utah, and western Colorado?

In their analysis, Karlstrom et al. (2017) made two unsupported assumptions. The first is that when the Colorado River first arrived in the Marble Canyon area (ca. 6 Ma according to them), the area had already been stripped of all Mesozoic rocks and was floored by the top of the Paleozoic section (Kaibab Formation), which today forms the rim of Marble Canyon.

There are two relevant points with regard to the first assumption: (1) At present, Mesozoic rocks crop out 15–20 km east of the confluence. (2) An ~300 m section of the entire Moenkopi-Shinarump sequence crops out beneath a ca. 9 Ma basalt cap on Red Butte ~48 km SW of the confluence. Using the ~4–6 km/m.y. retreat rates for Mesozoic scarps obtained by Lucchitta and by Holm (see above), it is more than likely that Mesozoic rocks were present in the Marble Canyon area ca. 6 Ma, so the Colorado River most likely was present in the area and flowed on Mesozoic rocks before it started incising into the Paleozoic rocks.

The second unsupported assumption is that the Colorado River has always flowed approximately along the course of the present-day Marble Canyon. In reality, it is likely that before 6 Ma, the river was flowing at a higher elevation west of Marble Canyon in one of the various strike valleys developed in the east-dipping Mesozoic strata along the flank of the Kaibab Plateau. As the scarps bordering the strike valleys migrated downdip (eastward) with time, the ancestral river did the same by following the strike valley at the foot of the scarp, but at the same time, the river also cut downward into the soft rocks underlying the valley. When it reached the next-lower resistant cap rock, the river was constrained to cut vertically downward. With enough downcutting, however, the river reached the soft unit forming the next-lower strike valley in the Mesozoic sequence, and this process may well have happened several times over the course of millions of years. The resulting overall path of the river channel would have been inclined down the structural slope, but at a steeper angle than the slope itself, as shown diagrammatically in cross section in Figure 11. Thermochronologic information based on the present-day Marble Canyon would show none of this history.

It is worth mentioning that the same mechanism may have occurred in eastern Grand Canyon, where the path is that of curved scarps (“racetracks”) formed along the south-plunging axis of the Kaibab-Coconino upwarps and migrating southward with time. If this is true, the age of the river crossing...
the Kaibab Plateau may be even older than the ages obtained by geomorphic or analytical data.

The conclusion is that we do not know where the river flowed before it started incising into the Kaibab Formation in Marble Canyon, but we cannot assume that no Colorado River existed east of the Kaibab Plateau before 6 Ma. An older river is in better accord with the upstream data from Aslan et al. (2011), and with our proposal that Crooked Ridge river was beheaded by a San Juan River extending itself headward from a Colorado River that was older and topographically lower than Crooked Ridge river and had a course on the west side of the Monument upwarp.

The Combined River

Considering all data, analyses, and conclusions, we suggest that the eastern Grand Canyon was carved by a river that combined the flow of the ancestral Colorado, Crooked Ridge river, and Little Colorado Rivers, and did so well before 6 Ma.

Karlstrom et al. (2014) used AFT data to conclude that the paleocanyon along today’s eastern Grand Canyon was carved between 25 and 15 Ma, which is permissive for the combined river. As is the case with Marble Canyon, however, this age only dates the beginning of incision into the Kaibab Limestone on the Kaibab Plateau, whereas earlier courses of the river, when it was flowing in Mesozoic rocks, may well have been up the structural slope, that is to say, north of the present eastern Grand Canyon. This means that the paleoriver could have been older than 25–15 Ma.

The issue now is where the combined river went after crossing the Kaibab Plateau. Lucchitta (1975, 1984, 1989) showed a hypothetical course toward the northwest, which is roughly the regional strike of the strata in the region. However, no definite evidence for that course of the river has been found so far, and perhaps it never will.

Lucchitta (1975) described a gravel deposit containing exotic clasts beneath a ca. 6 Ma basalt flow at Grassy Mountain, on the Shivwits Plateau. He originally thought the clasts might have come from the Proterozoic terrane in central Arizona because Crooked Ridge river had not yet been analyzed, but more recent information suggests that they could as well have come, directly or indirectly, from the paleoriver that crossed the Kaibab Plateau. Unfortunately, the outcrop has disappeared, probably because of collapse of the overlying basalt cap, but exotic granitic, metamorphic, and volcanic clasts are still present in the float beneath the basalt, so study of these clasts might yield valuable information. Currently, Steelquist et al. (2019) are conducting a study in which they state that they have found no southerly derived clasts in the gravel, but that the clasts may have been derived from the San Juan Mountains; further study is needed.

J.W. Sears (2013) proposed an old and long course for the Colorado paleoriver west of the Kaibab Plateau, which, however, differs considerably in detail from what is proposed here. This hypothesis must also be integrated into any reconstruction of the drainage evolution in Oligocene and Miocene time.

CONCLUSIONS

The arguments and data presented by Hereford et al. (2016) do not diminish or falsify the conclusions of Lucchitta et al. (2011, 2013). These conclusions are:

1. Crooked Ridge river was a river of regional importance that was headed in the San Juan volcanic field of SW Colorado.
2. The river flowed in a wide and deep valley.
3. The alluvium in the White Mesa region was deposited chiefly by local tributaries to Crooked Ridge river. The course of Crooked Ridge river can be traced through White Mesa on the basis of exotic clasts, which are not present in the alluvium of the tributaries. The Crooked Ridge river alluvium thus is the significant stratigraphic unit, not Hereford et al.’s (2016) “Alluvium of White Mesa.”
4. The river was beheaded by the developing San Juan River, which was a tributary of an ancestral Colorado River. The latter was older and topographically lower than Crooked Ridge river.
5. Crooked Ridge river joined the ancestral Colorado River and the ancestral Little Colorado River somewhere east of the Kaibab Plateau. From there, the combined rivers flowed across the upwarp in a valley located at or near the present eastern Grand Canyon. The subsequent course probably was toward the northwest, but the exact location is not known at the present time.

The validity and significance of the ca. 2 Ma age obtained by Hereford et al. (2016) for the Crooked Ridge river can be determined only by additional data.
Ridge river alluvium are problematic because of the extreme scarcity of detrital sanidine and the absence of detrital zircon of that age in the allu- vium. However, even a valid 2 Ma age only gives a maximum age for the death of the river, but it says nothing about the time of the river’s birth or its history.

Our hypothesis regarding the age of Crooked Ridge river is that it came into being as a result of the formation of the high andesitic volcanoes of the southern San Juan volcanic field. This event occurred chiefly in Oligocene time, so it is reasonable to place the birth of Crooked Ridge river in that time interval. Because of the southward progres- sion of volcanism in that field, the Colorado River would have developed earlier than Crooked Ridge river because it drained the northern and older part of the volcanic field.

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