CROOKED RIDGE RIVER (CRR) REDUX

by

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INTRODUCTION

The conspicuous wind gap in the 100-km-long Echo Cliffs of Northern Arizona (Figs. 1, 2, 3, 4 and 5) has long attracted the attention of geologists because it is evidence for some ancient river. The questions have been: Whence did the river come? Where did it go? How big was it? How old?

Geologists such as M.E. Cooley (Cooley et al., 1969) and C.B. Hunt (1969) found far-traveled gravel near the gap, leading them to conclude that the river originated in the San Juan Mountains of S.W. Colorado (Fig. 4). Hunt suggested that the river was an ancestral San Juan River, but the actual course of the river remained invisible and unknown until satellite images, when combined with Digital Elevation Models (DEM), burst upon the scene, revealing the course of the river in inverted relief, as shown by a winding ridge known to the Navajo residents of the area as Crooked Ridge (Figs. 1, 2 and 3).

Intrigued by this discovery, 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 it, naming it Crooked Ridge River, CRR, (Lucchitta et al., 2013).

The conclusions were that CRR was a river of regional extent that headed in the San Juan Mountains of Colorado, flowed in a substantial valley, probably came into being when these mountains were formed, so would be of Miocene and possibly Oligocene age, and died when it was beheaded by the San Juan River.

Later, Hereford et al. (2016) contended that CRR was of only local significance because the exotic clasts were derived from recycling of pre-existing piedmont gravels; that its valley was not large; 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; and that the presently-exposed alluvium, and thus (according to them) the river as a whole, has an age of ~2 Ma.

Because CRR is the only ancient river whose course is exposed so perfectly, making it of potentially critical importance for deciphering the alluvial history of the Colorado Plateau, we will analyze here the issues that are the subject of debate.

EXOTIC PEBBLES AT CROOKED RIDGE

Lucchitta et al. (2013) concluded that ancestral Crooked Ridge River carried clasts of all lithologies exposed along its course from the San Juan Mountains to the Kaibito Plateau Figs. 1, 2 and 4)

Hereford et al. (2016) cited Cather et al. (2008) for the basis of their idea that the exotic pebbles at Crooked Ridge were recycled from ancient gravel deposits on a regional piedmont described and depicted by Cather et al., 2008, Figure 14, p. 28.

Gravel in Crooked Ridge

The gravel deposits contain clasts derived locally and distally. Far-traveled clasts are considered exotic. Most locally-derived clasts are sandstones from Jurassic and Cretaceous formations on the Kaibito Plateau, Black Mesa, and the Four-corners area.

Exotic clasts include many types of volcanic, hypabyssal, plutonic, metamorphic, and hydrothermal lithologies. Percentages of these lithologies in controlled statistical samples confirm significant contributions to the Crooked Ridge deposit.

1. Composition of gravel

COMPOSITION OF GRAVEL SAMPLES

Statistical Samples	Percent		Grab Samples	
Lithology	CRR-2	CRR-3	Lithology	Percent
Mesozoic sedimentary	53	61	Quartzite	47.8
Quartzite	13	19	Chert	11.2
Chert	12	5	Mesozoic sandstone	7.3
Felsic volcanic	5	7	Metaconglomerate	5.1
Minette	9	2	Quartz	5.1
Granite	5	1	Granite	4.5
Intermediate volcanic	1	2	Metawacke	3.9
Quartz	1	1	Microcline	3.4
Metaconglomerate	0	1	Intermediate porphyry	2.8
Gneiss	0	1	Felsic volcanic	2.8
Earthy hematite	1	0	Minette	2.2
			Monchiquite	1.7
			Intermediate volcanic	1.1
			Earthy hematite[3]	1.1

CRR-2: 100 contiguous clasts from top surface of the deposit at big quarry on Kaibito road, White Mesa. c-axes =15-72 mm.
CRR-3: 100 contiguous clasts from bottom of vertical face in big quarry on Kaibito road, White Mesa. c-axes = 15-83 mm.
Grab Samples: Percent of 178 clasts picked up randomly (cherry picked) at eight sites; includes 68 clasts from Black Mesa. c-axes = 10-200 mm.

Exotic clasts are 23, 15 and 32.7%, respectively. Not "rare", as stated by Hereford et al. (2016)

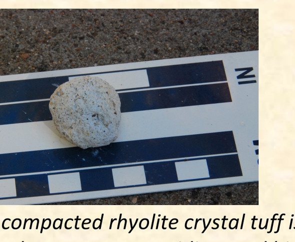
2. Some lithologies are diagnostic of specific sources
- **minette**: dikes and diatremes in the Navajo volcanic field.
- **monchiquite**: Wildcat Peak on the Kaibito Plateau.
- **intermediate porphyry**: Colorado Plateau laccoliths.
- **felsic volcanics** (rhyolite tuff, welded tuff, lava, vitrophyre): San Juan volcanic field.
- **intermediate volcanics** (andesite, latite): San Juan volcanic field.
- **metawacke, metaconglomerate**: Needle Mountains (Fig. 4).
- **gneiss**: Needle Mountains.
- **hydrothermal**: (argillic-altered rhyolite, propylitic-altered andesite, earthy hematite with calcite veins): San Juan volcanic field.

3. Clast size and rounding

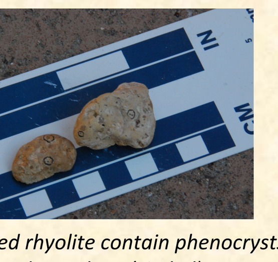
Clast size up to 200 mm indicate transport by a moderately vigorous stream, and rounded to subrounded shapes are consistent with long-distance transport.

4. Reworking

Friable pebbles such as rhyolite crystal tuff, and soft pebbles, such as hydrothermally altered rhyolite and andesite, are considered first-cycle clasts because it is unlikely they would survive reworking. Vitrophyre pebbles are also considered first-cycle because glassy clasts in buried deposits in the Chinle Formation and Chuska Sandstone are devitrified.



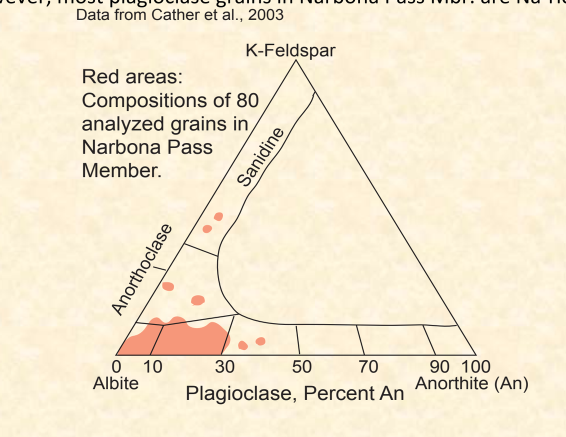
Rounded, friable pebble of compacted rhyolite crystal tuff is about 1 inch in diameter. Crystals are quartz, sanidine, and biotite



Soft pebbles of argillitic-altered rhyolite contain phenocrysts of quartz, sanidine, and amethyst (circled)

Are the pebbles recycled from a regional piedmont, or did they arrive at Crooked Ridge by direct fluvial delivery?

1. From Cather et al., 2003:
- Piedmont deposits extended down-slope from San Juan Mtns. to Chuska Mtns. ~35 to >25 Ma.
- Sources of piedmont deposits include Conejos Fm. ~35 to 31 Ma.
- Upper Piedmont Facies of Deza Mbr. and Narbona Pass Mbr. of the Chuska Sandstone contain similar provenance indicators and share the same source regions.
- However, most plagioclase grains in Narbona Pass Mbr. are Na-rich, <An30.



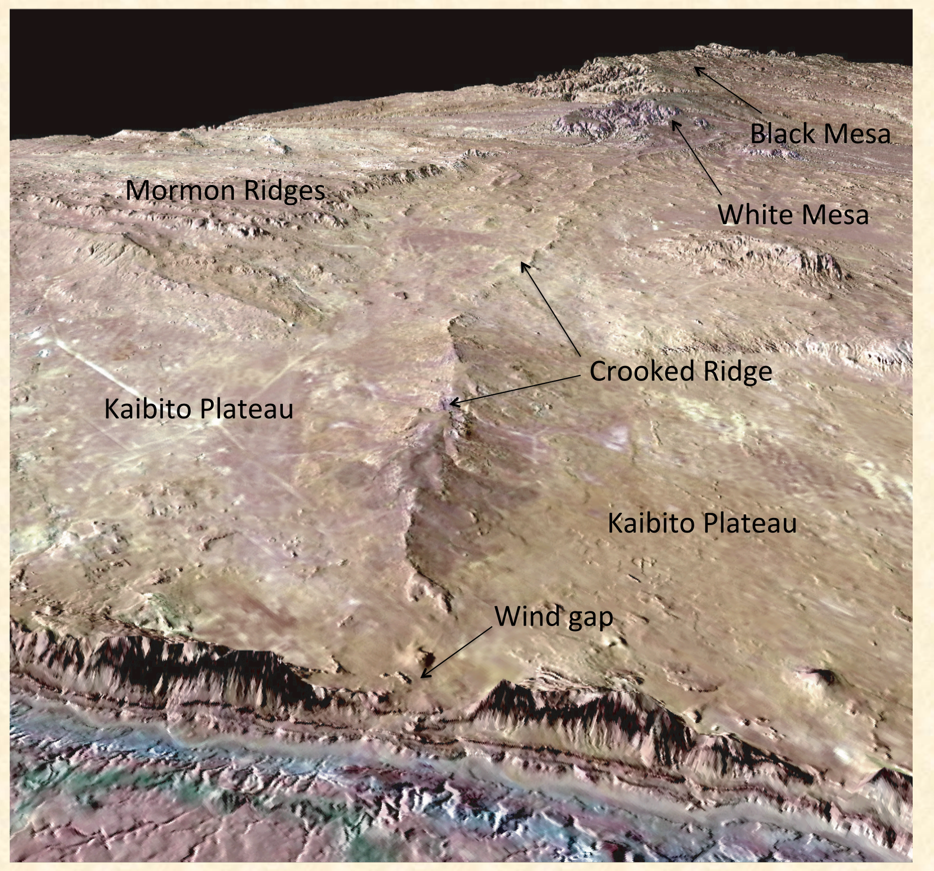
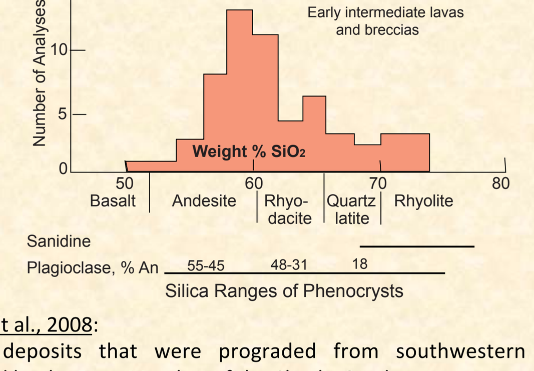
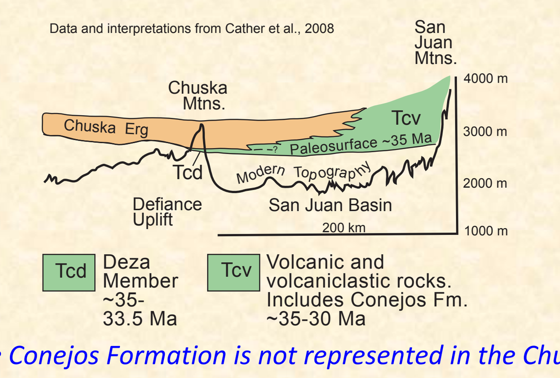


Figure 2. Crooked Ridge seen looking eastward from the wind gap to White Mesa

2. Lipman, 1975, documented:
- The Conejos Fm. is dominated by andesite and low-silica rhyodacite.
- Plagioclase is the only feldspar phenocryst in these lithologies.
- The plagioclase is An55-45.

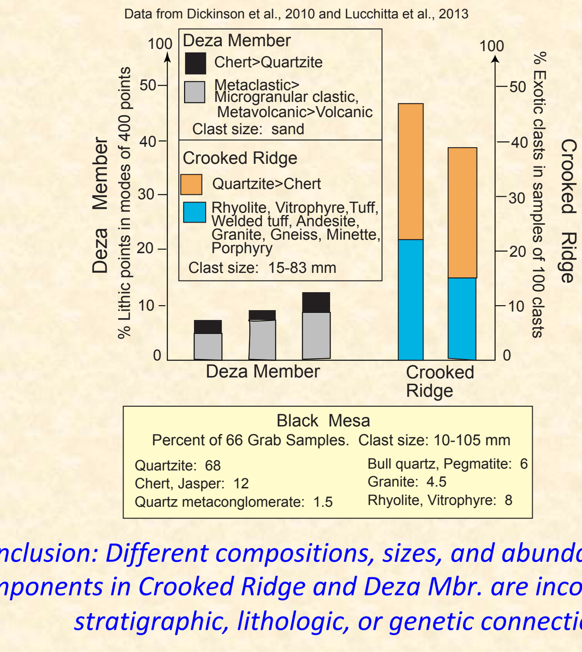


3. From Cather et al., 2008:
- Piedmont deposits that were prograded from southwestern Colorado are now represented by the Deza Member of the Chuska Sandstone.
- Outcrops in the San Juan Mtns. and Chuska Mtns. are 200+ km apart.
- No remnants of the piedmont exist between the two outcrop locations.



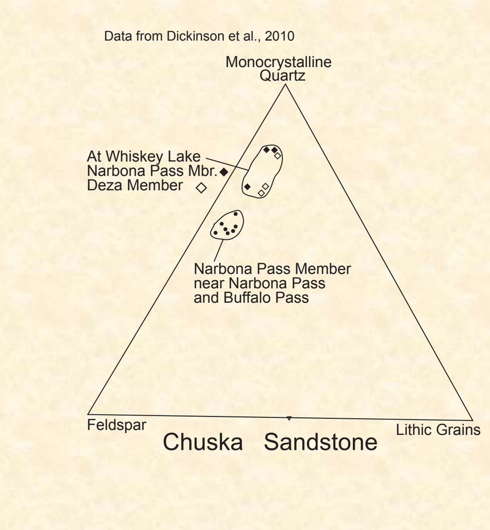
Conclusion: the Conejos Formation is not represented in the Chuska Sandstone

4. Data from Lucchitta et al., 2013 and Dickinson et al., 2010:
- Gravel deposits at Crooked Ridge contain abundant pebbles and cobbles of lithologies characteristic of:
  - **San Juan Mtns.** volcanic, plutonic and metamorphic rocks;
  - **Colorado Plateau diatremes;**
  - **Colorado Plateau laccoliths.**
- Similar lithologies occur on **Black Mesa.**
- Lithic clasts in the **Deza Mbr.** are mostly sand and silt size, have limited variety, and have low abundances.



Conclusion: Different compositions, sizes, and abundances of lithic components in Crooked Ridge and Deza Mbr. are inconsistent with stratigraphic, lithologic, or genetic connections

5. Dickinson et al., 2010:
- Ages of zircon grains in Narbona Pass Mbr. indicate derivation from Precambrian sources in central Arizona:
  - Yavapai (1800-1700 Ma)
  - Mazatzal (1700-1600 Ma)
  - Anorogenic plutons (1450-1400 Ma
- Sandstone petrography shows Deza Mbr. and Narbona Pass Mbr. are identical in principal components and probably had similar sources



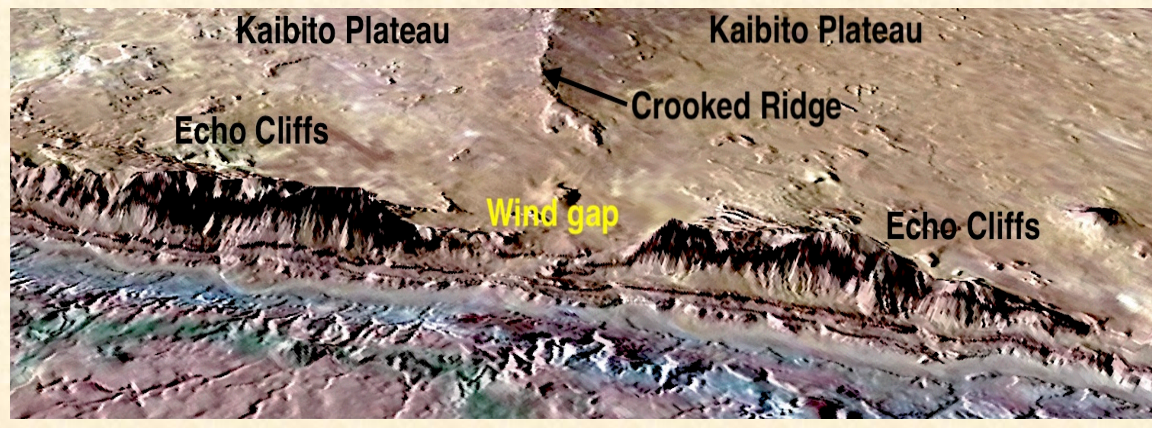


Figure 1. The wind gap

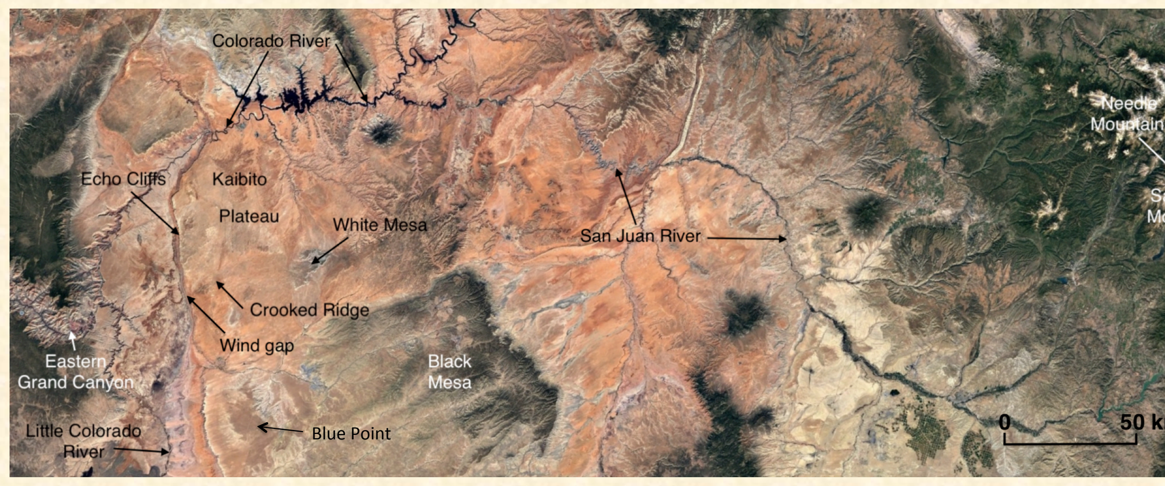


Fig. 4. Location Map

ABSTRACT

CROOKED RIDGE RIVER (CRR) REDUX

Information on pre-incision drainage on the Colorado Plateau is scanty, so the wind gap in the Echo Cliffs at The Gap has long been of interest. Far-traveled clasts in the area were attributed by early geologists to a river originating in the San Juan Mtns., BUT THE COURSE WAS NOT KNOWN. Satellite and DEM data NOW show the sinuous course of the river on the Kaibito Plateau in inverted relief.

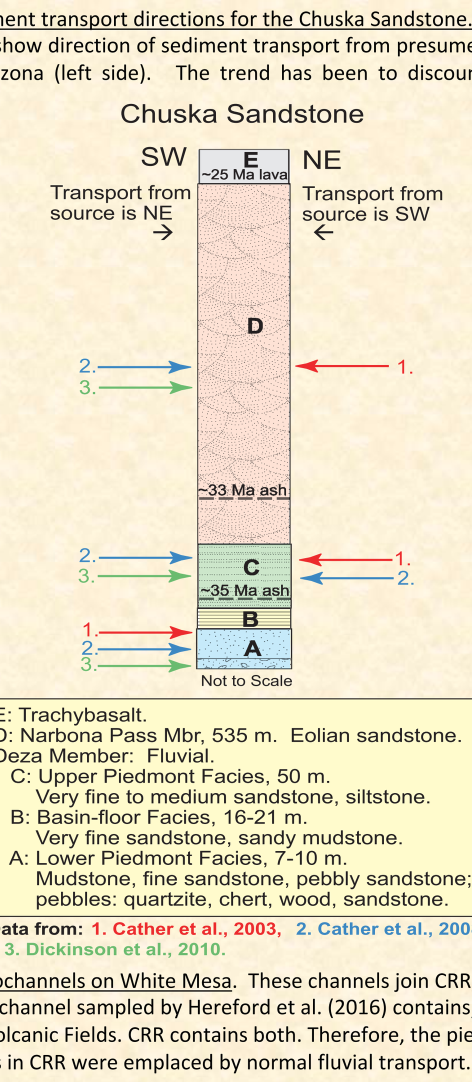
On the basis of these new data, Lucchitta et al. (2013) concluded that
- The river originated in the San Juan Mtns. and carried clasts of all lithologies exposed along its course from these mountains to the Kaibito Plateau
- CRR was the master stream of the region because NO other ancient river courses are visible on the Kaibito Plateau or the Echo Cliffs
- The valley of the river was wide (10-15 km) and at least 270 m, but possibly ~700 m deep on the basis of clasts in the alluvium derived from the valley walls
- The alluvium now exposed is the last deposited by CRR before it died, as shown by the massive calcrete that overlies it.
- The initial age of the river was not known, but probably much older than the present alluvium and possibly Oligocene because the river flowed from the high San Juan Mtns. as they were formed

Hereford et al. (2016) then proposed instead that
- The exotic clasts in CRR came from reworking an older nearby piedmont
- CRR was a local stream
- The river valley was not especially large
- All the alluvium on White Mesa and Crooked Ridge was deposited by local streams and tributaries
- The river was early Pleistocene on the basis of an interbedded 2 Ma tuff

We disagree
- No older piedmonts containing exotic clasts are exposed, documented, or even known
- Several of the clast lithologies would not survive recycling
- CRR was the master stream of the region because no other old streams are known and three of the paleochannels on White Mesa contain no exotics, so are tributaries
- Because some of the White Mesa alluvium was deposited by tributaries, alluvium of CRR is the important stratigraphic unit.
- CRR died sometime after 2 Ma, but was born much earlier

Conclusions: CRR was a major stream that originated in the San Juan Mtns., was born possibly in the Oligocene, eroded The Gap, crossed the Kaibab upwarp with the Colorado River (and the Little Colorado River?) along the alignment of the eastern Grand Canyon, and finally died sometime after 2 Ma.

6. Changes in inferred sediment transport directions for the Chuska Sandstone. Arrows are numbered and color-coded to publications, and show direction of sediment transport from presumed sources in San Juan Mountains (right side) and central Arizona (left side). The trend has been to discount derivation from the San Juan Mountains



Data from: 1. Cather et al., 2003, 2. Cather et al., 2008, 3. Dickinson et al., 2010.

7. Characteristics of paleochannels on White Mesa. These channels join CRR, the trunk stream. None contain exotic clasts and the one channel sampled by Hereford et al. (2016) contains no detrital zircons of the age of the Navajo or San Juan Volcanic Fields. CRR contains both. Therefore, the piedmont did not exist in this area, and the clasts and zircons in CRR were emplaced by normal fluvial transport.

Conclusion: The assumed piedmont is an unsubstantiated idea, and the concept of recycling pebbles from it lacks validity

CONCLUSIONS: The arguments presented by Hereford et al. (2016) do not invalidate the findings of Lucchitta et al. (2013), which are: 1) CRR was a regional river that flowed in a valley of substantial width and depth, and that originated in the San Juan Mountains.
2) CRR possibly died around 2 Ma, but probably came into being when the San Juan Volcanic mountains were formed in Oligocene time. 3) The channels on White Mesa were local and tributary to CRR, so the alluvium of CRR, not that of White Mesa, is the significant unit in the area. 4) CRR joined with the (somewhat) older ancestral Colorado and Little Colorado Rivers west of the present LCR confluence, then crossed the Kaibab upwarp along the trend of the Eastern Grand Canyon, continuing northwestward from there.

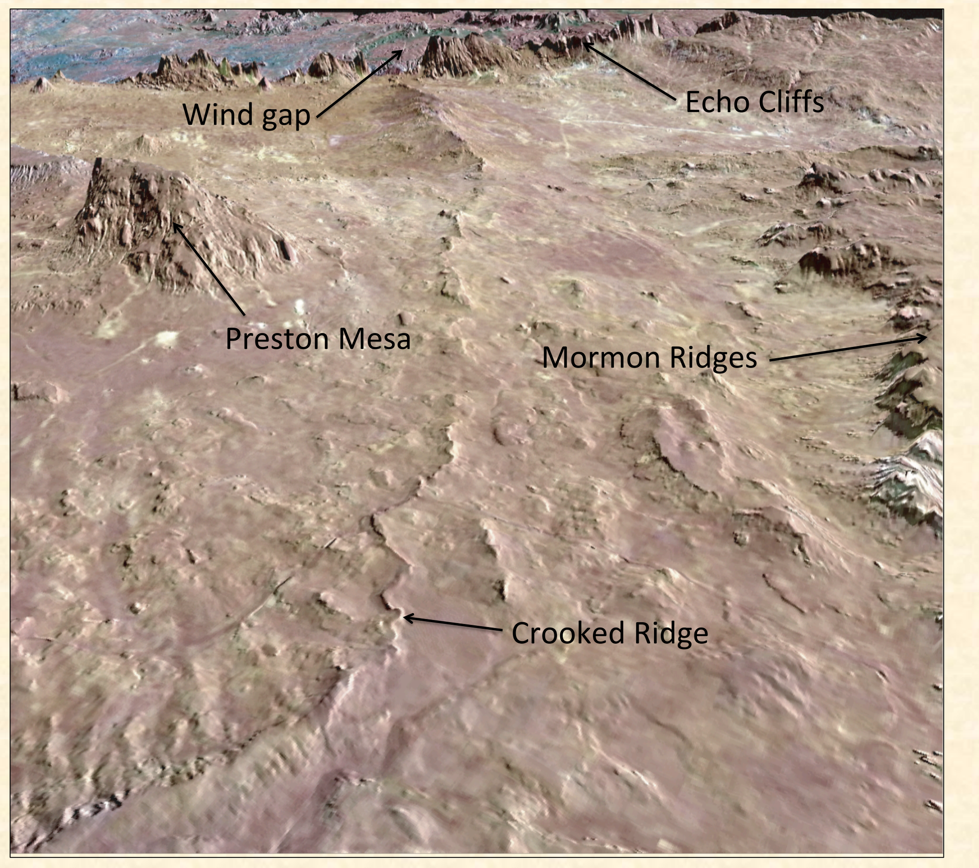


Figure 3. Crooked Ridge seen looking westward from White Mesa to the wind gap

CRR: A LOCAL OR A REGIONAL RIVER?

CRR is a regional river because:
- Excepting one smaller one to south, the CRR wind gap is the only one in 100 km of Echo Cliffs, (Fig.5), indicating that no other rivers were present.
- No other similar river courses are known in the region or in the Colorado Plateau
- CRR Contains far-traveled clasts and detrital zircon from as far as San Juan Mtns. of Colorado
- Channels on White Mesa that form "White Mesa Alluvium" have no far-traveled clasts, so are local tributaries to CRR
- Valley of CRR is large and deep. No other such valleys are present in the region

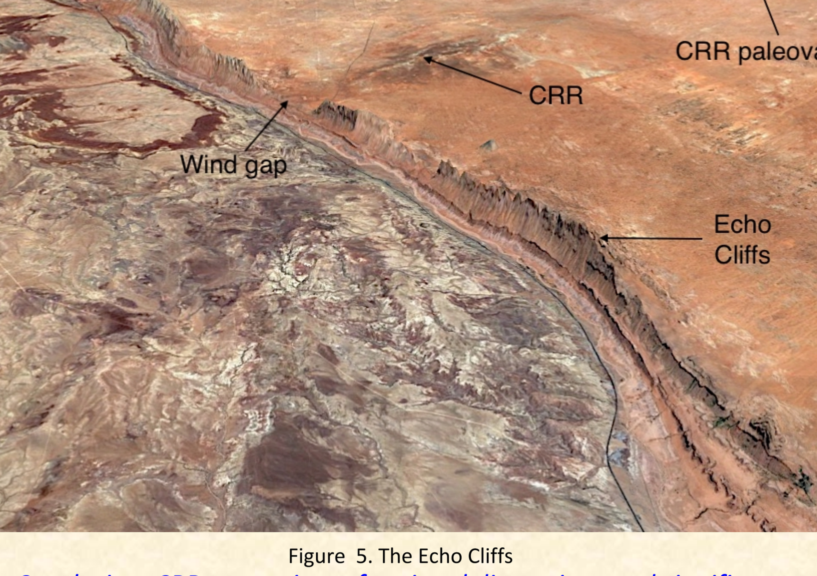


Figure 5. The Echo Cliffs

Conclusion: CRR was a river of regional dimensions and significance

SIZE OF CRR PALEOVALLEY

The CRR paleovalley had a considerable width and depth. The width cannot be determined with accuracy because of the erosion that has occurred since CRR 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 CRR was active. The gap is about 3.3 km wide at the top and 1.8 km at the base.
- The scarp that truncates Mormon Ridges at their south end is quite straight and little embayed, suggesting that it has been eroded relatively little. This scarp is 7 to 8 km from the CRR ridge; allowing 20% erosional retreat, it would be 5.5 to 6 km away from the thalweg.
- At Preston Mesa, bedrock probably near the south side of the valley is 3-4 km from the thalweg.
- At White Mesa, the crest of the ridge is ~1.5 km north of the northernmost exposures of the resistant Entrada bedrock, which presumably are not far from the edge of the paleovalley.

From these measurements one can estimate approximate widths of the valley: **3-4 km** in constricted reaches, and three to four times that figure, or **10 to 15 km** in open reaches. That was a substantial valley.

Depth

The depth of the paleovalley can be reconstructed with some accuracy.
- 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, about 270 m above the CRR thalweg (Fig. 6)
- Abundant oysters in the CRR deposits came from the upper Dakota Sandstone and lower Mancos Shale, an estimated 300-330 m above the thalweg. Unprotected Mancos shale erodes very quickly, so it is likely that it was protected by a cap of Mesaverde Sandstone.
- 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. 6). By comparison, the 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 CRR would have had an elevation ~2400 m, comparable to the present-day altitude of the Defiance Plateau, and thus a source of considerable runoff.

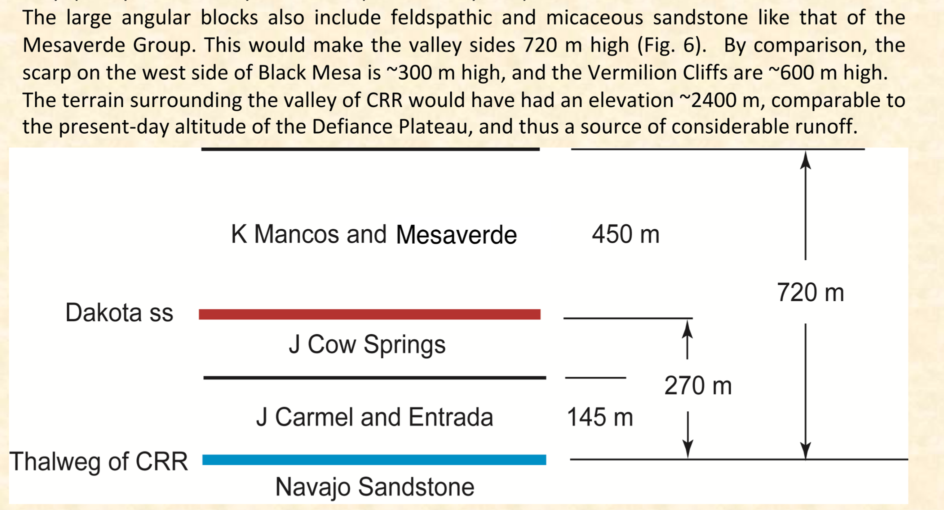


Figure 6. Stratigraphic section and thicknesses in CRR area

Conclusion: CRR was a river that flowed in a large and deep valley and was surrounded by terrain high enough to be a source of runoff.

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CRR ALLUVIUM OR WHITE MESA ALLUVIUM?

Several side streams join CRR in the White Mesa area. Because of this, the alluvium is wider here than anywhere else along the course of CRR. Should this alluvium therefore be called the "Alluvium of White Mesa"?
- CRR is the only one of the streams to carry far-traveled material
- CRR is longer than any of the other streams
- CRR has the most complete section
- This section is the best exposed
- The side streams at White Mesa are short and carry no exotic material, so are tributary to CRR
- The side streams are localized in strike valleys along a monoclinal flexure (Fig. 7). CRR cuts across the ridges forming the strike valleys.

Fig. 7. View northeast along Klethla Valley. CRR crosses valley southwestward from Black Mesa to White Mesa. Tributary channels on White Mesa are parallel to trend of monoclinal flexure.

Conclusion: alluvium of CRR is the significant unit, not that of White Mesa

AGE OF CROOKED RIDGE RIVER AND PROVENANCE OF ITS ALLUVIUM

Hereford et al (2016) proposed that CRR is "…no older than ca. 25 Ma…" on the basis of detrital zircon ages from the CRR alluvium, and ca. 2 Ma on the basis of a tuff interbedded with alluvium at Blue Point on the Moenkopi Plateau (Fig. 4), together with detrital sanidine from the CRR alluvium.

Blue Point tuff

Blue Point is more than 50 km away from Crooked Ridge and White Mesa, with which there is no known geologic or documentable geomorphic connection. According to Hereford et al., 2016, the lithologic characteristics of the Blue Point alluvium "resemble" those of the alluvium on White Mesa, on which grounds the Blue Point alluvium is declared to be part of the White Mesa alluvium. Therefore, the age of the tuff interbedded with the Blue Point alluvium is taken to be a primary evidence for the age of the White Mesa (and CRR) alluvium, that is, ~2 Ma.

There is no reason to consider the Blue Point and White Mesa/CRR alluviums to be continuous or stratigraphically equivalent: they are not connected, and the Blue Point alluvium contains none of the exotic clasts that are characteristic of CRR/WM alluvium. Furthermore, the tuff at Blue Point is a distinct layer in the stratigraphic sequence, whereas material of similar age is only present as a few grains of detrital sanidine in the CRR/White Mesa alluvium, suggesting contamination (see below).

Detrital zircon ages and provenance

The detrital zircon data presented by Hereford et al. (2016) are not clear. Apparently, the younger grains include 18 with a weighted mean average age of ~33 Ma; the 12 youngest grains in this range have a weighted mean average ~23 Ma, and the two youngest grains have imprecise ages of ~15 and ~19 Ma. On these grounds the authors conclude that the CRR alluvium is "younger than 20-15 Ma", and "possibly younger than ca. 15 Ma". The significance of this for the age of CRR is discussed below.

Regarding provenance, some ages around 25 Ma are those of volcanic rocks of the San Juan and Navajo Volcanic Fields, and of the younger laccoliths in SW Colorado and SE Utah. Additional prominent age peaks are in the ~1400 to ~1700 Ma range, which is the age of Proterozoic basement rocks exposed to the northeast in Colorado, but also to the south in the Mogollon Highlands of Arizona. Because of this, Hereford et al. (2016) do not consider the Proterozoic rocks to be unequivocal indicators of provenance. However, the minettes of the Navajo Volcanic Field and the laccolithic rocks are exposed only to the north and northeast, and the abundant 85-225 Ma ages also present in the samples are those from Mesozoic rocks exposed only to the north and northeast; these rocks contain tuffs and volcanic debris of that age.

Taken together, these zircon ages indicate provenances that match well and reinforce those indicated by the clast lithologies in the CRR gravel as given by Lucchitta et al. (2013, Tables 1 and 2). When these provenances are combined with physical characteristics of the CRR alluvium, which indicate that the paleoriver flowed toward the southwest, the clear conclusion is that the river originated in the San Juan Mountains, as indicated by Lucchitta et al. (2013).

Detrital sanidine geochronology

As discussed above, we dismiss the Blue Point ages as not pertinent to this discussion. This leaves the ages obtained directly from the CRR/WM alluvium.

Approximately 100 grains were obtained by Hereford et al (2016) from each of two bulk samples collected from near the wind gap and from White Mesa.

Of the 200 grains, a total of 6, or 3%, yielded ages of ~2 Ma, as indicated by the authors and shown in the "N" row of figure 13B. This is an extraordinarily low percentage. Presumably, the sanidines were derived from airfall tuff(s) that blanketed the region and then were washed down into the river bed. Would one not expect a higher proportion of ~2 Ma sanidine grains? Why are they so few? In contrast, grains giving the ages of rocks exposed to the north and northeast are abundant, again confirming the provenance of the alluvium indicated by the exotic casts. Could the very young grains be the result of contamination?

Whether the 2 Ma ages are real or not, it is appropriate to analyze their significance in terms of the overall history of CRR.

Significance of the analytical ages

All the ages were obtained from the CRR alluvium that is preserved today. Is this the only alluvium that the river deposited in its entire history? Do the ages tell us when the river was born? They do not.

The present-day alluvium is the last alluvium deposited by the river before it died. This is documented by the massive 2-3m-thick calcrete that overlies the alluvium. It is this calcrete that protected the alluvium from erosion, resulting in the preservation of the river's course in inverted relief as a sinuous ridge.

Calcrete does not form in active floodplains, so the CRR calcrete must have formed after the river ceased to flow. Therefore, ages obtained from the alluvium only give a maximum age for the death of the river. They say nothing about when the river came into being.

To give an outrageous example, consider a hypothetical Colorado River terrace. Assume it has yielded an age of 0.5 Ma. Does this age say anything about when the Colorado River or the Grand Canyon came into being? It does not; it is simply the age when that terrace became detached from the river and was no longer part of the active floodplain. In other words, when it died.

Likely origin and age of CRR

We are left with the problem of when CRR was actually born, and we have no firm data that bear on this. However, any river has to be linked to a source of water, which generally (especially in the western U.S.) is in terrain high enough to create its own weather. In case of the San Juan Mountains, volcanism first manifested itself in the form of central-peak andesitic volcanoes that reached impressive altitudes, probably 5-7 km, in any case amply high enough to generate abundant precipitation, and continuing to be high in the subsequent phases of volcanism. These mountains are still high today and give rise to many large rivers There was no high terrain in the area beforehand, so the birth of rivers such as CRR is most likely linked to the formation of the mountains starting in early Oligocene time.

This is a reasonable, though unproven, proposition, and we set it forth as such, meaning that CRR may well have started life in the Oligocene.

Continuation of CRR

West of the Echo Cliffs, CRR first flowed south in a strike valley, then westward to a junction with the ancestral Colorado River, and probably also the ancestral Little Colorado River, but some distance west of the present confluence. Thence, it flowed across the Kaibab upwarp in a curved strike valley congruent with the present Eastern Grand Canyon (Fig. 4). From there, it continued in a northwest direction across what is now the Arizona Strip to destinations that are suspected but not known with any certainty.