Late Oligocene–early Miocene Grand Canyon: A Canadian connection?

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ABSTRACT

Remnants of fluvial sediments and their paleovalleys may map out a late Oligocene–early Miocene "super-river" from headwaters in the southern Colorado Plateau, through a proto–Grand Canyon to the Labrador Sea, where delta deposits contain microfossils that may have been derived from the southwestern United States. The delta may explain the fate of sediment that was denuded from the southern Colorado Plateau during late Oligocene–early Miocene time.

I propose the following model:

1. Uplift of the Rio Grande Rift cut the southern Colorado Plateau out of the Great Plains at 26 Ma and tilted it to the southwest.
2. The upper Colorado River and its tributaries began as consequent streams that flowed down the structural plunge of the basin toward the southwest corner of the Colorado Plateau, where the river passed through a Paleogene canyon.
3. The river turned north in the Lake Mead region to enter Paleogene rifts of the eastern Great Basin.
4. NE-trending grabens across the Idaho and Montana Rockies provided the final link to the Great Plains, where the Miocene drainage joined the "Bell River" of Canada, which drained to the Labrador Sea.
5. Faulting and volcanism began to segment the paleo-river by ca. 16 Ma.
6. Faulting dammed Miocene Grand Canyon, creating a large ephemeral lake that persisted until after 6 Ma, when the Colorado River was captured by the Gulf of California.
7. The resulting shortcut to sea level greatly increased the gradient of the Colorado River, leading to headward incision of the Inner Gorge of Grand Canyon along the trace of the Miocene bedrock valley floor and renewed late Miocene-Holocene erosion of the Colorado Plateau.
8. The Yellowstone hotspot cut the river off in Idaho after 6 Ma.
9. Pleistocene continental glaciation destroyed the Canadian Bell River and diverted Montana's drainage into the modern Missouri River.

INTRODUCTION

Apatite fission track and (U-Th)/He data indicate that Grand Canyon probably existed in some form by late Oligocene–early Miocene time (Flowers et al., 2008; Wernicke, 2011; Cather et al., 2012; Flowers and Farley, 2012; Lee et al., 2013). However, the fate of its eroded sediment remains uncertain, as does the outlet of a hypothetical late Oligocene–early Miocene Colorado River (Karlstrom et al., 2012); the river did not reach the Gulf of California until 5.3 Ma (Dorsey et al., 2005). Several researchers have concluded that an early Miocene Colorado River most likely would have flowed northwest from a proto–Grand Canyon, because geologic barriers blocked avenues to the south and east (Lucchitta et al., 2011; Cather et al., 2012; Dickinson, 2013).

Here I propose that a late Oligocene–early Miocene Colorado River could have turned north in the Lake Mead region to follow paleovalleys and rift systems through Nevada and Idaho to the upper Missouri River in Montana. The upper Missouri joined the South Saskatchewan River of Canada before Pleistocene continental ice-sheets deflected it to the Mississippi (Howard, 1958). The South Saskatchewan was a branch of the pre-ice age "Bell River" of Canada (Fig. 1), which discharged into a massive delta in the Saglek basin of the Labrador Sea (McMillan, 1973; Balkwill et al., 1990; Duk-Rodkin and Hughes, 1994). Could the late Oligocene–early Miocene Colorado River have ultimately discharged into the Labrador Sea?

The following paragraphs outline geologic evidence for the evolution of a proposed late Oligocene–early Miocene paleovalley from Canada upstream to the Colorado Plateau, and suggest tests at

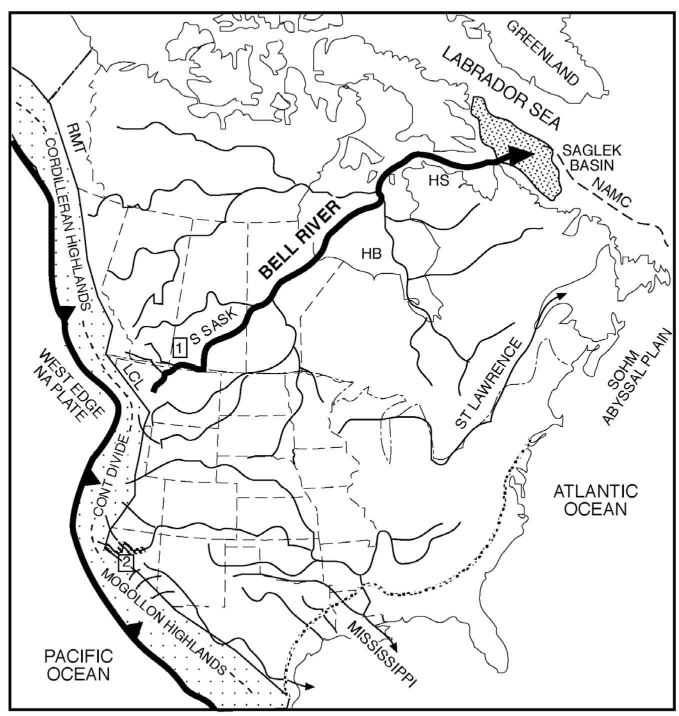

Figure 1. Early Oligocene drainage off North American Cordilleran highlands. 1—Cypress Hills and Wood Mountain; 2—Western Grand Canyon; after Duk-Rodkin and Hughes (1994). See Figure 2 for key to abbreviations.

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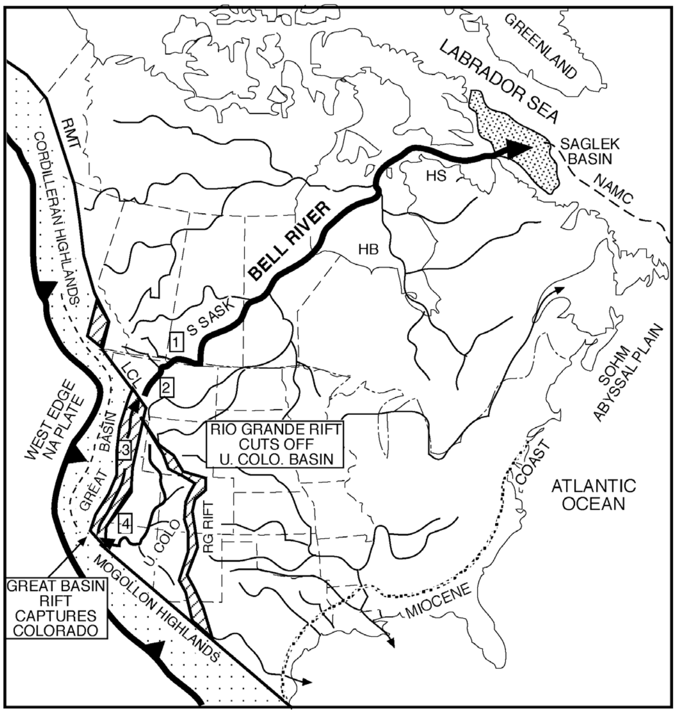

Figure 2. Miocene North American drainage. Rio Grande Rift has cut off western headwaters of Mississippi River and created upper Colorado basin, which drains into eastern Great Basin rift. 1—Cypress Hills and Wood Mountain; 2—Upper Missouri River; 3—Eastern Great Basin rift; 4—Early Grand Canyon; HB—Hudson Bay; HS—Hudson Strait; LCL—Lewis and Clark Line; NAMC—Northwest Atlantic Mid-Ocean Channel; RG—Rio Grande; RMT—Rocky Mountain Trench; S SASK—South Saskatchewan River; U. COLO—Upper Colorado River.

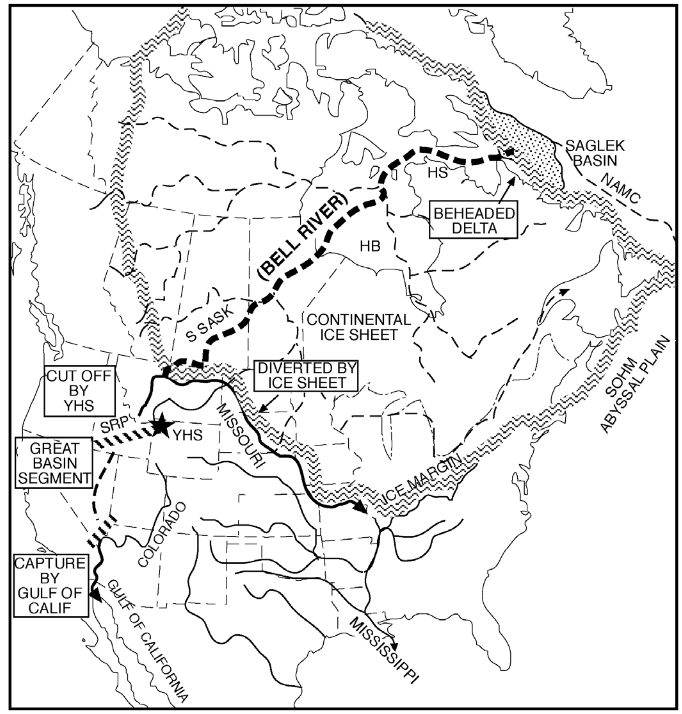

Figure 3. Pleistocene North American drainage. Continental ice sheets turn Montana drainage into modern Missouri. Yellowstone hotspot track has cut off Miocene River. Faulting in SE Nevada has diverted Colorado River to Gulf of California. HB—Hudson Bay; HS—Hudson Strait; NAMC—North Atlantic Mid-Ocean Channel; SRP—Snake River Plain, S SASK—South Saskatchewan River; YHS—Yellowstone hotspot.

critical linkages between proposed paleovalley segments. Figures 1, 2, and 3 summarize the proposed evolution of the drainage.

BELL RIVER OF CANADA AND ITS DELTA

The Cenozoic Bell River basin (McMillan, 1973) drained most of Canada before the basin was destroyed by Pleistocene continental glaciation. The tributaries gathered in the area of Hudson Bay and flowed out to sea through Hudson Strait (Duk-Rodkin and Hughes, 1994). Headwater valleys are preserved in the Rocky Mountains, Mackenzie Mountains, and northern Great Plains. The South Saskatchewan River, its main southern tributary, had sources in the Montana Rockies (Leckie et al., 2004).

The Bell River fed the >8-km-thick Saglek delta deposit in the Labrador Sea (Jauer and Budkewitsch, 2010). This delta comprises the largest sedimentary depocenter on the Atlantic seaboard of North America (Balkwill et al., 1990). An indication of the magnitude of the Bell River basin is given by the Northwest Atlantic Mid-Ocean Channel, one of the longest in the world, which winds along the seafloor for 3400 km, from the foot of the delta to the Sohm Abyssal Plain, east of New England. Continental glaciation beheaded the Saglek delta at Hudson Strait (Jauer and Budkewitsch, 2010).

Reworked fossil pollen recovered from exploration wells in the delta may support a direct link to headwaters in the Colorado Plateau. The pollen and associated sediment was derived from the western interior of North America (Hiscott, 1984; Williams, 1986). More than 15 recyclant palynomorphs identified by Williams (1986) match fossil pollen found in upper Paleozoic and lower Mesozoic continental strata that are widespread on the Colorado Plateau, but rarely crop out farther north (cf. Cook and Bally, 1975). From upper Eocene to lower Miocene muds drilled in the Roberval K-92 well of the Saglek basin, Williams (1986) identified *Calamospora, Convolutispora, Densoisporites, Foveotriletes, Matonisporites,* and *Osmundacidites wellmanii*, which are also known from the Chinle Formation of northern Arizona (cf. Litwin et al., 1991), and a *Lycospora-Triquitrites-Punctatisporites* assemblage, which is also known from the Supai Group of Grand Canyon (cf. McKee, 1982).

The Bell River drainage has been traced up the South Saskatchewan paleovalley to the Cypress Hills and Wood Mountain, river-gravel-capped nunatak ridges on the southern Canadian plains (Prest 1970). The gravel fills broad, overlapping Eocene to early Miocene paleovalleys (Leckie et al., 2004). Paleocurrent measurements indicate that the gravel was deposited by NNE flow in braided channels (Leckie et al., 2004). Provenance of placer gold, alkalic volcanics, and Belt Supergroup pebbles indicates derivation from the Montana Rockies (Leckie et al., 2004).

UPPER MISSOURI PALEOVALLEY, MONTANA

The South Saskatchewan paleovalley trends directly toward the upper Missouri River of northwest Montana (Fig. 4). Remnants of Miocene river gravel trace the ancestor of the upper Missouri for 350 km, from Great Falls southwest to the Continental Divide (Sears et al., 2009). Upper Missouri paleovalley segments are as

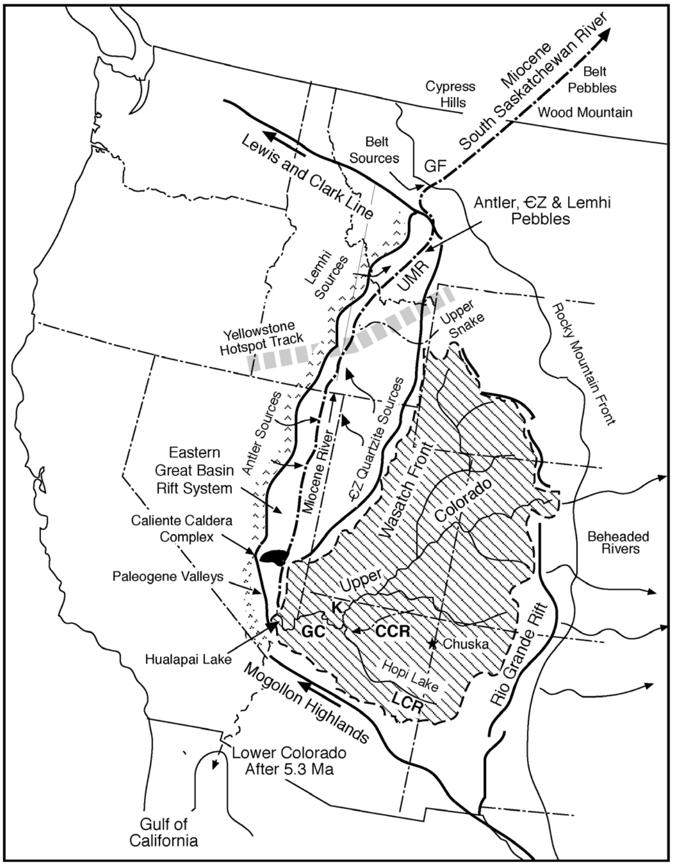

Figure 4. Miocene central-western United States drainage. Upper Colorado River basin (cross-hatched) drains structural trough toward southwest corner of Colorado Plateau, leading to rift systems through Nevada, Idaho, and Montana, to headwaters of South Saskatchewan River. Antler orogenic belt, Cambrian-Precambrian Z (€Z) quartzite, Lemhi Group, and Belt Supergroup bedrock sources feed gravel northeast along Miocene river. CCR—Crooked Ridge River; GC—Grand Canyon; GF—Great Falls; K—Kaibab Upwarp; LCR—Little Colorado River; UMR—Upper Missouri River; black—Caliente caldera complex; dotted, inverted Vs—uplifts on west flank of Miocene river. Dashed gray line—Yellowstone hotspot track. Note that northern part of upper Colorado River basin was not integrated with southern part until late Miocene (Cather et al., 2012).

broad as 10–15 km and contain Miocene fluvial deposits as thick as 200 m. The paleovalley was carved into beds as young as the Arikareean Renova Formation, and was filled by river beds as old as the Barstovian Sixmile Creek Formation (Fields et al., 1985). Active faults of the Intermountain Seismic Belt have disrupted the paleovalley (Stickney, 2007).

The upper Missouri paleovalley was superimposed over a Paleogene rift system that linked western Montana with Idaho, Nevada, and Utah (Janecke, 1994; Axen et al., 1993). The rift system and associated core complexes and high topography had propagated from Montana to southern Nevada in Eocene and Oligocene time in association with the southward-migrating Cordilleran magmatic arc (Mix et al., 2011). The rift system may have channeled volcanic ash from the magmatic in arc Nevada and Utah to Idaho and Montana, where it accumulated as thick claystone deposits in the Renova and correlative formations.

The Miocene fluvial deposits of the upper Missouri paleovalley contain an assemblage of exotic pebbles and cobbles that have no possible bedrock sources in Montana (Sears et al., 2009). These clasts diminish in grain size northeast along the paleovalley, in accord with prevailing paleocurrents (Landon and Thomas 1999). They include abundant roundstone cobbles likely derived from Cambrian-Precambrian Z quartzites of southeastern Idaho and western Utah (cf. Oriel and Armstrong, 1971), along with pebbles that match distinctive lithologies of the Antler belt of Nevada, including: (1) Eureka Quartzite, (2) Valmy chert and Vinnini quartzite of the Roberts Mountain allochthon, and (3) Diamond Peak conglomerate of the Antler overlap assemblage (cf. Coats, 1987). These lithologies were exposed on the shoulders of the Paleogene rift that linked western Montana with Idaho and Nevada. Fluvial transport down the rift axis could have brought the exotic clasts into Montana.

The gravel-filled Miocene paleovalley crosses the Continental Divide from Montana into Idaho, where it is buried by Pliocene volcanics of the Yellowstone hotspot track and Pleistocene basalt of the Snake River Plain (cf. Pierce and Morgan, 1992). The distinctive river gravel reappears in windows through the basalt more than 100 km south of the Continental Divide, where it has been exploited in gravel pits. Detrital zircon studies show that, after 6 Ma, the Continental Divide migrated east from the Idaho batholith to its present location on the Montana border (Beranek et al., 2006), where it crosses the trend of the paleovalley.

Remnants of middle and upper Miocene fluvial and lacustrine deposits occur in isolated patches above a regional unconformity along the trend of the Paleogene rift system in Nevada (Coats, 1987; Stewart and Carlson, 1978). The Paleogene rift system was segmented by basin-range faulting, and the paleovalley deposits have been variably tilted, faulted, eroded, and buried in the modern landscape (cf. Henry et al., 2011).

The Caliente caldera complex erupted near the southern end of the rift system from 26 to 15 Ma (Axen, 1998). North of the caldera complex, north-trending paleochannels contain volcanic ash and well-rounded river pebbles of Caliente volcanics along with metamorphic lithologies that were ultimately derived from basement complexes exposed farther to the south.

Remnants of Paleogene paleovalleys may connect the Paleogene rift system to western Grand Canyon. Reconstruction of basin-range faulting in the Lake Mead region restores the pre-extensional, 26–16-Ma basal Horse Spring Formation against the southwest corner of the Colorado Plateau near the western edge of Grand Canyon (Umhoefer et al., 2010). The formation was deposited on alluvial plains that sloped off the flanks of Laramide ridges into a broad north-trending paleovalley on the west edge of the plateau (Anderson and Beard, 2010). The Laramide ridges coincide with the shoulder of the Paleogene rift system mapped by Mix et al. (2011), which had propagated south to that latitude by 28 Ma. Until basin-range faulting began at 17 Ma, most of the sediment in the Horse Spring paleovalley bypassed the system toward the northeast (Lamb et al., 2010).

EARLY MIOCENE PROTO–GRAND CANYON?

An early Miocene paleocanyon floor may transect the entire length of Grand Canyon, midway between the rim and the river. The feature is represented by a ~5-km-wide terrace that is incised by the deep and narrow Inner Gorge. The terrace transects hundreds of meters of tilted stratigraphy as it crosses the Kaibab

Upwarp, a major Laramide anticline in eastern Grand Canyon (Dickinson, 2013). It is offset by Pliocene and younger normal faults. It comprises the Hualapai Plateau in western Grand Canyon, the Esplanade terrace atop the Supai Group in central Grand Canyon, and a series of concordant buttes, mesas, spurs, and terraces on top of the Redwall Limestone in eastern Grand Canyon (Fig. 5). River-polished and fluted limestone and beheaded fluvial channels are locally preserved on the surface. The Redwall bench and Esplanade terrace are mutually exclusive; there is no Redwall bench in central and western Grand Canyon, and no Esplanade terrace in eastern Grand Canyon. They appear to be concordant parts of the same erosional surface.

The Hualapai Plateau is a mature cuestaform terrace cut by deep paleocanyons that are filled with Paleogene fluvial/alluvial sediments (Young, 2008). Wernicke (2011) and Flowers and Farley (2012) deduced from apatite dating that the paleocanyons may have been cut by 70 Ma. Wernicke (2011) proposed that the Late Cretaceous "California River" flowed eastward through the proto–Grand Canyon and delivered feldspathic sediment from the Sierra Nevada to the Cretaceous Interior Seaway in southern Utah, and later reversed its flow.

The Hualapai terrace is capped by 20- to 16-Ma volcanics that flowed across the filled paleocanyons, and is incised by the narrow, 1-km-deep Inner Gorge, which cuts across ca. 6-Ma dike swarms (Billingsley and Wellmeyer, 2003).

Lee et al. (2013) concluded from apatite dating that a canyon had eroded through the Kaibab Upwarp of eastern Grand Canyon in latest Oligocene–early Miocene time (28–20 Ma). Flowers et al. (2008) deduced from apatite dating that from 23 to 16 Ma erosion had cut a ~1-km-deep canyon through the Kaibab rim. That depth would correspond to the level of the mid-canyon bedrock bench.

East of Grand Canyon, Lucchitta et al. (2011) interpreted a meandering ridge of fluvial sediment as a topographically inverted Miocene paleovalley—the "Crooked Ridge River." The feature crosses >100 km of the Navajo Nation and may have been a major tributary or even the main stem of the ancestral Colorado River. The fluvial sediment includes minor amounts of stream-rounded gravel ultimately derived from the San Juan and Needle Mountains of Colorado (Hunt, 1969). The gradient of the Crooked Ridge River projects toward that of the 16-Ma paleovalley of the Little Colorado River basin as well as toward that of the mid-canyon bedrock bench in eastern Grand Canyon (Dickinson, 2013).

COLORADO PLATEAU

Continental rifting separated the southern Colorado Plateau from the Great Plains beginning ca. 26 Ma (Chapin and Cather, 1994). Prior to the rifting, the region had relatively low relief and drained east from the Cordilleran highlands toward the mid-continental lowlands (Cather et al., 2008; Wernicke, 2011) (Fig. 1). The rifts formed when the western North American plate boundary became dextral-transtensional, and the crustal block that became the Colorado Plateau rotated clockwise relative to North America (Chapin and Cather, 1994). The basin is bordered by rift systems (Fig. 4). On the west is the eastern Great Basin rift and Wasatch Front, on the south, the Mogollon Highlands, on the east, the Rio Grande Rift (Chapin and Cather, 1994). The Wyoming part of the basin was not integrated until late Miocene (Cather et al., 2012).

Figure 5. Miocene(?) mid-canyon bench as seen on Cheops Pyramid and adjacent ridges on top of Redwall Limestone, near Phantom Ranch, eastern Grand Canyon, USA. Photo by J.W. Sears.

Uplift of the rift zones created a broad structural trough that warped the mature, early Oligocene (ca. 35 Ma) Rocky Mountain erosional surface (Cather et al., 2008). The upper Colorado River and its tributaries formed a consequent drainage system that flowed down the structural trough toward the southwest corner of the Colorado Plateau. Since 26 Ma, the east side of the basin has risen nearly 3 km relative to the southwest corner (Epis and Chapin, 1975; Liu and Gurnis, 2010).

A number of erosional remnants document the timing of incision and the depth of erosion of the Colorado Plateau. For example, an Oligocene erg that caps the Chuska Mountains lies 1.2 km above the 16-Ma floor of the Little Colorado paleovalley (Dallegge et al., 2003; Cather et al., 2008).

I propose that much of the sediment that was denuded from the southern Colorado Plateau in late Oligocene–early Miocene time could have been deposited in the Labrador Sea and on the Sohm Abyssal Plain. The upper Oligocene to lower Miocene Mokami Formation of the Saglek basin received a tremendous influx of clay and silt during that interval, and the silt included palynomorphs of fossils from the western interior (Balkwill et al., 1990). The sediment largely bypassed deposition in the fluvial system leading to the Labrador Sea.

The deep erosion of the southern Colorado Plateau was coeval with the lead-up to the Miocene climatic optimum, ca. 20–17 Ma (Zachos et al., 2001). In the western U.S., this period experienced significantly elevated weathering and rainfall with the development of thick laterite soils (Thompson et al., 1982).

COLORADO RIVER DURING THE 16–5-MA INTERVAL

There is no record of Colorado River gravel in Grand Wash graben to the immediate west of Grand Canyon until after ca. 6 Ma, even though thick sections of Miocene sediment are well exposed in the graben (Lucchitta, 1972; Young, 2008). The graben sediment consists mainly of locally derived alluvium and lacustrine deposits of "Hualapai Lake"—evidence of closed-basin deposition; no Miocene Colorado River delta occurs in the graben (Anderson and Beard, 2010; Howard et al., 2010). Could the river have begun to carve the canyon before 6 Ma, if the adjacent downstream graben contains no river delta (Pederson, 2008)?

To address this problem, Lucchitta et al. (2011) and Dickinson (2013) proposed that the river flowed through eastern Grand Canyon, as also suggested here, but turned north before reaching Grand Wash, and proceeded on a hypothetical route through southern Utah.

Alternatively, Young (2008) proposed that, before 5 Ma, Hualapai Lake had flooded Grand Wash and western Grand Canyon and had trapped clastic fluvial sediment far upstream. The lake could have been dammed by uplift of basin-range fault blocks on the west side of Grand Wash at 16–14 Ma (cf. Howard et al., 2010). A structural cross section indicates that 3 km of structural relief was attained between the fault blocks and western Grand Canyon by 16 Ma (Karlstrom et al., 2010).

Given the reconstructed gradient of the proposed Miocene river, a lake dammed by the basin-range fault blocks at the mouth of Grand Canyon could conceivably have backed water up to Miocene Hopi Lake on the Little Colorado River (Fig. 4), if Grand Canyon had already cut across the Kaibab Plateau. At present, the top of 16–6-Ma deposits of Hualapai Lake (~900 m) is ~1 km lower in elevation than the top of the lacustrine facies of the 16–6 Ma Bidahochi Formation of Hopi Lake (~1900 m), but in the past 3.5 m.y., the Grand Canyon east of the Hurricane and Toroweap fault systems has been uplifted ~600 m relative to the west (Karlstrom et al., 2008). Hualapai and Hopi lakes could have been parts of the same impoundment, if eastern Arizona shared the regional late Miocene–Holocene isostatic rock uplift that is indicated to measure ~1 km in southeastern Utah (cf. Cather et al., 2012). At full lake pool, coarse fluvial sediment would have been restricted to deltas at the mouths of drowned canyons, tens to hundreds of kilometers upstream of Grand Wash. Delta facies indeed occur in the Bidahochi Formation of Hopi Lake at the mouths of paleovalleys (Dickinson, 2013).

The lakes existed during a 15–6-m.y. period of erosional stagnation on the Colorado Plateau, according to apatite (U-Th)/He data (Cather et al., 2012). Lacustrine deposition of the Bidahochi Formation at Hopi Lake gave way to fluvial deposition ca. 6 Ma, after which the formation began to be incised by the Little Colorado River (Dickinson, 2013). Incision of the Bidahochi Formation coincided with incision of the Inner Gorge in western Grand Canyon and dissection of Hualapai Lake beds at Grand Wash graben by the integrated Colorado River system (Pederson, 2008; Karlstrom et al., 2008; Howard et al., 2010). Howard et al. (2010) mapped a series of Late Miocene paleovalleys across the fault blocks on the west side of Grand Wash that could mark successive outflow channels.

Cather et al. (2012) determined that the southern Colorado Plateau was denuded by ~1–2 km between 27 and 15 Ma, and that the northern plateau was denuded by about the same amount between 6 Ma and the present. There was apparently a relative lack of erosion between 15 and 6 Ma (Cather et al., 2012), the interval during which Hualapai and Hopi lakes were accumulating modest sediment loads. After 6 Ma, the sediment could have washed to the Gulf of California.

Consistent with the present model, comparisons of freshwater fish fossils indicate that the Bidahochi Formation and the upper Snake River of eastern Idaho occupied a common drainage basin during Miocene time (Lucchitta et al., 2011) (Fig. 4). DNA studies show that fish of the upper Snake and upper Colorado basins have more in common with each other than they do with fish in the lower parts of their respective basins (Spencer et al., 2008).

DISCUSSION AND CONCLUSION

Capture of the Colorado River by the Gulf of California would have shortened its route to sea level from the ~5000 km proposed here (Lake Mead to Labrador Sea) to ~500 km (Lake Mead to the Gulf of California). Steepened gradients and deep erosion of side canyons would have permitted the transport of a gravel bedload, so that the first bona-fide Colorado River gravel appears above the 6-Ma Hualapai Limestone (Lucchitta, 1972; Karlstrom et al., 2008).

In the Great Basin, extension intermittently interrupted the flow of the proposed paleoriver after 17 Ma, so that ephemeral lakes formed and filled with sediment until river flow was restored. Thus, most upper Miocene sections include lacustrine, fluvial, and alluvial beds.

The Yellowstone hotspot crossed the proposed paleovalley between 10 and 6 Ma (cf. Pierce and Morgan, 1992). After 6 Ma, the Snake River first delivered sediment to the Boise area, the Continental Divide shifted eastward (Beranek et al., 2006), and the Montana reach of the paleovalley was cut off from former sources to the southwest.

In summary, the upper Colorado River may have been the southern tributary of one of the largest river basins in the world during the lead-up to the Miocene climatic optimum. Runoff may have carried a sediment load for >5000 km from the southern Colorado Plateau, through an early Grand Canyon, down rift zones in Nevada, Idaho, and Montana, and across the Canadian plains to the Labrador Sea. Turbidity flows from the delta then carved the 3400-km-long Northwest Atlantic Mid-Ocean Channel to spill out onto the Sohm Abyssal Plain southeast of New England.

A number of standard provenance tests could be made to evaluate the hypothesis at key locations along the trace of the proposed paleoriver—for example, detrital zircon analyses of paleoriver deposits, detailed petrographic comparisons of suggested sources and pebbles, and further analysis of palynomorphs from samples of Saglek delta muds and proposed source regions.

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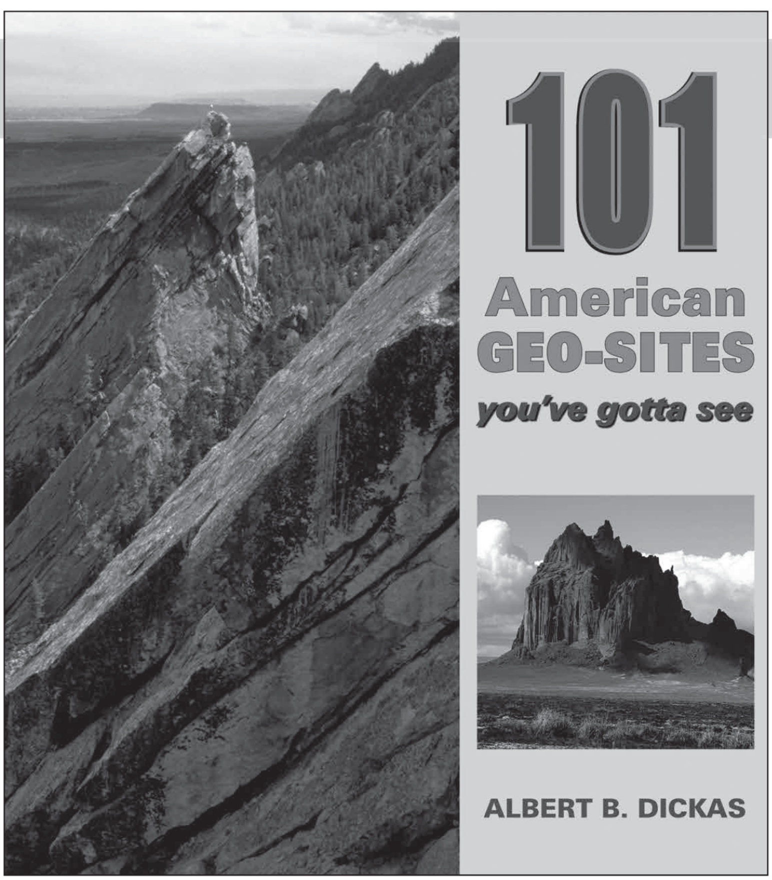

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