# The mystery of the pre–Grand Canyon Colorado River—Results from the Muddy Creek Formation

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## ABSTRACT

The Colorado River's integration off the Colorado Plateau remains a classic mystery in geology, despite its pivotal role in the cutting of Grand Canyon and the region's landscape evolution. The upper paleodrainage apparently reached the southern plateau in the Miocene, and recent work supports the longstanding idea that the river was superimposed over the Kaibab uplift by this time. Once off the plateau, the lower river integrated to the Gulf of California by downstream basin spillover from ca. 6–5 Ma. An unknown link remains: the history of the river in the western Grand Canyon region in Miocene time. One of the viable hypotheses put forward by previous workers—that the late Miocene Muddy Creek Formation represents the terminal deposits of the paleo–Colorado River in the Basin and Range northwest of Grand Canyon—is tested in this paper. Results indicate instead that local drainages along with the paleo–Virgin River are the likely sources of this sediment. The remaining hypothesis—that the paleo-upper Colorado River dissipated and infiltrated in the central-western Grand Canyon area—has modern analogs, provides a potential source for extensive Miocene spring and evaporite deposits adjacent to the southwestern plateau, and implies a groundwater-driven mechanism for capture of the upper drainage.

## INTRODUCTION—THE GRAND DEBATE

The path of the pre–Grand Canyon Colorado River and how it came to its present course off the Colorado Plateau and into the lowlands of the Basin and Range have been debated for decades. Solving the problem of how the river came to flow off the plateau is key to understanding the formation of Earth's most famous erosional landscape—the Grand Canyon region. The Colorado River did not tap into its potential energy for erosion until it was integrated over the Grand Wash Cliffs and off the Colorado Plateau, dropping its base level ~1500 m and driving much of the subsequent canyon incision upstream (Pederson et al., 2002a). Understanding how this happened has been hampered by a lack of data, mostly the result, ironically, of erosion having removed much of the geologic record of the river's history.

Based on his early river expeditions, John Wesley Powell believed the Colorado River to be antecedent—relatively old, with younger uplifts raised across its path (Powell, 1875). However, it was soon thereafter established that the monoclinal uplifts of the Colorado Plateau formed in the early Cenozoic Laramide orogeny and that the Colorado River and its major tributaries are younger. Walcott (1890) first suggested that the river was superimposed across the southern flank of the Kaibab uplift while still flowing in overlying, less resistant Mesozoic strata (Fig. 1). William Morris Davis likewise recognized that the Colorado River is superimposed across the exhumed older uplifts of the plateau (Davis, 1901). He envisioned ancestral drainages that flowed northeast and then reversed direction due to down-faulting to the west, with recent uplift of the plateau rejuvenating the Colorado River and forming Grand Canyon.

Broadly speaking, Davis' model was validated and supplemented by the work of subsequent workers. It was recognized early on that the upper basin fill in the Lake Mead region, southwest of the plateau margin, is relatively young and that it precludes the existence of the present Colorado River in that area (Blackwelder, 1934; Longwell, 1946). Closer analysis of the sedimentary record of the Grand Wash Trough, where the Colorado River enters the Basin and Range, revealed a switch from internal basin deposition to subsequent dissection upon the arrival of the exotic Colorado River at 6 Ma (Lucchitta, 1966). Thus, the Colorado River was integrated ca. 6 Ma and carried out most of the incision of Grand Canyon since then (Lucchitta, 1972; McKee and McKee, 1972).

How the river reorganized to flow west and what the drainage was like before that time are elusive problems. After the Laramide orogeny, drainages in the Grand Canyon region were directed northeast off the ancestral Mogollon highland (Young and McKee, 1978). In Oligocene time, these consequent drainages were disrupted by magmatism in the central plateau, by the onset of arid climate, and potentially by epeirogenic uplift (e.g., Cather et al., 2008). In Charlie Hunt's extensive work (1956, 1969), he concluded that much of the upper Colorado River drainage had established itself on the northern and central plateau by Miocene time. So where did the drainage go when it reached the southern plateau? Research along the Mogollon Rim indicates that there was no Miocene exit route for the river to the southwest (Young and Brennan, 1974). Therefore, the main working hypotheses have been that the ancestral upper Colorado River: (a) issued southeast along the Little Colorado River trough either off the plateau or into the Bidahochi Formation of the south-central plateau (McKee et al., 1967); (b) crossed the Kaibab uplift and terminated in the southwestern Colorado Plateau (Hunt, 1956); or (c) crossed the Kaibab uplift and continued northwest across the low plateaus and into the Basin and Range (Fig. 1; Lucchitta, 1990).

Regarding hypothesis (a), researchers proposed that the Miocene river exited the plateau to the southeast to account for earlier Miocene erosion in the area (McKee et al., 1967). But there is no evidence for such a river, and the presence of the Bidahochi Formation along this path is a problem (e.g., Hunt, 1969). The Bidahochi dates to the time in question, but it

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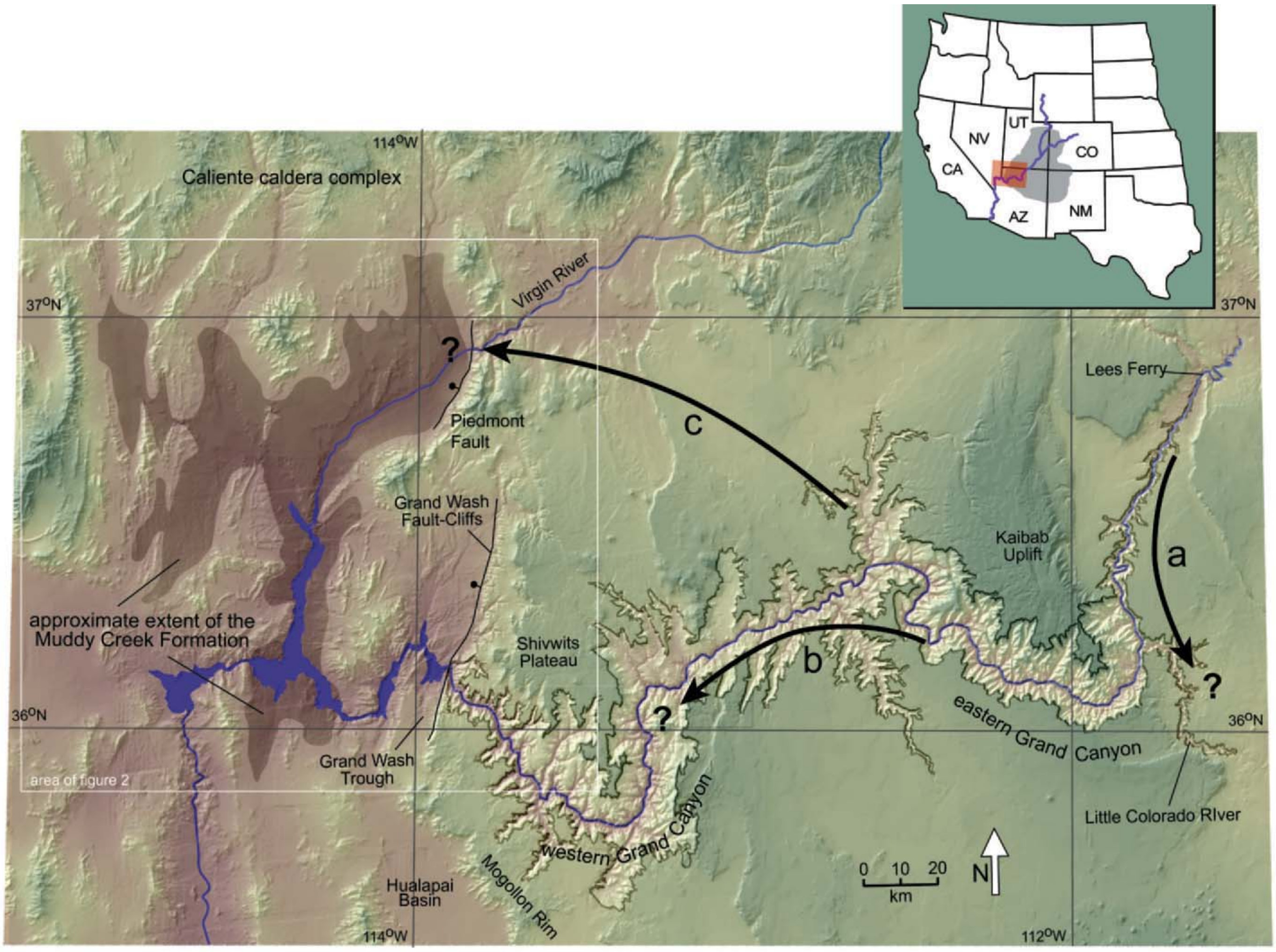

Figure 1. Regional geography and topography of Grand Canyon and Lake Mead region along the Colorado River at the edge of the Colorado Plateau (gray area of inset), southwestern United States. Large arrows indicate hypothetical paths of late Miocene upper Colorado River before major incision of Grand Canyon, with letters matching the hypotheses as reviewed in the text.

comprises local fluvial and volcaniclastic deposits rather than basin fill from an exotic river, and it is a small-volume unit with low sediment accumulation rates (Love, 1989; Dallegge et al., 2001).

Hunt's hypothesis (b), that the river arrived in the central-western Grand Canyon area and simply infiltrated and terminated, never gained traction—and was not well loved even by Hunt himself. The final hypothesis (c), that the river exited the Colorado Plateau to the northwest and debouched into the Basin and Range, has been described by Lucchitta (1990). These two ideas are both predicated upon the Colorado River gaining its path across the Kaibab uplift in middle Cenozoic time (Fig. 1). Davis (1901) and Strahler (1948) long ago recognized that the river's maneuver across this particular uplift does not require a different explanation than the one evident for the other Laramide orogens of the plateau—superposition. Indeed, thermochronological data indicate that significant canyon relief developed across the Kaibab uplift ca. 30–25 Ma, when a thick Mesozoic sedimentary section remained in the area east of the Kaibab uplift where there is now an erosional declivity (Lee, 2007; Flowers et al., 2008). It therefore seems likely that as it established its present path through the central plateau in late Oligocene–early Miocene time, the paleoriver flowed westward on the Mesozoic section, was superimposed along the curving south edge of the Kaibab uplift, and crossed into the central-western Grand Canyon region (Lucchitta, 1990).

The most viable candidate for a sedimentary record of this potential drainage in hypothesis (c) is the Muddy Creek Formation in the basins north of Lake Mead (Fig. 1). To understand the origin of this basin fill, a series of exposures and samples along a west-to-east transect from the Table Mesa basin through the Glendale Basin and into the Virgin Basin were studied to determine provenance and record how the exposed upper Muddy Creek facies change laterally (Fig. 2). Could this basin fill represent the terminus of the ancestral upper Colorado River? Longwell's (1928) original assessment of the Muddy Creek in the southern Virgin Basin was that its fine-grained sedimentary fill is incompatible with a Colorado River origin. But the Colorado River's famously large sediment load is ~90% clay, silt, and sand, and recent research on the Muddy Creek basin fill has resurrected the idea that the ancestral Colorado may have been a sediment source (Pederson et al., 2000). If this is true, then the Muddy Creek would be a slightly older analog for a series of units along the lower

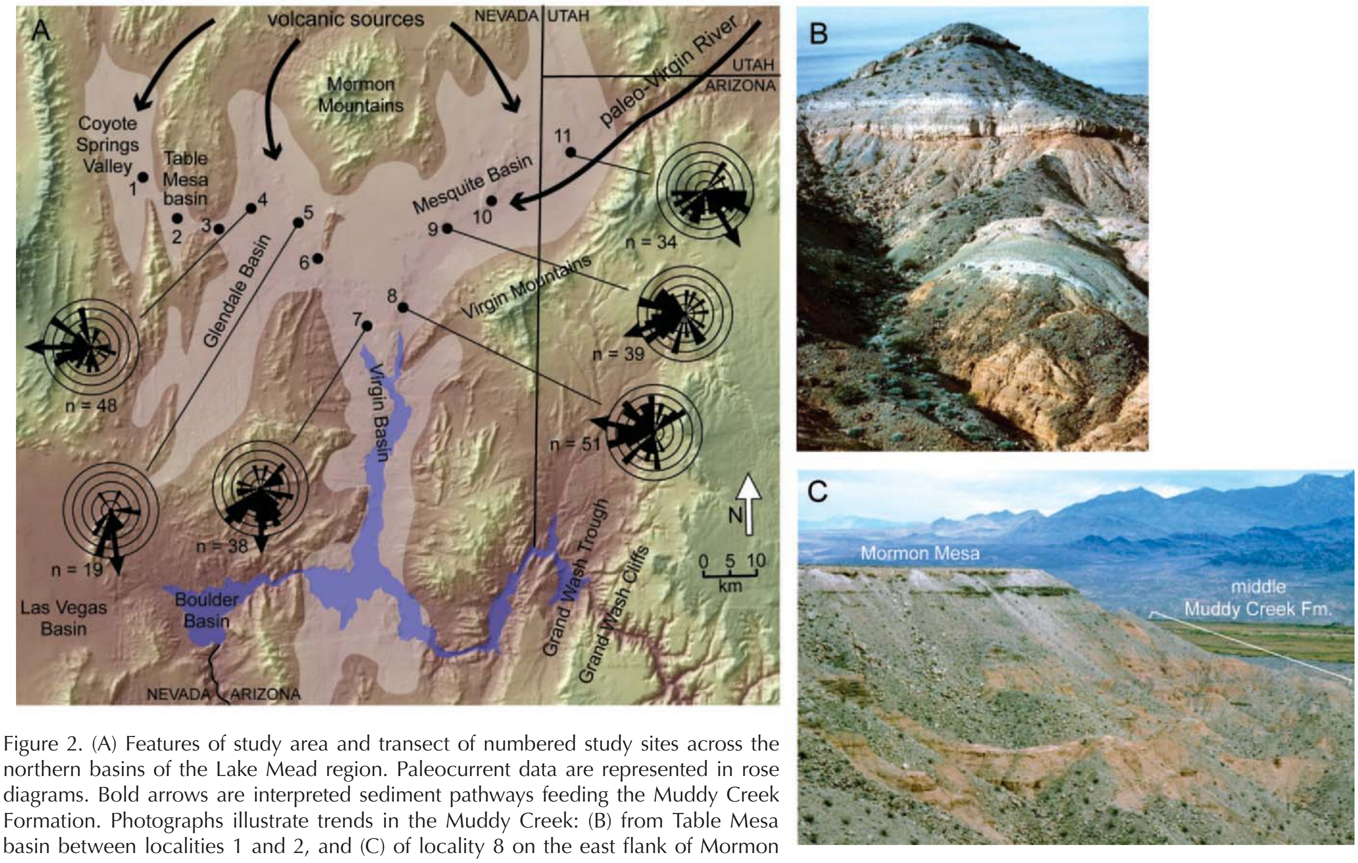

Figure 2. (A) Features of study area and transect of numbered study sites across the northern basins of the Lake Mead region. Paleocurrent data are represented in rose diagrams. Bold arrows are interpreted sediment pathways feeding the Muddy Creek Formation. Photographs illustrate trends in the Muddy Creek: (B) from Table Mesa basin between localities 1 and 2, and (C) of locality 8 on the east flank of Mormon Mesa. The unit generally coarsens upward, and finer-grained sediment of alluvial slope and lacustrine environments (B) transitions eastward to coarser fluvial sediment. Studied exposures of the middle member of the Muddy Creek lie below the younger capping or inset gravels in these photos.

Colorado River corridor and the Salton Trough, which record the progressive southward arrival and deltaic sedimentation of the early Pliocene Colorado River (cf. Lucchitta, 1972; Buising, 1990; House et al., 2005; Dorsey et al., 2007).

## MUDDY CREEK FORMATION NORTH OF LAKE MEAD

The Muddy Creek Formation has been defined as the late-stage (mostly post-faulting) basin fill of a series of somewhat connected extensional basins in the Lake Mead area (Stock, 1921; Bohannon, 1984). The Muddy Creek Formation has been dated by fossils, absolute dating, and tephra correlation as from 11 Ma to ca. 5 Ma. Neither the basin fill of the Grand Wash Trough, which is termed Muddy Creek Formation by some workers, nor the Muddy Creek in the Las Vegas and Boulder basins to the southwest are included here because they were sedimentologically and topographically disconnected from the study basins (Fig. 2).

Basin-forming extension, accommodated by dip-slip on normal faults, detachment faulting, and large-scale transfer zones with oblique-slip, tapered off in the study area after middle Miocene time (e.g., Anderson, 1973; Bohannon, 1984; Duebendorfer and Simpson, 1994). An exception to this is the eastern margin of the Mesquite Basin (Fig. 1), where Pliocene and Pleistocene faulting has deformed the Muddy Creek Formation (Williams, 1996; Billingsley and Bohannon, 1995). Generally, the unit was accommodated in basins that were underfilled as local tectonic activity waned. Although these structural basins had internal surface drainage during their formation, depositional systems overtopped low divides between basins, and the region became hydrologically and sedimentologically interconnected in the late Miocene, though not externally drained. This area was subsequently integrated into the greater present-day Colorado River drainage, which ended Muddy Creek deposition and led to downcutting and incision of the fill in latest Miocene to early Pliocene time, varying according to the timing of local drainage integration (Bohannon, 1984).

The Muddy Creek Formation contains laterally gradational facies that are interpreted to range from evaporate- and travertine-rich lake deposits lower in the stratigraphy and to the south and west to pebbly fluvial gravel as the unit coarsens upward and to the east (Longwell, 1946; Bohannon, 1984; Kowallis and Everett, 1986; Dicke, 1990; Schmidt, 1994; Billingsley, 1995; Schmidt et al., 1996; Williams, 1996; Pederson et al., 2000). In the westernmost basins, the upward transition from saline-lacustrine deposits to the overlying subaerial, siliciclastic-rich deposits of the middle Muddy Creek is abrupt, suggesting basin interconnection and the introduction of extrabasinal sediment at this time (Pederson et al., 2000). The siliciclastic middle member thickens greatly to the east from ~80 m in Table Mesa basin to ~2000 m, mostly in the subsurface, in the Mesquite Basin (Bohannon et al., 1993). It is dominated by pink to light red, laminated, cross-stratified or bioturbated and massive, calcareous and gypsiferous, thin to medium interbeds of mud and sand. This fine-grained, monotonous Muddy Creek is characteristic of sediment deposited in late-stage continental basins having mostly subaerial, sedimentary environments, such as alluvial slopes (Langford et al., 1999; Smith, 2000). In most areas, coarse facies are absent in the lower and middle Muddy Creek or are restricted to piedmont gravels found at the very basin edges.

The contrasting, strongly upward-coarsening capping beds of the upper Muddy Creek Formation have been recognized across the study area and are generally early Pliocene in age (Schmidt, 1994; Williams, 1996; Pederson et al., 2001). In the western study basins, these capping beds reflect a climate-driven change to the strong progradation of piedmont gravel from local mountainsides into the basins (Pederson et al., 2001). At the east end of the study transect, part of this capping unit has been identified as Virgin River gravel entering the Mesquite Basin from the Colorado Plateau (Billingsley, 1995; Billingsley and Bohannon, 1995; Williams, 1996). The early Pliocene change from Muddy Creek deposition to incision of the basin fill is marked by the first of a series of inset piedmont gravels and Virgin River gravels in the Mesquite Basin (Schmidt, 1994; Williams, 1996).

The new data here are from outcrops of the fine-grained, siliciclastic middle member of the Muddy Creek Formation, not from the capping or inset gravels. These outcrops are probably all sediment of latest Miocene age, and the study basins were apparently connected at this stratigraphic level. The gradation from finer and more lacustrine to coarser, thicker fluvial deposits from west to east, as well as upward within the unit at a given locality, is broadly consistent with the hypothesis that a river source entered the Mesquite Basin from the east. Regarding the sources of this sediment, one may infer that, like most of the Basin and Range, the basin fill was derived from surrounding mountainsides. The Virgin Mountains on the south flank of the Mesquite Basin include Proterozoic metamorphic rock, but the mountains surrounding Coyote Springs Valley, Table Mesa basin, Glendale Basin, and Virgin Basin are dominated by a 3000-m-thick Paleozoic sedimentary succession, almost entirely of marine carbonates. Carbonate rock is strong and difficult to weather in an arid climate, and petrologic studies in the western study basins confirm that the local mountains were not a major source of the siliciclastic middle member (Pederson et al., 2001). What, then, are the extrabasinal sources of this sediment?

## SEDIMENT SOURCES FOR THE MUDDY CREEK FORMATION

A series of outcrops along a west-to-east transect from the east edge of the Coyote Springs Valley and Table Mesa basin through the Glendale Basin and into the Virgin and Mesquite basins were described and sampled (sites 1–11, Fig. 2; see GSA Data Repository Table DR1[1]). All sampled localities lie ~30 m below the top of the siliciclastic middle member. Where possible, paleocurrent indications were recorded from cross-bedding and pebble imbrication. To explore the provenance of sediment, samples were collected from the study sites and their fine-sand fractions were mounted and thin-sectioned, stained for K-feldspar, and grain mineral types were counted under a microscope to a total of 400 (see data repository Table DR2 [footnote 1]). In addition, heavy-mineral suites from samples were separated using a heavy liquid. These were mounted, and minerals were counted until >400 non-opaque grains were recorded (data repository Table DR3 [footnote 1]). At localities 5, 8, and 10, vertical transects of three subsamples were taken (a, b, and c) and spaced through the entire exposure of the middle member, in order to explore trends as the unit coarsens upward.

Petrographic analyses were also made on samples of unconsolidated sand representative of five distinct sediment sources: a lower-member sample from Table Mesa basin derived from local Paleozoic bedrock (sample LoC); a sample from Pleistocene alluvium of Beaver Dam Wash in the Mesquite Basin derived from volcanic terrain of the Caliente caldera complex (sample LoV); Pleistocene piedmont alluvium on the north flank of the Virgin Mountains derived from metamorphic bedrock (sample LoM); Pleistocene Virgin River sand sampled from a terrace where the river enters the eastern Mesquite Basin upstream of Littlefield, Arizona (sample VR); and Pleistocene Colorado River sand from a terrace at Lees Ferry (sample CR). This last sample is intended to approximate the composition of sand from an ancestral Colorado River. The Miocene upper drainage would have been eroding mostly the Mesozoic and early Cenozoic sections of the plateau, just as the present river above Lees Ferry does, and the paleodrainage would have lacked Paleozoic detritus before the deep incision of Grand Canyon downstream of Lees Ferry (Fig. 1; Pederson et al., 2002b).

The sedimentology of the upper-middle member of the Muddy Creek at the study sites is consistent with the overall trend of coarsening upward and coarsening to the east, becoming more fluvial in depositional environment (Table DR1 [see footnote 1]). For example, localities 1–3 on the western end of the transect are characterized by sandy calcareous and gypsiferous mud likely deposited in shallow lacustrine or alluvial slope environments (Fig. 2B). Starting at locality 4 in the western Glendale Basin, these facies become interbedded with lenticular channel sand and gravel bodies; a few eolian sand beds confirm subaerial deposition. Eastward to the Virgin Basin, the predominant facies is lenticular crossbedded pebbly sand interbedded with overbank fines (Table DR1; Fig. 2C). This general picture is, however, locally complicated. Paleocurrent indicators at localities 5, 7, and 11 are south- or southeast-directed instead of westward, and the sediments at these same localities do not follow the trend of coarsening to the east (Fig. 2; Table DR1). Localities 1 and 5 are anomalously coarser-grained relative to neighboring localities, and the easternmost of all localities (11), near the hypothetical mouth of the paleoriver source, has fine-grained deposits and southeast-directed paleocurrents.

Transect and source-area samples are plotted in ternary diagrams (Tables DR2 and DR3 [see footnote 1]) with endpoint grain types chosen to best distinguish sediment sources (Fig. 3), because traditional quartz-feldspar-lithics (QFL) plots do not

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[1] GSA Data Repository item 2008077, sedimentary descriptions and petrographic point-count data, is available at www.geosociety.org/pubs/ft2008.htm. You can also obtain a copy by writing to editing@geosociety.org.

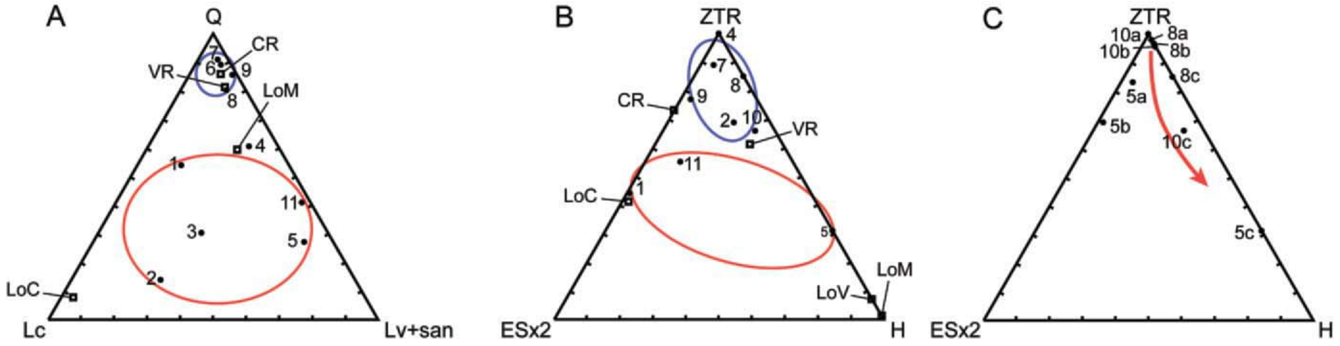

Figure 3. Ternary plots of Muddy Creek Formation samples representing possible sediment sources (data are summarized in GSA Data Repository Tables DR2 and DR3 [see text footnote 1]). Plotted numbers correspond to samples from locations on Figure 2 and Table DR1. Plotted letters are samples representing sediment sources: CR—Colorado River; VR—Virgin River; LoM—local metamorphic terrain; LoC—local carbonate terrain; LoV—volcanic bedrock source. (A) Plot of grain-mount results with corner points designed to distinguish potential sediment sources; Q—quartz; Lc—carbonate lithics; Lv+san—volcanic lithics and sanidine. Ovals outline two populations: one with a compositionally mature exotic river source and another that is a combination of local and volcanic sediment sources. No data for location 10. (B) Plot of heavy mineral results: ZTR—zircon, tourmaline, and rutile maturity index distinguishing exotic fluvial sources; ES×2—epidote and sphene counts multiplied by two in order to draw from the right axis those samples with a component of local Paleozoic sources; H—hornblende for sediment with volcanic and metamorphic bedrock sources. Ovals outline the same two populations of samples. (C) Heavy mineral plot showing vertical transect samples at localities 5, 8, and 10, going from base (a) to top (c) of exposed middle member. Note trend of increasing volcanic input upward in the section (red arrow).

succeed in this. The "Lc" apex represents lithic carbonate grains derived from Paleozoic carbonate bedrock of the surrounding mountains. "Lv+san" comprises volcanic lithic clasts and sanidine, which must be derived from the volcanic terrain to the north of the basins. Likewise, the "ES×2" apex of the heavy mineral plots is intended to draw out local carbonate bedrock sources, which produce very low heavy-mineral yields. The low abundances of epidote and sphene, perhaps recycled from yet older basement sources, are amplified and used in the absence of more indicative minerals. Hornblende is abundant in the heavy-mineral suites of both metamorphic and volcanic bedrock sources. Finally, quartz and the zircon-tourmaline-rutile (ZTR) heavy-mineral maturity index are intended to distinguish the mature compositions of the Colorado and Virgin rivers.

The ternary plots reveal two populations of samples (Figs. 3A and 3B). One set is interpreted as a mixture of local carbonate and metamorphic sources, as well as slightly farther-traveled volcanic detritus (red oval). The other population is similar to sediment of the Colorado and Virgin rivers (blue oval). Only the three westernmost samples (localities 1–3) have significant local Paleozoic carbonate bedrock contributions. Volcanic sources are strongly represented at localities 5 and 11, and samples from localities 6–10 in the central part of the transect are compositionally mature (relatively rich in quartz and ZTR), like Colorado and Virgin rivers samples (Figs. 3A and 3B). Heavy-mineral results are less distinct than light mineral grains, but the vertical transects at locations 5, 8, and 10 indicate an increased contribution from volcanic sources upward through the sections, from subsamples a–c (Fig. 3C). The result that local sources dominate areas to the west and north, whereas compositionally mature sediment is more abundant in the southern Mesquite Basin, confirms that an exotic sediment source from the east (the Colorado Plateau) provided sand lacking in carbonate-, volcanic-, and basement-derived grains.

If a major paleo–Colorado River entered the east end of the Mesquite Basin, sample compositions from locations 1–11 should become increasingly similar to Colorado River sediment from west to east. However, they do not (Figs. 3A and 3B). Petrographic results instead indicate a significant contribution to the Muddy Creek Formation by volcanic sources, including at the easternmost sample locality, consistent with the sedimentologic and paleocurrent observations (Table DR1 [see footnote 1]; Fig. 2). The middle member also becomes more volcanically derived as it coarsens upward (Fig. 3C). This matches the present-day pattern of large drainages that have source areas in the volcanic terrain of the Caliente and Kane Springs caldera complexes to the north (Figs. 1 and 2). Colorado River and Virgin River sands are compositionally similar and cannot be distinguished by these petrographic data alone. In fact, sample compositions may be explained entirely with an ancestral Virgin River source, consistent with field evidence for a Virgin River source in the Muddy Creek Formation of the Mesquite Basin (Billingsley, 1995; Billingsley and Bohannon, 1995; Williams, 1996).

## DISCUSSION

Geographically, the Muddy Creek Formation is a logical candidate for terminal deposits of a pre–Grand Canyon Colorado River. There is evidence for a moderate amount of extra-basinal fluvial sediment entering the Mesquite Basin in late-Miocene time, but the most likely candidate for this is the ancestral Virgin River. Sedimentological, petrographic, and field data indicate that Miocene sediment pathways imitated present-day drainage patterns into these basins (Fig. 2) and that much of the Muddy Creek is derived from volcanic terrain to the north of the Mormon Mountains. Therefore, a northwest passage out of the Grand Canyon region with a Muddy Creek Formation terminus for the ancestral Colorado River can be ruled out.

A single hypothesis for the fate of the Miocene Colorado River remains: Hunt's largely forgotten idea that a relatively meager paleo–Colorado River made its way to the central-western Grand Canyon region and infiltrated into the cavernous

Paleozoic limestones that dominate the bedrock there. The concept of a major drainage area terminating in a desert basin is not far-fetched. Modern analogs of the same scale as the upper Colorado or larger include (1) the greater Tarim River system and tributaries draining the high Kunlun and Tien Shan and ending in the deserts of northeast China's Tarim Basin; (2) the Cubango-Okavango River rising in Angola and terminating in its famous delta at the edge of the Kalahari; and (3) the large drainages leading to Lake Eyre and other central basins of Australia. Closer by are the significant, mountain-fed drainages of the northern Great Basin that terminate in the saline lakes and pans of the Bonneville and Lahontan Basins.

The infiltration and dissipation hypothesis may help resolve more than one conundrum, including the mechanics of the capture of the upper Colorado River. Blackwelder (1934) and Longwell (1946) recognized early on that the upper Colorado River could have been captured by either top-to-bottom spilling over divides or by headward erosion. Headward erosion as a process has an inherent shortcoming, expressed by Charlie Hunt as the problem of the "precocious gully" (Hunt, 1969). How could the head of a single drainage along a desert escarpment have the necessary stream power or mass-movement activity to erode headward and shift its divide hundreds of kilometers, when none of its neighbors could lengthen measurably at all? On the other hand, although House et al. (2005) have shown that the lower Colorado River corridor was integrated by spilling over topographic divides, there are problems in applying this mechanism to the drainage in the Grand Canyon region. Specifically, why are there no distinctive lacustrine and deltaic sedimentary remnants in the southern plateau like the younger examples that record basin spillover along the lower Colorado corridor? Instead, there are late Miocene volcanic rocks and deposits attributed to local streams (Lucchitta and Jeanne, 2001; Love, 1989).

Perhaps the best solution for the integration of the Colorado River involves different styles of both headward erosion and basin spillover, with the key factor being groundwater. Surface drainage capture typically follows capture of the groundwater drainage by lower, adjacent topography (Pederson, 2001). Groundwater sapping and spring discharge then provide viable erosion mechanisms for a surface drainage to extend headward. There is also the possibility that a karst plumbing system formed by this groundwater could have collapsed, aiding in surface drainage development. The now-dissected karst system exposed in the walls of western Grand Canyon is impressive and may provide a history of Neogene groundwater lowering and canyon formation (Polyak et al., 2007). Finally, infiltrated water from the Miocene plateau likely would have resurfaced through springs in the low basins neighboring the plateau edge. Hunt (1969) suggested this was the source of the Hualapai Limestone of the Grand Wash Trough, and Colorado River infiltration could have provided the needed source for the voluminous Miocene spring deposits in the Hualapai Basin and elsewhere in the Lake Mead region (Fig. 1; Faulds et al., 1997, 2001).

In summary, the ancestral Colorado River itself may not have made it off the plateau until 6 Ma, although it seems likely that part of its water did. But where is the paleoriver's sediment? The Miocene upper drainage, having lower relief, a relatively steady, arid climate, and not having been fully integrated to its present size, must have had a relatively minor sediment load. The burden it did carry may have been transported away by wind or stored elsewhere along its path through the central plateau, a region that subsequently has been deeply exhumed. This remains yet another conundrum. For now, Hunt's dissipation and infiltration hypothesis is the last one left standing against the geologic evidence in the region.

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## REFERENCES CITED

Anderson, R.E., 1973, Large-magnitude Late Tertiary strike-slip faulting north of Lake Mead, Nevada: U.S. Geological Survey Professional Paper 794, 18 p.

Billingsley, G.H., 1995, Geologic map of the Littlefield quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 95-559, 15 p., scale 1:24,000.

Billingsley, G.H., and Bohannon, R.C., 1995, Geologic map of the Elbow Canyon quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 95-560, 16 p., scale 1:24,000.

Blackwelder, E., 1934, Origin of the Colorado River: Geological Society of America Bulletin, v. 45, p. 551–566.

Bohannon, R.G., 1984, Nonmarine sedimentary rocks of Tertiary age in the Lake Mead region, southeastern Nevada and northwestern Arizona: U.S. Geological Survey Professional Paper 1259, 72 p.

Bohannon, R.G., Grow, J.A., Miller, J.J., and Blank, R.H., Jr., 1993, Seismic stratigraphy and tectonic development of Virgin River depression and associated basins, southeastern Nevada and northwestern Arizona: Geological Society of America Bulletin, v. 105, p. 501–520, doi: 10.1130/0016-7606(1993)105<0501:SSATDO>2.3.CO;2.

Buising, A.V., 1990, The Bouse Formation and bracketing units, southeastern California and western Arizona: Implications for the evolution of the proto–Gulf of California and the lower Colorado River: Journal of Geophysical Research, v. 95, p. 20,111–20,132.

Cather, S.M., Connell, S.D., Chamberlin, R.M., Jones, G.E., Potochnik, A.R., Lucas, S.G., and Johnson, P.S., 2008, The Chuska erg: Paleogeomorphic and paleoclimatic implications of an Oligocene sand sea on the Colorado Plateau: Geological Society of America Bulletin, v. 120, p. 13–33, doi: 10.1130/B26081.1.

Dallegge, T.A., Ort, M.H., McIntosh, W.C., and Perkins, M.E., 2001, Age and depositional basin morphology of the Bidahochi Formation and implications for the ancestral upper Colorado River, *in* Young, R.A., and Spamer, E.E., eds., The Colorado River: Origin and evolution: Grand Canyon, Arizona, Grand Canyon Association Monograph 12, p. 47–52.

Davis, W.M., 1901, An excursion to the Grand Canyon of the Colorado: Bulletin of the Museum of Comparative Zoology, Harvard College, v. 38, Geological Series, no. 4, p. 107–201.

Dicke, S.M., 1990, Stratigraphy and sedimentology of the Muddy Creek Formation, Southeastern Nevada [M.S. Thesis]: Lawrence, University of Kansas, 36 p.

Dorsey, R.J., Fluette, A., McDougall, K., Housen, B.A., Janecke, S.U., Axen, G.J., and Shirvell, C.R., 2007, Chronology of Miocene-Pliocene deposits at Split Mountain Gorge, southern California: A record of regional tectonics and Colorado River evolution: Geology, v. 35, p. 57–60, doi: 10.1130/G23139A.1.

Duebendorfer, E.M., and Simpson, D.A., 1994, Kinematics and timing of Tertiary extension in the western Lake Mead region, Nevada: Geological Society of America Bulletin, v. 106, p. 1057–1073, doi: 10.1130/0016-7606(1994)106<1057:KATOTE>2.3.CO;2.

Faulds, J.E., Schreiber, B.C., Reynolds, S.J., Gonzalez, L.A., and Okaya, D., 1997, Origin and paleogeography of an immense, nonmarine Miocene salt deposit in the Basin and Range (western USA): The Journal of Geology, v. 105, p. 19–36.

Faulds, J.E., Price, L.M., and Wallace, M.A., 2001, Depositional environment and paleogeographic implications of the Late Miocene Hualapai Limestone, northwestern Arizona and southern Nevada, *in* Young, R.A., and Spamer, E.E., Colorado River Origin and Evolution: Grand Canyon, Arizona, Grand Canyon Association Monograph No. 12, p. 81–87.

Flowers, R.M., Wernicke, B.P., and Farley, K.A., 2008, Unroofing, incision and uplift history of the southwestern Colorado Plateau from (U-Th)/He apatite thermochronometry: Geological Society of America Bulletin, in press.

House, P.K., Pearthree, P.A., Howard, K.A., Bell, J.W., Perkins, M.E., and Brock, A.L., 2005, Birth of the lower Colorado River—Stratigraphic and geomorphic evidence for its inception near the conjunction of Nevada, Arizona, and California, *in* Pederson, J., and Dehler, C.M., eds., Interior western United States: Geological Society of America Field Guide 6, p. 357–388.

Hunt, C.B., 1956, Cenozoic geology of the Colorado Plateau: U.S. Geological Survey Professional Paper 279, 99 p.

Hunt, C.B., 1969, Geologic history of the Colorado River, *in* The Colorado River Region and John Wesley Powell: U.S. Geological Survey Professional Paper 669-C, p. 59–130.

Kowallis, B.J., and Everett, B.H., 1986, Sedimentary environments of the Muddy Creek Formation near Mesquite, Nevada, *in* Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Salt Lake City, Utah Geological Association Publication 15, p. 69–75.

Langford, R.P., Jackson, M.L.W., and Whitelaw, M.J., 1999, The Miocene to Pleistocene filling of a mature extensional basin in Trans-Pecos Texas: Geomorphic and hydrologic controls on deposition: Sedimentary Geology, v. 128, p. 131–153, doi: 10.1016/S0037-0738(99)00065-2.

Lee, J.P., 2007, Cenozoic unroofing of the Grand Canyon region, Arizona [M.S. Thesis]: Lawrence, University of Kansas, 119 p.

Longwell, C.R., 1928, Geology of the Muddy Mountains, Nevada: U.S. Geological Survey Bulletin 798, p. 91–97.

Longwell, C.R., 1946, How old is the Colorado River?: American Journal of Science, v. 244, no. 12, p. 817–835.

Love, D.W., 1989, Bidahochi Formation: An interpretive summary, *in* Anderson, O.J., ed., Southwestern Colorado Plateau: Socorro, New Mexico Geological Society Fortieth Field Conference Guidebook, p. 273–280.

Lucchitta, I., 1966, Cenozoic geology of the upper Lake Mead area adjacent to the Grand Wash Cliffs, Arizona [Ph.D. dissertation]: State College, Pennsylvania State University, 218 p.

Lucchitta, I., 1972, Early history of the Colorado River in the Basin and Range Province: Geological Society of America Bulletin, v. 83, p. 1933–1948, doi: 10.1130/0016-7606(1972)83[1933:EHOTCR]2.0.CO;2.

Lucchitta, I., 1990, History of the Grand Canyon and of the Colorado River in Arizona, *in* Beus, S., and Morales, M., eds., Grand Canyon geology: New York, Oxford University Press, p. 311–332.

Lucchitta, I., and Jeanne, R.A., 2001, Geomorphic features and processes of the Shivwits Plateau, Arizona, and their constraints on the age of western Grand Canyon, *in* Young, R.A., and Spamer, E.E., eds., The Colorado River: Origin and evolution: Grand Canyon, Arizona, Grand Canyon Association Monograph 12, p. 65–70.

McKee, E.D., and McKee, E.H., 1972, Pliocene uplift of the Grand Canyon region—Time of drainage adjustment: Geological Society of America Bulletin, v. 83, p. 1923–1932, doi: 10.1130/0016-7606(1972)83[1923:PUOTGC]2.0.CO;2.

McKee, E.D., Wilson, R.F., Breed, W.J., and Breed, C.S., eds., 1967, Evolution of the Colorado River in Arizona: Flagstaff, Arizona, Museum of Northern Arizona Bulletin 44, 74 p.

Pederson, D.T., 2001, Stream piracy revisited: A groundwater sapping solution: GSA Today, v. 11, no. 9, p. 4–10, doi: 10.1130/1052-5173(2001)011<0004:SPRAGS>2.0.CO;2.

Pederson, J.L., Pazzaglia, F.J., Smith, G.A., and Mou, Y., 2000, Neogene through Quaternary hillslope records, basin sedimentation, and landscape evolution of southeast Nevada, *in* Lageson, D.E., Peters, S.G., and Lahren, M.M., eds., Great Basin and Sierra Nevada: Geological Society of America Field Guide 2, p. 117–134.

Pederson, J.L., Smith, G.A., and Pazzaglia, F.J., 2001, Comparing the Neogene, Quaternary, and modern records of climate-controlled hillslope sedimentation in southeast Nevada: Geological Society of America Bulletin, v. 113, p. 305–319, doi: 10.1130/0016-7606(2001)113<0305:CTMQAN>2.0.CO;2.

Pederson, J., Karlstrom, K., Sharp, W., and McIntosh, W., 2002a, Differential incision of Grand Canyon related to Quaternary faulting—Constraints from U-series and Ar/Ar dating: Geology, v. 30, p. 739–742, doi: 10.1130/0091-7613(2002)030<0739:DIOTGC>2.0.CO;2.

Pederson, J.L., Mackley, R.D., and Eddleman, J.L., 2002b, Colorado Plateau uplift and erosion—amounts and causes evaluated with GIS: GSA Today, v. 12, no. 8, p. 4–10, doi: 10.1130/1052-5173(2002)012<0004:CPUAEE>2.0.CO;2.

Polyak, V.J., Hill, C.A., and Asmerom, Y., 2007, Timing of formation of Grand Canyon from U-Pb dates on groundwater-table speleothems: Geological Society of America Abstracts with Programs, v. 39, no. 6, p. 513.

Powell, J.W., 1875, Exploration of the Colorado River of the West and its tributaries: Washington, D.C., U.S. Government Printing Office, 291 p.

Schmidt, D.L., 1994, Preliminary geologic map of the Farrier Quadrangle, Clark and Lincoln Counties, Nevada: U.S. Geological Survey Open File Report OF 94-625, 31 p., scale 1:24,000.

Schmidt, D.L., Page, W.R., and Workman, J.B., 1996, Geologic map of the Moapa West quadrangle, Clark County, Nevada: U.S. Geological Survey Open File Report OF 96-521, 17 p., scale 1:24,000.

Smith, G.A., 2000, Recognition and significance of streamflow-dominated piedmont facies in extensional basins: Basin Research, v. 12, p. 399–411, doi: 10.1046/j.1365-2117.2000.00125.x.

Stock, C., 1921, Later Cenozoic mammalian remains from Meadow Valley Region, southeastern Nevada: American Journal of Science, 5th series, v. 2, p. 250–264.

Strahler, A.N., 1948, Geomorphology and structure of the West Kaibab fault zone and Kaibab Plateau, Arizona: Geological Society of America Bulletin, v. 59, p. 513–540, doi: 10.1130/0016-7606(1948)59[513:GASOTW]2.0.CO;2.

Walcott, C.D., 1890, Study of a line of displacement in the Grand Canyon of the Colorado, in northern Arizona: Geological Society of America Bulletin, v. 1, p. 49–64.

Williams, V.S., 1996, Preliminary Geologic Map of the Mesquite Quadrangle, Clark and Lincoln Counties, Nevada and Mohave Counties, Arizona: U.S. Geological Survey Open-File Report OF 96-676: http://pubs.usgs.gov/of/1996/ofr-96-0676/, scale 1:24,000.

Young, R.A., and Brennan, W.J., 1974, Peach Springs Tuff: Its bearing on structural evolution of the Colorado Plateau and development of Cenozoic drainage in Mohave County, Arizona: Geological Society of America Bulletin, v. 85, p. 83–90, doi: 10.1130/0016-7606(1974)85<83:PSTIBO>2.0.CO;2.

Young, R.A., and McKee, E.H., 1978, Early and middle Cenozoic drainage and erosion in west-central Arizona: Geological Society of America Bulletin, v. 89, p. 1745–1750, doi: 10.1130/0016-7606(1978)89<1745:EAMCDA>2.0.CO;2.

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