Detrital-zircon U-Pb evidence precludes paleo–Colorado River sediment in the exposed Muddy Creek Formation of the Virgin River depression

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ABSTRACT

Only since 5–6 Ma has the Colorado River flowed through the western Grand Canyon into the Grand Wash Trough at the eastern end of Lake Mead. Before then, the river may have flowed through a paleocanyon transiting the Kaibab uplift at a stratigraphic level above the present eastern Grand Canyon to cross the Shivwits Plateau north of the western Grand Canyon and enter the Virgin River drainage, which exits the Colorado Plateau into the Virgin River depression north of Lake Mead. U-Pb age spectra of detrital zircons from Miocene–Pliocene basin fill of the Muddy Creek Formation in the Virgin River depression preclude any paleo–Colorado River sand in Muddy Creek exposures but fail to show that a Miocene Colorado River sand in Muddy Creek exposures from available surface collections cannot test for the presence of Colorado River sediment within unexposed lower Muddy Creek or sub–Muddy Creek strata in the subsurface of the Virgin River depression. Alternate scenarios include rejection of paleo–Colorado River flow into the Virgin River drainage at any time, or exit of the pre–6 Ma paleo–Colorado River from the upper Virgin paleodrainage toward the northwest into the eastern Great Basin without flowing southwest into the Virgin River depression through the Virgin River gorge, which may be younger than ca. 6 Ma.

INTRODUCTION

Only since 5–6 Ma, after deposition of the Hualapai Limestone, has the Colorado River exited the Colorado Plateau along its present course through the Grand Canyon to enter the Grand Wash Trough at the eastern end of modern Lake Mead (Blair and Armstrong, 1979; House et al., 2005; Crosse et al., 2014). Various lines of evidence (Lucchitta, 1989; Pelletier, 2010; Dickinson, 2013; Lucchitta et al., 2013) argue that a Miocene Colorado River transited the Kaibab uplift through a paleocanyon north of the present site of the eastern Grand Canyon, but then crossed the Shivwits Plateau north of the western Grand Canyon to enter the paleodrainage of the Virgin River, from which it could then exit the Colorado Plateau into the Virgin River depression (Bohannon et al., 1993) north of Lake Mead (Fig. 1). In this paper, we evaluate available U-Pb data (Forrester, 2009; Muntean, 2012) from detrital zircons in Miocene–Pliocene strata of the Muddy Creek Formation, which forms the basin fill of the Virgin River depression, to test for the presence of Colorado River sand in the local stratigraphic record. The age spectra of the sampled detrital-zircon populations in exposed Muddy Creek strata reflect exclusively Virgin River parentage with no discernible component of admixed Colorado River sand, as Pederson (2008) concluded from petrographic studies. We are unable, however, to test fully for a Miocene influence of the Colorado River on sediments of the Virgin River depression because no sampled horizons of the Muddy Creek Formation are older than ca. 6 Ma. First, we review the age and stratigraphy of the Muddy Creek Formation in the Virgin River depression; next, we present the detrital-zircon evidence from Muddy Creek strata; then, we discuss the additional studies needed to assess the detrital-zircon record for older Miocene strata within the subsurface of the Virgin River depression; and, finally, we discuss alternate scenarios for Colorado River history not requiring any paleo–Colorado River flow into the Virgin River depression. For comparative purposes, previously unpublished detrital-zircon data for the Chuska Sandstone are included in the Supplemental File.

For visual comparisons of detrital-zircon populations, we use frequency plots of grain ages, with analytical age uncertainties (±1σ) for each grain age taken into account, normalized to subend equal areas beneath each curve of graphical displays. For statistical comparisons of detrital-zircon age populations and subpopulations, we use Kolmogorov-Smirnov (K-S) statistics to calculate the probability (P) that two age populations of grains, selected randomly from detrital-zircon concentrates, could have been derived from the same parent population, and thereby assess the likelihood that two detrital-zircon populations differ significantly in age distribution. Where P ≥ 0.05, there is ≤95% probability (~2σ) that the two age populations could not have been derived by random selection from a common parent population. Higher P values denote progressively more age congruence of paired detrital-zircon populations. As there is no current consensus whether the most appropriate P values derive from K-S analysis “with error,” including uncertainties in the construction of the cumulative distribution function (CDF), or “without error” in the CDF, we report P as calculated in both of the two alternate ways.

VIRGIN RIVER DEPRESSION

The Virgin River depression is the deepest locus of crustal subsidence in the Lake Mead region west of the Grand Wash and Piedmont

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1Supplemental File. Excel file containing detrital-zircon data for the Chuska Sandstone. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES01097.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.
faults marking the edge of the high-standing Colorado Plateau transected by the Grand Canyon (Fig. 2). Within the 1250 km² depression, Cenozoic basin fill extends to depths ≥500 m below sea level (Fig. 3), and it is thicker than elsewhere in the Lake Mead region, except within the Overton Arm pull-apart basin (Campana and Aydin, 1994). The latter depocenter between parallel strands of the sinistral Lake Mead fault system (Fig. 2) is adjacent on the south and contiguous with the Virgin River depression. Precambrian basement below a thick Paleozoic–Mesozoic succession lies at depths of 3000–6000 m below sea level in the structural keels of the Mesquite and Mormon Basins, occupying the eastern and western lobes, respectively, of the Virgin River depression (Fig. 2).

The Mormon and Mesquite Basins of the Virgin River depression are each buried half grabens, bounded on the east by normal faults (Bohannon et al., 1993). Subsurface strata are inclined eastward into the bounding faults, but fanning dips in Cenozoic strata of both basins...
Figure 2. Pre-Quaternary geologic map of the Lake Mead region (cross-hatched area of White Basin is discussed in the text) showing the locations of key detrital-zircon samples from (1) the Miocene–Pliocene Muddy Creek Formation (solid squares) including three Forrester (2009) samples from the Mesquite Basin at Flat Top Mesa (F36) and Beaver Dam Wash (F11, F18), and nine Muntean (2012) samples including four from the Mormon Basin (M1–M4) and five from the Overton Arm Basin (OAB; M5, M8–M9, M11–M12) within 1 km to 5 km of Overton Arm (the latter are not plotted for reasons of scale); (2) post–Muddy Creek Pliocene–Pleistocene terrace deposits (open squares) inset into incised Muddy Creek Formation of the Virgin River depression (F9 of Forrester, 2009; M13 of Muntean, 2012); (3) Miocene–Pliocene (LMSP2, H5HW) deposits (solid circles) of the Colorado River (Kimbrough et al., 2015); and (4) modern sand (open circles) of the Virgin River (VR20 of Forrester, 2009; 806–10 of Kimbrough et al., 2015). Map was compiled from Anderson and Beard (2010), Beard et al. (2007, 2010), Blair and Armstrong (1979), Bohannan (1983, 1984), Campagna and Aydin (1994), Felger and Beard (2010), Forrester (2009), House et al. (2005), Howard et al. (2010), Muntean (2012), Schmidt et al. (1996), Swaney et al. (2010), Umhoefer et al. (2010), and Wallace et al. (2005). Faults (half-arrows denote relative motions on strike-slip faults, barbells denote downthrown blocks at normal faults): BRF—Bitter Ridge, BSF—Bitter Spring Valley, CCF—Cabin Canyon, CWF—California Wash, GBF—Gold Butte, GWF—Grand Wash, HBF—Hamblin Bay, LCF—Lost Cabin Range, LMF—Lakeside Mine, LRF—Lime Ridge, PF—Piedmont, RSF—Rogers Spring, SSF—Salt Spring Wash, WRF—Wheeler Ridge. Selected streams: CR—Colorado River (above and below Lake Mead), DW—Detrital Wash, GW—Grand Wash, HW—Hualapai Wash, MR—Muddy River, MVW—Meadow Valley Wash. Circled dots denote the towns of Mesquite in the Virgin River depression and Moapa in the Glendale Basin.
Figure 3. Geologic units (Bohannon et al., 1993) penetrated by the Mobil Virgin River 1A test well (Fig. 2) in the Mormon Basin of the Virgin River depression. Annotated ages of pre–Muddy Creek Cenozoic units are projected into the well bore from areas outside the Mormon Basin using data from Harlan et al. (1998), Castor et al. (2000), Beard et al. (2007), and Anderson and Beard (2010).

Muddy Creek Formation Stratigraphy

Apart from narrow bands of Quaternary sediment along the Virgin River and its tributaries, the youngest strata within the Virgin River depression form the Miocene–Pliocene Muddy Creek Formation. This unit extends across the full extent of the Mormon and Mesquite Basins, except for isolated outcrops of older Cenozoic strata along the structurally shallow western flank of the Mormon Basin (Fig. 2) and Pliocene–Pleistocene terraces inset into Muddy Creek basin fill (Forrester, 2009). The full thickness (885 m) of the Muddy Creek Formation was penetrated by the Mobil Virgin River 1A test well near the center of the Mormon Basin (Figs. 2–3), but only the uppermost 250 ± 50 m section of the Muddy Creek Formation (<30% of its total thickness) is exposed in the Virgin River depression (Forrester, 2009).

The Muddy Creek Formation of the Mesquite Basin is composed dominantly of fine- to medium-grained fluvial sandstone with subordinate intercalated conglomerate and siltstone, some of which is lacustrine (Billingsley, 1995; Williams, 1996; Williams et al., 1997; Forrester, 2009). The lacustrine beds, in part gypsiferous, are more abundant southward in the Mormon Basin and into the Overton Arm Basin, but these beds are subordinate in surface outcrops (Muntean, 2012). Logical options for delivery of sandy Muddy Creek detritus to the Virgin River depression and the associated Overton Arm Basin include the ancestral Virgin River, a paleo–Colorado River that had entered the ancestral Virgin River drainage basin, and tributaries to the ancestral Virgin River that tapped igneous sources associated with Tertiary calderas north of the Virgin River depression (Pederson, 2008).

The Muddy Creek Formation of the Glendale Basin (Fig. 2), west of the Virgin River depression, is dominantly lacustrine claystone, deposited in “Muddy Creek lake” (Schmidt et al., 1996) as upper green claystone, 5–30 m thick, and lower red claystone, of which only 45 m are exposed, but which reaches total thicknesses of 350–380 m where penetrated in water wells. Fluvial terrace gravels overlying lacustrine claystones of the Glendale Basin were deposited during dissection of the lakebeds after integration of the local watershed into the Virgin River fluvial system of the Virgin River depression by breaching of a low divide between the Glendale and Mormon Basins after deposition of the Muddy Creek Formation. There is uncertainty (Schmidt et al., 1996) whether the lower red claystone of the Glendale Basin is properly assigned to the Muddy Creek Formation, or is instead the local expression of the “red sandstone unit” of Bohannon (1984) that underlies the Muddy Creek Formation in the Mormon Basin to the east (Fig. 3). In either case, the thickness of Muddy Creek Formation in the Glendale Basin is much less (<50%) than in the Virgin River depression.

Muddy Creek Formation Age

Basalt that is interbedded within the uppermost Muddy Creek Formation in exposures near Mesquite (Fig. 2) in the Mesquite Basin has yielded a whole-rock K-Ar age of 4.1 ± 0.2 Ma (Williams, 1996), which is Zanclean (Lower Pliocene) according to Hilgen et al. (2012) and Walker et al. (2013), and which provides close age control for the top of the Muddy Creek Formation in the Virgin River depression (Fig. 4). A younger tuff, ca. 3 Ma in age, intercalated within Muddy Creek Formation of the Glendale Basin (HH of Fig. 4) implies that Muddy Creek deposition continued longer in the Glendale Basin before the latter was incorporated into the Virgin River drainage. An older horizon of the Muddy Creek Formation in the Mesquite Basin has yielded a Miocene mammalian fauna (Williams et al., 1997) of the Hemphillian North American Land Mammal Age (NALMA), which began as early as ca. 9 Ma (Woodburne and Swisher, 1995; Hilgen et al., 2012) but lasted until 4.9 Ma (Hilgen et al., 2012) or even 4.8–4.7 Ma (Flynn et al., 2005).

Dated basalt interbedded within the lowest informally named member of exposed Muddy Creek Formation (Muntean, 2012) in outcrops west of Overton Arm in the Overton Arm Basin (Fig. 2) provides age control for the oldest exposed Muddy Creek Formation. A whole-rock K-Ar age of 8 Ma (with no ± uncertainty cited), was reported for an Overton Arm basalt by Eberly and Stanley (1978) in a paper focused on Cenozoic basins of southwestern Arizona, but their age for the basalt is older than younger isotopic ages for Overton Arm basalts from more recent geochronology, and it is discounted here as an unreliable age control for exposed Muddy Creek Formation.

Feuerbach et al. (1991) obtained a K-Ar age of 6.02 ± 0.39 Ma (their sample 6) for a plagioclase concentrate from an Overton Arm basalt, and Beard et al. (2007) reported preliminary 40Ar/39Ar isochrons of 6.15 Ma and 6.60 Ma for the same basalt flow. Felsic tephra in the Muddy Creek Formation exposed not far below the Overton Arm basalts correlates well geochemically with the Blacktail Creek ash (Muntean, 2012), and another tephra layer in the same general stratigraphic position has been correlated with the Walcott ash (Beard et al., 2007). The
two ashes have been dated to 6.62 ± 0.003 Ma (Morgan and McIntosh, 2005).

We accordingly infer that exposed Muddy Creek horizons of the Overton Arm Basin and the Virgin River depression are no older than 6.6–6.0 Ma, in latest Miocene (Messinian) time (Hilgen et al., 2012; Walker et al., 2013). The oldest exposed horizons of the Muddy Creek Formation are thus coeval with uppermost Hualapai Limestone (Crossley et al., 2014) exposed near Lake Mead 50–65 km to the south, near the mouth of the modern Grand Canyon (Fig. 4). A detrital-zircon sample collected from strata interbedded with 6.6–6.0 Ma basalts near Overton Arm (Fig. 4) yielded only seven zircon grains that do not cluster in age and are too few for rigorous analysis of their age distribution.

All other available detrital-zircon samples from the Muddy Creek Formation (see following discussion) are from overlying horizons younger than 6 Ma in age.

Given that the ~250 m of Muddy Creek Formation exposed in the Virgin River depression were deposited largely, if not entirely, during the interval between 6.6–6.0 Ma and ca. 4 Ma, the implied net rate of sedimentation was 110 ± 15 m/m.y. during latest Miocene and earliest Pliocene time. If that sedimentation rate is projected backward in time for deposition of the unexposed ~635 m of lower Muddy Creek Formation penetrated by the Mobil Virgin River 1A test well in the subsurface of the Mormon Basin (Fig. 3), then the indicated age of the base of the Muddy Creek Formation is ca. 12 Ma. That projected basal age for the Muddy Creek Formation is almost certainly too old, for the underlying “red sandstone unit” of Bohannan (1984) has yielded multiple isotopic ages (N = 8) of 1.9–10.05 Ma (Harlan et al., 1998; Castor et al., 2000; Beard et al., 2007) where exposed within and near White Basin (Fig. 2), ~40 km south-southwest of the test well. The lowest 215 m section of Muddy Creek Formation in the test well is reported as gypsiferous (Fig. 3), suggestive of playa deposition within an undrained depression. The base of overlying nongypsiferous Muddy Creek Formation in the well is calculated to be ca. 10 Ma using a sedimentation rate of 110 m/m.y. for the formation, and that date can perhaps be taken as a maximum age for the base of fluvial Muddy Creek Formation in the Virgin depression. A basal age of 10 Ma for fluvial Muddy Creek Formation matches the youngest known isotopic age for the “red sandstone unit” and also the estimate of Beard et al. (2007) for initiation of Muddy Creek sedimentation.

Lake Hualapai Extent

There is widespread agreement (Lucchitta, 1989; Faulds et al., 2001a, 2001b; House et al., 2005, 2008; Spencer et al., 2001, 2008b) that the course of the Colorado River was not integrated through the western Grand Canyon (Fig. 1) into the Grand Wash Trough at the eastern end of Lake Mead until after deposition of the lacustrine Hualapai Limestone, which extends eastward to the Grand Wash Cliffs at the mouth of the modern Grand Canyon. All preserved exposures of the Hualapai Limestone (Fig. 2) are restricted to a belt, 42.5 km (east-west) by 17.5 km (north-south), in the Grand Wash Trough and the downfaulted Gregg and Temple Basins to the west (Fig. 4). House et al. (2008) suggested that the original extent of Lake Hualapai can be reconstructed by projecting a paleo-

**Figure 4.** Isotopic and fossil ages for late Neogene (<16 Ma) stratigraphic units in sedimentary basins of the Lake Mead region including the Virgin River depression (Fig. 2). Age uncertainties <1 Ma are not plotted, some closely spaced ages are combined, and some redundant ages are omitted. Ages for the “red sandstone unit” of Bohannan (1984) within and near White Basin (Fig. 2) are identified from correlations by Beard et al. (2007). Sources of data (numbers in parentheses): 1—Anderson et al. (1994), 2—Beard et al. (2007), 3—Blair (1978), 4—Blythe et al. (2010), 5—Castor et al. (2000), 6—Crossey et al. (2014), 7—Dueben-dorfer and Sharp (1998), 8—Faulds et al. (2001a), 9—Feuerbach et al. (1991), 10—Harlan et al. (1998), 11—Howard et al. (2010), 12—Metcalf (1982), 13—Muntean (2012), 14—Pederson et al. (2001), 15—Schmidt et al. (1996), 16—Spencer et al. (2001), 17—Swaney et al. (2010), 18—Theodore et al. (1987), 19—Umhoefer et al. (2001), 20—Williams (1996).
shoreline at the elevation of the top of exposed Hualapai Limestone across modern topography, thereby inferring that Lake Hualapai filled the Virgin River depression and spilled into the Glendale Basin farther west. The most favored elevation for the reconstructed paleoshoreline is 720 m (Spencer et al., 2008b, 2013), the elevation at the top of Hualapai Limestone in the White Hills of Temple Basin to the south of the Virgin Basin of Lake Mead (Fig. 2). To accommodate exposures of Hualapai Limestone that reach elevations in excess of 900 m on Grapevine Mesa in the Grand Wash Trough (Wallace et al., 2005), an eastern arm of Lake Hualapai is conventionally added to the lake (Roskowski et al., 2010; Dickinson, 2013), or else a separate “Lake Grand Wash” is postulated with a surface elevation of 912 m within the Grand Wash Trough (Spencer et al., 2013). The latter postulate is disfavored here because deposition of Hualapai Limestone was contiguous westward from Grand Wash Trough into Gregg and Temple Basins (Blair and Armstrong, 1979; Wallace et al., 2005), with only limited relief on the sedimented floor of Lake Hualapai from local algal terracing (Crossey et al., 2014).

We note that projecting elevations of Hualapai Limestone across modern topography is not a reliable means for reconstructing Lake Hualapai paleoshorelines because the modern distribution of Hualapai Limestone reflects fault offsets of ~275 m ( Faulds et al., 2001b; Wallace et al., 2005) across the Lost Cabin Range–Wheeler Ridge fault system (Fig. 2) between the Grand Wash Trough and Gregg Basin, and of ~125 m from the western flank of Gregg Basin to the eastern flank of Temple Basin (Fig. 4). Syn-Hualapai as well as post-Hualapai faulting is implied by fanning dips in Hualapai Limestone, which thickens toward bounding faults of all three tilted basin fault blocks (Crossey et al., 2014).

There is no direct evidence that Lake Hualapai ever flooded the Virgin River depression, where no Hualapai Limestone is known from either the surface (Fig. 2) or the subsurface (Fig. 3). Posing that Hualapai Limestone was deposited in the Virgin River depression, but has since been removed by erosion, seems implausible because the surface of basin fill forming the Muddy Creek Formation is as young as ca. 4 Ma, postdating the youngest known Hualapai Limestone by ~2 m.y. It has been suggested that the “marl of White Narrows” in the Glendale Basin west of the Virgin River depression is a record of Lake Hualapai (Spencer et al., 2008b; Roskowski et al., 2010), but vertebrate and invertebrate fossils from that unit (Schmidt et al., 1996) are Pliocene (5.0–4.5 Ma), at least a million years younger than uppermost Hualapai Limestone. Gypsiferous lacustrine strata in the lower Muddy Creek Formation penetrated by the Mobil Virgin River 1A test well in the Mormon Basin may be correlative with lower horizons of the Hualapai Limestone but are lithologically dissimilar and now lie near sea level more than 600 m below the elevation of the lowest exposed Hualapai Limestone.

The oldest known Hualapai Limestone (ca. 12 Ma) occupies the floor of Grand Wash Trough at the foot of the escarpment marking the edge of the Colorado Plateau, and the top of the Hualapai Limestone is estimated to be ca. 6 Ma from exposures in the White Hills of Temple Basin, ~35 km to the west (Fig. 4). The base of Hualapai Limestone is clearly time-transgressive, onlapping its substratum westward from the Grand Wash Trough to the Temple Basin (Fig. 4). The “rocks of Overton Arm” (Beard et al., 2007), which underlie Hualapai Limestone in the Temple Basin, overlap in age with the “rocks of Grand Wash Trough” (Bohanon, 1984), but their deposition continued until ca. 8 Ma, ~4 m.y. after deposition of Hualapai Limestone had begun in the Grand Wash Trough (Fig. 4). Currently available age controls for Hualapai Limestone (Fig. 4) permit the view that Hualapai deposition was migratory, with Hualapai Limestone of the Temple Basin largely or even entirely younger than Hualapai Limestone of the Grand Wash Trough, but we discount that interpretation as less likely than incremental expansion of a lacustrine environment westward over time. soling of Hualapai Limestone from east to west (Fig. 4) is compatible with a quasi-constant net rate of limestone accumulation at 45–60 m/m.y.

**DETRITAL-ZIRCON DATA**

All available detrital-zircon samples from the Muddy Creek Formation of the Virgin River depression and the Overton Arm Basin derive from informally named upper members of the exposed Muddy Creek succession (Forrester, 2009; Muntean, 2012). The collected strata were deposited during the interval from ca. 6 Ma to ca. 4 Ma and are therefore all younger than Hualapai Limestone (Fig. 4).

**Muddy Creek Formation**

Nearly all detrital-zircon grains in 13 samples from the Muddy Creek Formation represent two distinct age subpopulations: (1) late Cenozoic grains ≤28 Ma (10% of total grains), and (2) Cretaceous or older grains ≥81 Ma (90% of total grains). Only two grains (0.2% of 894 total grains) at 34 Ma and 65 Ma fall between those two age limits. The older (pre–75 Ma) of the two age subpopulations is not separable with confidence from comparable age populations in either modern or Pliocene Colorado River or Virgin River sands, nor from upstream sands of modern or Miocene Colorado River tributaries. Kolmogorov–Smirnov analysis (Table 1) shows that pre–75 Ma Muddy Creek sands are largely congruent with both Virgin-related and Colorado-related sands, there being <95% confidence (P ≥ 0.05) that most sample subsets could not have been derived from the same parent population. The exceptions are sands from the modern Little Colorado River and the Miocene Bidahochi Formation upstream to the southeast from the Grand Canyon. Those two sample subsets are themselves mutually congruent (P = 0.48/0.33), but their incongruence with other Colorado-related sands shows that detritus of Little Colorado River or Bidahochi Formation parentage is not and has not been a significant factor volumetrically for net Colorado River sand composition. That inference is reinforced by the observation that modern Colorado River sand collected at Kwagunt Rapids (CR-1 of Fig. 1) above the junction with the Little Colorado River is congruent with modern Colorado River sands collected at Hance Rapids (CR-2 of Fig. 1; P = 0.20/0.16) and Bass Rapids (CR-3 of Fig. 1; P = 0.59/0.54) below the Colorado–Little Colorado junction.

Figure 5 shows graphically the overall similarity of pre–75 Ma detrital-zircon subpopulations in sands from the Virgin River depression and from the Colorado River in and near the Grand Canyon, and Figure 6 shows the similarities of the same age subpopulation in sands of the Virgin River depression and key Colorado-related sands at a more regional scale. Note the close matches of the peaks for detrital-zircon grains of Paleozoic and Precambrian ages on the curves of Figure 6. We attribute the similarity of pre–75 Ma age subpopulations in Muddy Creek Formation and Colorado-related sands to the recycling of detrital zircons from Paleozoic–Mesozoic strata of the Colorado Plateau, for essentially the entire Colorado Plateau sedimentary succession is exposed and available for potential recycling within the Virgin River drainage basin (Rowley et al., 2008; Biek et al., 2009). Unlabeled Triassic, Jurassic, and Cretaceous age peaks on Figure 6 reflect the Mesozoic transport of detritus from the Cordilleran magmatic arc along the western continental margin eastward to the Colorado Plateau, to mingle there with older detrital zircons derived in large part from eastern and southern Laurentia (Dickinson and Gehrels, 2010), and to be recycled jointly with the latter into modern river systems.

One of the 13 Muddy Creek samples, FTM29 of Forrester (2009) from near the base of the
Detrital-zircon U-Pb evidence precludes paleo–Colorado River sediment in Virgin River depression’s exposed Muddy Creek Formation

Table 1. Probability (P) values from statistical Kolmogorov-Smirnov (K-S) analysis of U-Pb ages for >75 Ma subpopulations of detrital zircons in subsets of Virgin-related and Colorado-related fluvial sands

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Note: N—number of samples, n—number of U-Pb ages per subset; bold print denotes P ≥ 0.05 (≤0.05% confidence that the U-Pb ages in the paired subsets could not have been derived by random selection of detrital-zircon grains from the same parent population; italics denote P for comparisons of individual samples within each subset. MeB—Muddy Creek Formation of the Mesquite Basin (Forrester, 2009): F11 (BDW11), F18 (BDW 18), FTMS36 plotted on Figure 2; N = 3, n = 127. MoB—Muddy Creek Formation of the Mormon Basin (Muntean, 2012): M1, M2, M3, M4 (TMSS1, 2, 3, 4) plotted on Figure 2 as M1-M4; N = 4, n = 311. OAB—Muddy Creek Formation of the Overton Arm Basin (Muntean, 2012): TMSS 5, 8, 9, 11, 12 (not plotted individually on Figure 2 for reasons of scale; N = 5, n = 356. MCF—Miocene–Pliocene Muddy Creek Formation of the Virgin River depression: Mesquite Basin + Mormon Basin + Overton Arm Basin; N = 12, n = 794. VPP—Inset Pliocene– Pleistocene terraces of the Virgin River depression: F9 (P-P09) of Forrester, 2009) and M13 (TMSS13 of Muntean, 2012) plotted on Figure 2; N = 2, n = 162. VVR—modern Virgin River: 806-10 (CR806-10 of Kimbrough et al., 2015) and VR-20 (of Forrester, 2009) plotted on Figure 2; N = 2, n = 156. CGC—modern Colorado River in the Grand Canyon (Kimbrough et al., 2015); CR1, CR2, and CR3 plotted on Figure 1; N = 3, n = 187. HCR—Holocene lower Colorado River and delta downstream from Lake Mead (Kimbrough et al., 2015); CR5-1, CR5-2, 1-23-6-1, Yuma, San Felipito, Santa Clara; N = 6, n = 574. PCR—Pliocene lower Colorado River (Bullhead alluvium) and 4.9–3.0 Ma delta (Winker and Kidwell, 1986; Dorsey et al., 2011) downstream from Lake Mead (Kimbrough et al., 2015); two river samples (6322-6, 6322-7) and four delta samples (FCS-5, FCS-1, FCS-2, 4-2-6-1); N = 6, n = 551. CRR—Miocene Crooked River (Fig. 1), an inferred tributary of the paleo–Colorado River (Lucchitta et al., 2011, 2013); N = 5, n = 457 (data from Hereford et al., 2015). LCR—modern Little Colorado River (Kimbrough et al., 2015); 806-6 (CR806-6 near Winslow, Arizona) and 806-7 (CR806-7 near Cameron, Arizona) plotted on Figure 1; N = 2, n = 123. BFM—fluvial Miocene Badahochi Formation (Kimbrough et al., 2015): CR806-12 and CR806-13 near Sanders, Arizona, not plotted on Figure 1 (sample localities upstream off the map area); N = 2, n = 114.

Exposed succession on the face of Flat Top Mesa in the Mesquite Basin, is omitted from Table 1 and Figures 5-6 because its pre–75 Ma detrital-zircon subpopulation is anomalous with respect to the other 12 Muddy Creek samples. P values are less than 0.025 for comparisons of pre–75 Ma detrital-zircon U-Pb ages in FTM29 with other Muddy Creek samples, apparently because of a slight excess of 2000–1600 Ma grains in FTM29 derived from basement rocks exposed nearby.

The younger (post–75 Ma) age subpopulation in the Muddy Creek Formation of the Virgin River depression is distinctly different, however, from Colorado River sands (Fig. 7). P values for all sample subsets, some of which must be composited to achieve the minimum number of ages (n = 20) needed for reliable Kolmogorov-Smirnov (K-S) statistics, are uniformly 0.00 for all comparisons of Muddy Creek Formation samples with Colorado-related sands (Table 2). The latter display multiple <75 Ma age peaks spaced quasi-uniformly from 73 Ma to 6 Ma, although the exact positions of the age peaks vary because of the limited census provided by only 24–56 detrital-zircon grains contributing to each plotted curve. By contrast, the Muddy Creek Formation displays a unitary age peak at 19 Ma. The total number (n = 14) of <75 Ma detrital-zircon grains in the composited subset of samples from the modern Virgin River and Pliocene–Pleistocene terrace deposits of the Virgin River depression (VPP and VCR of Table 1) are too few for reliable Kolmogorov-Smirnov analysis, but they have a mean age of 20 ± 3 Ma, which is indistinguishable from the unitary age peak for the Muddy Creek Formation. We conclude that no paleo–Colorado River sediment contributed detritus to the exposed Muddy Creek Formation, which was instead deposited entirely by a paleo–Virgin River and its tributaries uncontaminated by paleo–Colorado River detritus. The age distribution curve for the Miocene Crooked River (Fig. 1) has a more restricted population of Cenozoic grains than the main stem of the Colorado River, but it displays a broad age peak spanning 40–22 Ma, with only a minimal “shoulder” at the Muddy Creek peak of 19 Ma.

Provenance Considerations

Pederson (2008) inferred from petrographic studies that some detritus was contributed to the Muddy Creek Formation of the Virgin River depression from Tertiary caldera complexes to the north in Nevada (Fig. 8), but our detrital-zircon data appear to rule out that inference except in limited measure. The unitary peak of 19 Ma for Muddy Creek detrital zircons does not permit significant contributions from caldera detritus, which should display greater age spreads (Fig. 9). The detrital-zircon age peak instead points to derivation of Tertiary detrital zircons dominantly from the Iron Axis igneous belt (Fig. 9), which includes the Pine Valley laccolith and associated extrusive latite exposed in the upstream Virgin River drainage above the Virgin River gorge (Fig. 8).
Figure 5. Age distribution curves for >75 Ma detrital-zircon (DZ) subpopulations in sands from the Virgin River depression and the Colorado River in and near the Grand Canyon (see Table 1 and Figure 2 for sources of data). N is the number of samples for each detrital-zircon data set, and n is the number of U-Pb ages for individual detrital-zircon grains. From Kolmogorov-Smirnoff (K-S) analysis, P = 0.33–0.74 with error in the CDF (P = 0.11–0.50 without error in the CDF) for curve D paired with curves A-B-C (mean P = 0.56 ± 0.17; 0.36 ± 0.18), and P = 0.00 for curve E paired with any of the other four curves. Color bands: A—post–mid-Permian and Mesozoic, B—pre–mid-Permian and Paleozoic, C—late Neoproterozoic (accreted peri-Gondwanan terranes and Rodinian rift granites), D—late Mesoproterozoic and early Neoproterozoic (Grenville orogen), E—early Mesoproterozoic (anhydrous alkalic Laurentian granites), F—late Paleoproterozoic (Yavapai and Mazatzal age belts).

Figure 6. Age distribution curves for >75 Ma detrital-zircon (DZ) subpopulations in sands from the Virgin River depression and the Colorado River system. N is the number of samples for each detrital-zircon data set, and n is the number of U-Pb ages for individual detrital-zircon grains (14 detrital-zircon grains >3000 Ma or 0.5% of total detrital-zircon grains are omitted from the plots). Numbers above curves denote the ages in Ma of key detrital-zircon age peaks: 425 ± 10 Ma (Silurian)—Appalachian orogen of eastern Laurentia; 610 ± 10 Ma (Ediacaran)—Gondwanan terranes accreted to eastern and southern Laurentia; 1070 ± 15 Ma (Stenian)—Grenville orogen of eastern and southern Laurentia; 1705 ± 10 Ma (Statherian)—combined Yavapai and Mazatzal age belts of southwest Laurentia.
Detrital-zircon U-Pb evidence precludes paleo–Colorado River sediment in Virgin River depression’s exposed Muddy Creek Formation

Slight displacement of the Muddy Creek detrital-zircon age peak of 19 Ma from the 22–20 Ma age range (Hacker et al., 2007) of Iron Axis intrusives and extrusives requires comment. The largest Iron Axis body is the Pine Valley laccolith, 250–300 km² in area and 900 m thick, which has yielded ⁴⁰Ar/³⁹Ar ages of 20.5–20.3 Ma (Hacker et al., 2007; Biek et al., 2009). Associated Pine Valley latite, erupted by flank collapse of the Pine Valley laccolith (Hacker et al., 2007) and 335 m thick (Biek et al., 2009), has yielded a concordant ⁴⁰Ar/³⁹Ar age of 20.4 Ma (Biek et al., 2009). By contrast, Muddy Creek U-Pb age peaks for detrital zircons are 19.2 ± 0.3 Ma, 19.5 ± 0.3, and 19.7 ± 0.3 Ma in the Mesquite, Mormon, and Overton Arm Basins, respectively. The 0.3–0.8 m.y. age discrepancy between Pine Valley ⁴⁰Ar/³⁹Ar ages and Muddy Creek U-Pb ages is unexplained but may stem from analytical imprecision or a difference in the ages of presently exposed Pine Valley source rocks and Pine Valley detritus that was eroded during the interval 6–4 Ma. In either case, the minor age dichotomy (~0.5 m.y.) is not viewed here as significant for provenance considerations.

Samples from the Muddy Creek Formation containing significant contributions of Tertiary detrital-zircon grains older or younger than ca. 19 Ma derive exclusively from samples collected along Beaver Dam Wash in the Mesquite Basin (Fig. 9A), for which laterally extensive sources in outflow tuffs from the Caliente caldera and virtual point sources from the Mineral Mountain (12 ± 2 Ma), Bull Valley (ca. 22 Ma), and Big Mountain (ca. 22 Ma) intrusions (Fig. 8) are both feasible. Downstream dilution of Caliente detritus with more voluminous detritus delivered to the Virgin River depression by the main stem of the ancestral Virgin River presumably accounts for its paucity in other detrital-zircon samples from the Virgin River depression. Volcaniclastic detritus from the Caliente, Indian Peak, and Kane Spring Wash calderas (Fig. 9) may be present in the Muddy Creek Formation of the Glendale Basin, into which Meadow Valley Wash flows from headwaters in the caldera complexes (Fig. 8), but no detrital-zircon data are currently available to test that possibility.

Limited petrofacies data for the Muddy Creek Formation and the Pliocene Colorado River delta are supportive of our conclusion from detrital-zircon data that the Colorado River did not flow into the Virgin River depression during sedimentation of at least the exposed strata of the Muddy Creek Formation (Fig. 10). The Colorado delta sands are more feldspathic, by a factor of perhaps three, than any sampled Muddy Creek assemblages. The ratio of lithic fragments to quartz mineral grains is highest for the Mesquite and Glendale Basins, where the highest percentages of volcaniclastic detritus containing abundant volcanic lithic fragments can be anticipated from subregional drainage patterns (Fig. 8).

Music Mountain Formation

The Eocene Music Mountain Formation of the Hualapai and Coconino Plateaus east of the Grand Wash Trough contains a detrital-zircon population unlike that of the Muddy Creek Formation (Fig. 11B). The Music Mountain Formation was deposited by a Paleogene drainage system flowing from south to north across the site of the modern Grand Canyon (Fig. 1)
toward the Claron depocenter in southern Utah (Fig. 1) before dissection of the Colorado Plateau led to Neogene evolution of the Colorado River (Cather et al., 2012). In common with mid-Cretaceous to mid-Miocene sedimentary assemblages across the breadth of the southern Colorado Plateau from the Grand Canyon region eastward into New Mexico, the Music Mountain Formation was derived dominantly from Precambrian basement of central Arizona. For multiple assemblages of that provenance family (Fig. 11), dual U-Pb age peaks for detrital zircons are dominant and not influenced by any notable sediment recycling from Paleozoic–Mesozoic plateau strata: (1) Paleoproterozoic (1745–1655 Ma), reflecting derivation from the Yavapai and Mazatzal orogenic belts of the Mogollon Highlands and descendants, and (2) Mesoproterozoic (1445–1385 Ma), reflecting derivation from younger granitic plutons intrusive into Yavapai–Mazatzal wall rocks. Derivation of the Precambrian detritus from the south is confirmed in the case of the Mogollon Rim Formation (Fig. 11C) by the presence of 21–18 Ma detrital zircons (n = 5), presumably derived from the Superstition volcanic field (McIntosh and Ferguson, 1998; Potochnik et al., 2012).

**WIDER PERSPECTIVES**

Despite previous tentative arguments (Dickinson, 2013), our detrital-zircon U-Pb data demonstrate that no paleo–Colorado River sediment is present in the exposed Muddy Creek Formation of the Virgin River depression and the associated Overton Arm Basin, as others have concluded on various grounds (Pederson, 2001, 2008; Kimbrough et al., 2015). The only local exposures not adequately sampled for detrital zircons are strata of the informally named lower member (Muntean, 2012) of the Muddy Creek succession. We also have no detrital-zircon data from the Glendale Basin west of the Virgin River depression, but it seems illogical to suppose that paleo–Colorado River sediment could have reached the Glendale Basin if it is not present within the Virgin River depression. The observational constraints lead to four postulates:

First, if the detrital-zircon data from the post-Hualapai (<6 Ma) Muddy Creek Formation are assumed from their overall congruence to be representative of the entire Muddy Creek Formation (<107 Ma), then no paleo–Colorado River entered the Virgin River depression during Muddy Creek sedimentation.

Second, if a syn-Hualapai (12–6 Ma) or pre-Hualapai paleo–Colorado River entered the Virgin River depression before sampled horizons of the Muddy Creek Formation were deposited, then its sediment load must be present in (1) unsampled older Muddy Creek horizons exposed near Overton Arm (Muntean, 2012), (2) unexposed lower Muddy Creek Formation known only from cuttings in the Mobil Virgin 1A well of the Mormon Basin (Bohannon et al., 1993), or (3) pre–Muddy Creek strata presented by the well (Fig. 3). In principle, those potential repositories of paleo–Colorado River sediment can be tested by further investigations of detrital-zircon populations that might record a different provenance signal than the uppermost ~250 m of the Muddy Creek Formation. As yet unsampled cuttings (but not cores) from the Mobil Virgin 1A well are available through the Nevada Bureau of Mines and Geology (George A. Davis, 2013, personal commun.).

Our second postulate is difficult to evaluate without relevant data, but it is worth noting that most of the unsampled subsurface units have lithologies suggestive of internal drainage difficult to reconcile with flooding of the Virgin River depression by a major regional river. The basal 215 m of Muddy Creek Formation penetrated by the well are described as "gypsiferous," suggestive of playa deposition and leaving only the middle 420 m of Muddy Creek Formation in the subsurface as an attractive candidate for riverine deposition that might have included a contribution of paleo–Colorado River sediment. The syn-Hualapai (12–10 Ma) "red sandstone unit" (Fig. 4) underlying Muddy Creek Formation in the well bore (Fig. 3) is interpreted as largely playa lake and eolian deposits (Bohannon, 1984), and it is unattractive as a possible record of riverine sedimentation. The Horse Spring Formation below the "red sandstone unit" (Fig. 3) is a heterogeneous assemblage of alluvial and lacustrine deposits interpreted as the record of locally developed basins of internal drainage filled with sediment derived from bounding uplands or deposited in basinal lakes that developed downslope from clastic aprons shed from bounding uplands (Bohannon, 1983, 1984; Lamb et al., 2005). Strata of the Horse Spring Formation encountered in the test well (Bohannon et al., 1993) include only the uppermost Lowell Wash Member, dated elsewhere at 14–12 Ma (Harlan et al., 1998; Beard et al., 2007; Lamb et al., 2010), and the lowermost Rainbow Gardens Member, dated elsewhere at 24–18 Ma (Beard, 1996; Beard et al., 2007, 2010), suggesting that an intraformational unconformity spanning ~5 m.y. breaks the Horse Spring succession in the subsurface of the Virgin River depression. That inference challenges the notion that a major regional river delivering a steady input of voluminous sediment could be responsible for deposition of any Horse Spring strata present in the subsurface beneath the Virgin River depression.

Third, if no detrital-zircon signal of paleo–Colorado River sediment is found in subsurface units of the Virgin River depression, then the concept of either syn-Hualapai or pre-Hualapai paleo–Colorado River flow across the Kaibab uplift and into the Virgin River paleodrainage...
Detrital-zircon U-Pb evidence precludes paleo–Colorado River sediment in Virgin River depression’s exposed Muddy Creek Formation

may be invalid. That perspective is difficult to reconcile, however, with several observations: (1) Projection of the Crooked Ridge River and Bidahochi fluvial systems of northern Arizona (Fig. 1) downstream from known outcrops suggests that both descended to an elevation near 1625 m near the confluence of the modern Colorado and Little Colorado Rivers (Dickinson, 2013), and from that spatial position, flowage of a paleo–Colorado River could have been triggered by a stream working headward from the Grand Wash Trough to capture the paleo–Colorado River at ca. 6 Ma in the area of the modern central Grand Canyon midway along its postulated course across the Shivwits Plateau from the Kaibab uplift to the Virgin River paleodrainage.

Fourth, flowage of a paleo–Colorado River crossing the Kaibab uplift into the Virgin River paleodrainage does not necessarily require exit of that river into the Virgin River depression. The Virgin River now enters the Virgin River gorge, a steep narrow canyon that may not have formed until a stream working headward from the Virgin River depression had broken through the rim of the Colorado Plateau, flexed upward by structural unloading along the Piedmont fault (Fig. 2), which bounds the Virgin River depression on the east. Incorporation of the headwaters of the Virgin River into a drainage system integrated into the Virgin River depression may have been a later development than paleo–Colorado River flow into upper reaches of the Virgin River paleodrainage. A potential alternate exit of a postulated paleo–Colorado River from the upper Virgin drainage is provided by Kanarraville gap (Fig. 1), which leads into the Great Basin north of the Virgin River depression. The gap is now blanketed by a thin veneer of Neogene sediment overlying strata of TERTIARY IGNEOUS CENTERS

Iron Axis igneous centers
Tpv - Pine Valley laccolith - latite
Tbm - Big Mountain
Tbv - Bull Valley
Tmn - Mineral Mountain

KSC - Kane Springs Wash caldera
CCC - Caliente caldera complex
IP - Indian Peak outflow tuffs (IP)

Muddy Creek Formation
GB - Glendale Basin
MeB - Mesquite Basin
MoB - Mormon Basin
OAB - Overton Arm Basin
TMB - Table Mesa Basin

If Kanarraville gap is accepted as a potential route for paleo–Colorado River flow, then the Miocene Colorado River may have been tributary to the postulated Bell River of Sears (2013) flowing across Laurentia through the eastern Great Basin and the Pacific Northwest toward a terminus at Saglek Basin of the Labrador Sea in northeast Canada. That hypothesis is beyond the scope of this paper to address, but it offers one means by which to reconcile the lack, to date, of any detrital-zircon evidence for paleo–Colorado flowage into the Virgin River depression with considerations of regional drainage evolution. Flowage of a paleo–Colorado River into and through the Pacific Northwest as an upstream tributary of the Bell River might explain the observation that fossil fishes of the Miocene Bidahochi Formation (Fig. 1) have close biotic affinities with fossil fishes related to the Snake River in the Pacific Northwest (Spencer et al., 2008a).

**CONCLUSIONS**

U-Pb ages for detrital zircons collected from exposed horizons of the Miocene–Pliocene Muddy Creek Formation preclude flowage of a 6–4 Ma paleo–Colorado River into the Virgin River depression during deposition of the youngest ~250 m of the Muddy Creek Formation. All the sampled strata were deposited after ca. 6 Ma during a time frame when the Colorado River was already flowing through the western...
Figure 10. Upper three-quarters (Qm > 25%) of a Qm-F-Lt petrofacies diagram of the mean modal compositions (symbols) of Miocene–Pliocene sandstones from the Muddy Creek Formation (Glendale, Mesquite, Mormon, and Overton Arm Basins) and Pliocene sandstones from ancestral Colorado River deltaic deposits exposed in southern California (Dorsey et al., 2007, 2011). N is the number of thin sections point counted for each sample set plotted, and hexagons surrounding symbols for mean compositions delimit standard deviations for each sample set.

Figure 11. Age distribution curves for detrital zircons (DZ) in mid-Cretaceous to mid-Miocene sands of Yavapai–Mazatzal provenance on the southern Colorado Plateau. N is the number of samples for each detrital-zircon data set, and n is the number of U-Pb ages for individual detrital-zircon grains. Sources of data: A—Crossey et al. (2014), B—Dickinson et al. (2012), C—Potochnik et al. (2012), D—Supplemental File (see text footnote 1; partial data in Dickinson et al., 2010), E—Dickinson and Gehrels (2008). Color bars highlight anorogenic granite (1445–1385 Ma) and Yavapai-Mazatzal (1745–1655 Ma) age peaks.
Grand Canyon into the Grand Wash Trough, 75 km to the south (Fig. 2). If a pre–6 Ma paleo–Colorado River flowed into the Virgin River depression before deposition of exposed Muddy Creek Formation, then the detrital-zircon record of its influence is hidden from view in older unsampled subsurface strata of the Muddy Creek Formation or of underlying Miocene strata penetrated by the Virgin M1A test well in the Mormon Basin (Fig. 3). If that potential evidence for paleo–Colorado River flow is tested and found also to be negative, then the alternatives are to abandon the postulate of paleo–Colorado River flow across the Kaibab uplift and the Shiwwits Plateau into the Virgin River paleo-depression, or to infer that the paleo–Colorado River exited into the Great Basin from upper reaches of the Virgin River paleo-depression through Kanarraville gap ~100 km north of the Virgin River depression.

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