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Detrital zircon U-Pb provenance of the Colorado River: A 5 m.y. record of incision into cover strata overlying the Colorado Plateau and adjacent regions

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ABSTRACT

New detrital zircon U-Pb age distributions from 49 late Cenozoic sandstones and Holocene sands (49 samples, n = 3922) record the arrival of extra-regional early Pliocene Colorado River sediment at Grand Wash (western USA) and downstream locations ca. 5.3 Ma and the subsequent evolution of the river's provenance signature. We define reference age distributions for the early Pliocene Colorado River (n = 559) and Holocene Colorado River (n = 601). The early Pliocene river is distinguished from the Holocene river by (1) a higher proportion of Yavapai-Mazatzal zircon derived from Rocky Mountain basement uplifts relative to Grenville zircon from Mesozoic supracrustal rocks, and (2) distinctive (~6%) late Eocene–Oligocene (40–23 Ma) zircon reworked from Cenozoic basins and volcanic fields in the southern Rocky Mountains and/or the eastern Green River catchment. Geologic relationships and interpretation of 135 published detrital zircon age distributions throughout the Colorado River catchment provide the interpretative basis for modeling evolution of the provenance signature. Mixture modeling based upon a modified formulation of the Kolmogorov-Smirnov statistic indicate a subtle yet robust change in Colorado River provenance signature over the past 5 m.y. During this interval the contribution from Cenozoic strata decreased from ~75% to 50% while pre-Cretaceous strata increased from ~25% to 50%. We interpret this change to reflect progressive erosional incision into plateau cover strata. Our finding is consistent with geologic and thermochronologic studies that indicate that maximum post–10 Ma erosion of the Colorado River catchment was concentrated across the eastern Utah–western Colorado region.

INTRODUCTION

The Colorado River drainage basin is a subcontinental catchment that covers 640,000 km² of southwestern North America (Fig. 1). Initiation of the Neogene Colorado drainage network was marked by a major eastward shift in the position of the continental divide and was arguably the most important hydrographic transformation to affect southwestern North America since the construction of the mid-Cretaceous batholith along its western margin (Spencer et al., 2008). Development of the modern river course through the western Grand Canyon and lower Colorado River region took place after ca. 6 Ma in conjunction with rifting of the Gulf of California and Salton Trough (Lucchitta, 1972, 1989; Howard and Bohannon, 2001; House et al. 2005, 2008; Dorsey et al., 2007, 2011; McDougall, 2008). However, despite more than a century of investigation, the means by which the Colorado River established its course through the western Grand Canyon into the Basin and Range at Grand Wash remains disputed (Hunt, 1956; Lucchitta, 1989, 2013; Flowers et al., 2008; Pederson, 2008; Polyak et al., 2008; Pelletier, 2010; Wernicke, 2011; Flowers and Farley, 2012; Karlstrom et al., 2013; Dickinson, 2013).

Most investigators agree that Late Cretaceous uplift of the Mogollon Highlands during Laramide flat-slab subduction created a high-elevation northwest-trending topographic divide that isolated much of southern California and southwestern Arizona from the Colorado Plateau region (Lucchitta, 1972; Dickinson et al., 1988; Flowers et al. 2008; Liu and Gurnis, 2010; Jacobson et al., 2011; Ingersoll et al., 2013). This divide directed northeast-flowing streams into the continental interior (Spencer et al., 2008; Dickinson et al., 2012) and forced southwest-flowing streams into coastal southern California (Howard, 1996,

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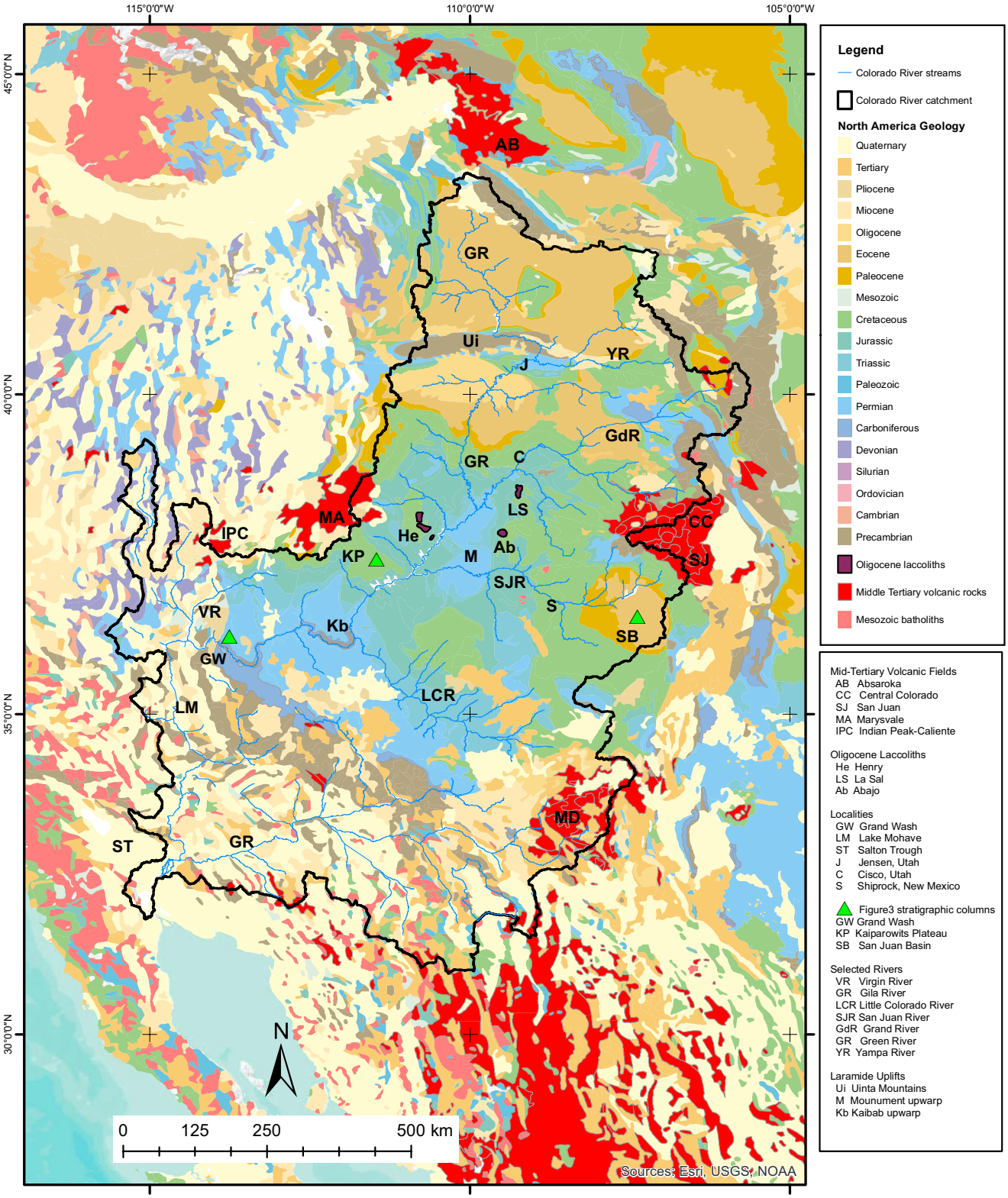

Figure 1. Generalized geologic map of the southwestern United States with Colorado River catchment adapted from Garrity and Soller (2009). The catchment area of the Colorado River system primarily contains Paleozoic and Mesozoic rocks of the Colorado Plateau and southern Rocky Mountains. Proterozoic basement is exposed in the deeply eroded southwestern portion of the Colorado Plateau, transition zone, and adjacent Basin and Range. Cenozoic strata and volcanic rocks predominate in the eastern and northern domains of the catchment.

2000; Jacobson et al., 2011; Ingersoll et al., 2013). Tertiary Basin and Range extension broke up this topographic barrier but just how the subsequent Colorado River breached it remains poorly understood.

The first Colorado River sediments at Grand Wash at the mouth of the Grand Canyon were deposited after 6 Ma (Faulds et al., 2001; Howard and Bohannon, 2001; Spencer and Pearthree, 2001). Integration of the Colorado River from Grand Wash southward through the Basin and Range to the Gulf of California involved sequential development and subsequent failure of a chain of lakes that deposited the lacustrine Bouse Formation (House et al., 2005, 2008; Spencer et al., 2013; Pearthree and House, 2014). Colorado River sediment filled these valleys between ca. 5.6 and 4.1 Ma. Ultimately the river reached the Gulf of California, where deltaic sedimentation was initiated (Merriam and Bandy, 1965; Winker, 1987; Fleming, 1994). Paleomagnetic and biostratigraphic data from delta deposits in the western Salton Trough date the arrival of Colorado River sediment at ca. 5.3 Ma (Dorsey et al., 2007, 2011).

The path of any possible pre–Grand Canyon Colorado River and how the river became established through the western Grand Canyon area is much less clear. Lucchitta (1989) proposed that headward erosion across the western Grand Canyon region formed the modern Colorado River by capturing an ancestral Colorado River that transited the Kaibab uplift through a paleocanyon near the present eastern Grand Canyon and crossed the Shivwits Plateau north of the western Grand Canyon into the Virgin River depression (cf. Pelletier, 2010; Dickinson, 2013; Lee et al., 2013). However, paleo–Colorado River sediment is absent in the exposed Miocene–Pliocene basin fill of the Virgin River depression (Dickinson et al., 2014). Blackwelder (1934) proposed an alternative lake spillover model for integration of the river across the Kaibab uplift that was supported by Scarborough (2001) and Meek and Douglass (2001), who interpreted the Bidahochi Formation as deposits within a large Hopi Lake that overtopped the Kaibab upwarp to establish the path of the modern river. Paleocanyons carved during the Cenozoic or as early as the Late Cretaceous figure prominently in more recent models (Young and Spamer, 2001; Hill and Ranney, 2008; Karlstrom et al., 2014). Wernicke (2011) proposed that southwest tilting produced by post–80 Ma erosion of the Mogollon Highlands made it possible for a southwest-flowing Arizona River to access a paleocanyon previously carved by a northeast-flowing river to direct it from the plateau region into southern California throughout the early Cenozoic. This hypothesis is contradicted by evidence for a contemporaneous California River that flowed from California to Utah (e.g., Dickinson et al., 2012) and by detrital zircon results that preclude Colorado Plateau–derived sediments from reaching coastal southern California in Late Cretaceous to Pliocene time (Ingersoll et al., 2013).

The very different conceptual models outlined above for the late Cenozoic history of the Colorado River make different predictions for the evolution of its sedimentary provenance. An effective way to characterize sedimentary provenance is to examine detrital zircon U-Pb age distributions. A sizeable body of detrital zircon age data exists for the Colorado Plateau region, including the southern Rocky Mountains (Dickinson and Gehrels, 2008a, 2008b, 2009a, 2009b, 2010; Gehrels et al., 2011; Dickinson et al., 2012) (Fig. 2). Combined with geologic relationships (Fig. 1), the 12,852 analyses from 135 samples in these cited works provide leverage for predicting variation of the Colorado River provenance signature over time for different river integration models.

To evaluate competing hypotheses for the evolution of the Colorado River, we present 3922 new detrital zircon U-Pb age analyses from 49 samples from 5 different sample suites (Fig. 2): (1) Holocene sands from the delta region between Yuma and the Gulf of California; (2) Holocene sands from major branches of the catchment including the Green, Grand (the upper Colorado above the confluence with the Green, referred to here by its name prior to 1921), San Juan, Little Colorado, Virgin, and Gila Rivers; (3) earliest Pliocene to Pleistocene sandstones from the western Salton Trough that include the oldest deposits sourced from the Colorado River; (4) earliest Pliocene to Pleistocene sandstones sampled along the Colorado River corridor; and (5) Miocene sandstone from former Lake Bidahochi on the Colorado Plateau.

BACKGROUND

Colorado River System Overview

The Colorado River drains an expansive watershed that encompasses most of the Colorado Plateau and parts of the surrounding Basin and Range and Southern and Central Rocky Mountains physiographic provinces (Figs. 1 and 2). The three main tributaries feeding the upper basin are the Green River, San Juan River, and upper Colorado above the confluence with the Green (referred to herein as the Grand; Fig. 2; Table 1). Downstream the Little Colorado River and Virgin Rivers feed into the middle basin (Fig. 2; Table 1). The Gila River joins the Colorado River near Yuma shortly before it drains into the Gulf of California. These six tributaries represent ~78% of the total catchment area (Table 1).

Water and sediment are not contributed uniformly into the Colorado drainage network (La Rue, 1916; Howard, 1947; Irons et al., 1965; Andrews, 1991). Most of the river's flow (75%) originates as snowmelt in high mountain headwater streams in the Rocky Mountains; the majority of the sediment is contributed by the semiarid central part of the Colorado Plateau upstream from the Grand Canyon. This large area is 37% of the total basin area but currently contributes ~69% of the basinwide sediment discharge. Major sediment sources here are areas of badland topography developed on Mesozoic and Cenozoic mudstone and shale, principally the Wasatch, Morrison, Chinle, and Moenkopi Formations and Mancos Shale (Andrews, 1991). These sources occupy a central part of the plateau that has undergone rapid Quaternary incision (Pederson et al., 2013) and broadly corresponds to the area of maximum post–10 Ma erosion of the Colorado River catchment (Lazear et al., 2013).

Rocks currently exposed in the Colorado River catchment define an oblique crustal section that was established prior to the Neogene (Figs. 1 and 3). Geologic relationships and low-temperature apatite (U-Th)/He thermochronology indicate that virtually all of the Mesozoic sedimentary section, including more

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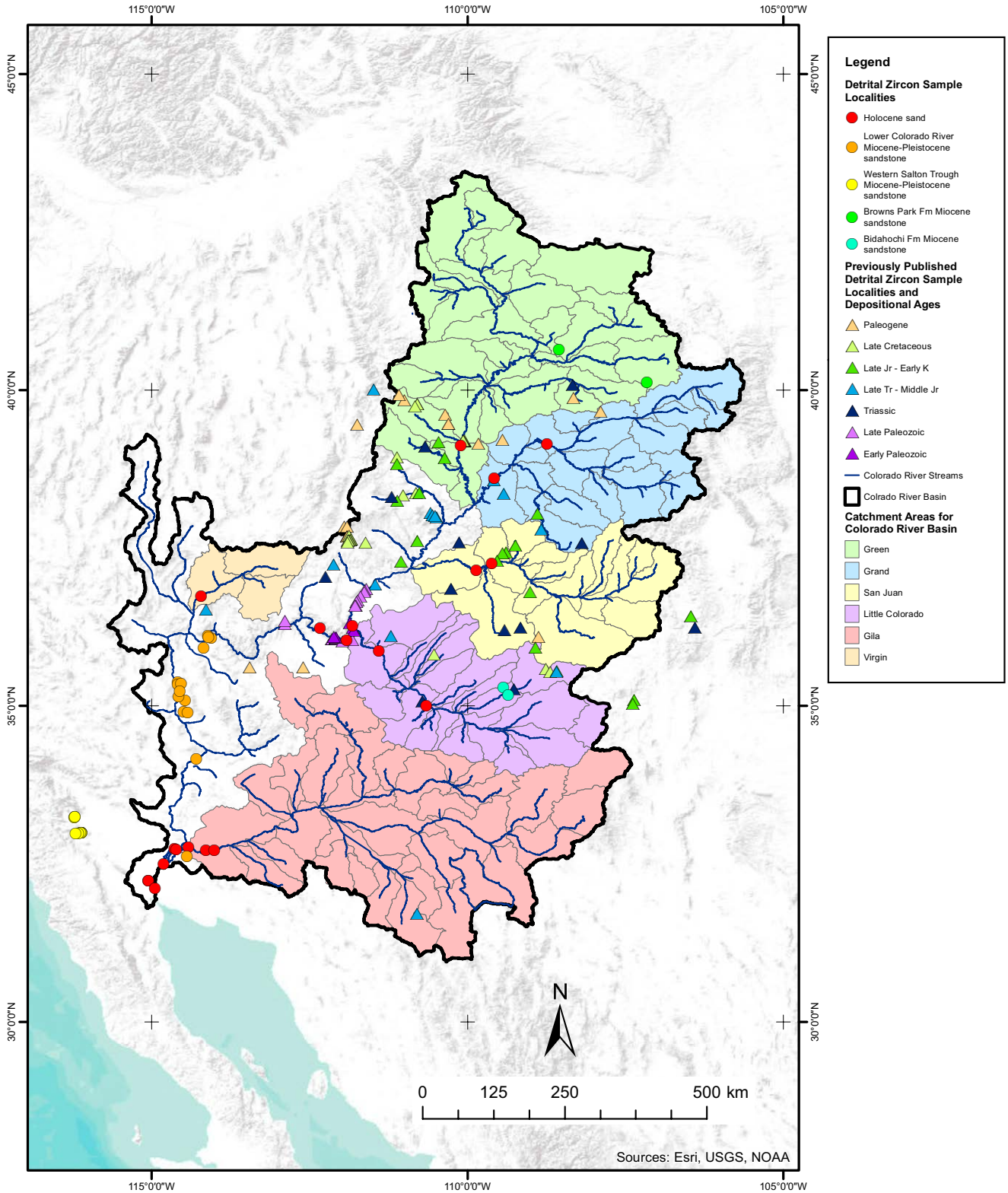

Figure 2. Sample location map. Samples from this study are shown as red circles for Holocene sands and yellow circles for sandstones. Sample sites for previously published results are shown as filled triangles color coded as a function of depositional age. Data sources include Dickinson and Gehrels (2008a, 2008b, 2009b), Davis et al. (2009, 2010), Larsen et al. (2010), Lawton and Bradford (2011), Gehrels et al. (2011), and Dickinson et al. (2012).

TABLE 1. MEAN ANNUAL RUNOFF AND SEDIMENT LOAD IN THE COLORADO RIVER BASIN (1941–1957) AFTER ANDREWS (1991)

Tributary	Catchment area (km^2)	Catchment area (%)	Mean discharge (10^9 m^3/yr)	Mean sediment load (10^6 t/yr)
Green River	116200	18.1	5.618	17.78
Grand	67081	10.4	6.53	8.84
San Juan River	63714	9.9	2.01	19.9
Little Colorado River	69000	10.7	0.185	9.27
Virgin River	31727	4.9	0.185	2.27
Gila River	149832	23.3	1.7	–
Total catchment	642000	–	–	–

Note: Grand refers to the pre-1921 name of the upper Colorado above the confluence with the Green. Dash indicates no data.

than 1 km of Cretaceous strata, was eroded from the Mogollon Highlands of the transition zone and southwestern Colorado Plateau between 80 and 40 Ma (Flowers et al., 2008; Lee et al., 2013). Where the Colorado River enters the Basin and Range at the southwestern plateau margin, only Permian and older pre-Miocene rocks are preserved (Figs. 1 and 3A). Farther northeast, the extent of Late Cretaceous–early Cenozoic erosion was much less significant. At Glen Canyon, >2 km of the Triassic, Jurassic, and Cretaceous succession is preserved and the depth of present-day erosion barely reaches the top of the Permian section (Figs. 1 and 3B). Continued preservation of the Mesozoic sequence but locally deeper erosion occurs even farther northeast in the southern Rocky Mountains. While localized Laramide uplifts within the Rocky Mountains expose Paleozoic strata and Precambrian basement, Mesozoic strata crop out over much of the central Colorado Plateau. At the eastern and northeastern limits of the Colorado River catchment, Cenozoic deposits occur in the southern Rocky Mountains and within northeastern Utah and western Colorado (Figs. 1 and 3C).

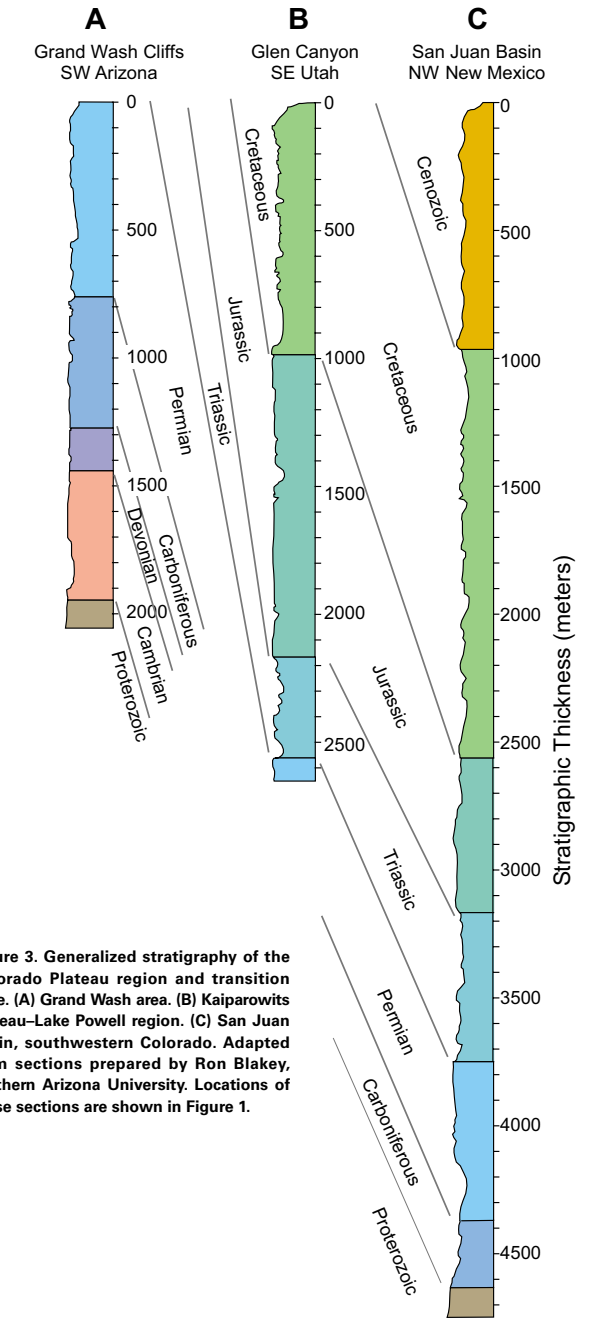

Figure 3. Generalized stratigraphy of the Colorado Plateau region and transition zone. (A) Grand Wash area. (B) Kaiparowits Plateau–Lake Powell region. (C) San Juan Basin, southwestern Colorado. Adapted from sections prepared by Ron Blakey, northern Arizona University. Locations of these sections are shown in Figure 1.

Provenance Signature of Rocks within the Colorado River Catchment

Over the past decade, a significant effort has been undertaken to characterize the detrital zircon U-Pb age provenance signature of rocks within the region of the Colorado Plateau (e.g., Dickinson and Gehrels, 2010; Gehrels et al., 2011). Figure 4 and Table 2 summarize how detrital zircon age distributions for sedimentary rocks within the Colorado catchment have varied throughout the Phanerozoic. Ancient zircon (older than 2015 Ma) was most likely ultimately derived from the Wyoming, Superior, and other Archean basement provinces of North America (Foster et al., 2006). Zircon within the 2015–1810 Ma bin reflects Paleoproterozoic crust that accreted around the Archean craton. The Paleoproterozoic Yavapai-Mazatzal orogenic belts and younger ca. 1.45 Ga granitic basement underlie southwestern North America and represent the primary

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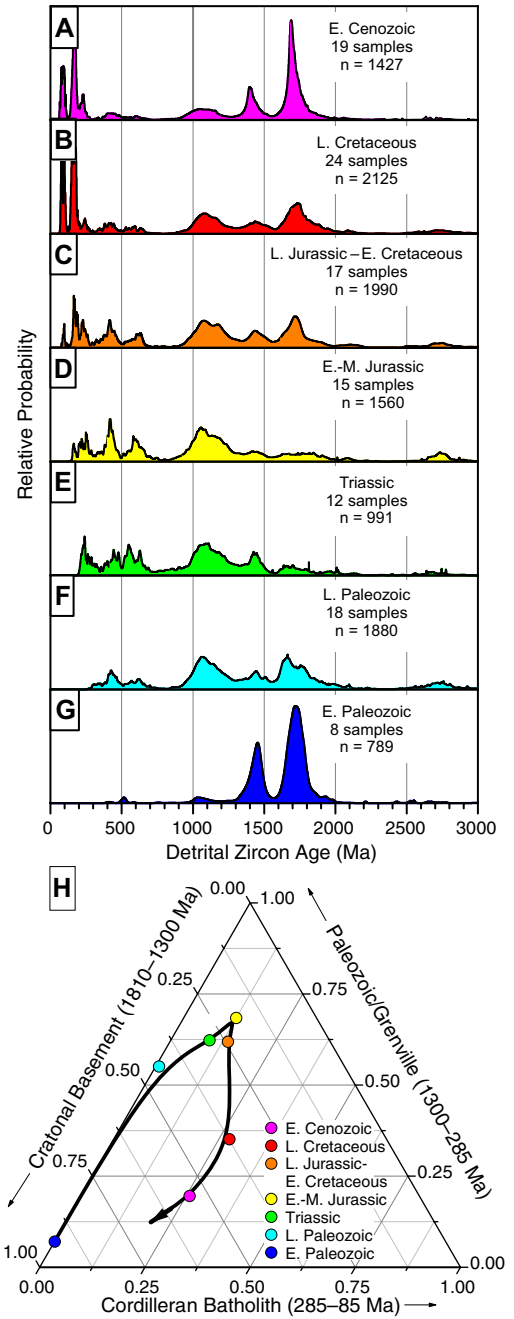

Figure 4. Representative detrital zircon U-Pb age distributions for the Colorado Plateau. See Figure 2 for locations. (A) Paleocene and Eocene strata (Davis et al., 2009, 2010; Larsen et al., 2010; Dickinson et al., 2012). (B) Late (L.) Cretaceous strata (Dickinson and Gehrels, 2008b; Larsen et al., 2010; Lawton and Bradford, 2011; Dickinson et al., 2012). (C) Late Jurassic and Early (E.) Cretaceous strata (Dickinson and Gehrels, 2008b, 2009b). (D) Early and Middle (M.) Jurassic strata (Dickinson and Gehrels, 2009b). (E) Triassic strata (Dickinson and Gehrels, 2008a). (F) Late Paleozoic (Carboniferous–Permian) strata of the Grand Canyon area (Gehrels et al., 2011). (G) Early Paleozoic (Cambrian–Devonian) strata of the Grand Canyon area (Gehrels et al., 2011). (H) Ternary mixing diagram showing evolution of Colorado Plateau zircon compositions from Early Paleozoic to Early Cenozoic time.

sources for zircon within the 1810–1535 Ma and 1535–1300 Ma bins, respectively (CD-Rom Working Group, 2002; Gehrels et al., 2011). In contrast, Grenville age zircon (1300–900 Ma), late Neoproterozoic–Cambrian (725–515 Ma), and Paleozoic (510–285 Ma) zircon was principally supplied by the Appalachian and Ouachita orogenic sources in southeastern and southern North America (Dickinson and Gehrels, 2008a, 2008b, 2009a, 2009b; Gehrels et al., 2011). Cordilleran arc sources are approximated by Permian–Triassic (285–200 Ma), Early Cretaceous–Jurassic (200–125 Ma), mid-Cretaceous (125–85 Ma), and Late Cretaceous–early Cenozoic (Laramide) (85–40 Ma) age bins (Barth et al., 2004; Jacobson et al., 2011; Dickinson et al., 2012). The mid-Cenozoic ignimbrite flareup (Lipman and Glazner, 1991) and Basin and Range magmatism (e.g., Best et al., 2013) account for the 40–23 Ma and 23–5 Ma age bins (Fig. 1; Table 2).

Late Miocene–Early Pliocene Deposits Related to the Colorado River

The oldest known deposits of the Colorado River occur along the lower corridor of the river between Grand Wash and Lake Mohave–Cottonwood Valley and within the Salton Trough (locations in Fig. 1). The Lake Mead area near the mouths of the Grand Canyon and the Virgin River gorge holds key evidence for the initial entry of far-traveled fluvial sediments from distant Colorado Plateau sources into the Basin and Range province (Fig. 5A). The Hualapai Limestone Member and interfingered and underlying clastics (Muddy Creek beds) in Grand Wash Trough record late Miocene sedimentation in local basins before the arrival of Colorado River fluvial sediment through the western Grand Canyon (Longwell, 1936).

The Hualapai Limestone (Fig. 5A) bridges across two or three local basins and accumulated between 12 and 6 Ma. The easternmost Grand Wash Trough basin occupies the margin of the Basin and Range against the Grand Wash Cliffs and Colorado Plateau. Reddish siltstone and sandstone and conglomerate containing locally derived granite boulders interfinger with the Hualapai Limestone (Faulds et al., 2001). The earliest Colorado River sediments near Grand Wash overlie the Hualapai Limestone, which has a 5.97 ± 0.07 Ma tuff near its top (Spencer et al., 2001). Colorado River sediment is overlain by a 4.4 Ma basalt within a channel incised below the Hualapai Limestone (Faulds et al., 2001; Howard and Bohannon, 2001) (Fig. 5A).

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TABLE 2. DETRITAL ZIRCON AGE DISTRIBUTIONS OF COLORADO PLATEAU STRATA

Age bin (Ma)	Lower Paleozoic strata* (n = 789)	Upper Paleozoic strata† (n = 1880)	Triassic strata§ (n = 1091)	Lower–middle Jurassic strata** (n = 1374)	Upper Jurassic–Lower Cretaceous strata†† (n = 1587)	Upper Cretaceous strata§§ (n = 2125)	Early Cenozoic strata*** (n = 1427)
5–23 (%)	–	–	–	–	–	–	–
23–40 (%)	–	–	–	–	–	–	0.0
40–85 (%)	–	–	–	–	–	5.2	2.9
85–125 (%)	–	–	–	–	0.0	5.5	4.6
125–200 (%)	–	–	–	2.0	6.6	15.5	14.7
200–285 (%)	–	0.1	8.9	8.8	4.9	2.8	4.1
285–510 (%)	0.6	8.2	11.7	13.1	12.8	5.2	3.4
510–725 (%)	0.8	5.4	13.2	10.5	8.1	3.6	1.8
725–900 (%)	0.3	0.7	2.3	1.6	1.2	0.2	0.4
900–1300 (%)	4.6	32.1	28.3	35.7	32.5	19.9	11.9
1200–1535 (%)	28.0	12.4	15.3	7.6	11.3	9.5	13.7
1535–1810 (%)	57.7	24.7	10.2	8.1	10.7	20.0	35.4
1810–2015 (%)	6.1	6.6	3.2	4.2	4.3	6.1	3.7
>2015 (%)	2.0	9.7	6.9	8.4	7.7	6.5	3.5

*Lower Paleozoic (Cambrian–Devonian) strata of the Grand Canyon area (Gehrels et al., 2011).
†Upper Paleozoic (Carboniferous–Permian) strata of the Grand Canyon area (Gehrels et al., 2011).
§Triassic strata (Dickinson and Gehrels, 2008a).
**Lower and middle Jurassic strata (Dickinson and Gehrels, 2009b).
††Upper Jurassic and lower Cretaceous strata (Dickinson and Gehrels, 2008b; Dickinson and Gehrels, 2009b).
§§Late Cretaceous strata (Dickinson and Gehrels, 2008b; Larsen et al., 2010; Lawton and Bradford, 2011; Dickinson et al., 2012).
***Paleocene and Eocene strata (Davis et al., 2009, 2010; Larsen et al., 2010; Dickinson et al., 2012).

Less-well-dated deposits of the early Pliocene Colorado River near Lake Mohave include the Bullhead Alluvium that postdates deposition of the Bouse Formation at 4.8 Ma (Spencer et al., 2013) (Fig. 5B). Locally derived alluvial deposits underlie the Bouse Formation. The Bouse Formation was deposited in a series of lakes following first arrival of Colorado River water into closed basins inherited from Basin and Range extension (Spencer et al., 2013). The Chemehuevi Formation records a major late Pleistocene episode of fluvial aggradation along the lower Colorado River corridor (Malmon et al., 2011).

A dipping, >5-km-thick section of fluvial and marine sedimentary rocks derived from Colorado River and local sources is exposed in the western Salton Trough, in the Fish Creek–Vallecito and Borrego Badlands basins (Fig. 6). These strata provide a record of Colorado River deposition that spans the interval from the first arrival of Colorado River sediments ca. 5.3 Ma until the time of basin inversion and uplift ca. 1 Ma (Dorsey et al., 2007, 2011).

METHODS

Detrital zircons were separated from modern river sand and sandstone samples using standard methods at San Diego State University (San Diego, California). Sample locations and details are presented in Figure 2, Table 3, and Table DR1 in the Supplemental File[1]. With the exception of gravelly sandstones from the Bullhead alluvium, samples are typically fine- to medium-grained moderately well-sorted subarkosic sand and sandstone with zircon yields typically 0.01–0.05 wt% of the bulk sample. Comparison of zircon yields to sandstone Zr content reported for lower Colorado River sands (Zimbelman and Williams, 2002) indicate efficient recovery of zircon.

Samples were comounted with either Sri Lanka zircon standard SL2 ($^{206}Pb/^{238}U$ age 564 Ma) or SL-Marty ($^{206}Pb/^{238}U$ age 557 Ma) and a secondary standard 49127 ($^{206}Pb/^{238}U$ age 137 Ma). U-Pb analyses of individual zircons were obtained by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) over a total of seven sessions at the University of Arizona Laserchron Center (Tucson). Laser ablation was conducted with an Excimer laser beam diameter of 30 or 35 µm and a pulse frequency of 8 Hz. Measurements were performed with the GVI Isoprobe and Nu ICP-MS systems (Gehrels et al., 2008; Johnston et al., 2009). Analysis sites were randomly targeted. Most zircon yielded U-Pb results that were concordant to within 10%. Overall, >90%–95% of the analyses were retained for analysis after filtering highly discordant, high common ^{204}Pb, and/or low ^{206}Pb analyses. Interpreted ages are based on $^{207}Pb/^{206}Pb$ ratios for grains older than 850 Ma, and $^{206}Pb/^{238}U$ ratios for grains younger than 700 Ma. Intermediate results (850–700 Ma) required care because minor discordance was capable of causing improper selection of $^{206}Pb/^{238}U$ ages and were evaluated on a case-by-case basis. Complete data tables, including the 49127 secondary standard data, and statistical

SUPPLEMENTARY MATERIAL: Detrital Zircon U-Pb Provenance of the Colorado River: A Five Million Year Record of Incision into Cover Strata Overlying the Colorado Plateau and Adjacent Regions

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SUMMARY OF DATA RESPOSITORY CONTENT

1. SAMPLE DETAILS. Table DR1. Location and description of U-Pb zircon samples analyzed for this study.

2. LA-ICP-MS METHODS. Description of analytical methods associated with zircon U-Th-Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

3. KOLMOGOROV-SMIRNOV (K-S) STATISTIC. Description of statistical comparisons based upon the Kolmogorov-Smirnov (K-S) statistic.

4. K-S STATISTICS FOR COLORADO RIVER SAMPLES. Tables DR2-6. K-S test comparisons for sandstone and Holocene sand samples from Colorado River basin and associated samples.

5. GENERALIZING THE K-S TEST TO MIXTURES. Explanation of how the K-S statistic is generalized for mixtures.

6. U-PB ZIRCON RESULTS. Table DR7. LA-ICP-MS U-Pb zircon geochronologic analysis results of Colorado River basin and associated samples.

8. U-PB ZIRCON RESULTS FOR SECONDARY STANDARD 49127. Table DR8-9.

[1]Supplemental File. Sample details, LA-ICP-MS methods, Kolmogorov-Smirnov (K-S) statistical comparisons, K-S statistics for Colorado River samples, Explanation of how the K-S statistic is generalized for mixtures, U-Pb zircon analysis results for the Colorado Basin and associated samples, and U-Pb zircon results for secondary standard 49127. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00982.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.

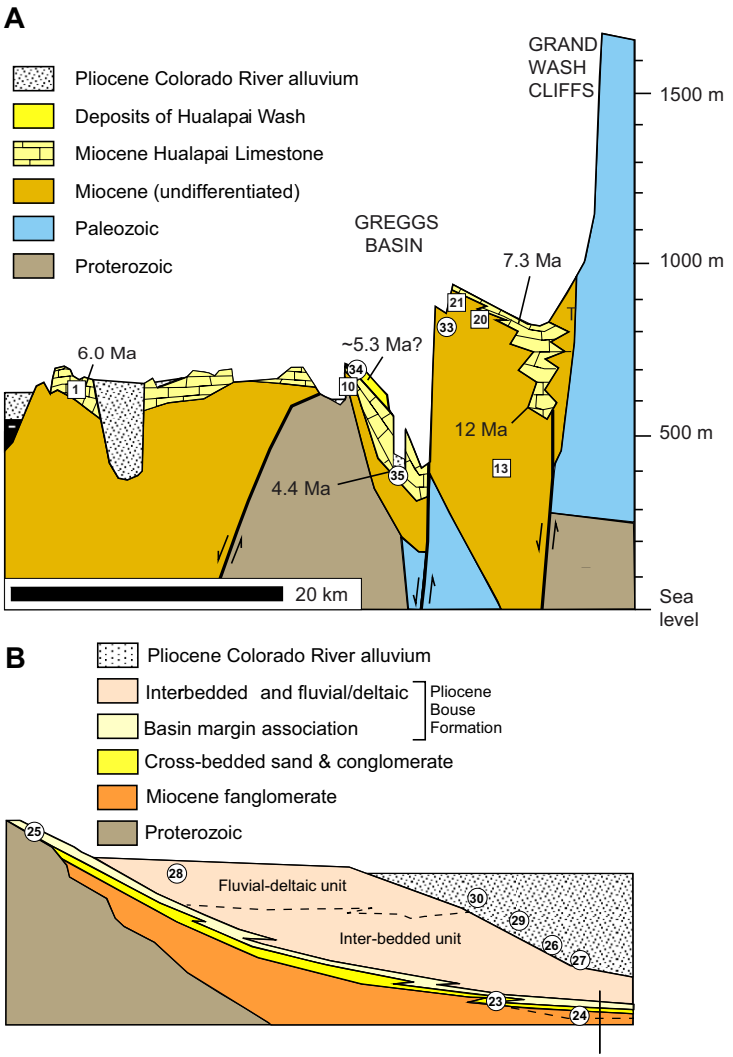

Figure 5. Lower Colorado River stratigraphy showing sample localities. (A) Grand Wash area. Samples locations are for this study and previous data from Lopez-Pearce et al. (2011). (B) Lake Mojave–Parker area. Sample locations are from this study.

comparisons between samples using the Kolmogorov-Smirnov (K-S) test, are provided in the Supplemental File (see footnote 1).

The extensive database illustrated in Figure 4 and Table 2 provides the basis to define geologically meaningful end members that can be used to decipher the Colorado River provenance signature over time. To interpret our results in terms of this database, we have adapted the K-S test to be applicable to mixtures. Our approach is detailed in the Supplemental File (see footnote 1). We perform readily visualized ternary mixing calculations that clearly illustrate the compositional range over which end members can be mixed to reproduce (or be distinguished from) a given age distribution at 95% confidence. Specifically, the P = 0.05 contours in these ternary plots define three-dimensional error bars that represent 95% confidence.

RESULTS

Lowermost Colorado River Modern Sands

A total of 601 zircon U-Pb analyses were measured from 6 samples of Holocene river sand from the Colorado River delta between Yuma and the mouth of the Colorado River in the Gulf of California (Table 3; Figs. 2 and 7A–7F). The observed differences in detrital zircon age distribution reflect the inherent variability of detrital zircon populations within hydraulically sorted fluvial systems (Slingerland, 1984). Variation in magnetic susceptibility and the measured zircon yields of the individual samples is further reflection of this natural variability (Table 3).

Zircon age distributions for all of the delta sand samples are indistinguishable with one another at 95% confidence based upon the 2-sample Kolmogorov-Smirnov (K-S) test (Supplemental File [see footnote 1]). We have thus pooled results from these six samples to obtain a reference for the Holocene Colorado River (HCR) (Fig. 7H). The HCR reference provides an important basis for comparison with other Holocene sand and Neogene sandstone samples. For the HCR reference, the average percentages and ranges of 1810–1300 Ma, 1300–285 Ma, and 285–85 Ma zircon are 8% (5%–11%), 39% (29%–46%), and 39% (29%–51%), respectively. This can be compared with results from sedimentary rocks of the Colorado Plateau and southern Rocky Mountain region (Fig. 4H; Table 2) to infer the sources contributing to the modern river. The Cenozoic age distributions, notably late Eocene–Oligocene (40–23 Ma) and Miocene (23–5 Ma), are useful for distinguishing Colorado Plateau from Basin and Range sources (Figs. 1 and 2; Supplemental File [see footnote 1]).

Holocene Sands from Major Trunks of the Colorado River System

A total of 680 detrital zircon U-Pb analyses were measured from 12 samples representing six major tributaries of the Colorado River (Fig. 8; Table 3). Also included are 99 results from Virgin River sample 08MC20 (Forrester, 2009). Except for the Green River, two or more samples per tributary are available. Samples from the same tributaries yield K-S tests results that are indistinguishable at 95% confidence (Supplemental File [see footnote 1]). Accordingly, we have pooled results from the individual tributaries and plotted their relative probability plots in Figures 8A–8F.

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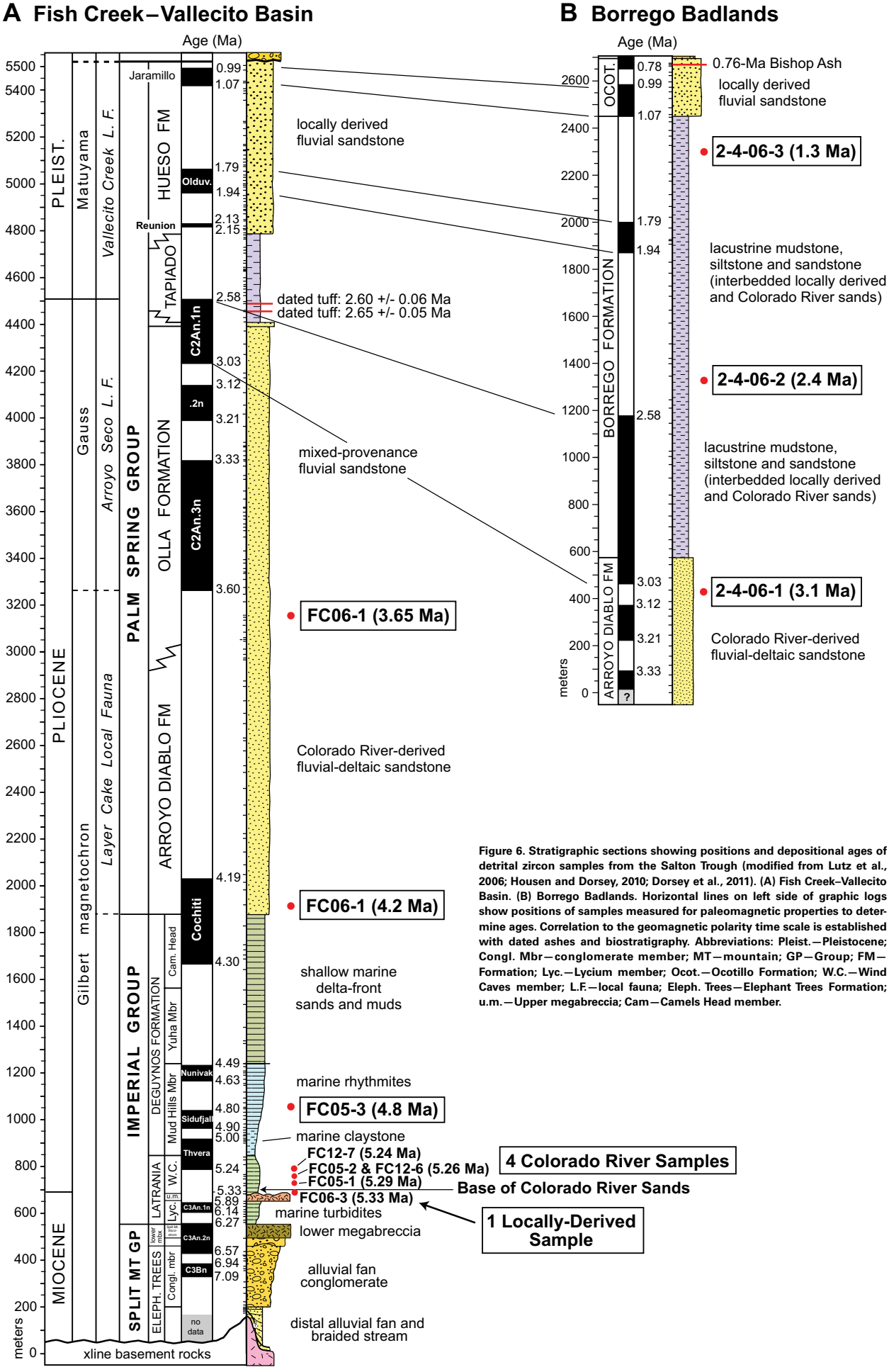

Figure 6. Stratigraphic sections showing positions and depositional ages of detrital zircon samples from the Salton Trough (modified from Lutz et al., 2006; Housen and Dorsey, 2010; Dorsey et al., 2011). (A) Fish Creek–Vallecito Basin. (B) Borrego Badlands. Horizontal lines on left side of graphic logs show positions of samples measured for paleomagnetic properties to determine ages. Correlation to the geomagnetic polarity time scale is established with dated ashes and biostratigraphy. Abbreviations: Pleist.—Pleistocene; Congl. Mbr—conglomerate member; MT—mountain; GP—Group; FM—Formation; Lyc.—Lycium member; Ocot.—Ocotillo Formation; W.C.—Wind Caves member; L.F.—local fauna; Eleph. Trees—Elephant Trees Formation; u.m.—Upper megabreccia; Cam—Camels Head member.

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TABLE 3. SAND AND SANDSTONE DETRITAL ZIRCON U-Pb SAMPLES

ID	Name	Lat (°N)	Long (°W)	Magnetic susceptibility	Zircon (wt%)	Depositional age	Stratigraphic unit
01	CR05-1	32.2353	115.0553	65	–	Holocene	Colorado River
02	CR05-2	32.4943	114.8149	60	–	Holocene	Colorado River
03	1-23-06-1	32.7325	114.6409	225	0.037	Holocene	Colorado River
04	Yuma	32.7293	114.6152	125	0.002	Holocene	Colorado River
05	San Felipito	32.2376	115.0556	50	0.037	Holocene	Colorado River
06	Santa Clara	32.1055	114.9488	70	0.029	Holocene	Colorado River
07	CR-1	36.2613	111.8269	20	0.067	Holocene	Grand Canyon
08	CR-2	36.0443	111.9187	40	0.093	Holocene	Grand Canyon
09	CR-3	36.2295	112.3388	25	0.130	Holocene	Grand Canyon
10	CRT0806-1	39.1470	108.7442	90	0.024	Holocene	Grand River
11	CRT0806-3	38.6035	109.5760	45	0.009	Holocene	Grand River
12	CRT0806-2	39.1152	110.1098	30	0.008	Holocene	Green River
13	CRT0806-4	37.2596	109.6178	50	0.034	Holocene	San Juan River
14	CRT0806-5	37.1501	109.8659	25	0.031	Holocene	San Juan River
15	CRT0806-6	35.0070	110.6532	30	0.054	Holocene	Little Colorado River
16	CRT0806-7	35.8757	111.4057	10	0.048	Holocene	Little Colorado River
17	CRT0806-8	32.7089	114.1433	30	0.015	Holocene	Gila River
18	CRT0806-9	32.7148	114.0128	600	0.010	Holocene	Gila River
19	32406-1	32.7593	114.4215	275	0.011	Holocene	Gila River
20	CRT0806-10	36.7325	114.2226	70	0.059	Holocene	Virgin River
21	CRT0806-12	35.2944	109.4383	30	0.011	Miocene–Pliocene	Bidahochi Formation
22	CRT0806-13	35.1697	109.3620	60	0.011	Miocene–Pliocene	Bidahochi Formation
23	32706-3	34.1613	114.3005	45	–	late Miocene	Sub-Bouse sandstone
24	32306-175	35.3781	114.5904	200	0.010	ca. 5.5 Ma	Lost Cabin beds
25	32506-1	35.0871	114.4697	175	0.008	4.8 Ma	Bouse Formation
26	32103-1	35.1458	114.5774	90	0.010	4.8–3.3 Ma	Bullhead alluvium
27	320013-13	35.3422	114.5883	125	0.014	4.8–3.3 Ma	Bullhead alluvium
28	32003-7	35.3536	114.5391	50	0.038	4.8 Ma	Bouse Formation
29	06322-6	34.9036	114.5002	200	–	4.8–3.3 Ma	Bullhead alluvium
30	06322-37	34.8901	114.4328	250	0.014	4.8–3.3 Ma	Bullhead alluvium
31	32506-3	35.2256	114.5573	25	0.059	ca. 0.05 Ma	Chemehuevi Formation
32	1-22-06-2	32.6189	114.4468	60	0.010	Irvingtonian	Upper Trash Canyon
33	32606-1	36.0747	114.0601	65	0.024	late Miocene	Muddy Creek beds
34	H5HW-21	35.9177	114.1813	150	0.014	Miocene–Pliocene	Hualapai Wash
35	LMSP2	36.1156	114.1103	65	–	early Pliocene	Sandy Point
36	DM305	36.0878	114.1015	55	0.026	ca. 0.05 Ma	Chemehuevi Formation
37	FC06-3	32.9951	116.1181	15	0.008	late Miocene	Imperial Group
38	FC05-1	32.9914	116.1121	50	0.007	5.35–5.24 Ma	Latrania Formation Wind Caves Member
39	FC12-6	32.9940	116.1195	250	–	5.35–5.24 Ma	Latrania Formation Wind Caves Member
40	FC05-2	32.9939	116.1195	60	0.009	5.35–5.24 Ma	Latrania Formation Wind Caves Member
41	FC12-7	32.9941	116.1202	55	–	5.35–5.24 Ma	Latrania Formation Wind Caves Member
42	FC05-3	32.9855	116.1271	15	0.002	4.90–4.80 Ma	Deguynos Formation Mud Hill Member
43	FC06-1	32.9748	116.1625	250	0.047	4.30–4.19 Ma	Palm Spring Group Diablo Formation
44	FC06-2	32.9746	116.2072	150	0.035	ca. 3.6 Ma	Palm Spring Group Diablo or Olla Formation
45	2-4-06-1	33.2402	116.2223	35	–	ca. 3.0 Ma	Palm Springs Group Upper Diablo Formation
46	2-4-06-2	33.2402	116.2223	25	–	ca. 2.0–2.5 Ma	Lower Borrego Formation
47	2-4-06-3	33.2464	116.2236	25	0.044	ca. 1.2 Ma	Upper Borrego Formation
48	TBP81412-1	40.1208	107.1670	–	–	late Miocene	Browns Park Formation
49	TBP7912-2	40.6482	108.5560	–	–	late Miocene	Browns Park Formation

Note: Grand River refers to the pre-1921 name of the upper Colorado above the confluence with the Green. Dash indicates no data.

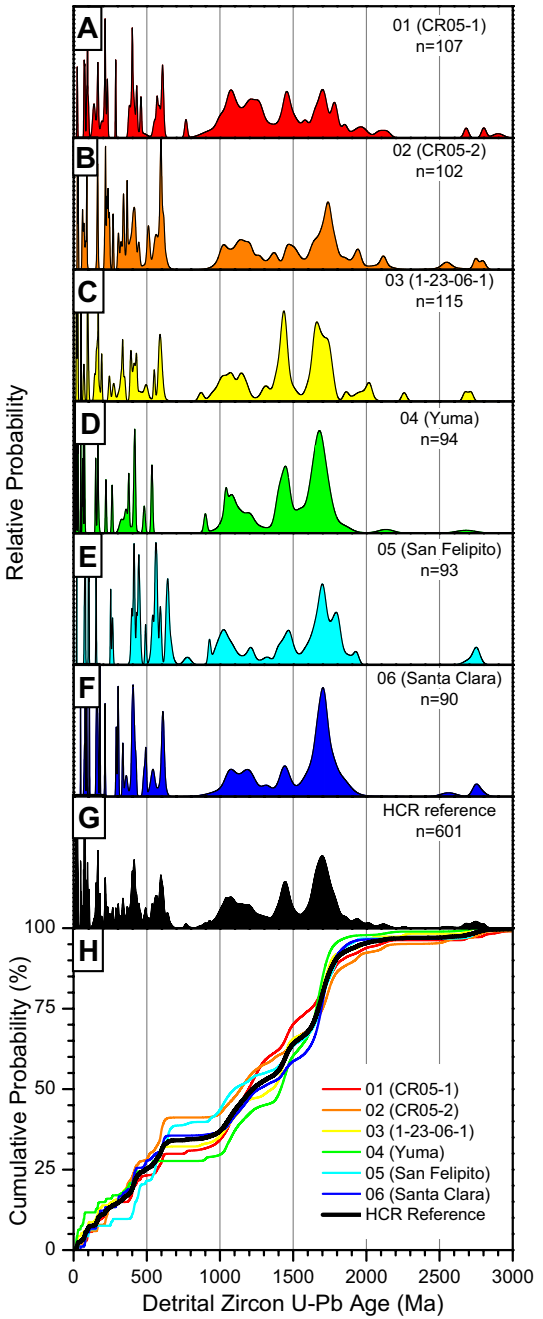

Figure 7. Detrital zircon U-Pb results from the lowermost Colorado River modern sands. Sample locations are shown in Figure 2 and listed in Table 3. (A–H) Relative probability plots. (A) Sample 1 (CR05-1). (B) Sample 2 (CR05-2). (C) Sample 3 (1-23-06-1). (D) Sample 4 (Yuma). (E) Sample 5 (San Felipito). (F) Sample 6 (Santa Clara). (G) Holocene Colorado River (HCR) reference age distribution defined by pooled results from all six Holocene sand samples. (H) Cumulative probability plots for all six samples plus the HCR reference. All samples are statistically equivalent at 95% confidence based upon the Kolmogorov-Smirnov test (Table 5).

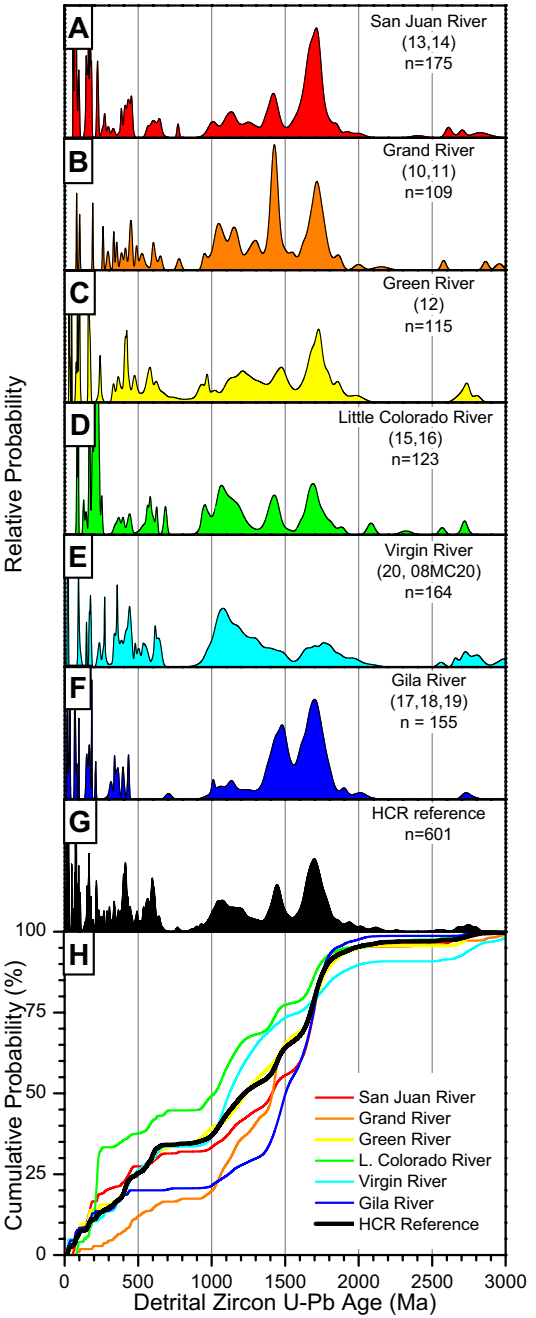

Figure 8. Detrital zircon U-Pb results from Holocene sands representing the major trunks of the Colorado River system. Sample locations are shown in Figure 2 and listed in Table 3. (A–G) Relative probability plots. (A) San Juan River (samples 13, 14). (B) Grand River (see text) (samples 10, 11). (C) Green River (sample 12). (D) Little Colorado River (samples 15, 16). (E) Virgin River (sample 20 and 08MC20) (Muntean, 2012). (F) Gila River (samples 17–19). (G) Holocene Colorado River (HCR) reference. (H) Cumulative probability plot of A–G.

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Most of the major tributaries of the modern Colorado River exhibit distinctive age distributions as reflected by differences of the percentages of 1810–1300 Ma, 1300–285 Ma, and 285–85 Ma zircons (Fig. 8). Two major tributaries from the upper basin of the Colorado River (Green and San Juan Rivers) yield U-Pb zircon age distributions that are indistinguishable from the HCR reference (Figs. 8A, 8C; Supplemental File [see footnote 1]). The single Green River sample has 36% 1810–1300 Ma, 39% 1300–285 Ma, and 10% 285–85 Ma zircon. These percentages are very similar to the HCR reference (39% 1810–1300 Ma, 39% 1300–285 Ma, and 8% 285–85 Ma). While indistinguishable at 95% confidence from the HCR reference (Supplemental File [see footnote 1]), the San Juan River composite age distribution is less similar to it than the Green River because of more 1810–1300 Ma (49%) than 1300–285 Ma (23%) zircon (Fig. 8A; Table 4). The Grand River is distinguished from the HCR at 95% confidence by the abundance of 1810–1300 Ma (52%) zircon relative to 1300–285 Ma (38%) and very sparse (3%) 285–85 Ma zircon (Fig. 8B; Table 4).

All three major tributaries in the lower basin (Little Colorado, Virgin, and Gila Rivers) are distinguishable from the HCR reference at 95% confidence (Supplemental File [see footnote 1]). The Little Colorado River has proportions of 1810–1300 Ma and 1300–285 Ma zircon similar to those of the HCR reference (32% and 35%, respectively), but has abundant 285–85 Ma (primarily Permian–Triassic) zircon (26%) (Fig. 8D; Table 4). The Virgin River is resolved at 95% confidence from the HCR reference because of its higher proportion of 1300–285 Ma (52%) to 1810–1300 Ma (18%) zircon (Fig. 8E; Table 4). In addition, while the Virgin has a percentage of 285–85 Ma zircon similar to that of the HCR reference (10%), it contains much more abundant Miocene (23–5 Ma) zircon. The Gila River is easily resolved from the HCR reference by its high abundance of 1810–1300 Ma (65%) to 1300–285 Ma (16%) zircon (Fig. 8F; Table 4).

Three additional samples (n = 189) are Holocene sands within the Grand Canyon that were collected above and below the confluence of the Colorado River and Little Colorado River. Each yields a U-Pb age distribution that is indistinguishable from each other at 95% (Supplemental File [see footnote 1]). Aggregating all the results produces an age distribution that is indistinguishable from the HCR reference at 95% confidence (Supplemental File [see footnote 1]). The percentages of 1810–1300 Ma, 1300–285 Ma, and 285–85 Ma zircon in the composite eastern Grand Canyon sample (33%, 41%, and 12%, respectively) resemble the HCR reference (39%, 39%, and 8%, respectively) (Table 4). The Grand Canyon results demonstrate that the provenance signature of the Colorado River is established by the confluence with the Little Colorado River.

Miocene–Pleistocene Sandstones along the Colorado River Corridor

Grand Wash–Lake Mead Area

Three samples (n = 169) were analyzed from the Grand Wash–Lake Mead area (Figs. 1 and 5A; Table 3). These include a sample of Miocene sandstone conformably below the Hualapai Limestone (Muddy Creek beds) from Grand Wash (sample 33) and two Miocene–early Pliocene samples (34, 35) from the earliest known Colorado River deposits in the area (Figs. 9A, 9B, 9H). Five previously reported results from this area (Lopez-Pearce et al., 2011; Crossey et al., 2015) are sandstone beds interbedded with and underlying the Hualapai Limestone (Fig. 5A). Our Miocene sandstone sample (33) is similar to five results of Lopez-Pearce et al. (2011) in that all samples almost exclusively contain 1810–1300 Ma zircon (samples K-09-HUAL-13, K-09-HUAL-20, K-09-HUAL-21) (Figs. 9E–9H). Although samples K-09-HUAL-10 (Fig. 9C) and K-09-HUAL-1 (Fig. 9D) yield significant 1300–900 Ma and 725–285 Ma zircon absent from stratigraphically lower rocks, the paucity of 200–0 Ma zircon clearly distinguishes Hualapai Limestone sandstone interbeds from Colorado River sand (Fig. 9I).

Samples 34 and 35 were collected stratigraphically above the Hualapai Limestone (Fig. 5A) and represent the earliest Colorado River sand. Sample 35 is overlain by the 4.4 Ma Sandy Point basalt while 34 overlies Hualapai Limestone (Fig. 5A). These early Pliocene Colorado River samples contain 48% 1810–1300 Ma, 19% 1300–285 Ma, and 7% 285–85 Ma zircon. They both differ from the HCR reference by containing 10%–11% 40–23 Ma zircon and only scarce Miocene zircon (Figs. 9A, 9B; Table 4). Moreover, both samples 34 and 35 contain 200–40 Ma zircon well above the proportions present within the HCR reference (Fig. 9I; Table 4).

Parker–Lake Mohave Area

We analyzed 8 samples totaling 458 analyses in the Parker–Lake Mohave area (Figs. 5B and 10). Two late Miocene samples deposited before the appearance of Colorado River deposits here (samples 23, 24) are dominated by late Paleoproterozoic and early Mesoproterozoic zircon with only a minor amount of Miocene, Late Cretaceous, and Jurassic zircon (Figs. 10G, 10H; Table 4). Two samples were analyzed from the Bouse Formation (samples 25, 28) (Fig. 5B). The topographically higher of these (sample 25) contains only a few Miocene (19–17 Ma) and Late Cretaceous zircons among abundant 1.7–1.6 Ga zircon (Fig. 10F). In contrast, Bouse Formation sample 28 yields an age distribution consistent with Colorado River sand that is statistically indistinguishable from the HCR reference at 95% confidence (Fig. 10E). It is interesting that it also contains 40–23 Ma zircon as noted from the Grand Wash area (Table 4). Four samples of early Pliocene Bullhead alluvium (samples 26, 27, 29, 30) represent early river aggradation and were deposited in erosional topography cut into Bouse deposits (Fig. 5B). All but sample 27 are statistically indistinguishable from the HCR reference (Figs. 10A–10D). The anomalous sample 27 has 6% Miocene zircon; samples 26, 28, 29, and 30 all lack this component. Sample 27 is the farthest upstream in Cottonwood Valley below Miocene volcanics in the Black Canyon, a likely local source of Miocene zircon. In contrast, samples 26, 29, and 30 contain 10%, 2%, and 8% Oligocene and Eocene (40–23 Ma) zircon (Table 4). Excluding 27, these samples contain 43% 1810–1300 Ma, 26% 1300–285 Ma, and 11% 285–85 Ma zircon and resemble the early Pliocene Colorado River sand at Grand Wash.

TABLE 4. U-Pb AGE DISTRIBUTIONS OF SANDSTONES AND HOLOCENE SAND SAMPLES

ID	N	23–5 Ma	40–23 Ma	85–40 Ma	125–85 Ma	200–125 Ma	285–200 Ma	510–285 Ma	725–510 Ma	900–725 Ma	1300–900 Ma	1535–1300 Ma	1810–1535 Ma	2015–810 Ma	>2015 Ma
01	107	0.0	0.9	1.9	2.8	4.7	3.7	9.3	6.5	0.9	29.0	13.1	16.8	4.7	5.6
02	102	0.0	2.0	2.9	1.0	2.0	6.9	14.7	11.8	0.0	16.7	8.8	20.6	4.9	7.8
03	115	0.9	3.5	1.7	2.6	5.2	1.7	10.4	6.1	0.9	14.8	19.1	25.2	3.5	4.3
04	94	4.3	2.1	5.3	0.0	3.2	2.1	8.5	2.1	0.0	18.1	16.0	35.1	1.1	2.1
05	93	1.1	0.0	3.2	2.2	1.1	2.2	11.8	17.2	1.1	15.1	9.7	29.0	3.2	3.2
06	90	0.0	0.0	4.4	2.2	5.6	1.1	14.4	7.8	0.0	15.6	7.8	33.3	4.4	3.3
07	59	0.0	0.0	0.0	1.7	5.1	1.7	16.9	3.4	1.7	32.2	10.2	15.3	1.7	10.2
08	65	0.0	0.0	1.5	1.5	7.7	1.5	10.8	9.2	0.0	15.4	20.0	12.3	10.8	9.2
09	65	0.0	1.5	0.0	0.0	7.7	7.7	13.8	4.6	1.5	13.8	20.0	21.5	3.1	4.6
10	56	0.0	0.0	1.8	1.8	0.0	1.8	7.1	5.4	0.0	26.8	17.9	28.6	3.6	5.4
11	53	0.0	0.0	0.0	0.0	1.9	0.0	9.4	3.8	1.9	20.8	30.2	26.4	1.9	3.8
12	115	0.0	1.7	3.5	4.3	4.3	1.7	10.4	7.8	0.9	20.0	12.2	23.5	5.2	4.3
13	55	0.0	0.0	12.7	1.8	5.5	5.5	5.5	3.6	0.0	9.1	12.7	41.8	1.8	0.0
14	120	0.0	0.0	4.2	1.7	9.2	2.5	8.3	4.2	0.8	14.2	10.8	33.3	4.2	6.7
15	59	0.0	0.0	1.7	1.7	10.2	25.4	1.7	11.9	0.0	20.3	6.8	15.3	0.0	5.1
16	64	0.0	0.0	1.6	3.1	6.3	17.2	6.3	3.1	0.0	26.6	12.5	17.2	1.6	4.7
17	52	0.0	0.0	1.9	0.0	5.8	0.0	9.6	0.0	0.0	11.5	21.2	48.1	0.0	1.9
18	56	1.8	3.6	3.6	0.0	3.6	1.8	7.1	0.0	0.0	10.7	23.2	35.7	7.1	1.8
19	47	6.4	2.1	4.3	2.1	4.3	0.0	2.1	2.1	0.0	4.3	31.9	36.2	2.1	2.1
20	65	3.1	0.0	0.0	4.6	4.6	3.1	16.9	4.6	0.0	30.8	9.2	10.8	4.6	7.7
08MC20*	99	2.0	2.0	0.0	1.0	2.0	5.1	11.1	8.1	0.0	33.3	7.1	9.1	5.1	9.1
21	65	0.0	1.5	1.5	1.5	9.2	24.6	4.6	1.5	3.1	13.8	12.3	20.0	1.5	4.6
22	54	1.9	3.7	1.9	3.7	7.4	9.3	7.4	3.7	0.0	18.5	9.3	31.5	1.9	0.0
23	58	0.0	3.4	1.7	5.2	13.8	0.0	0.0	0.0	0.0	1.7	39.7	32.8	1.7	0.0
24	53	9.4	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	88.7	0.0	0.0
25	33	9.1	0.0	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	84.8	0.0	0.0
26	71	0.0	9.9	2.8	1.4	4.2	4.2	4.2	4.2	0.0	19.7	12.7	21.1	7.0	8.5
27	69	5.8	2.9	2.9	4.3	1.4	1.4	10.1	4.3	0.0	7.2	5.8	47.8	4.3	1.4
28	61	0.0	3.3	3.3	6.6	4.9	3.3	0.0	3.3	3.3	8.2	23.0	36.1	4.9	0.0
29	49	0.0	2.0	2.0	2.0	6.1	0.0	8.2	6.1	0.0	18.4	22.4	18.4	10.2	4.1
30	63	0.0	7.9	3.2	4.8	6.3	1.6	6.3	7.9	0.0	14.3	9.5	30.2	1.6	6.3
31	59	3.4	1.7	5.1	5.1	5.1	10.2	3.4	1.7	0.0	18.6	11.9	28.8	3.4	1.7
32	123	1.6	2.4	2.4	1.6	5.7	3.3	5.7	5.7	0.0	23.6	16.3	24.4	1.6	5.7
33	51	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	47.1	45.1	2.0	2.0
34	139	0.7	11.5	2.2	5.0	4.3	0.7	2.9	5.8	0.0	12.2	16.5	30.9	2.2	3.6
35	143	0.0	9.1	6.3	0.7	4.9	4.9	2.8	2.1	0.7	18.9	17.5	25.9	2.8	3.5
36	55	0.0	0.0	1.8	0.0	3.6	1.8	3.6	3.6	0.0	14.5	50.9	12.7	1.8	5.5
37	58	0.0	0.0	0.0	36.2	55.2	1.7	0.0	0.0	0.0	1.7	0.0	5.2	0.0	0.0
38	86	0.0	9.3	1.2	2.3	4.7	3.5	8.1	3.5	0.0	10.5	20.9	23.3	5.8	7.0
39	129	0.0	6.1	6.1	0.0	0.0	9.1	4.5	7.6	0.0	13.6	19.7	25.8	1.5	6.1
40	57	0.0	3.5	1.8	3.5	12.3	3.5	1.8	5.3	0.0	15.8	24.6	26.3	1.8	0.0
41	127	0.0	5.9	8.8	1.5	5.9	2.9	7.4	5.9	0.0	11.8	20.6	23.5	5.9	0.0
42	124	0.0	5.6	4.8	0.8	5.6	0.8	9.7	12.9	0.0	13.7	16.9	20.2	0.8	8.1
43	117	0.9	3.4	2.6	2.6	6.0	0.0	4.3	8.5	0.9	21.4	20.5	21.4	4.3	3.4
44	114	0.0	0.9	3.5	3.5	3.5	4.4	8.8	3.5	0.0	24.6	13.2	27.2	3.5	3.5
45	124	0.0	8.9	1.6	6.5	6.5	4.8	12.9	2.4	0.8	15.3	7.3	21.8	3.2	8.1
46	117	0.0	0.9	5.1	3.4	6.0	2.6	14.5	10.3	0.9	17.1	15.4	20.5	2.6	0.9
47	126	0.0	1.6	2.4	5.6	5.6	5.6	10.3	5.6	0.8	15.9	9.5	27.8	5.6	4.0
48	95	0.0	18.9	9.5	0.0	3.2	3.2	1.1	1.1	0.0	5.3	28.4	25.3	0.0	4.2
49	92	1.1	12.0	5.4	5.4	6.5	1.1	0.0	0.0	0.0	13.0	17.4	27.2	4.3	2.2

*Forrester (2009).

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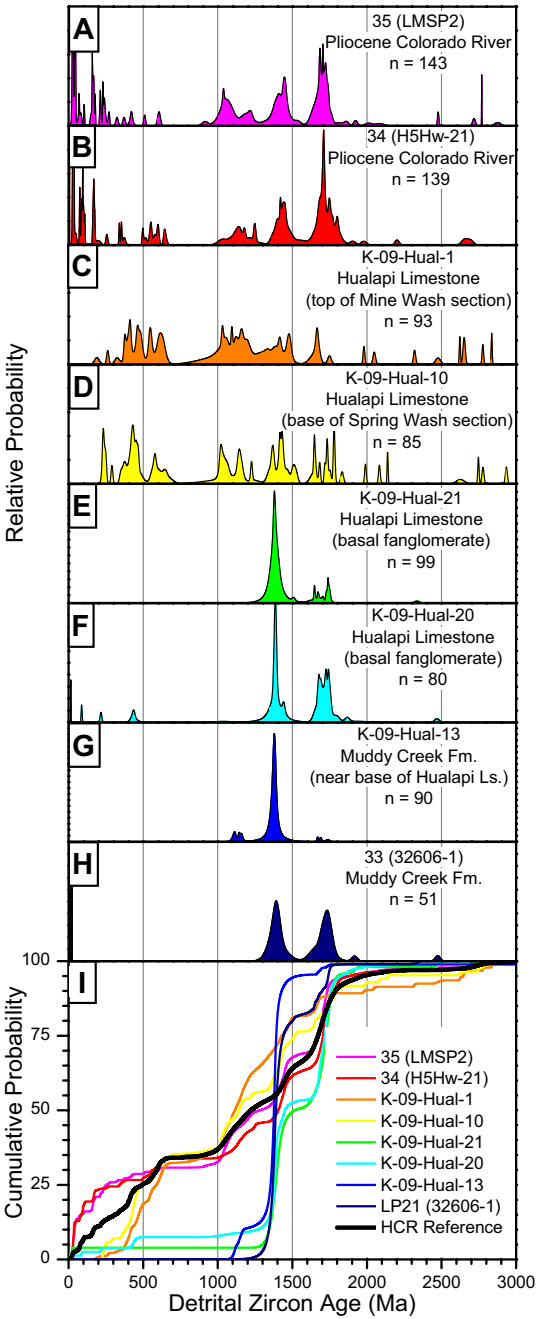

Figure 9. Detrital zircon U-Pb results from the Grand Wash area. Sample locations are represented in Figure 5A and listed in Table 3. All K-09-Hual samples are from Lopez-Pearce et al. (2011). (A–H) Relative probability plots. (A) Early Pliocene Colorado River sandstone sample 35 (LMSP2). (B) Early Pliocene Colorado River sandstone sample 34 (H5HW-21). (C) Siltstone in Hualapai Limestone sample K-09-Hual-1. (D) Siltstone in Hualapai Limestone sample K-09-Hual-10. (E) Basal fanglomerate of Hualapai Limestone sample K-09-Hual-21. (F) Basal fanglomerate of Hualapai Limestone sample K-09-Hual-20. (G) Muddy Creek beds near base of Hualapai Limestone sample K-09-Hual-13. (H) Muddy Creek beds sample 33 (32606–1). (I) Cumulative probability plots of above samples; also includes Holocene Colorado River (HCR) reference. Samples 34 and 35 included in early Pliocene Colorado River (PCR) reference.

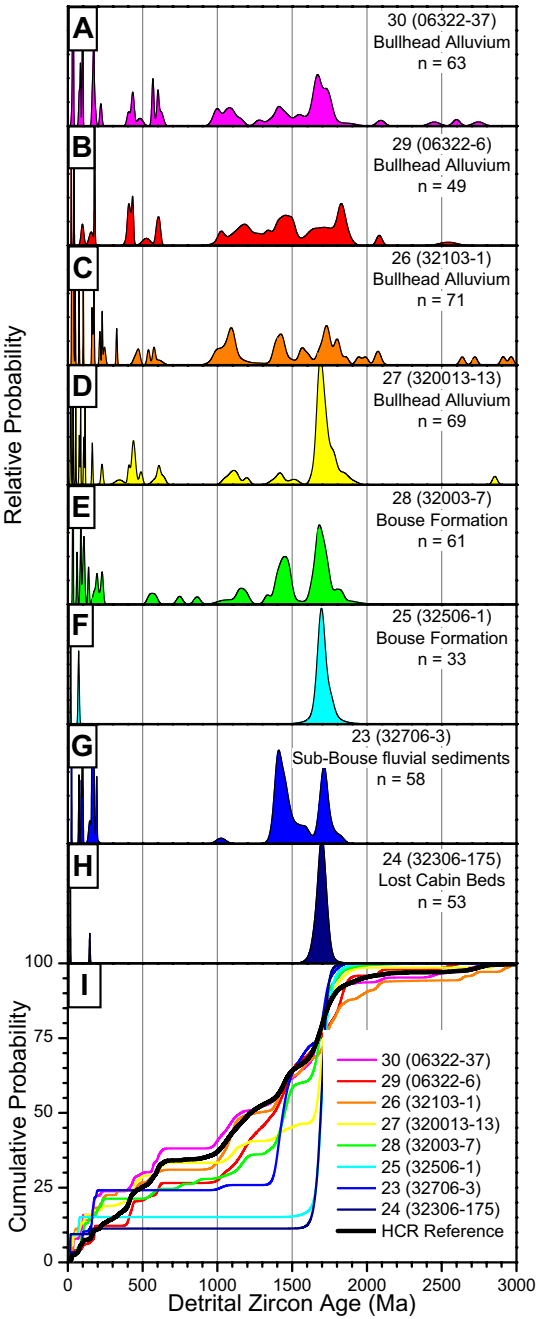

Figure 10. Detrital zircon U-Pb results from Lake Mohave and Cottonwood Valley. Sample locations are shown in Figure 5B and listed in Table 3. (A–I) Relative probability plots. (A) Bullhead alluvium sample 30 (06322–37). (B) Bullhead alluvium sample 29 (06322–6). (C) Bullhead alluvium sample 26 (32103–1). (D) Bullhead alluvium sample 27 (320013–13). (E) Bouse Formation sample 28 (32003–7). (F) Bouse Formation sample 25 (32506–1). (G) Sub-Bouse fluvial sediments sample 23 (32706–3). (H) Late Miocene Lost Cabin Beds sample 24 (32306–175). (I) Cumulative probability plots of above samples; also includes Holocene Colorado River (HCR) reference. Samples 26, 28, 29, and 30 are included in PCR reference.

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Pliocene–Pleistocene Sandstones from the Western Salton Trough

Marine and nonmarine sandstone samples (n = 10) from the Fish Creek–Vallecito and Borrego Badlands basins (samples 38–47) represent the early Pliocene–Pleistocene Colorado River and delta (Figs. 1 and 6; Table 3). Another sample, the oldest (FC063, sample 37), is from the lower Imperial Group and immediately predates the first appearance of Colorado River sediment in the region (Fig. 6A). Locally derived Cretaceous and Jurassic zircon dominate this sample with minor Proterozoic grains (Fig. 11H; Table 4). The oldest Colorado River sands are represented by samples 38–41 from the Wind Caves member of the Latrania Formation in the Fish Creek–Vallecito Basin (Fig. 6A). These were deposited ca. 5.3–5.2 Ma (Dorsey et al., 2007, 2011). The four Wind Caves member samples average 46% 1810–1300 Ma, 24% 1300–285 Ma, and 12% 285–85 Ma zircon, similar to the early Pliocene Colorado River results from the Grand Wash and Parker–Lake Mohave areas (Fig. 11G; Table 4). The four samples have 4%–9% 40–23 Ma zircon and no Miocene (23–5 Ma) zircon.

The next sample upsection in the Fish Creek–Vallecito Basin (sample 42) is the ca. 4.8 Ma Mud Hills member of the Deguynos Formation (Fig. 11F). It has 37% 1810–1300 Ma, 36% 1300–285 Ma, and 7% 285–85 Ma zircon (Table 4). Sample 43 was collected from a younger interval (ca. 4.2 Ma) in the Arroyo Diablo Formation and has 42% 1810–1300 Ma, 37% 1300–285 Ma, and 9% 285–85 Ma zircon (Fig. 11E). Similarly, sample 44, which was selected from a ca. 3.7 Ma horizon within the Arroyo Diablo Formation, has 40% 1810–1300 Ma, 37% 1300–285 Ma, and 11% 285–85 Ma zircon (Fig. 11D). Based upon the K-S test, samples 42, 43, and 44 are all indistinguishable at 95% confidence. Three additional samples (45–47) are from the nearby Borrego Badlands (Fig. 6B). The depositional ages of these samples range from ca. 3.1 to 1.1 Ma (Fig. 6B). Collectively, they average 34% 1810–1300 Ma, 36% 1300–285 Ma, and 16% 285–85 Ma zircon (Figs. 11A–11C). A Pleistocene sample (32, 1–22–06–2) collected from Irvingtonian fossil-bearing Colorado River sandstone exposed near the coastal town of El Golfo de Santa Clara in northwestern Mexico (Croxen et al., 2007) yields a similar age distribution.

Definition of the Early Pliocene Colorado River Reference

The strong similarity in provenance signature of the early Pliocene Wind Caves sandstones in the Salton Trough to the early Pliocene Colorado River samples from the Grand Wash area forms the basis for establishing an early

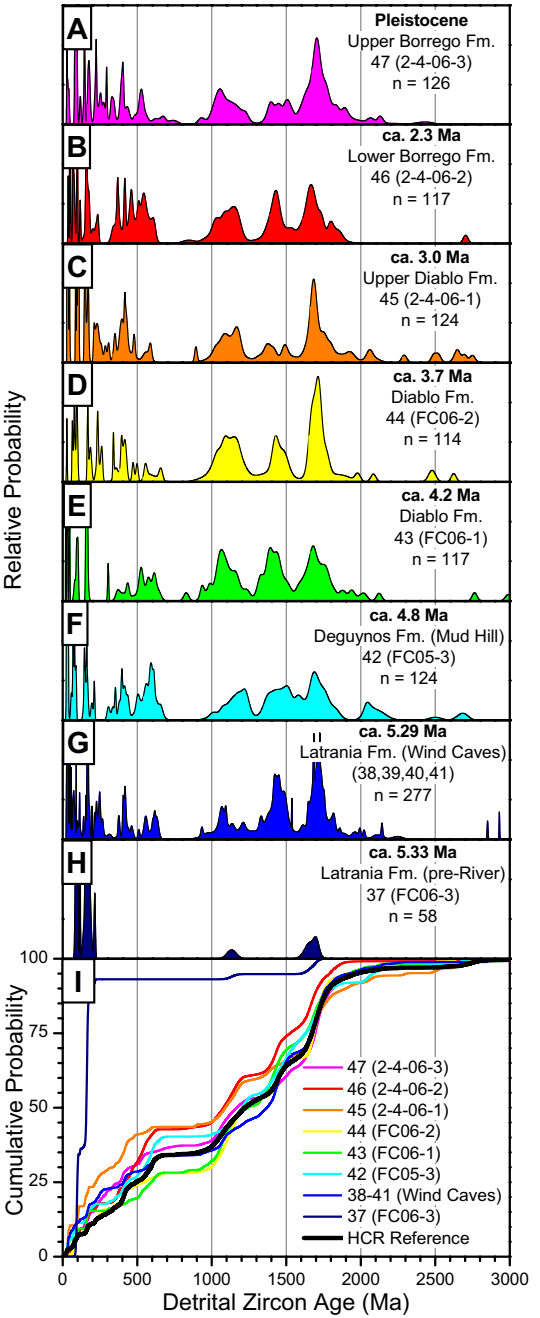

Figure 11. Detrital zircon U-Pb results from the Salton Trough. Sample locations for 37–43 and 44–47 are shown in Figures 6A and 6B, respectively. Additional sample details listed in Table 3. (A–I) Relative probability plots. (A) Pleistocene upper Borrego Formation (Fm.) sample 47 (2-4-06-3). (B) Ca. 2.3 Ma lower Borrego Fm. sample 46 (2-4-06-2). (C) Ca. 3.0 Ma upper Diablo Fm. sample 45 (2-4-06-1). (D) Ca. 3.7 Ma Diablo Fm. sample 44 (FC06-2). (E) Ca. 4.2 Ma Diablo Fm. sample 43 (FC06-1). (F) Ca. 4.8 Ma Deguynos fm. (Mud Hill) sample 42 (FC05-3). (G) Latrania fm. (Wind Caves) samples 38–41. (H) Sub-river Latrania fm. sample 37 (FC06-3). (I) Cumulative probability plots of above samples. Includes Holocene Colorado River (HCR) reference. Samples 38–41 are included in PCR (early Pliocene Colorado River) reference.

Pliocene Colorado River reference (PCR). The cumulative distributions for samples 34 and 35 from Grand Wash are plotted in Figure 12A. The inset shows that the 50–0 Ma segment of the cumulative age distribution lacks Miocene zircon. Based upon the K-S test, the two samples are equivalent within 95% confidence (Supplemental File [see footnote 1]). Based upon this, we define a pooled age distribution (n = 282) for early Pliocene Colorado River sand from Grand Wash. The cumulative age distributions for the four samples representing the oldest known Colorado River sand in the Salton Trough (Wind Caves member; samples 38–41) are shown in Figure 12B. These samples also have statistically equivalent age distributions (Supplemental File [see footnote 1]). The pooled age distribution for the four Wind Caves samples consists of 277 analyses.

The pooled distributions for early Pliocene Colorado River samples from the Grand Wash and Salton Trough (Wind Caves) areas are compared in Figure 12C. Application of the K-S test to the pooled distributions from these two groups indicates that they are indistinguishable at 95% confidence (P = 0.32). The overall PCR reference for all 6 samples (n = 559) has 43%, 22%, and 10% 1810–1300 Ma, 1300–285 Ma, and 285–85 Ma zircon, respectively.

Relative probability distributions for the HCR and PCR references are compared in Figures 13A and 13B. Although the difference between them is relatively subtle, the PCR is enriched in 1810–1300 Ma zircon and depleted in 1300–285 Ma zircon relative to the HCR (Fig. 13C). Coupled with the abundance of 40–23 Ma grains in the PCR reference, the differences in the proportions of 1810–1300 Ma and 1300–285 Ma zircon allow the PCR and HCR references to be distinguished at 95% confidence (P = 0.03). In summary, a small but potentially meaningful difference exists between the source region for the early Pliocene and modern Colorado Rivers.

Modeling the Early Pliocene and Modern Colorado Rivers

The change in the detrital zircon age distribution between the early Pliocene and Holocene Colorado River deposits (Fig. 13) contains important information for deciphering the evolution of the sedimentary sources of the river through time. We analyze the change in two ways: (1) spatially, in terms of the detrital zircon age distributions supplied by major tributaries (Figs. 2 and 8), and (2) temporally, in terms of supracrustal rocks within the source region (Fig. 4). Both approaches shed light upon the geologic controls that shaped the evolution of Colorado River system zircon provenance.

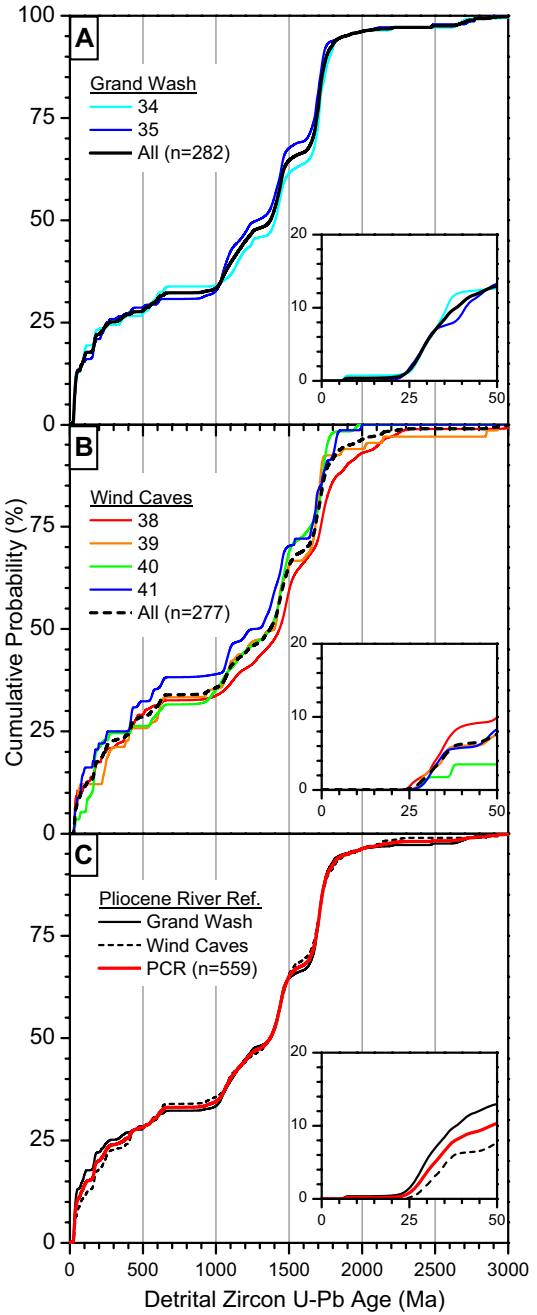

Figure 12. Cumulative probability plots of early Pliocene samples. Insets show 50–0 Ma age distributions. (A) Lower Colorado River corridor (samples 34 and 35 are indistinguishable at 95% confidence; see the Supplemental File [see footnote 1]). (B) Salton Trough (samples 38–41 are all indistinguishable at 95% confidence). (C) Pooled distributions from the lower Colorado River corridor, the Salton Trough, and the overall early Pliocene Colorado River (PCR) reference detrital zircon age distribution. The pooled distributions for the lower Colorado River corridor and the Salton Trough are indistinguishable at 95% confidence (Supplemental File [see footnote 1]).

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Calculations Involving Age Distributions from Modern Tributaries

The most basic calculation that can be performed with the modern Colorado River is to weight the age distributions associated with its major tributaries according to sediment load and compare this with the HCR reference (Fig. 14; Table 1). Because no sediment load data exist for the Gila River, we calculated the mixture for the other five tributaries (dashed blue line labeled 0% in Fig. 14). As indicated, addition of 3.85% Gila River produces the best fit to the HCR.

Figure 14 is based upon fixed weighting factors (Table 1). We can explore what happens if the weighting factors are permitted to vary by using a modified form of the K-S statistic described in the Supplemental File (see footnote 1). The exercise shows how extensively the tributaries can be mixed and still reproduce the modern Colorado River age distribution. We perform ternary mixing with the three major tributaries from the upper basin and lower basins of the Colorado River (Fig. 15). All filled contour intervals indicate that a mixture reproduces the HCR reference age distribution to within 95% confidence (Supplemental File [see footnote 1]).

Results for the upper basin (Fig. 15A) reveal that any mixture of the detrital zircon age distributions from the Green and San Juan Rivers will reproduce the HCR reference within 95% confidence. This is unsurprising since the age distributions from both tributaries are indistinguishable from the HCR reference to within 95% confidence (Supplemental File [see footnote 1]). Between 12% and 37% of the Grand River age distribution can be accommodated, although these proportions are diminished when the independent end-member assumption is applied. The best-fit mixture involves 94.4% Green River and 5.6% Grand River, and corresponds to D_{max} and P values of 0.026 and 0.938, respectively (Fig. 15B).

A significantly different result is obtained when we carry out the same exercise with the major tributaries of the lower basin of the Colorado River (Fig. 15C). All tributaries from the lower basin have age distributions that are distinct from the HCR at 95% confidence. Binary mixing between the Virgin and Gila Rivers can produce results that are indistinguishable from the HCR reference at 95% confidence (Fig. 15C). The best-fit ternary mixture involves 50.3% Virgin, 31.2% Gila, and 18.5% Little Colorado River and corresponds to D_{max} and P values of 0.034 and 0.516, respectively (Fig. 15D). In general, however, the ways in which sand from the tributaries from the lower basin can be mixed

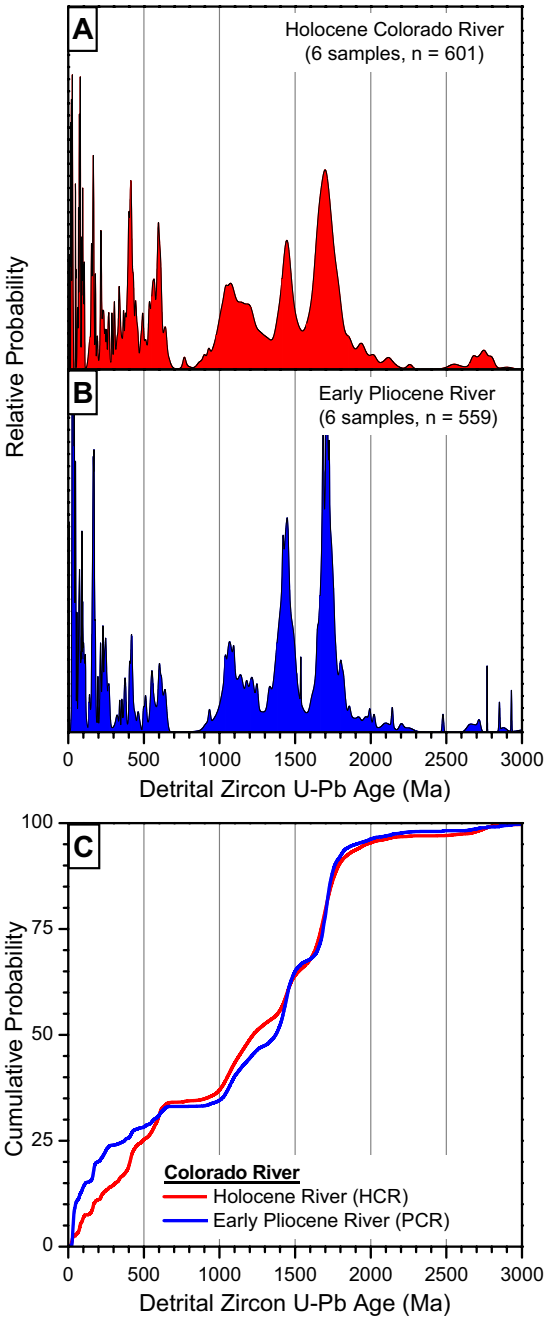

Figure 13. Relative probability plots. (A) Pooled Holocene Colorado River (HCR) age distribution. (B) Pooled early Pliocene Colorado River (PCR) age distribution. (C) Cumulative age for the Holocene and early Pliocene Colorado Rivers. The HCR and PCR reference age distributions are just distinguishable at 95% confidence (Supplemental File [see footnote 1]). Also shown are cumulative age distributions for Colorado Plateau strata shown in Figure 5. The early Pliocene river is enriched in late Eocene–Oligocene zircon and has minor though important differences in the proportions of Proterozoic zircon relative to the Holocene River (see 40–23 Ma and 1810–1300 Ma, 1300–285 Ma, and 285–85 Ma age bins). Overall, the early Pliocene Colorado River is most similar to the early Cenozoic age distributions for the Colorado Plateau strata.

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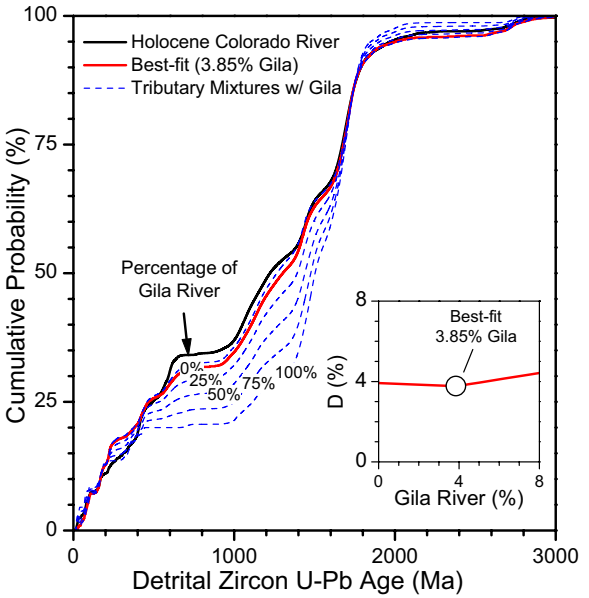

Figure 14. Cumulative probability plots of mixtures of age distributions from modern tributaries of the Colorado River. Age distributions from the Green, Grand (see text), San Juan, Little Colorado, and Virgin Rivers are weighted according to mean sediment discharge loads reported by Andrews (1991) for the 1941–1957 interval. These proportional contributions are combined with the age distribution from the Gila River in increments of 0%, 25%, 50%, 75%, and 100% to simulate the expected pattern of variation in cumulative age variation resulting from headward erosion from the Basin and Range into the Colorado Plateau. Inset shows that the best fit to the Holocene Colorado River reference occurs at ~3% contribution from the Gila River. D in inset refers to the Kolmogorov Smirnov D statistic (Supplemental File [see footnote 1]).

to match the HCR reference is significantly more restricted than is the case for the upper basin. This implies that the Holocene Colorado River sand derives its detrital zircon age distribution primarily from the upper Colorado catchment.

Having demonstrated our ability to model the Holocene Colorado River from its modern tributaries, we now attempt the exercise of fitting the early Pliocene Colorado River age distribution with the same data (Fig. 16). While we have no expectation that the modern tributaries existed in their present-day configuration during the early Pliocene, the exercise is useful because of the insights it provides into the spatial controls on provenance. When we fit the PCR reference with the major tributaries from the upper basin, the result obtained is broadly similar to that for the Holocene Colorado River, although the range of mixtures that are indistinguishable from the PCR is more limited (cf. Figs. 15A and 16A). The best-fit mixture involves 75.7% Green River, 17.3% San Juan River, and 7.00% Grand River, and corresponds to D_{max} and P values of 0.062 and 0.229, respectively (Fig. 16B). We interpret the results shown in Figures 15 and 16 to indicate that the Green and San Juan Rivers age distributions are important to both the modern and early Pliocene Colorado River age distributions.

When we attempt the same procedure to fit the PCR with age distributions produced by rivers from the lower basin of the Colorado River (Figs. 16C, 16D) we achieve limited success. While the Virgin River was able to contribute heavily in the best fit to the HCR reference, it can barely contribute to the Pliocene Colorado River. This is because of the Grenville-rich nature of the Virgin River and its abundance of Archean zircon relative to the PCR reference (Fig. 16D). Moreover, the fact that the age distributions from the Gila and Little Colorado Rivers can be combined over a range of mixtures to reproduce the PCR reference to within 95% confidence is not meaningful. Specifically, it is improbable that the Gila River could have contributed to the early Pliocene Colorado River at Grand Wash and Lake Mojave–Parker given its southern location (Fig. 2), lower elevation, and late Pliocene development (Huckleberry, 1996; Menges and Pearthree, 1989). In summary, the early Pliocene Colorado River is best explained by the sediment currently carried by the Green and San Juan Rivers.

Calculations Involving Age Distributions from Supracrustal Strata

Before undertaking calculations involving previously published detrital zircon data for the supracrustal rocks of the Colorado Plateau, mixing end members must be defined. The Triassic, Jurassic, and Early Cretaceous strata in the Colorado Plateau and southern Rocky Mountains regions represent an obvious end member because rocks of these ages tend to be characterized by similar age distributions (Fig. 4; Table 2). In the calculations that follow, we refer to this end member as Mesozoic strata. Although the Late Cretaceous and early Cenozoic age distributions are also broadly similar (Fig. 4; Table 2), the Late Cretaceous age distribution is transitional in character between age distributions of the Mesozoic and early Cenozoic, the early Cenozoic representing a logical second end member that we refer to as early Cenozoic strata. In order to compare similarly sized age distributions, we randomly sampled the very large size of the pooled Mesozoic and early Cenozoic age distributions (Fig. 5; Table 2) down to a sample size of ~600 for each distribution.

None of the published age distributions in Figure 4 are young enough to account for the Oligocene and late Eocene zircon characteristic of the Pliocene Colorado River. We consider three Oligocene to Miocene sources that might serve as proxies for this signal (Fig. 17).

The late Miocene Muddy Creek Formation in the Virgin River area (Fig. 1) has been explored as possible terminal deposits of an ancestral paleo–Colorado River prior to the integration of the river through the western Grand Canyon (Pederson, 2008). However, the Muddy Creek Formation there lacks Oligocene zircon and contains abundant Miocene zircon (Fig. 17A). Moreover, the abundant 1300–285 Ma zircon in the locally derived Muddy Creek Formation allows it to be easily distinguished from the PCR at 95% confidence (Table 5).

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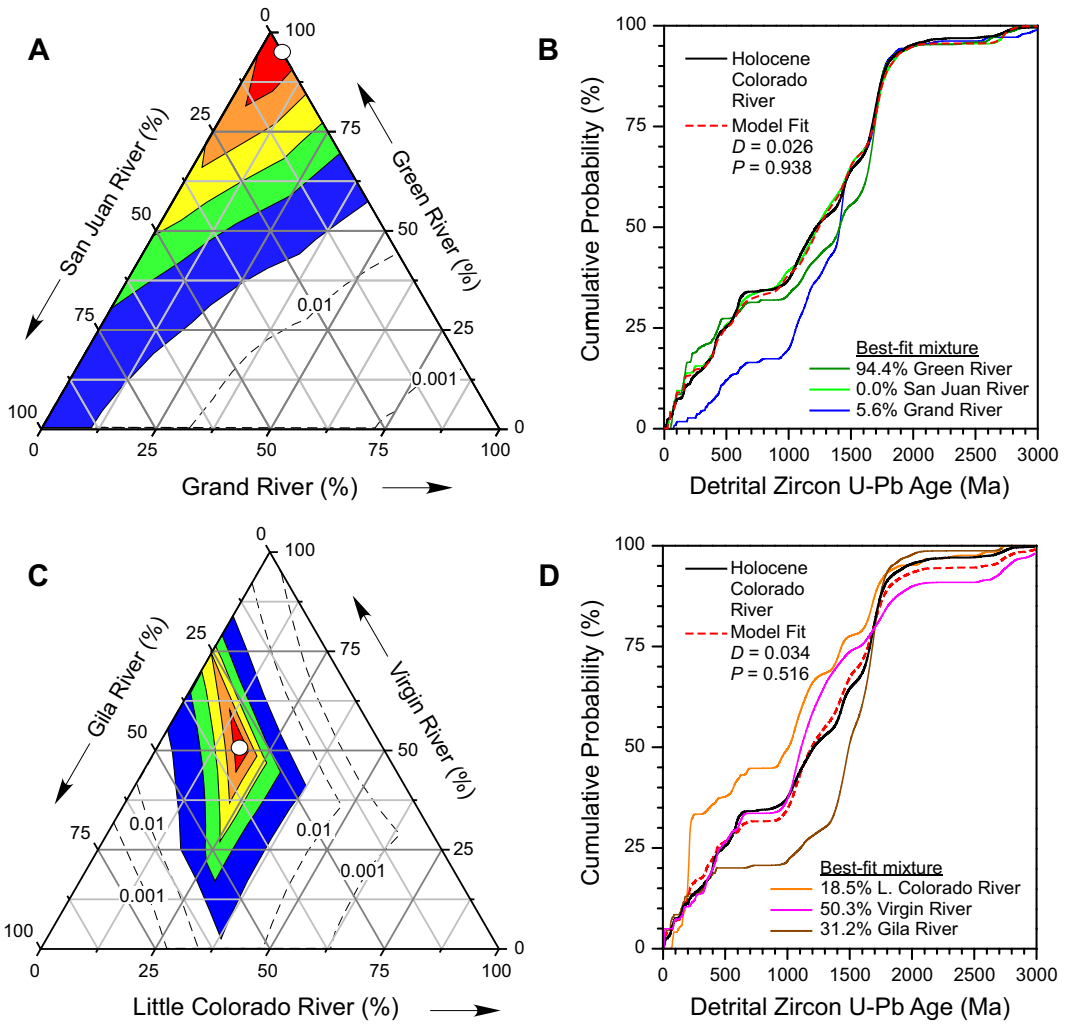

Figure 15. Ternary mixing calculations for the modern Colorado River based upon age distributions for modern tributaries. Size of mixtures calculated using Equation 7 in the Supplemental File (see footnote 1). Calculations are for identical distribution limiting case. (A) Ternary mixing of tributaries of the upper Colorado basin [Grand (see text), Green, and San Juan Rivers]. All colored contours represent mixtures indistinguishable from the Holocene Colorado River (HCR) reference age distribution at 95% confidence. Each contour division represents 20% of the span between P = 0.05 and the maximum value of P determined for the best-fit solution (circle). Dashed contours represent P = 0.01 and P = 0.001. (B) Cumulative probability plot for the tributary mixing end members and the HCR reference. Best fit is dashed red line and corresponds to 94.4% Green and 5.6% Grand Rivers. This corresponds to D_{max} = 0.026 and P = 0.938. (C) Ternary mixing of tributaries of the lower Colorado basin (Little Colorado, Virgin, and Gila Rivers). Same explanation as for A. (D) Same explanation as in B. Best fit corresponds to 50.3% Virgin, 31.2% Gila, and 18.5% Little Colorado Rivers. This corresponds to D_{max} = 0.034 and P = 0.516.

Miocene Lake Bidahochi has been regarded as a possible repository of sand that fed the Pliocene Colorado River (Meek and Douglas, 2001). A composite detrital zircon age distribution (n = 119) calculated from two sandstone samples (21, 22) from the upper fluvial member of the Bidahochi Formation at the eastern end of its outcrop area (Fig. 2) is shown in Figure 17B (see Table 3). The U-Pb age distributions from each are indistinguishable at 95% confidence. The combined age distribution is easily distinguished from the HCR reference due to the very high relative abundance (18%) of Permian–Triassic zircon. The similarity of samples 21 and 22 to the modern Little Colorado River age distribution (Table 4) indicates that the sampled portion of the Bidahochi Formation (Table 3) is a locally derived deposit endemic to the Little Colorado River catchment.

Oligocene to Miocene stream deposits of poorly constrained depositional age occur within the central Colorado Plateau region (Fig. 1). Detrital zircon ages from sandstone associated with the pre–late Miocene Crooked Ridge River (Lucchitta et al., 2011) demonstrates that west-flowing streams carried

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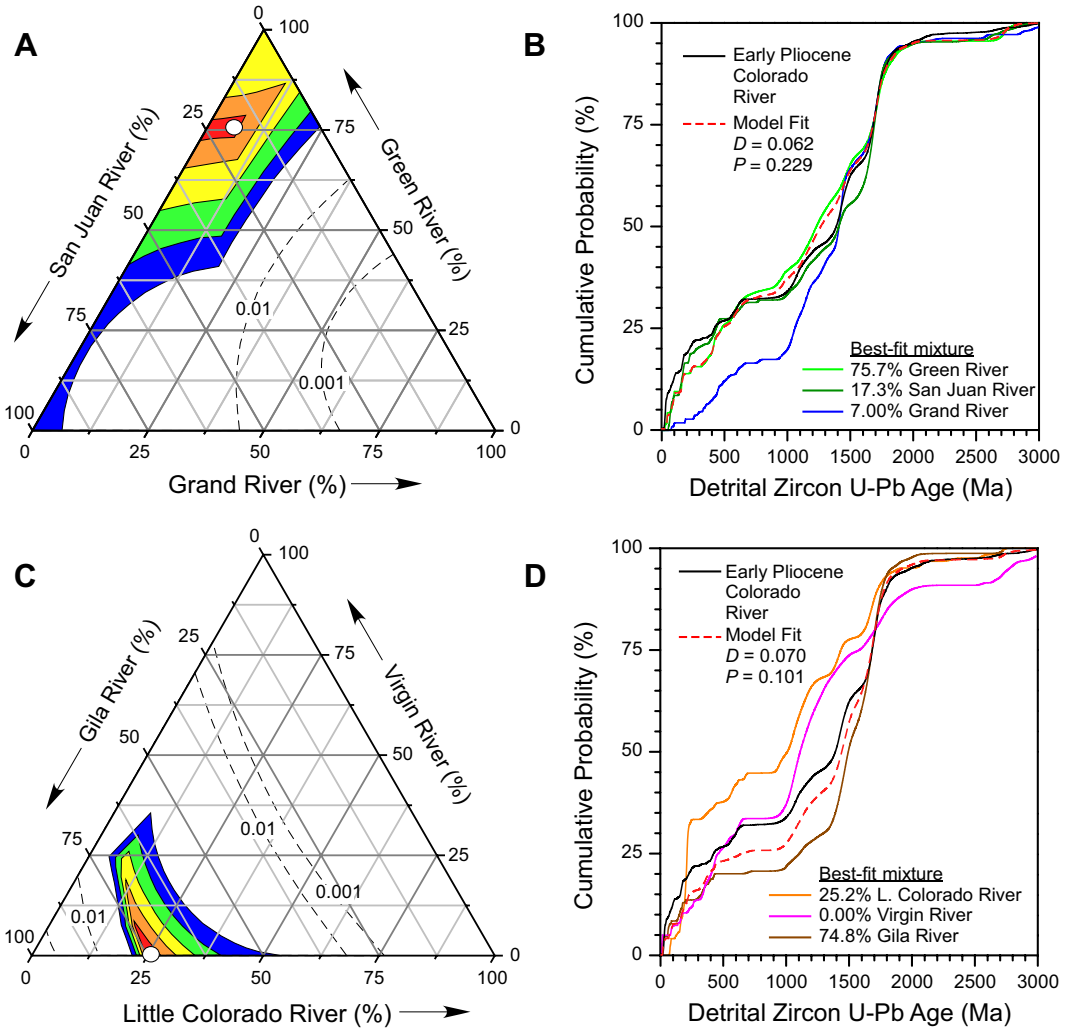

Figure 16. Ternary mixing calculations for the early Pliocene Colorado River (PCR) based upon age distributions for modern tributaries. See Figure 18 for explanation (see text for details). (A) Ternary mixing of tributaries of the upper Colorado basin [Grand (see text), Green, and San Juan Rivers]. (B) Cumulative probability plot for the tributary mixing end members and the PCR reference. Best fit is dashed red line and corresponds to 75.6% Green, 17.3% San Juan, and 7.0% Grand Rivers. This corresponds to D_{max} = 0.062 and P = 0.229. (C) Ternary mixing of tributaries of the lower Colorado basin (Little Colorado, Virgin, and Gila Rivers). Same explanation as in A. (D) Same explanation as in B. Best fit corresponds to 74.8% Gila and 25.2% Little Colorado Rivers. This corresponds to D_{max} = 0.070 and P = 0.101. Note that the Virgin is the leading contributor to the Holocene Colorado River reference in Figure 18D.

low concentrations of Oligocene zircon from volcanic fields in the southern Rocky Mountains toward the southwestern Colorado Plateau (Price et al., 2012; Fig. 17A). In spite of similarity to the PCR, the Crooked Ridge River distribution does not serve as a useful end member because the concentration of Oligocene zircons in it is too low.

Terrace deposits within the Green River catchment contain abundant Oligocene zircon (Price et al., 2012). Farther upstream, two samples from the Browns Park Formation (samples 48, 49) in the Yampa River catchment east of the Uinta uplift (Fig. 1) contains high concentrations of late Eocene–Oligocene zircon (Fig. 17D; Table 3). The similarity of the proportions of Oligocene to Eocene (Fig. 17E) zircon and the absence of Miocene zircon in both the Browns Park Formation and the PCR identify the pooled age distribution from these samples as useful proxies for the third, late Cenozoic, end-member age distribution in our mixing calculations.

Figure 18 displays the outcome of ternary mixing calculations in which all possible combinations of the Mesozoic, early Cenozoic, and late Cenozoic age

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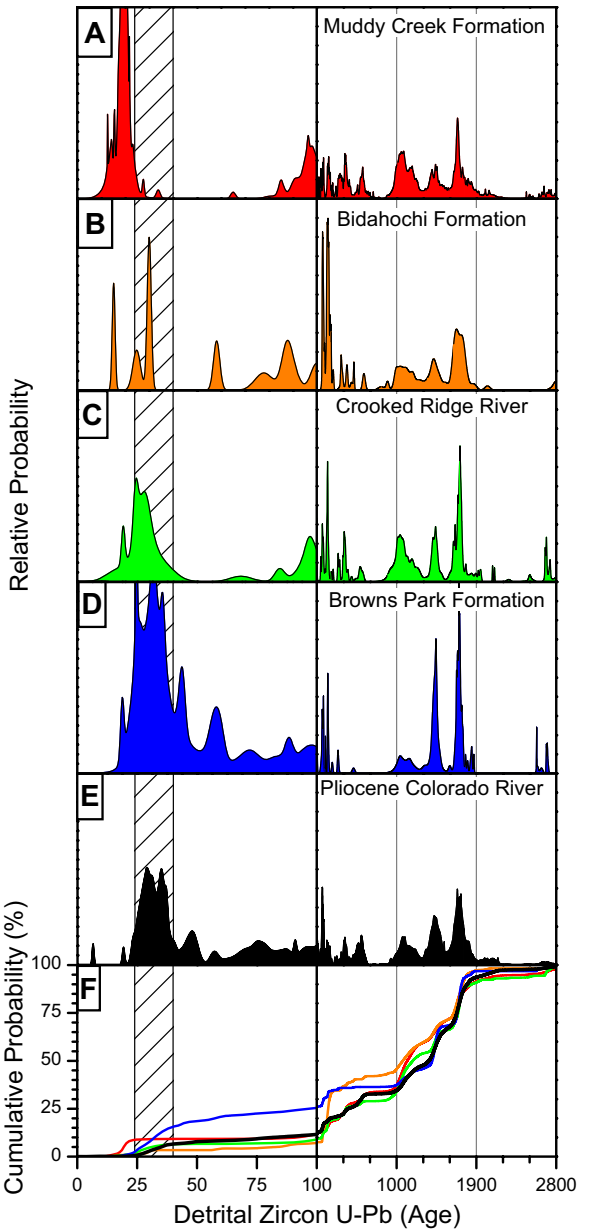

Figure 17. Relative probability plots for Oligocene and Miocene sedimentary deposits that could have been reworked into the early Pliocene Colorado River. Note split scale and hachured area to highlight 40–23 Ma age bin. (A) Miocene Muddy Creek Formation (Forrester, 2009; Muntean, 2012). (B) Upper member of Miocene Bidahochi Formation; includes samples 21 (CRT080612) and 22 (CRT080613). See Figure 2 and Table 3. (C) Oligocene–Miocene(?) Crooked Ridge River (Price et al. 2012). (D) Miocene Browns Park Formation; includes samples 48 (TBP814) and 49 (TBP71912-2). (E) Early Pliocene Colorado River PCR reference.

distributions are compared to the PCR and HCR reference curves. The best-fit mixture for the PCR reference is 50.7% early Cenozoic, 25.7% late Cenozoic, and 23.7% Mesozoic, and yields D_{max} = 0.041 and P = 0.232 (Fig. 18B). A distinctly higher proportion of the Mesozoic age distribution and almost no contribution from the late Cenozoic distribution is required to fit the HCR reference (Fig. 18C). The best-fit mixture for the HCR reference is 50.8% Mesozoic, 46.4% early Cenozoic, and 2.80% late Cenozoic, and yields D_{max} = 0.042 and P = 0.240 (Fig. 18D).

Overall, our mixing calculations indicate that the early Pliocene Colorado River was primarily sourced from Late Cretaceous–Cenozoic strata that predominately crop out in the southern Rocky Mountains and/or the eastern Green River catchment (Fig. 1). We interpret the greater proportion of the Mesozoic age distribution required to fit the Holocene Colorado River in terms of progressive erosion of the pre-Mesozoic supracrustal sequence within the central region of the modern Colorado River catchment in eastern Utah and western Colorado that diluted the contribution from the late Cenozoic sediments by enriching the Colorado River in early Paleozoic, latest Neoproterozoic, and Grenville detrital zircon derived from the Mesozoic supracrustal rocks that crop out in this region.

DISCUSSION

Exactly when, and how, the modern course of the Colorado River was established remains unclear (Hunt, 1956; Lucchitta, 1989, 2013; Flowers et al., 2008; Pederson, 2008; Polyak et al., 2008; Pelletier, 2010; Wernicke, 2011; Flowers and Farley, 2012; Karlstrom et al., 2013, 2014; Dickinson, 2013). The late Miocene Muddy Creek Formation in the Virgin River area has been explored as possible terminal deposits of an ancestral paleo–Colorado River prior to the integration of the river through the western Grand Canyon. Pederson (2008) ruled this out, noting evidence for moderate amounts of extrabasinal fluvial sediment in the Mesquite Basin portion of the Muddy Creek deposits attributed to the ancestral Virgin River mixed with locally derived sands. Comparison of the PCR reference to detrital zircon ages from the Muddy Creek Formation support this conclusion (Dickinson et al., 2014). The PCR almost completely lacks Miocene zircon, while sandstones of the Muddy Creek Formation in the Virgin River area feature a strong, persistent, early Miocene (dominantly 19 Ma) zircon component throughout the section (Forrester, 2009; Muntean, 2012) (Fig. 17A). Virgin River sands carry the same ca. 19 ± 2 Ma signal (Fig. 8). Less dramatic but more significant is the strong enrichment of 1300–285 Ma zircon in virtually all

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TABLE 5. U-Pb AGE BIN PROPORTIONS OF MIOCENE, PLIOCENE, AND HOLOCENE DEPOSITS

ID*	N	23–5 Ma	40–23 Ma	85–40 Ma	125–85 Ma	200–125 Ma	285–200 Ma	510–285 Ma	725–510 Ma	900–725 Ma	1300–900 Ma	1535–1300 Ma	1810–1535 Ma	2015–1810 Ma	>2015 Ma
HCR	601	1.0	1.5	3.2	1.8	3.7	3.0	11.5	8.5	0.5	18.3	12.6	26.3	3.7	4.5
PCR	559	0.2	7.0	3.9	2.7	4.9	3.3	4.7	5.3	0.3	13.5	18.3	26.9	4.7	4.4
MCF	1162	8.4	0.8	0.3	3.0	2.3	3.9	9.3	5.6	0.4	25.4	11.1	18.1	4.5	6.9
HL	178	0.0	0.0	0.0	0.0	0.6	3.4	18.5	11.2	0.6	27.0	18.0	10.7	1.7	8.4
BF	119	0.8	2.5	1.7	2.5	8.4	17.6	5.9	2.5	1.7	16.0	10.9	25.2	1.7	2.5
CRR	288	1.4	5.2	0.7	2.1	3.8	5.9	7.3	2.4	0.0	25.0	11.8	23.3	3.1	7.6
BPF	187	0.5	15.5	7.5	2.7	4.8	3.7	1.1	0.5	0.0	9.1	23.0	26.2	2.1	3.2

*Identification: HCR—Holocene Colorado River, PCR—Pliocene Colorado River, MCF—Muddy Creek Formation, HL—Hualapai Limestone, BF—Bidahochi Formation, CRR—Crooked Ridge River, BPF—Browns Park Formation.

Muddy Creek samples relative to the early Pliocene Colorado River (Fig. 17A; Table 5). The distinctly quartzose composition of modern Virgin River sand and local Muddy Creek Formation sandstone (~$Q_{92}F_5L_3$, i.e., quartz, feldspar, lithics) contrasts sharply with Colorado River sand composition (Merriam and Bandy, 1965; Van De Kamp, 1973; Potter, 1978; Girty and Armitage, 1989). For example, the Girty and Armitage (1989) results from a large sample suite (n = 25) demonstrate that modern Colorado River sands average $Q_{67}F_{18}L_{15}$. Overall, the data support Pederson's (2008, p. 8) conclusion that "a northwest passage out of the Grand Canyon region with a Muddy Creek Formation terminus for the ancestral Colorado River can be ruled out." However, Colorado River sediment could still be present in unexposed lower Muddy Creek or sub–Muddy Creek strata in the subsurface of the Virgin River depression (Dickinson et al., 2014).

Middle Miocene to lowermost Pliocene(?) lacustrine and fluvial strata of the Bidahochi Formation deposited east of, and topographically below, the Kaibab uplift have seemingly precluded the possibility that the Colorado River cut through the Kaibab uplift prior to ca. 6 Ma (Dallegge et al., 2001). Following Blackwelder (1934), Scarborough (2001), and Meek and Douglass (2001) interpreted the Bidahochi Formation as deposits of a large Hopi Lake (Lake Bidahochi) that overtopped the Kaibab upwarp along the path of the modern river. Our limited results from the upper fluvial portion of the Bidahochi Formation (Fig. 2; Table 2) indicate that it is a local deposit endemic to the catchment and source region of the Little Colorado River (Fig. 17B; Table 4). This part of the Bidahochi Formation is easily distinguished from the early Pliocene Colorado River at 95% confidence (Table 5).

Pre–late Miocene deposits related to the Crooked Ridge River occur east of the Grand Canyon (Fig. 1), and have been hypothetically linked to a paleo–Colorado River that extended to the southern Rocky Mountains (Lucchitta et al., 2011; Price et al., 2012). Three of four Crooked Ridge River sandstone samples carry distinctive Oligocene zircon and yield a detrital zircon age distribution (Fig. 17C) that is indistinguishable from that of the early Pliocene Colorado River at 95% confidence (Table 5). In summary, although rivers with a provenance signature similar to the early Pliocene Colorado River flowed within the Colorado Plateau region, their distribution and ultimate sink remains unclear.

Integration of the Early Pliocene Colorado River through Grand Wash

The Grand Wash area (Figs. 1 and 5A) provides key evidence for initial integration of the Colorado River off the Colorado Plateau and into the Basin and Range province (Lucchitta, 1972). Our results, combined with those of Lopez-Pearce et al. (2011) and Crossey et al. (2015), document a sharp local to extraregional provenance shift, expressed both sedimentologically and in the detrital zircon age distributions, that records arrival of the Colorado River at Grand Wash between 6.0 and 4.4 Ma (Fig. 9). Local deposition predating arrival of the Colorado River indicated by predominately Proterozoic zircon (Figs. 9E–9H) has long been recognized from conglomerate clasts (Longwell, 1936; Lucchitta, 1966). The progressive arrival of Paleozoic and latest Neoproterozoic detritus derived from Mesozoic strata recorded in the Hualapai Limestone (Figs. 9C, 9D) may be supportive of Young's (2008) model for a late Miocene Colorado River precursor canyon that incised the Hualapai Plateau by slow headward erosion (e.g., Pelletier, 2010). However, the appearance of extraregional Colorado River sand in Hualapai Wash (sample 34) was an abrupt event that supplied a distinctive detrital zircon distribution (Figs. 9A, 9B) and clast assemblage (Howard and Bohannon, 2001; Faulds et al., 2008). The deposits directly overlie Hualapai Limestone and predate fluvial incision (Fig. 5A). Matmon et al. (2012) estimated a crude ca. 5.3 Ma burial age for sandstone collected in these deposits (sample 34; Figs. 5A and 9B). Sample 34 arguably represents the oldest Colorado River sample analyzed in this study. Both its age distribution and that of sandstone beneath the 4.4-Ma basalt at Sandy Point (sample 35; Figs. 5A and 9A) are statistically indistinguishable from other earliest Pliocene Colorado River samples (Fig. 12; see the Supplemental File [see footnote 1]).

Early Pliocene Colorado River Sand in Lower Colorado River Corridor and Salton Trough

The distinctive extraregional detrital zircon age distribution associated with the earliest Colorado River deposits at Grand Wash is seen in samples collected downstream through the southern Basin and Range along the lower Colorado

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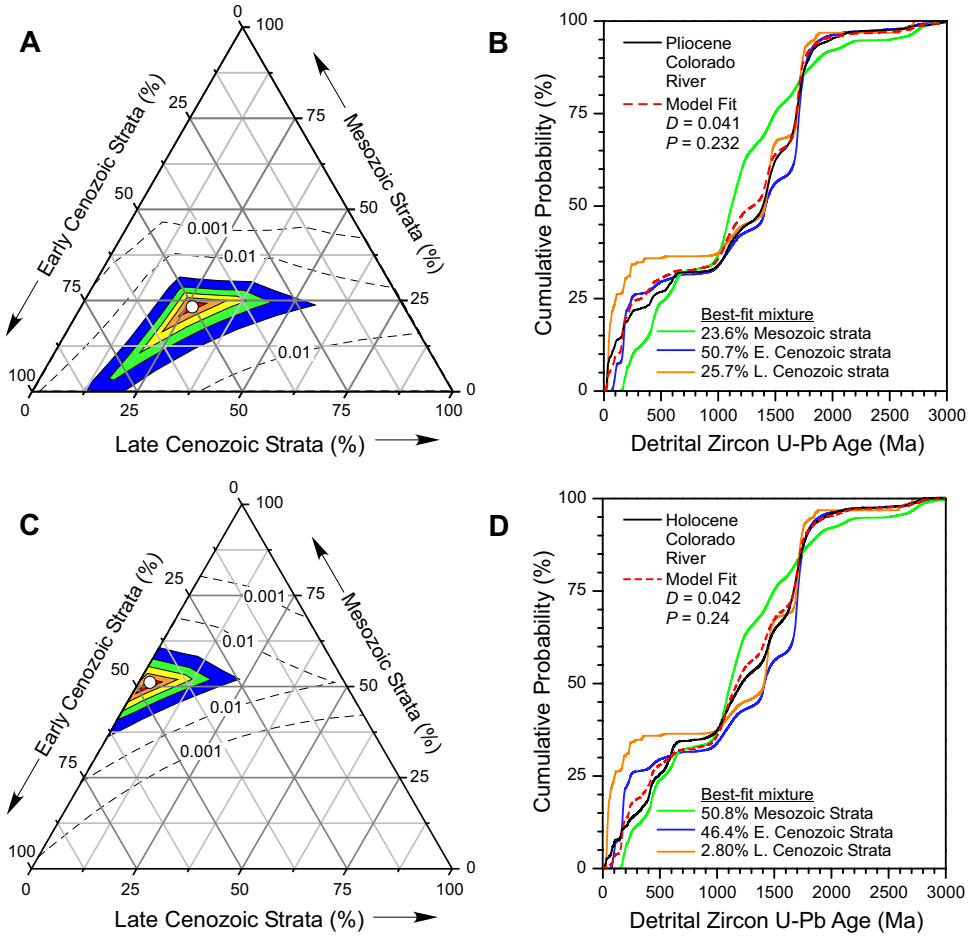

Figure 18. Ternary mixing model to illustrate the provenance shift between early Pliocene and modern Colorado River. Early (E.) Cenozoic and Mesozoic strata are calculated from results summarized in Figure 4 (see text). The third component is a proxy for late (L.) Cenozoic strata (Browns Park Formation) that can supply the Oligocene zircon required by the Pliocene river (see text). (A) Ternary mixing results for the early Pliocene Colorado River. Best fit is indicated by open circle. Mixtures within the color-filled contours yield P values > 0.05 (see text for details). Note that only 33% Mesozoic strata are required in the best-fit mixture. (B) Cumulative probability of best-fit solution shown together with mixing end members. (C) Ternary mixing results for the Holocene Colorado River. Best fit is indicated by open circle. Note that the locus of acceptable solutions has shifted away from the late Cenozoic strata end member and that the 51% Mesozoic strata is now required. (D) Cumulative probability of best-fit solution. Overall, the results demonstrate that the enrichment of the early Pliocene River in Oligocene and Mesoproterozoic zircon is consistent with derivation of sediment from the eastern and northern regions of the modern Colorado River catchment where Cenozoic strata are present (see Fig. 1).

River corridor and ultimately into fluvial-deltaic deposits in the western Salton Trough (Fig 1). In Cottonwood Valley, Colorado River–like sand from the Bouse Formation (sample 28) (Fig. 5B) yields a statistically indistinguishable age distribution confirming the association of the Bouse deposits with the arrival of Colorado River water and sediment. Similarly, the Bullhead alluvium records massive aggradation of Colorado River sediments following divide breaching floods as part of the lake spillover river integration process (House et al., 2005; Howard et al., 2015). Most samples analyzed from the Bullhead carry the early Pliocene river detrital signature (Figs. 10A–10D; Supplemental File [see footnote 1]). Although nearby age constraints based upon age of the Lawlor Tuff suggest depositional ages younger than 4.8 Ma (Sarna-Wojcicki et al., 2011), the material contained within the Bullhead alluvium samples is likely partly recycled from older Pliocene sand deposited within lakes that spilled over into the lower Colorado River corridor.

The oldest Colorado River–derived marine sands in the lower part of the Salton Trough and Fish Creek–Vallecito Basin (Wind Caves Member of the Latrania Formation, Imperial Group) were deposited ca. 5.3–5.2 Ma, based on paleomagnetism, micropaleontology, and U-Pb dating of tuffs (Dorsey et al., 2007, 2011) (Fig. 6A). The Wind Caves samples (Figs. 6A and 11G) yield detrital zircon age distributions that are indistinguishable from the Grand Wash early Pliocene Colorado River samples at 95% confidence (Fig. 12; Supplemental File [see footnote 1]).

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Figure 13A displays the pooled results from the six early Pliocene Colorado River samples used to define the PCR age reference. While the PCR is just barely resolved from the HCR at 95% confidence (Supplemental File [see footnote 1]), the K-S test is insensitive to several important differences between the two distributions. The first is the dominance of 1810–1300 Ma zircon over Grenville, latest Neoproterozoic, and Paleozoic (1300–285 Ma) zircon. The early Pliocene river deposits contain 45% 1810–1300 Ma and only 24% 1300–285 Ma zircon. In contrast, the Holocene Colorado River deposits contain 39% 1810–1300 Ma and 39% 1300–285 Ma (39%) zircon. When the more abundant Cordilleran arc-derived (285–85 Ma) zircon present in the PCR is also taken into account, it is clear that the PCR carried a much larger proportion of detritus eroded from Cenozoic deposits that currently crop out primarily along the eastern and northeastern limits of the modern Colorado River catchment and could have overlain larger parts of the Colorado Plateau (Fig. 1). Below, we consider evidence that the early Pliocene Colorado River extended to the eastern and northeastern limits of the modern Colorado River catchment.

Detrital Zircon Derived From Laramide Basement Cored Uplifts

Nearly all Yavapai-Mazatzal age zircon within the Colorado Plateau region can be ascribed to erosion of local basement. In contrast, most of the older than 1810 Ma and 1300–285 Ma zircon is extraregional in origin and is in the supracrustal cover to Yavapai-Mazatzal basement (e.g., Gehrels et al., 2011). As indicated in Figure 4, the proportions of 1810–1300 Ma zircon relative to Grenville and younger (1300–285 Ma) zircon increased significantly in the Late Cretaceous and early Cenozoic. We attribute this increase in 1810–1300 Ma zircon to erosion of basement cored uplifts that formed during the Laramide orogeny (Figs. 1 and 4).

Strong independent evidence that Laramide uplift–derived Yavapai-Mazatzal zircon was supplied to the early Pliocene Colorado River comes from coupled U-Pb and (U-Th)/He dating of detrital zircons from early Pliocene strata within the Salton Trough (Cloos, 2014). Overall, the detrital zircon U-Pb age distributions reported by Cloos (2014) for early Pliocene strata within the Salton Trough (Latrania, Deguynos, and Arroyo Diablo Formations) and Holocene delta sediment are very similar to what we report here. In undertaking (U-Th)/He measurements from his independently analyzed materials, Cloos (2014) reported many Laramide (U-Th)/He ages for Yavapai-Mazatzal detrital zircon. For example, 81% (74 of 91) of the zircons yielding Yavapai-Mazatzal basement U-Pb ages from Pliocene strata of the Salton Trough yielded (U-Th)/He ages younger than 200 Ma with a maximum ca. 80 Ma. In contrast, <20% of the Grenville and younger (1300–285 Ma) detrital zircons from both the Pliocene and Holocene Colorado River yield (U-Th)/He ages younger than 200 Ma. The percentage of Yavapai-Mazatzal zircons yielding Laramide (U-Th)/He ages was distinctly smaller (50%, 20 of 40) in the Holocene Colorado River than for the Pliocene Colorado River.

We concur with the Cloos (2014) interpretation that Laramide basement-cored uplifts in the eastern and northeastern regions of the present-day catchment preferentially accounted for a significant amount of the Yavapai-Mazatzal detrital zircons present within the early Pliocene strata of the Salton Trough. How broadly distributed and voluminous Cenozoic deposits that contained detritus from the Laramide basement uplifts may have been across the Colorado Plateau region at the onset of the Pliocene is not well understood. However, both our results and those of Cloos (2014) argue against the headward erosion hypothesis, which predicts that Yavapai-Mazatzal zircon in the Pliocene Colorado River was preferentially supplied by erosion of the southwest margin of the Colorado Plateau. Geologic relationships (Figs. 1 and 4) coupled with low-temperature thermochronology studies indicate that maximum burial heating of the southwestern Colorado Plateau margin occurred during the Late Cretaceous (Dumitru et al., 1994; Flowers et al., 2008; Lee et al., 2013). During this time, heating of the Proterozoic basement along the southwestern Colorado Plateau margin was limited to the partial annealing zone for fission tracks in apatite (Dumitru et al., 1994). Temperatures well below 150 °C are insufficient to substantially degas He from zircon (Reiners, 2005). Because Yavapai-Mazatzal–age zircon present within the pre-Mesozoic supracrustal sequence throughout the Colorado Plateau existed at even lower temperatures than underlying basement during the late Mesozoic (Dumitru et al., 1994; Flowers et al., 2008; Lee et al., 2013), a Rocky Mountains source for these zircons that yields Laramide (U-Th)/He zircon ages is most probable.

Sources of Late Eocene–Oligocene Zircon in Colorado River

The distinctive late Eocene–Oligocene (40–23 Ma) zircons that represent ~6.5% of the PCR were produced by the middle Cenozoic ignimbrite flareup of the western United States during a period of intense explosive volcanism (ca. 40–25 Ma) that affected the interior of southwestern North America (Fig. 1) (Armstrong and Ward, 1991; Lipman and Glazner, 1991; McDowell and McIntosh, 2012). Mid-Tertiary centers associated with the flareup are widely distributed around the perimeter of the Colorado River catchment (Fig. 1) and include the Absaroka (Hiza, 1999), San Juan–central Colorado (McIntosh and Chapin, 2004; Lipman and McIntosh, 2008), Mogollon-Datil (McIntosh et al., 1992), Marysvale (Rowley et al., 1994), and Indian Peak–Caliente volcanic fields (Best et al., 1994, 2013). Now deeply eroded, Oligocene laccoliths in the central part of the Colorado Plateau around the Grand and Green confluence (Abajo–Henry–La Sal; Nelson et al., 1992; Fig. 1) may also have supported major volcanic edifices with volcaniclastic aprons >50 km in diameter (Lipman, 1989; Dickinson, 2013).

Ages from the major mid-Tertiary volcanic fields proximal to the Colorado River catchment are summarized in Figure 19. While the ages of volcanism of various centers overlap, the combined San Juan–central Colorado volcanic fields are appropriately positioned and provide a reasonably good match to the distribution of 40–23 Ma detrital zircon in the early Pliocene Colorado River (Fig. 19F). While the Mogollon-Datil field has a similar age distribution (Fig. 19E), it is currently tapped by the Gila River, which is unlikely to have extended

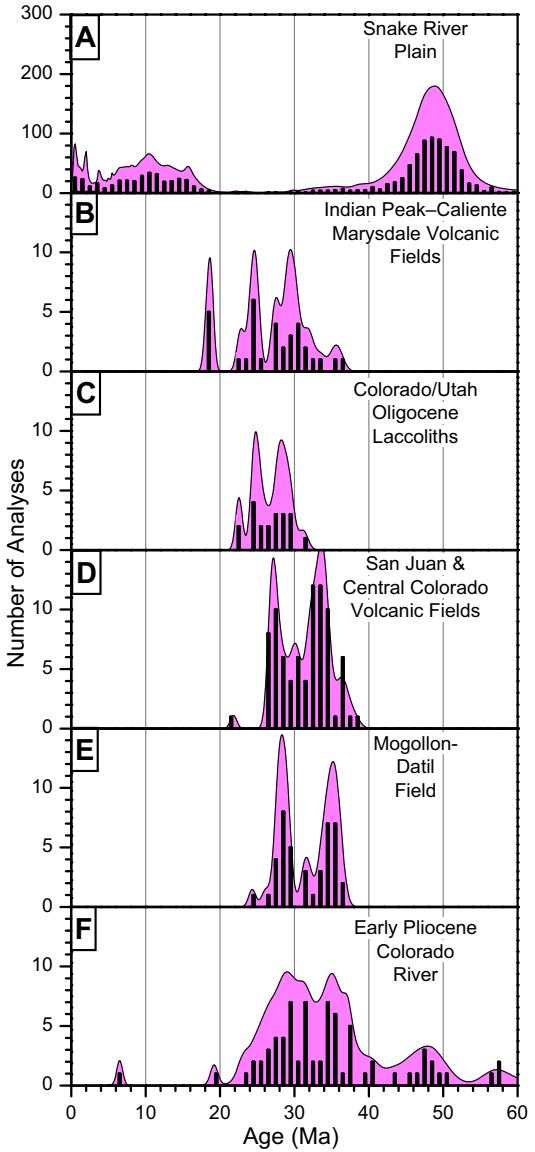

Figure 19. Cenozoic zircon age distributions in early Pliocene Colorado River versus Cenozoic volcanic fields. (A) Snake River Plain (Link et al., 2005; Beranek et al., 2006). (B) Indian Peak–Caliente–Marysvale volcanic fields (Rowley et al., 1994; Best et al., 1994, 2013). (C) Utah-Colorado laccoliths (Nelson et al., 1992). (D) San Juan and Central Colorado volcanic fields (McIntosh and Chapin, 2004; Lipman and McIntosh, 2008). (E) Mogollon-Datil volcanic field (McIntosh et al., 1992). (E) Early Pliocene Colorado River (this paper).

from the southern Rocky Mountains in the early Pliocene (Huckleberry, 1996; Menges and Pearthree, 1989). Further northwest, the dominantly 26–28 Ma Oligocene laccoliths (Fig. 19C) and Marysvale and Indian Peak–Caliente fields (Fig. 19B) are deficient in ca. 40–30 Ma zircon. Even further north, the Absaroka and Challis volcanic fields near and north of the Snake River Plain produce older 55–45 Ma zircon (Fig. 19A). While 55–45 Ma zircon is not abundant within the PCR, grains of this age are present.

Supply of 40–23 Ma zircon from the San Juan–central Colorado volcanic field to the PCR could have occurred either from direct erosion of the volcanic fields and/or via sediment recycling and storage in younger basins. While the majority of the San Juan–central Colorado field is outside of the present-day catchment of the modern Colorado River, Lipman and McIntosh (2008) inferred that the original extent of the volcanic field was much larger prior to erosion. The central and southern Colorado Plateau was blanketed by thick eolian sandstones of Oligocene age (the Chuska erg) that accumulated synchronously with the eruption of surrounding topographically high andesitic to rhyolitic volcanic fields (Cather et al., 2008). While arkosic Chuska eolianite collected near the center of the reconstructed sand sea for detrital zircon ages was primarily from Precambrian bedrock sources in central Arizona (Eichler and McGraw, 2008; Dickinson et al., 2010), eolianites to the south on the northern fringes of the Mogollon-Datil volcanic field are more volcaniclastic in character and interfinger with ignimbrites. These remnants as well as those in the subsurface of the Rio Grande Rift may thus contain large components of volcanic-derived mid-Tertiary zircons (e.g., Madole et al., 2008). Cather et al. (2012) suggested that ≥1 km of fluvial erosion occurred during the late Oligocene–early Miocene across a broad region of southwestern North America. Pre–late Miocene Crooked Ridge demonstrates that west-flowing streams carried Oligocene zircon (Price et al., 2012; Fig. 17A).

Younger sedimentary basins may have sequestered Oligocene zircon. Samples from the Miocene (ca. 25–7 Ma) Browns Park Formation in northeastern Utah and northwestern Colorado (Figs. 1 and 2) contain a high percentage (~25%) of 40–23 Ma zircon (Fig. 17D). The Yampa River traverses the Browns Park Formation and in turn feeds the upper Green River catchment south of the Uinta uplift. The Yampa River is thought to have played a key role in integrating the upper Green River across the transverse Uinta Mountains into the greater Colorado River drainage. Hunt (1969) proposed superposition of these rivers across the Uinta Mountains as they flowed along the top of the Browns Park Formation (see Pederson and Hadder, 2005).

There are two plausible sources of 40–23 Ma zircon in Browns Park Formation and in nearby Green River terrace deposits (Price et al., 2012). Ferguson (2011) proposed that a north-flowing river transported volcanic detritus from the San Juan–central Colorado fields into the Browns Park Formation. Alternatively, fluvial transport of mid-Tertiary zircon into the Browns Park basin from western sources in the Basin and Range is also possible (Henry et al., 2012; Chetel et al., 2011). Transport of volcanic ash from the Great Basin region eastward to basins like those filled by the Browns Park Formation could also have occurred.

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Late Neogene Evolution of the Colorado River System

The most complete record of the Pliocene to Holocene evolution of the Colorado River is preserved in marine and nonmarine Colorado River–derived sediments of the Salton Trough (Figs. 6 and 11). The age distributions of samples that overlie the Wind Caves Member evolved slowly and in nearly all cases are statistically indistinguishable (Table 4; Supplemental File [see footnote 1]). The same relationships generally hold true throughout the lower Colorado River corridor, including late Pleistocene Chemehuevi Formation sand (Table 4). The comparatively subtle but statistically meaningful shift in provenance signature over 5 m.y. (Fig. 13) is consistent with erosion toward base level within the Colorado River catchment after early Pliocene integration of the river system across a region similar to the modern catchment of the Colorado River.

Our conclusion that the proportion of Colorado River sediment derived from erosion of Cenozoic deposits decreased from 75% to 50% while the contribution from underlying Mesozoic strata increased from 25% to 50%, from early Pliocene to Holocene time (Fig. 18), mirrors the reduction in the proportion Yavapai-Mazatzal zircon that yield Laramide (U-Th)/He ages reported by Cloos (2014), from 81% to 50%. Because the Colorado Plateau south of the Kaibab uplift was uplifted and eroded during the Paleogene (Flowers et al., 2008; Lee et al., 2013), Cenozoic deposition primarily occurred in Laramide basins north of the Kaibab uplift (Fig. 1). Results from our calculations (Fig. 18) thus argue against the importance of headward erosion in influencing the provenance signature of the Colorado River over time. Instead our results indicate that erosion downward through the Cenozoic sequence into the Mesozoic sequence (Figs. 1, 2, and 4) was the primary source of Colorado River sand over the past 5 m.y. Because detritus derived from the southern Rocky Mountains and Green River catchment was prominent in the early Pliocene Colorado River sand, it is probable that Pliocene Colorado River catchment largely encompassed the same region as does the Holocene catchment (Figs. 1 and 2).

Our finding that downward erosion into the Mesozoic cover of the Colorado Plateau accounts for changes in the Colorado River provenance signature over the past 5 m.y. is supported by sediment transport records that show that most of the Colorado River sediment is supplied from easily eroded Cenozoic and Mesozoic strata in the semiarid central part of the Colorado Plateau upstream from the Grand Canyon (Andrews, 1991). Geologic and thermochronologic studies demonstrate that this central catchment region is a broad area of deep fluvial erosion across the eastern Utah and western Colorado that provided the bulk of the sediment to the river from late Miocene to Holocene time (Pederson et al., 2002b; Flowers et al., 2008; Hoffman et al., 2011; Cather et al., 2012; Lee et al., 2013; Lazear et al., 2013).

Patterns of occurrence of reworked Mancos Shale fossils in the Fish Creek–Vallecitos Basin strata of the western Salton Trough have been used to explore the erosion history of the upper Colorado catchment. Merriam and Brandy (1965) found that when the Colorado River began depositing sediment in the Fish Creek–Vallecito Basin it introduced reworked Cretaceous foraminifera from the upper Cretaceous Mancos Shale and equivalents that are widely exposed on the Colorado Plateau. Fleming (1994) subsequently defined a paleobiogeographic boundary that divided Cretaceous strata into northern and southern regions along the Arizona-Utah and Colorado–New Mexico borders. Fleming (1994) demonstrated that pollen from the southern domain arrived ~600 k.y. earlier into the basin than pollen from the northern domain, and concluded that the stratigraphic record corroborated a headward erosion model for the river (Lucchitta, 1972). We alternatively attribute the time lag to the time required to erode through younger strata into the older Mancos Shale in southern Utah.

Sustained late Miocene to Holocene erosion across the central catchment area was likely driven by a number of factors, including the river's sudden drop in base level associated with integration through the Grand Wash Cliffs into the Basin and Range (Pederson et al., 2002b), intensification of the North American monsoon due to opening of the Gulf of California (Chapin, 2008), isostatic uplift associated with erosional unloading (Pederson et al., 2002a; Lazear et al., 2013), and mantle buoyancy-driven uplift (Levander et al., 2011; Karlstrom et al., 2012). Whatever the cause, the Colorado River's detrital zircon provenance record provides a robust line of evidence that the central, eastern, and northeastern parts of the catchment have provided the bulk of sediment to the Colorado system throughout its ~6 m.y. history.

CONCLUSIONS

New detrital zircon U-Pb ages from Holocene Colorado River sand and older fluvial-deltaic Neogene sandstones from the lower river corridor and Salton Trough provide a high-fidelity provenance record for the latest Miocene–Holocene Colorado River.

1. Six samples collected across the Holocene delta provide a zircon reference signature for the Holocene Colorado River (n = 601). Holocene sands contain 39% 1810–1300 Ma, 39% 1300–285 Ma, and 8% 285–85 Ma detrital zircon.

2. Six early Pliocene samples collected from the Grand Wash area along the lower reach of the river and from equivalent marine deposits in the western Salton Trough define the early Pliocene Colorado River provenance signature (n = 559). Early Pliocene Colorado River sand differs from Holocene sand in that it has an elevated percentage (46%) of 1810–1300 Ma zircon and lower percentage (24%) of 1300–285 Ma zircon.

3. Early Pliocene Colorado River sand is also characterized by a distinct component (6.5%) of late Eocene–Oligocene (40–23 Ma) zircon derived from volcanic rocks associated mainly with the mid-Cenozoic ignimbrite flareup of the southern Rocky Mountains. This component diminished over time and composes only 1% of the Holocene river detrital zircon.

4. Mixing calculations that utilize age distributions measured from Holocene sand from major Colorado River tributaries indicate that both the early Pliocene and Holocene Colorado River were derived primarily from the eastern (San Juan River) and northern (Green River) regions of the modern catchment basin.

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5. Mixing calculations undertaken with age distributions representative of the Mesozoic, early Cenozoic, and late Cenozoic supracrustal strata of the Colorado Plateau and southern Rocky Mountains indicate that sediment carried by the early Pliocene Colorado River was sourced primarily from Cenozoic deposits that are present in the eastern and northeastern regions of the present-day Colorado River catchment. In contrast, Holocene Colorado River sediment is derived from equal proportions of material eroded from Cenozoic and Mesozoic strata. This finding appears to reflect deep erosion of predominately Mesozoic supracrustal strata within the central region of the modern Colorado River catchment (eastern Utah–western Colorado region).

6. The abrupt early Pliocene appearance, ca. 5.3 Ma, of sediment derived from the northern and eastern limits of the present-day catchment is evidence against a progressive headward erosion model for integration of the river across the Kaibab uplift.

7. Comparison of detrital zircon ages from the Colorado River and uppermost fluvial portion of the Bidahochi Formation do not support a lake spillover model for integration of the river across the Kaibab uplift.

8. Comparison of detrital zircon ages from the Colorado River and the exposed portions of the Muddy Creek Formation do not support the idea of the Virgin River depression as the terminus of an ancestral Colorado River.

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