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Detrital zircons indicate no drainage link between southern California rivers and the Colorado Plateau from mid-Cretaceous through Pliocene

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ABSTRACT

Central to debate about the age, origin, and evolution of Grand Canyon (southwestern United States) is the history of the Colorado River and its precursors. Reversal of dextral slip along the San Andreas fault system since the early Pliocene restores southern California to the downstream end of the Colorado River. If the Colorado River flowed to the Pacific Ocean prior to 6 Ma, then its sand would have the distinctive detrital-zircon age distributions of upper Paleozoic and Mesozoic strata of the Colorado Plateau, which contain 30%–46% 300–1100 Ma zircon originally transported from orogenic belts of southeastern Laurentia. In contrast, age distributions of 6662 detrital zircons from 167 Upper Cretaceous–Pliocene sandstone samples from southern California average 44%–88% Cretaceous, with only 0.4%–1.3% 300–1100 Ma grains, most of which can be attributed to local recycling from older deposits. No individual Upper Cretaceous to Pliocene sandstone sample from southern California contains >3% 300–1100 Ma zircon. Although Paleogene headwaters of southern California rivers extended into the eastern Mojave Desert, Sonoran Desert, and Mogollon Highlands, our results indicate that these headwaters did not extend as far as the Colorado Plateau. This conclusion conflicts with the hypothesis of a Paleogene southwest-flowing Arizona River, but supports late Miocene–Pliocene drainage reorganization and integration of the Colorado River coincident with development of the Salton Trough and Gulf of California.

INTRODUCTION

Central to debate about the age, origin, and evolution of Grand Canyon (southwestern United States) is the timing of river integration and canyon cutting by the Colorado River and its precursors (e.g., Longwell, 1946; Lucchitta, 1972, 2003; Spencer and Pearthree, 2001; Young and Spamer, 2001; Powell, 2005; Flowers et al., 2008; Karlstrom et al., 2008; Pederson, 2008, and references therein). Recent studies support models that the lower Colorado River and Grand Canyon have been incised since 6 Ma due to drainage integration over Grand Wash Cliffs (e.g., Pederson et al., 2002; Karlstrom et al., 2007, 2008; Dorsey, 2010; Kimbrough et al., 2010; Dorsey et al., 2011). Other studies have proposed precursor rivers, flowing from the craton into southern California, that may have headed in a proto–Grand Canyon (e.g., Howard, 2000; Wernicke, 2011). Wernicke (2011) proposed a three-stage cutting of the canyon by a Late Cretaceous northeast-flowing California River, a Paleogene southwest-flowing Arizona River, and the Neogene–Holocene southwest-flowing Colorado River. This model predicts that detritus carried by the precursor river should be found in Paleogene fluvial, deltaic, and marine strata of coastal southern California (Fig. 1). Wernicke's (2011) Arizona River is similar to Howard's (2000) model of a "Sespe-Colorado paleoriver," which also would have provided detritus to southern California; however, Howard's model did not include cutting of Grand Canyon.

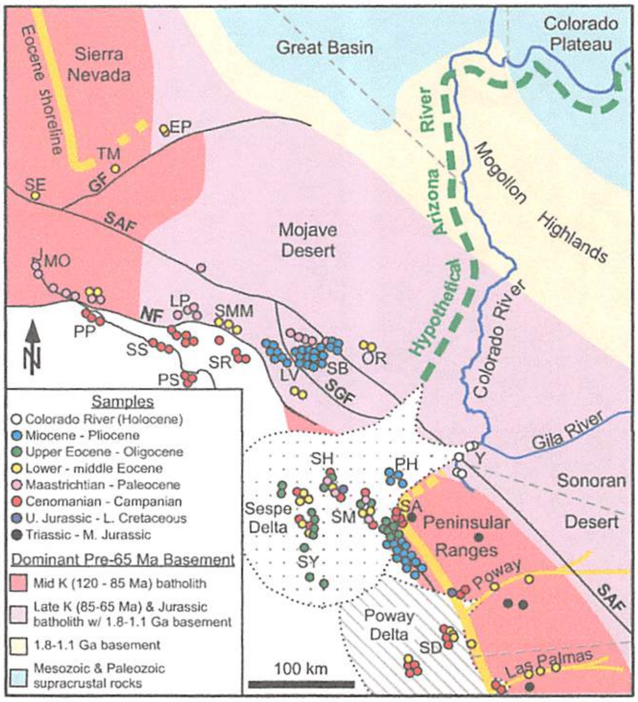

Figure 1. Simplified pre–15 Ma palinspastic restoration of southern California (after Jacobson et al., 2011) showing sample locations. Restored fault offsets include San Andreas fault (SAF) and San Gabriel fault (SGF), and San Gregorio–Hosgri and Rinconada faults (not shown). Garlock fault (GF) and Nacimiento fault (NF) have not been restored. Also shown are hypothetical Paleogene Arizona River (Wernicke, 2011), Eocene shoreline and river systems (bold yellow lines) (Abbott and Smith, 1989; Howell et al., 1974; Lechler and Niemi, 2011), and Oligocene Sespe deposystems (Howard, 2000). K—Cretaceous; U.—Upper; L.—Lower; M.—Middle; LP—La Panza Range; LV—Lockwood Valley; MO—Monterey; OR—Orocopia Mountains; PH—Puente Hills; PP—Pigeon Point; PS—Point Sur; SA—Santa Ana Mountains; SB—Soledad basin; SD—San Diego; SH—Simi Hills; SM—Santa Monica Mountains; SMM—Sierra Madre Mountains; SR—San Rafael Mountains; SS—San Simeon; SY—Santa Ynez Mountains; Y—Yuma. Localities of San Emigdio Mountains (SE), Tehachapi Mountains (TM), and El Paso Mountains (EP) are from Lechler and Niemi (2011).

Upper Paleozoic and Mesozoic strata of the Colorado Plateau have unique detrital-zircon age distributions ultimately derived from the ancestral central and southern Appalachian and Ouachita regions (southern United States), including accreted peri-Gondwanan terranes (e.g., Dickinson and Gehrels, 2003, 2009, 2010; Gehrels et al., 2011). This distinctive signature is clearly expressed in Pliocene to Holocene terrace and lacustrine deposits adjacent to the

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modern course of the Colorado River southwest of the Colorado Plateau and in sedimentary rocks as old as 5.3 Ma in the western Salton Trough (Dorsey, 2010; Kimbrough et al., 2010; Dorsey et al., 2011). Critical to questions of ancient drainage systems, however, is determination of the oldest Colorado Plateau–derived detritus in southern California. Reconstructions place the Los Angeles region adjacent to the modern course of the Colorado River prior to movement along the San Andreas fault system (ca. 5 Ma) (Fig. 1), a result consistent with mitochondrial DNA studies of fish (e.g., Spencer et al., 2008). If the hypothetical Arizona River had eroded Colorado Plateau strata, then their distinctive detrital-zircon age signature should be found in Paleogene strata of the Los Angeles region. Our purpose is to test this hypothesis.

METHODS AND RESULTS

Detrital-zircon U-Pb age distributions were generated primarily using laser-ablation–multicollector inductively coupled plasma–mass spectrometry (LA-ICPMS) at the University of Arizona LaserChron Center; methods of data acquisition were summarized in Grove et al. (2003), Gehrels et al. (2008), and Jacobson et al. (2011).

All available samples from southern California (both published and new) were grouped by age (Triassic to Pliocene) for comparison with distribution plots of lower Paleozoic, upper Paleozoic, Triassic, Jurassic, and Cretaceous strata of the Colorado Plateau, and Holocene sand of the Colorado River (Fig. 2; Table 1). The distinctive Colorado Plateau signal consists of age ranges of 300–750 Ma (middle Paleozoic through late Neoproterozoic) and 900–1150 Ma (Grenville age) (Figs. 2H–2K). Because 1100–1300 Ma Grenville rocks are minor components of southern California basement (e.g., Barth et al., 1997), we focus our attention on extraregional 300–1100 Ma detritus. Zircon in this age range is abundant in upper Paleozoic through Jurassic (and some Cretaceous) strata of the Colorado Plateau, Triassic through lowest Cretaceous metasedimentary wall rocks of southern California, and Holocene Colorado River sediments (Table 1). In contrast, mid-Cretaceous through Pliocene strata of southern California essentially lack 300–1100 Ma zircon and contain only small amounts of Grenville (dominantly 1200 Ma) zircon.

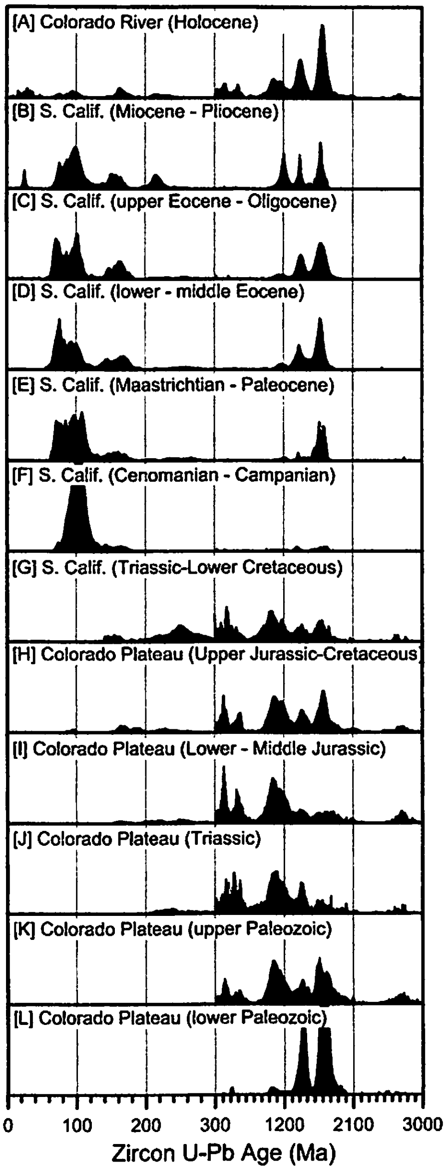

Figure 2. Detrital-zircon U-Pb age distributions. A: Holocene Colorado River. B–G: Southern (S.) California strata of indicated ages and palinspastically restored locations shown in Figure 1. H–L: Colorado Plateau strata. Data sources are summarized in Table 1. Note lack of 300–1100 Ma zircon in Upper Cretaceous to Pliocene strata from coastal southern California, and change of horizontal scale at 300 Ma (see Jacobson et al., 2011).

SOURCES OF SOUTHERN CALIFORNIA DETRITUS

The age distributions of Figure 2 and Table 1 place important constraints on Mesozoic through Cenozoic drainage evolution. The strong Colorado Plateau signature (i.e., 300–1100 Ma zircon) in Triassic through lowest Cretaceous sandstone from the southern California margin is particularly significant (Fig. 2G). This pattern implies that the Triassic to Jurassic magmatic arc (e.g., Schweickert, 1976; Barth et al., 1997) of the southwestern United States was a low-standing feature (Busby-Spera, 1988) that allowed eolian and fluvial transport from the northeast through the arc to the coast. In contrast, the middle to Late Cretaceous arc was a positive physiographic feature, mostly outboard of the older arc, that blocked transport from the interior to the coast. The drainage divide moved slowly to the east along with the magmatic arc during most of the Cretaceous; rapid eastward migration of the divide occurred during latest Cretaceous–Paleogene flattening of the subducting slab during the Laramide orogeny (e.g., Dickinson and Snyder, 1978; Livaccari et al., 1981; Bird, 1988; Saleeby, 2003; Jacobson et al., 2011). The Mogollon Highlands, which may have also undergone uplift during the Jurassic (Dickinson and Gehrels, 2008b), were elevated during the Laramide orogeny, resulting in erosion of ~1–2 km of strata (Flowers et al., 2008). Eocene rivers flowing toward the coast increased in length and magnitude to tap the eastern Mojave region (Jacobson et al., 2011). This process culminated with the Sespe River during late Eocene and Oligocene time, with headwaters as far northeast as the Mogollon Highlands (Howard, 2000, 2006); new detrital-zircon data (Fig. 2; Table 1) demonstrate that the Sespe River did not include detritus derived from Colorado Plateau strata (Spafford et al., 2009; Spafford, 2010). Starting in the Oligocene, slab rollback following the Laramide orogeny (Dickinson and Snyder, 1978) caused the drainage divide to migrate southwest. This process culminated in development of the southern Basin and Range Province during the middle Miocene (Dickinson, 2002). From the Oligocene through the Pliocene, local sources for sand in southern California dominated. The only direct provenance link with the Colorado Plateau is provided by uppermost Miocene to Holocene deposits of the Colorado River in the Salton Trough area (Dorsey, 2010; Kimbrough et al., 2010; Dorsey et al., 2011).

EVALUATION OF THE ARIZONA RIVER CONCEPT

Wernicke (2011) argued that the Paleogene Arizona River flowed largely along the modern course of the Colorado River, and transported detritus from the southwestern margin of the Colorado Plateau region into southern California (Fig. 1). Howard (2000, 2006) documented extraregional rivers flowing into southern California from the northeast, without suggesting that they helped cut Grand Canyon. The distinctive Colorado Plateau signal can be used to test whether these extraregional rivers extended beyond the Mogollon Highlands because lower Paleozoic, upper Paleozoic, Triassic, Lower to Middle Jurassic, and Upper Jurassic to Cretaceous sandstone of the Colorado Plateau contain average concentrations of 300–1100 Ma zircon of 4%, 32%, 46%, 44%, and 30%, respectively, and modern Colorado River sediment averages 29% 300–1100 Ma zircon (Table 1).

During the Paleogene, ~1.5 km of Cretaceous strata and some older Mesozoic and Paleozoic strata along the southwestern margin of the Colorado Plateau region were eroded (Flowers et al., 2008). Much of this detritus was transported northeastward to Utah and New Mexico (e.g., Dickinson et al., 1988). Some northeast-flowing

TABLE 1. PERCENTAGES OF DETRITAL ZIRCON U-Pb AGES

Colorado Plateau Sedimentary Strata and Colorado River

	Lower Paleozoic	Upper Paleozoic	Triassic	Lower–Middle Jurassic	Upper Jurassic–Cretaceous	Holocene Colorado River
Data source*	1	1	2	3	4	5
Samples/analyses	8/789	18/1880	11/991	17/1560	21/1990	5/558
<65	0.0	0.0	0.0	0.0	0.0	3.0
65–85	0.0	0.0	0.0	0.0	0.1	2.3
85–145	0.0	0.0	0.0	0.0	1.6	2.2
145–200	0.0	0.0	0.0	2.2	6.6	3.2
200–300	0.0	0.3	8.1	6.8	5.1	3.6
300–900	1.6	14.2	28.8	26.0	16.7	20.1
900–1100	2.4	17.3	17.0	18.3	13.1	9.0
1100–1300	2.2	14.8	17.6	16.9	15.4	9.3
1300–1550	28.1	12.8	13.2	8.5	11.5	12.5
1550–1800	57.2	23.6	6.9	7.7	18.7	26.7
>1800	8.5	17.0	8.7	13.5	11.3	8.1

Southern California Sedimentary Strata

	Triassic–Lower Cretaceous	Cenomanian–Campanian	Maastrichtian–Paleocene	Lower to middle Eocene	Upper Eocene–Oligocene	Miocene–Pliocene
Data source*	6,7	7	7	7, 8	9	10
Samples/analyses	7/700	42/1186	30/582	32/1218	22/1378	41/2298
<65	0.0	0.0	0.0	0.6	0.6	2.7
65–85	0.0	5.7	21.8	14.7	19.5	10.3
85–145	0.9	82.0	45.6	31.2	27.9	33.5
145–200	5.3	5.4	7.7	20.4	13.6	11.5
200–300	25.7	0.9	5.0	7.3	3.7	9.9
300–900	18.7	0.5	0.2	0.4	0.7	0.3
900–1100	15.0	0.4	0.2	0.6	0.6	0.1
1100–1300	9.4	0.8	1.2	2.1	2.7	11.6
1300–1550	8.7	1.4	2.2	7.6	10.2	7.2
1550–1800	11.6	2.4	15.1	14.3	19.2	12.4
>1800	4.7	0.3	0.7	1.1	1.3	0.5

*Data sources: 1—Gehrels et al. (2011), 2—Dickinson and Gehrels (2008a), 3—Dickinson and Gehrels (2009), 4—Dickinson and Gehrels (2008b), 5—Kimbrough et al. (2010), 6—this study, 7—Jacobson et al. (2011), 8—Lechler and Niemi (2011), 9—Spafford (2010), 10—this study. Shading indicates Grenville ages.

rivers may have originated in eastern California (Davis et al., 2010; Wernicke, 2011).

Our detrital-zircon data indicate that no significant Colorado Plateau–derived detritus was deposited in southern California by an Arizona river (Figs. 2B–2F). The 6662 detrital-zircon U-Pb ages from 167 broadly distributed Upper Cretaceous to Pliocene samples from coastal southern California contain 44%–88% Cretaceous (65–145 Ma) zircon, 6%–28% Jurassic and Permian–Triassic (145–300 Ma) zircon, and 4%–29% middle Proterozoic (1300–1800 Ma) zircon, but only 0.4%–1.3% of the 300–1100 Ma grains that are so abundant in Colorado Plateau strata (Table 1). These minor amounts are readily explained by recycling of pre-Cretaceous sedimentary rocks in southern California (Fig. 2G). No Upper Cretaceous to Pliocene sample from coastal California contains >2% 300–1100 Ma zircon. This includes all Eocene to lower Miocene samples of extraregional detritus (Sespe River and its precursors), which contain <1% 300–1100 Ma zircon.

CONCLUSIONS

Age distributions of detrital zircons from southern California document changing drainage patterns of the southwestern United States for the Mesozoic and Cenozoic. Distinctive age distributions of detrital zircons similar to those of upper Paleozoic and Mesozoic strata of the Colorado Plateau are evident in Triassic through Lower Cretaceous strata of coastal California, but are not found in any younger strata. This indicates the absence of any drainage connection between coastal southern California and the Colorado Plateau region since the mid-Cretaceous, in contradiction of a hypothetical southwest-flowing Arizona River during the Paleogene (i.e., Wernicke, 2011) to partially cut Grand Canyon. Our observations are most consistent with rapid latest Miocene–Pliocene integration of the Colorado River (e.g., Spencer and Pearthree, 2001; Dorsey, 2010; Kimbrough et al., 2010; Dorsey et al., 2011) and rapid cutting of Grand Canyon since that time (e.g., Karlstrom et al., 2007, 2008).

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