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2016, pp. 479-489. https://doi.org/10.56577/FFC-67.479

in:

Guidebook 67 - Geology of the Belen Area, Frey, Bonnie A.; Karlstrom, Karl E. ; Lucas, Spencer G.; Williams, Shannon; Zeigler, Kate; McLemore, Virginia; Ulmer-Scholle, Dana S., New Mexico Geological Society 67th Annual Fall Field Conference Guidebook, 512 p. https://doi.org/10.56577/FFC-67

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New Mexico Geological Society Guidebook, 67th Field Conference, Geology of the Belen Area, 2016, p. 479-489.

NEW INSIGHTS ON THE LATE PLEISTOCENE RIO GRANDE–RIO CHAMA FLUVIAL SYSTEM FROM DETRITAL ZIRCON DATING

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Abstract—Detrital zircon analysis has excellent potential to elucidate the evolution of the Rio Grande–Rio Chama fluvial system by characterizing the provenance of sediment and assessing fluvial connectivity of Rio Grande rift basins through time. This study uses U-Pb geochronology of detrital zircon separated from modern river sediment, terrace deposits with the Lava Creek B ash (640 ka), and three intermediate terraces to reconstruct the provenance of sediment carried by the Rio Grande–Rio Chama fluvial system over the last 640 ka. U-Pb detrital zircon ages for Red River sediment are further supported by high precision $^{40}Ar/^{39}Ar$ detrital sanidine dating, which has the ability to identify age populations that are not resolved by lower precision detrital zircon dates.

The detrital zircon age spectra of a 640 ka Rio Grande terrace in the Albuquerque Basin and a 640 ka Rio Chama terrace show a number of diagnostic age peaks: 1) 23-25 Ma characteristic of the Latir Volcanic Field, 2) 27-28 Ma that could be either from the Latir or San Juan Volcanic Fields, 3) 34-35 Ma characteristic of the San Juan Volcanic Field, 4) Cretaceous-aged peaks, and 5) a "triple peak" consisting of 1.7, 1.4, and 1.1 Ga zircon derived from Precambrian basement, which is common in Phanerozoic sediments throughout the western U.S. Based on two samples, we interpret relatively abundant 28-36 Ma zircon in river sediment to be characteristic of the Rio Chama. These similarities are compatible with models showing that the Rio Chama – with San Juan Mountain headwaters – dominated the river system at 640 ka. Similar 28-35 Ma zircon in a 250-350 ka Rio Grande terrace in the Española Basin is compatible with models positing a San Juan Mountain source of detritus for the Rio Grande after spillover of Lake Alamosa ~430 ka, and with reworking of Santa Fe Group sediment. The 27-28 Ma temporal overlap between the San Juan and Latir Volcanic Fields is problematic for provenance, but modern river sand samples suggest it is possible to distinguish the 28 Ma San Juan Volcanic Field (Fish Canyon Tuff) zircon peak from the 22-27 Ma Latir Volcanic Field zircon peak. Although the Latir Volcanic Field has a 28.2 Ma tuff (Tetilla Peak Tuff), its associated zircon is much less abundant than younger zircon (e.g., the 25.49 Ma Amalia Tuff). The similar pattern of age peaks between 640 ka fluvial sediment in the Albuquerque Basin and the Rio Chama indicates that the Rio Chama dominated the river system at 640 ka. Preliminary detrital sanidine data for Red River sediment that was derived from the Latir Volcanic Field show that 23-25 Ma sanidine is twice as abundant as 27-29 Ma sanidine, and therefore abundant 27-29 Ma zircon in the Rio Grande system is interpreted to indicate fluvial connectivity to the San Juan Mountains.

INTRODUCTION

The Rio Grande is the fifth longest river in North America and flows from its headwaters in the high elevation San Juan Mountains of Colorado over 3000 km to the Gulf of Mexico. Its drainage basin receives water from more than 675,000 km^2 of the southwestern United States east of the continental divide (Fig. 1). The major source of recharge is snowmelt from the headwater region of the San Juan and Sangre de Cristo mountains. Significant tributaries to the northern Rio Grande that contribute to its sediment supply include (from upstream to downstream): the Conejos River, Red River, Rio Hondo, Rio Pueblo de Taos, Rio Embudo, Rio Chama, and Jemez River.

This paper builds on earlier models developed for the Rio Grande fluvial system (Bachman and Mehnert, 1978; Wells et al., 1987; Newell et al., 2004; Connell et al., 2005; Love and Connell, 2005; Machette et al., 2007; 2013). The Rio Chama system likely extends back to at least 6.96 Ma (Smith et al., 2001) and possibly played an important long-term role in draining the southern Rocky Mountains before the development of the Rio Grande. Thus, we use the terms Rio Grande and Rio Chama for the specific rivers above their confluence (Fig. 1), and we use the term Rio Grande–Rio Chama system for the combined rivers and their tributaries.

As depicted by previous workers (e.g., Connell et al., 2005; Love and Connell, 2005; Mack et al., 2006), the Rio Grande–Rio Chama system was not integrated through the internally-drained basins of the central Rio Grande rift until after about 5 Ma, when this system in northern New Mexico integrated with basins in southern New Mexico (e.g. Connell et al., 2005). Development of the Rio Grande into its modern drainage configuration occurred largely during the Pleistocene by means of multi-stage downward integration, likely facilitated by groundwater sapping and fluvial and lake spillover events (Connell et al., 2012). Wells et al. (1987) first suggested that the Red River and other tributaries draining the Sangre de Cristo Mountains served as headwaters to the Rio Grande, and the Rio Grande did not extend to the San Juan Mountains until the last several hundred thousand years. With continued downward drainage basin integration, the Rio Grande likely reached the Gulf of Mexico before the system began incising at ~800 ka (Pazzaglia and Hawley, 2004; Mack et al., 2006). Later spillover of Lake Alamosa occurred ~430 ka (Machette et al., 2013), which introduced, or possibly re-introduced, drainage from the high elevation, glaciated San Juan Mountains.

Ancestral Rio Grande–Rio Chama Detrital Zircon Provenance

Research on the evolution of the Rio Grande–Rio Chama has been extensive and has involved stratigraphic studies on related terraces (Wells et al., 1987; Gonzalez and Dethier, 1991; Dethier and Reneau, 1995; Newell et al., 2004; Koning, 2005;

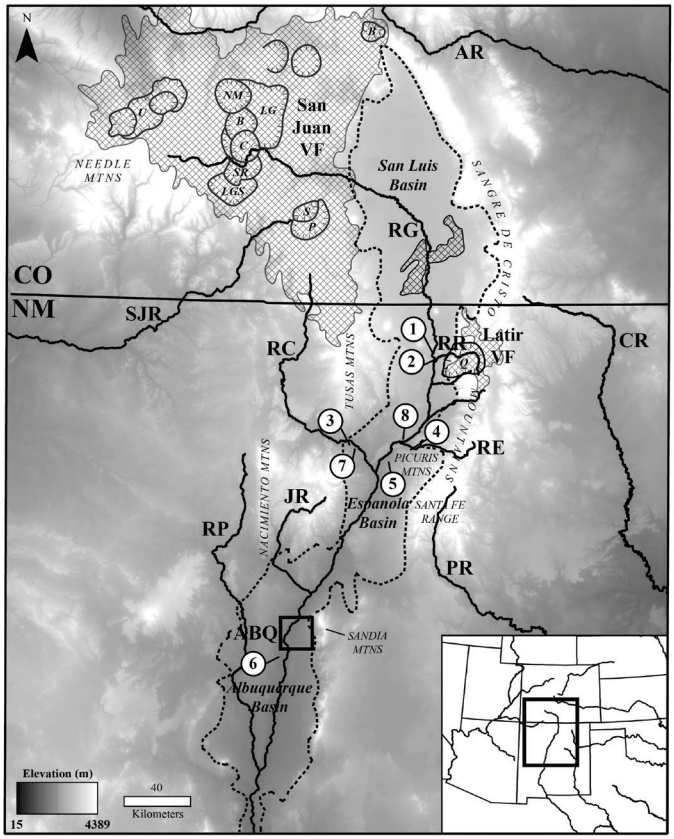


FIGURE 1. DEM of the southern Rocky Mountain-northern Rio Grande rift region showing modern drainage configurations in the Rio Grande-Rio Chama system, northern rift basins, and major calderas. Locations of the detrital zircon samples are as follows: 1) modern Rio Grande upstream of the Red River confluence, and 2) modern Red River, 3) ~30 ka Rio Chama terrace, 4) ~50 ka Rio Embudo terrace, 5) ~300 ka Espanola basin Rio Grande terrace, 6) 640 ka Albuquerque basin Rio Grande terrace, and 7) 640 ka Rio Chama terrace. Rivers: CR – Colorado River, AR – Arkansas River, RG – Rio Grande, SJR – San Juan River, RC -Rio Chama, RR – Red River, RE – Rio Embudo, RP – Rio Puerco, JR – Jemez River, PR – Pecos River, CR – Canadian River. Calderas: B –Bonanza, LG –La Garita, SR – South River, LGS – La Garita South, C – Creede, U – Uncompahgre, B – Bachelor, S – Summitville, P – Platoro.

Mack et al., 2006; Connell et al., 2007; Koning et al., 2011a), gravel provenance studies of terrace deposits (e.g., Koning et al., 2004; Koning and Manley, 2003), and chronologic studies of fluvial terraces using dates on associated volcanic ash, basalt, and biostratigraphic markers (e.g., Dethier et al., 1988). In particular, the Lava Creek B (LCB) tephra derived from the Yellowstone Caldera ca. 640 ka (Lanphere et al., 2002) provides excellent age control for many river terraces in the Rio Grande–Rio Chama system and throughout the Rocky Mountain region (Dethier, 2001). These LCB-aged terraces are inset against older Santa Fe Group sedimentary units and represent some of the earliest well dated fluvial terraces after the 0.8 Ma establishment of the through-flowing Rio Grande system to the Gulf of Mexico (Mack et al., 2006; Connell et al., 2005).

This paper focuses on analyzing the age distribution of upper Rio Grande detrital zircons collected from axial river deposits as old as 640 ka and as young as modern alluvium. The goal is to unravel the evolution of sediment sources in the tributaries of the upper Rio Grande since 640 ka. Utilizing modern alluvium and latest Pleistocene terraces provides a baseline from which to build a complete source-area characterization of the Rio Grande system. Comparison with detrital zircon populations in older mid-Pleistocene terraces may reveal any late Pleistocene changes in sediment sources that have occurred since then, and can highlight differences in sediment sources among tributaries. In particular, these detrital zircon data test the timing of the late-Pleistocene capture of upper San Luis Basin drainage for which Wells et al. (1987) had no age control, but Machette et al. (2007, 2013) proposed occurred ~430 ka.

U-Pb detrital zircon age data are reported here for five sand samples collected from Rio Grande, Rio Chama, Red River, and Rio Embudo fluvial terraces whose ages range from 640 ka to ~30 ka, two sand samples collected from modern Red River and upper Rio Grande channels above their confluence, and one sample of upper Santa Fe Group basin-fill sediment to evaluate reworking. Comprehensive detrital zircon research has been done on the Colorado River system (Kimbrough et al., 2015), but this is the first study of sediment transport for the Rio Grande system using detrital zircon geochronology. Additionally, this paper applies new techniques in detrital sanidine dating to complement detrital zircon dating for a modern sand sample from the Red River.

Detrital zircon geochronology can discern the provenance of sedimentary systems where zircon populations of a restricted age range can be identified in specific source regions. Conversely, detrital zircon age spectra can also be ambiguous where rocks of similar age occur in different source regions and where grains are recycled in multiple episodes of erosion and deposition. According to the summary in Love and Connell (2005), the post-640 ka headwaters of the Rio Chama and its tributaries (San Juan Mountains, Tusas Mountains, and Abiquiu embayment) have remained relatively unchanged over this time interval. In contrast, the headwaters of the Rio Grande, above its confluence with the Rio Chama, likely expanded into the San Juan Mountains and San Luis Basin after ~430 ka (Wells et al., 1987; Machette et al., 2007, 2013), with steady input of zircon from the Sangre de Cristo Mountains, Picuris Mountains, Jemez Mountains, and eroded Santa Fe Group in the Española and northern Albuquerque basins over the entire post-640 ka interval. A prelude to presenting and interpreting the detrital zircon data is to discuss possible detrital zircon that would be derived from different source regions and formulate tests of existing river integration models (e.g., Wells et al., 1987; Machette et al., 2007, 2013), which can be tested and improved based on our new detrital zircon geochronologic data. The following section reviews possible ages to be found in source regions of the Rio Chama and Rio Grande north of our southernmost sample near Albuquerque.

Sources of Sediment in the Rio Grande–Rio Chama Drainage System

Major sources of Rio Grande rift basin fill are reasonably constrained (e.g., Ingersoll et al., 1990; Smith, 2004), and regional basement uplifts are well dated. Below we summarize

zircon ages of possible sediment sources for the Rio Grande-Rio Chama system.

Precambrian sources

Karlstrom et al. (2004) summarized the Proterozoic tectonic evolution of northern New Mexico and reported U-Pb ages of Proterozoic plutonic and volcanic rocks. Jones et al. (2011) and Daniel et al. (2013) reported detrital zircon spectra from Proterozoic metasedimentary rocks whose associated zircon could have been recycled into Rio Grande–Rio Chama sediment. The oldest zircon populations in the Rio Grande-Rio Grande source regions are 1.8-1.7 Ga volcanogenic rocks that formed during the Yavapai orogeny; these are exposed in the Needle Mountains of Colorado, Tusas Mountains of northern New Mexico, and Sangre de Cristo Mountains near Taos. These basement rocks likely contributed 1.8-1.7 Ga zircon to the Rio Grande–Rio Chama system through tributaries that include Red River, Rio Hondo, Rio Pueblo de Taos, and Rio Ojo Caliente. Consequently, these ages are not useful to constrain exact source regions. Rhyolite-quartzite successions of the Vadito and Hondo groups dated at ~1.7 Ga are prevalent throughout northern New Mexico and include the Tusas Mountains on the western flank of the Rio Grande rift, the Needle Mountains of Colorado, and the southern Sangre de Cristo Mountains; these metasedimentary rocks also include Archean grains. Thus, 1.7-1.68 Ga and Archean grains may be derived from several locations and may have been extensively reworked; thus, they are not especially useful in determining source region. Proterozoic granite (1.66-1.63 Ga) rocks exposed in the southern Sangre de Cristo Mountains (Pedrick et al., 1998) may have provided a source of zircon to the Rio Grande near the Colorado-New Mexico border, as well as near Santa Fe, where granite is the dominant lithology (Metcalf and Stropky, 2011).

A 1.5-1.47 Ga succession of metasedimentary rocks called the Trampas Group (Daniel et al., 2013) is exposed only in the Picuris Mountains in the Rio Embudo drainage and contains a very distinctive age range of zircon from 1.6-1.5 Ga, an age range that is not found in igneous rocks of New Mexico (Karlstrom et al., 2004). Hence, this zircon age in the Rio Grande–Rio Chama system would be expected only from recycling of the Trampas Group in the Picuris Mountains. Granites dated at 1.45-1.35 Ga are present throughout the southern Rocky Mountain region, and zircons from these plutons could enter the Rio Grande system from the Needle Mountains near the Rio Grande headwaters in Colorado, as well as the Tusas, Picuris, Santa Fe, Nacimiento, and Sandia Mountains. Therefore, 1.45-1.35 Ga granites are not particularly useful in discriminating source regions.

A third Precambrian age peak at 1.0 Ga in many spectra may reflect recycled zircon from the de Baca Group (Karlstrom et al., 2004), recycled Pennsylvanian detritus derived ultimately from the Appalachian and Ouachita collisions (Gehrels et al. 2011), or recycled Jurassic eolian sandstones known to contain this zircon age (Dickinson and Gehrels, 2009). A similar-age pluton is present in the area of Pikes Peak that is outside of the Rio Grande drainage basin. Overall, the detrital zircon peaks at 1.7, 1.4 and 1.0 Ga are found throughout the southwestern United States, and therefore Precambrian grains have not been very useful in discriminating basement source terranes, but those from the 1.5-1.47 Ga Trampas Group offer potential.

San Juan Volcanic Field

The San Juan Volcanic Field lies in the Rio Grande headwaters and is expected to dominate the detrital zircon signature of the upper Rio Grande fluvial system (Fig. 1). Lipman (2007) provided a detailed summary of the eruptions that took place in the southern Rocky Mountains. The most voluminous eruption in the San Juan Volcanic Field (>5000 km^3) was that of the La Garita caldera at 28.20 ±0.05 Ma, which deposited the Fish Canyon Tuff (FCT). Detrital zircon from the FCT might be expected to have a dominant presence in the river systems that radially drain the southern Rocky Mountain region (Karlstrom et al., 2011). Drainage from the La Garita caldera enters directly into the uppermost reaches of the modern Rio Grande, suggesting that a large fraction of the zircon found in upper Rio Grande sediment should yield U-Pb ages of 28.20 ±0.05 Ma. While the modern Rio Chama has its headwaters in the southern San Juan Mountains, it does not have direct fluvial connectivity to the La Garita caldera. One might expect that detrital zircon samples from the Rio Grande will be rich in FCT-aged grains for periods of time when the river has direct fluvial connectivity to the southern San Juan Mountains. Thus, Rio Grande sediment deposited prior to the spillover of Lake Alamosa (>400 ka) should not be rich in FCT-aged zircon, unless grains were recycled from Santa Fe Group sediment.

Other significant eruptions in the Rio Grande headwaters occurred at 26.9 Ma (Nelson Mountain Tuff), 27.04±0.02 Ma (Snowshoe Mountain Tuff, Creede caldera), 27.56±0.05 Ma (Wason Park Tuff, South River caldera), and 27.73±0.05 Ma (Carpenter Ridge, Bachelor Mountain caldera) (Fig. 1; Lipman, 2007). In addition to these caldera events, voluminous eruptions from calderas outside of the Rio Grande headwaters resulted in deposition of older volcanic ash within the Rio Grande watershed. These include the 28 Ma eruption of the Uncompahgre caldera, several voluminous 29-30 Ma eruptions from the Platoro caldera in the southeastern San Juan Mountains, the 33.33±0.04 Ma (>1000 km^3-volume) eruption of the Bonanza caldera (Fig. 1), and the 37.25±0.08 Ma Wall Mountain Tuff (>100 km^3volume) that likely erupted near Mt. Princeton, Colorado (not shown on Fig. 1). Zircon from each of these eruptions could enter the headwaters of the Rio Grande and Rio Chama systems, and therefore we expect abundant zircon age populations ranging from 27-37 Ma for times when these paleorivers carried sediment sourced in the San Juan Mountains.

Latir Volcanic Field

The Latir Volcanic field lies within the Taos Range of the Sangre de Cristo Mountains in New Mexico, and is part of the greater southern Rocky Mountain Volcanic Field. Ages of caldera and pre-caldera eruptions within this field are reported in Zimmerer and McIntosh (2012). At present, volcanic rocks in the Latir Field cover an area roughly 1200 km^2, and are erosional remnants of what was once a much larger field. The Latir Volcanic field sits in the headwaters of the Red River, a major tributary to the Rio Grande in northern New Mexico and the

proposed pre-400 ka headwaters of the Rio Grande (Wells et al., 1987; Machette et al., 2013). The most significant eruption in the Latir Field was that of the Questa Caldera at 25.49 ±0.13 Ma, which deposited the (>500 km^3-volume) Amalia Tuff. Just prior to that event, the Cordova Creek rhyolite was emplaced at 25.57 ±0.04 Ma. Pre-caldera eruptions that were relatively low volume and intermediate in composition occurred synchronously with eruptions of the central San Juan Volcanic Field, including the 28.22 ±0.05 Ma eruption of the Tetilla Peak Tuff. Thus, zircon from the Latir Volcanic Field tuffaceous units would result in age peaks around 25.5 Ma (predominantly) and 28.22 Ma. The distinction between Latir field zircon and San Juan field zircon provides the opportunity to test the timing of the spillover of Lake Alamosa – when Rio Grande sediment became dominated by San Juan Volcanic Field sediment rather than Latir Volcanic Field sediment. One would expect very different chronological patterns of drainage integration for headward erosion vs. fluvial or lacustrine spillover. Headward erosion of the Rio Grande toward the San Juan Mountain headwaters might show gradual increases in proportions of San Juan volcanic detritus through time, whereas a spillover would result in an abrupt appearance of San Juan volcanic detritus in terraces younger than ~430 ka.

Santa Fe Group

Rio Grande rift basin fill (called the Santa Fe Group) is generally non- to moderately cemented and erodes relatively easily. Therefore, erosion of this basin fill in northern New Mexico likely provides a major proportion of sediment preserved in Lava Creek B deposits and younger terraces. Of particular interest in this paper is discrimination of two source areas in the middle to late Quaternary: the Latir versus San Juan Volcanic Field. Complicating this effort is the presence of older basin-fill lithologic units (Santa Fe Group and Los Pinos Formations) in the Española and San Luis Basins that were sourced from these two fields. This section summarizes previous provenance work in the San Luis and Española Basins, particularly that of Ingersoll et al. (1990), Smith et al. (2001), Smith (2004), and Koning et al. (2011b).

As far as is known, there was drainage connection between the southern San Luis Basin and the Española Basin throughout the Miocene (Smith, 2004). Clasts derived from the Latir Volcanic Field is seen in such units as the Abiquiu Formation, Cordito Member (Los Pinos Formation), Chama El Rito Member (Tesuque Formation) and the Picuris Formation. However, Oligocene-early Miocene Santa Fe Group sediment derived from the San Juan Volcanic Field is restricted to the Esquibel Member of the Los Pinos Formation (Manley and Wobus, 1982; Ingersoll et al., 1990). This lithologic unit is found on the eastern slopes of the Tusas Mountains (Butler, 1971; Manley and Wobus, 1982; Aby et al., 2010), and its detritus is currently shed into the Rio Grande in the southern San Luis Basin via Arroyo Aguaje de la Petaca.

METHODS

Seven detrital zircon samples were collected from Rio Grande–Rio Chama terrace deposits that have been dated at 640 ka or later, and one sample from the~10 Ma Ojo Caliente Sandstone of the Santa Fe Group. A sample of three to four liters of medium- to coarse-grained sand was collected from each locality shown in Figure 1. Samples underwent mineral separation and analysis at the Arizona Laserchron Center (Tucson, Arizona). Detrital zircon grains were analyzed using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), which yields ages with a precision and accuracy of ~1-2%. Although this analytical method has lower precision than other methods, its efficiency allows for a rapid analysis rate of more than one analysis per minute (Gehrels, 2014). In this study, we analyzed ~300 grains per sample to ensure enough data were collected to achieve a semi-quantitative representation of the age distribution of zircon in each unit, and to reduce the number of undetected age populations (Vermeesch, 2004; Andersen, 2005; Pullen et al., 2014). Sample descriptions are provided in the following section and are summarized in Table 1.

Detrital sanidine from the modern Red River was analyzed using $^{40}Ar/^{39}Ar$ geochronology, which yields higher precision ages relative to U-Pb geochronology. These data should help discriminate between volcanic sediment sourced in the Red River drainage versus in the upper San Luis Basin. Sanidine dating was performed at the New Mexico Geochronology Research Laboratory (Socorro, NM). K-feldspar was concen-

TABLE 1. Information for the eight detrital zircon samples.

Sample Number	Stratigraphic Unit	Age of Deposition (ka)	Number of zircon grains analyzed	Sample Elevation	Sample Location (UTM Zone 13S, NAD83)	
					Easting	Northing
1	Rio Grande	0	282	2020 m	438233	4056999
2	Red River	0	313	2130 m	440662	4059055
3	Qtc7	30	300	1804 m	387743	4007467
4	Qtes	50	279	1821 m	418517	4006805
5	Qtr1	300	321	1793 m	406565	3994976
6	Qtc3	640	288	1872 m	392584	4002545
7	Lomatas Negras Fm.	640	294	1561 m	341227	3869780
8	Ojo Caliente Sandstone	10,000	218	2103 m	417385	4011345

trated from the sand samples using heavy liquid mineral separation, and ~100 visibly clear individual sanidine grains were chosen in an attempt to concentrate sanidine from plutonic and metamorphic K-feldspars. Selected sanidine grains were irradiated at the U.S. Geological Survey TRIGA reactor in Denver, Colorado. Ages were obtained by single crystal laser fusion with a CO_2 laser and measured on an ARGUS VI noble gas mass spectrometer.

RESULTS

Rio Grande–Rio Chama System Detrital Zircon Analyses

Detrital zircon age data for the eight samples are displayed on age-frequency histograms with probability density curves that show the likelihood of a zircon grain within each sample falling within a given age distribution (Figs. 2 and 3). Figure 2 shows data for the four modern river zircon samples (samples 1-4) and Figure 3 shows data for the four oldest zircon samples (samples 5-8). The following sections describe their age distributions and sources (see also Tables 1 and 2).

Modern river sediment

Sample 1 is a medium- to coarse-grained sand collected from the channel bed of the modern Rio Grande approximately 1 km upstream of the Rio Grande-Red River confluence. Its detrital zircon fingerprint therefore characterizes the modern drainage configuration with the river fluvially integrated with the San Juan Mountains. A 28.6 Ma age-probability peak comprises 51% of this sample, whereas only 5% of the sample falls into the 23-26 Ma range of the Latir Volcanic Field. The mean of the zircon that fall within the 27-30 Ma range is 28.6, which is within analytical uncertainty of the FCT. The modern Rio Grande sample also yields Precambrian peaks at 1409 Ma and 1697 Ma. The latter peak has grain ages ranging from 1600 Ma to 1775 Ma and the most abundant 1685-1700 Ma population

TABLE 2. Detrital sanidine single crystal laser fusion analysis data.

Grain	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	$^{40}Ar^*$ (%)	Age (Ma)	±1s (Ma)
1	0.3770	0.0116	0.1892	0.228	44.0	85.1	2.189	0.084
2	1.886	0.0265	5.260	0.280	19.3	17.4	2.27	0.44
3	0.8262	0.0138	0.3710	0.212	37.0	86.7	4.945	0.092
4	2.613	0.0065	0.2428	0.419	78.1	97.3	17.596	0.049
5	2.983	0.0057	0.5618	0.524	89.1	94.4	19.501	0.042
6	3.365	0.0024	0.7423	0.952	212.6	93.5	21.767	0.026
7	8.846	0.0018	19.28	0.224	276.4	35.5	21.78	0.56
8	9.578	0.1220	21.64	0.021	4.2	33.3	22.1	1.0
9	4.557	0.0002	4.515	0.413	3069.8	70.7	22.300	0.074
10	4.177	0.0061	2.269	0.579	83.3	83.9	24.255	0.049
11	3.625	0.0070	0.1670	1.198	73.1	98.7	24.735	0.019
12	3.809	0.0064	0.7827	0.384	79.1	93.9	24.748	0.062
13	3.889	0.0010	0.9036	0.307	488.7	93.1	25.044	0.073
14	4.700	0.0129	3.163	0.162	39.5	80.1	26.04	0.74
15	4.052	0.0150	0.7435	0.086	34.0	94.6	26.50	0.24
16	4.306	0.0059	1.503	0.509	86.4	89.7	26.700	0.050
17	4.552	0.0004	1.931	0.391	1269.8	87.4	27.518	0.066
18	9.227	0.0111	17.65	0.066	46.0	43.4	27.7	1.8
19	5.291	0.0052	4.289	0.252	97.5	76.0	27.81	0.10
20	5.892	0.0292	6.242	0.120	17.5	68.7	28.0	1.0
21	5.713	0.0011	5.527	0.068	451.9	71.4	28.20	0.34
22	4.855	0.0068	2.056	0.374	75.1	87.5	29.345	0.068
23	6.004	0.0087	4.709	0.107	58.7	76.8	31.86	0.22
24	5.403	0.0049	2.627	0.160	104.1	85.6	31.95	0.15
25	38.52	0.1884	114.6	0.024	2.7	12.1	32.3	5.0
26	4.865	0.0161	0.4343	0.327	31.8	97.4	32.707	0.069
27	4.953	0.0059	0.4112	0.290	86.4	97.6	33.357	0.078

Analyses ran at the New Mexico Geochronology Research Laboratoy, Socorro, NM.
Ages are reported at 1σ uncertainty relative to FC-2 at 28.201 Ma and ^{40}K total decay constant of 5.543e-10/a.

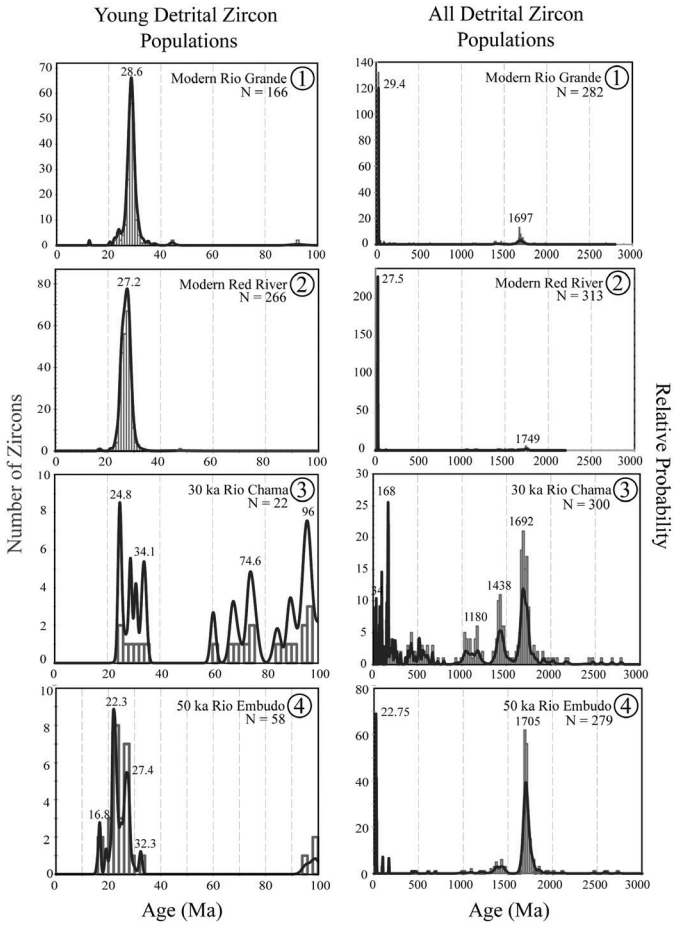


FIGURE 2. Detrital zircon age distributions for the four youngest detrital zircon samples discussed in this study (samples 1-4). Data are plotted on age-frequency histograms (gray bars), where the graphs in the right column show all zircon age populations from 0-3000 Ma in a sample and the graphs in the left column show only zircons younger than 100 Ma. The black curve shows the relative probability of a zircon falling within various age populations based on the density of ages and measurement precision. Note that while the same histogram bin-width was used in each plot, the frequency (y-axis) scale varies.

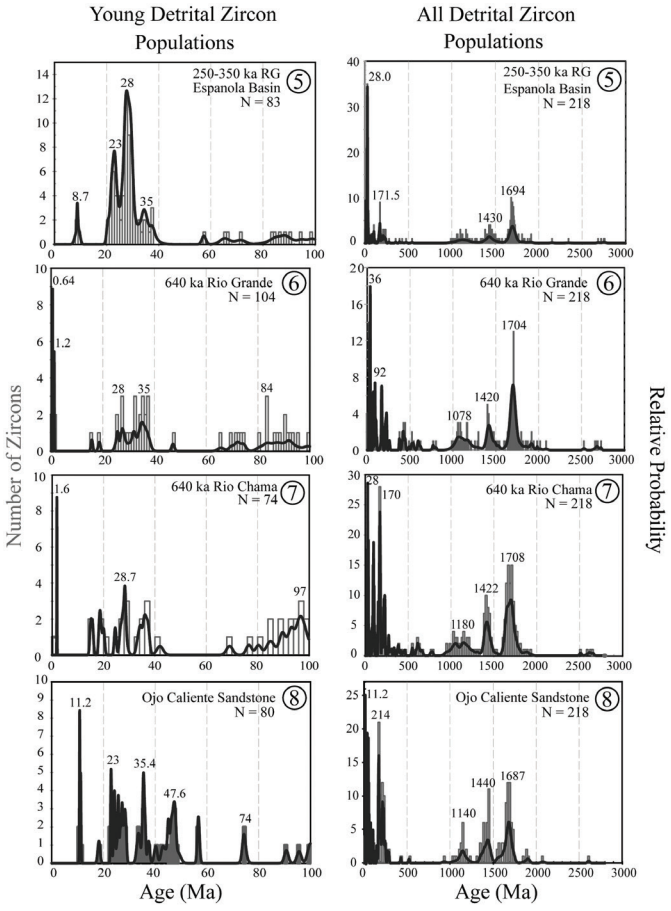


FIGURE 3. Detrital zircon age distributions for the four oldest detrital zircon samples discussed in this study (samples 5-8). See Figure 2 caption for explanation of plots.

is likely derived from the granites and quartzite-rhyolite sequences in the Taos range of the Sangre de Cristo Mountains. The small 1409 Ma age population may reflect sediment shed from the Needle Mountains in the Rio Grande headwaters as well as input from the modern Sangre de Cristo Mountains.

Sample 2 represents sediment deposited by the modern Red River, and its detrital zircon signature should help characterize one of the primary sediment sources in the Rio Grande that existed prior to the spillover of Lake Alamosa that was proposed by Machette et al. (2013). This sample consists of a medium-grained sand collected from the channel bed of the Red River ~3 km upstream of the Rio Grande confluence. More than 80% of the zircon in this sample is 23-30 Ma. The other 20% contains Proterozoic grains from the 1700-1450 Ma granites and 1800-1720 Ma volcanogenic rocks from the Taos Range. Forty-nine percent of the zircon is 23-26 Ma, with a population mean of 25.5 Ma, which is within analytical uncertainty of the Amalia tuff from the Latir Volcanic Field (see above). Eight percent of the zircon is 29-33 Ma, which we interpret as zircon ultimately derived from the San Juan Volcanic Field that were transported into the Red River drainage basin via eolian processes or were deposited in Santa Fe Group units preserved in the middle Miocene strata in the Valle Vidal graben within the Taos Range (Smith, 2004). Pilot detrital sanidine data for this sample was also collected (Table 2). Ages are reported at 1σ uncertainty relative to FC-2 at 28.201 Ma (Kuiper et al., 2008) and ^{40}K total decay constant of 5.643e-10/a (Min et al., 2000). The sanidine age distribution (N=27) plotted together with the detrital zircon age distribution (N = 265) for grains ranging from 0 Ma to 40 Ma. Because of the higher precision, the detrital sanidine age distribution reveals multiple peaks within the broad detrital zircon age peak (Fig. 4). The most prominent age peak is at 24.72, which is likely sanidine from the Amalia Tuff. Smaller peaks at 26.72, 27.52, 27.84, and 29.36 Ma may reflect erosion of Santa Fe Group sediment.

Sample 3 was collected from a ~30 ka Rio Chama terrace (Koning et al., 2004). We view this sample as representative of the young Rio Chama basin drainage configuration prior to influences of modern dams. The sample is a medium-coarse sand collected from terrace Qtc7 (Koning et al., 2004), one of the lowermost Rio Chama terraces. The gravel in this sample consists of coarse, well-rounded quartzite, granite, intermediate to felsic volcanic rocks, and basalt with a small percentage

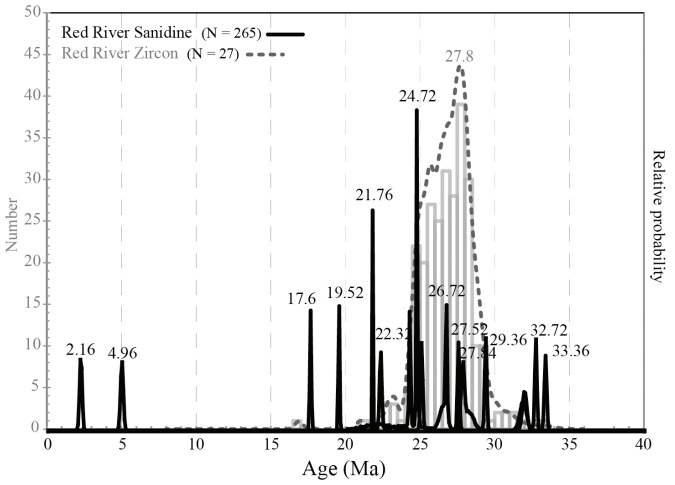


FIGURE 4. Normalized detrital zircon age probability plots for samples 1-8, showing probabilities for grains younger than 100 Ma normalized by the number of analyses used to generate the curves, such that each curve contains the same area. Shaded columns highlight the ranges of possible ages for Latir Field volcanic zircon (dark gray) and San Juan volcanic zircon (light gray). Narrow bands highlight the timing of the Amalia Tuff and Fish Canyon Tuff eruptions.

of Paleozoic-Mesozoic sandstone (Koning et al., 2004). The full detrital zircon age spectrum reflects all known rock ages in New Mexico, with dominant zircon age peaks at 24.8, 34.1, 74.6, 96, 168, 1180, 1438, and 1692 Ma (Fig. 2). The 24.8 Ma peak likely reflects reworking of the Abiquiu Formation immediately upstream of the sample site, which Smith (2004) and Smith et al. (2002) indicated is rich in Latir Field volcanic sediment. A relatively high frequency of zircon between 28 and 34.1 Ma reflects erosion of the San Juan Volcanic Field. The most dominant population is at 168 Ma, which reflects zircon eroded out of Jurassic sedimentary units in the Chama basin. A broad range of Proterozoic through Cambrian zircon is recognized, which likely reflects recycled grains shed from Mesozoic sandstones in the basin (Dickinson and Gehrels, 2009. The Precambrian populations are prominent and reflect recycled grains from Needle Mountain volcanogenic rocks and the Tusas Mountain quartzite-rhyolite successions.

Sample 4 consists of coarse sand from a late Pleistocene ancestral Rio Embudo terrace of estimated ~50 ka age based on 15 m height above the modern channel. This terrace was sampled to characterize sediment inputs from the Rio Embudo catchment in the Picuris and southern Sangre de Cristo Mountains. The detrital zircon spectrum is dominated by two prominent peaks: one at 22.3 Ma and the other at 1704 Ma. Additionally, there are smaller age peaks at 27.4 Ma and 1408 Ma. The 22.3 Ma peak is the center of a broad population spanning 19-25 Ma, which reflects reworking of the Picuris Formation, which was largely sourced from the Latir Field (Aby et al., 2004). The 22.8 Ma peak may be zircon eroded from the Rio Hondo pluton, which was emplaced between 22.8 and 22.6 Ma (Zimmerer and McIntosh, 2012). The 27.5 Ma peak is composed of grains ranging from 25.3 Ma to 28.6 Ma that were likely eroded from the middle tuffaceous member of the Picuris Formation (Aby et al., 2004). Some of these grains could have been derived from the 28.2 Ma Tetilla Peak tuff in the northern Latir Volcanic Field. The Precambrian ages are consistent with the ages of Precambrian basement exposed in the valley through which the Rio Embudo flows, including the ~1700 Ma rhyolite-quartzite successions and the ~1400 Ma granite. We did not observe 1.6-1.5 Ma zircon from the Trampas Group.

Pleistocene terraces

Sample 5 consists of coarse-grained sand collected from a Rio Grande terrace (Qtr1of Koning and Manley, 2003) near San Juan Pueblo, approximately 7.5 km northeast of the Rio Grande–Rio Chama confluence. The terrace is predominantly clast supported with lenses of medium- to coarse-grained sand, and the gravels are predominantly rounded to sub-rounded quartzite, amphibolite, granite, and basalt with some Paleozoic sedimentary rocks present. The Qtr1 strath sits ~90 meters above the modern Rio Grande. Koning and Manley (2003) suggested an age ranging from 250-350 ka for this terrace based on amino-acid ratio chronology data reported by Dethier and Reneau (1995) for Rio Grande terraces at similar elevations above the modern river channel. If this age constraint is correct, this terrace was abandoned by the Rio Grande after the proposed ~430 ka spillover of Lake Alamosa and this sample may provide a minimum age bracket for the drainage capture event. If upper San Luis basin zircon populations dominant relative to those sourced in the Red River drainage, this sample would reflect direct sediment connectivity to the modern headwaters in the San Juan Mountains in Colorado, or reworking of the Esquibel and Conejos Formations in the Tusas Mountains (Butler, 1971; Manley and Wobus, 1982; Aby et al., 2010). Three peaks at 23, 28, and 35 Ma dominate the age spectrum, which we interpret to represent sediment from both the Latir and San Juan Volcanic Fields. Relative to the Rio Chama terrace, there are very few Paleozoic and Mesozoic grains. Precambrian age peaks are 1694, 1430, and 1100 Ma, which arise mainly from sediment inputs from the Needle, Picuris, and Sangre de Cristo Mountains.

The 640 ka Lomatas Negras Formation is the oldest inset terrace deposit of the incising Rio Grande in the Albuquerque Basin (Connell et al., 2007). It is nicely exposed in an active gravel quarry 4.5 km west of and approximately 65 m above the modern Rio Grande channel. The gravel in this terrace is composed of quartzite, granite, and volcanic rocks derived from northern New Mexico source areas. Timing of terrace formation is constrained by a ~0.5 m thick, well-defined bed of fluvially reworked 640 ka LCB tephra that is interbedded with the sand and gravel (Connell et al., 2007). Sample 6 was extracted from medium-to coarse-grained, cross-bedded sand between moderately well sorted, subrounded to rounded axial river gravels approximately 6 m below a prominent ash layer. The detrital zircon fingerprint of this sample has dominant populations at 0.64, 1.2, 28-36, 92, 1078, 1420, and 1704 Ma. The 0.64 Ma peak represents the widespread fall of the LCB ash at 0.64 Ma, shortly before the Rio Grande deposited this sediment. The 1.2 Ma peak represents the Tshirege (upper) Member of the Bandelier Tuff, which was deposited by the 1.2 Ma eruption of the Valles Caldera and remains the predominant lithology in the Jemez Mountains today. The high proportion of 28-36 Ma zir-

con suggests fluvial connectivity between the San Juan Mountains and the Albuquerque Basin at 640 ka or reworking of the Esquibel and Conejos Formations in the Tusas Mountains from the Rio Ojo Caliente (Butler, 1971; Manley and Wobus, 1982; Aby et al., 2010). The 1070 Ma peak may reflect incorporation of grains reworked from Pennsylvanian-Permian or Jurassic units and are ultimately derived from Grenville-aged sources in the Appalachians (Gehrels et al., 2011).

A similar-aged terrace exists in the Rio Chama terrace sequence, where a single bed of reworked LCB ash (unit Qtc3 of Koning et al., 2004) constrains the age of the terrace at ~640 ka. The terrace strath sits 103 m above the modern Rio Chama. The sampled lowermost part of the fill is dominantly clast-supported with a gravel composition similar to that of the younger Rio Chama terrace Qtc7 (Koning et al., 2004). Sample 7 was collected from the sandy matrix of this terrace. Major zircon age probability peaks are at 1.6, 28.7, 97, 170, 1180, 1422, and 1708 Ma (Fig. 2). The population at 28-36 Ma indicates direct derivation from the San Juan Volcanic Field or reworking of the Ojo Caliente Sandstone, because the Esquibel Member of the Los Pinos Formation is not found upstream of this site (Smith et al., 2002; Smith, 2004). In contrast to sample 6, 1.6 Ma grains are present, but 1.2 and 0.6 Ma grains are absent. Similar to sample 6, Paleozoic and Mesozoic grains are present but not abundant. The small populations of Cretaceous and Paleocene zircon are likely derived from the San Juan Basin. There is 14-20 Ma detrital zircon as well as a prominent 1.6 Ma peak present in sample 7 that are not observed in sample 3, which is located 6.6 km upstream. This difference likely reflects input from erosion of early-middle-Miocene Santa Fe Group strata and terraces containing the 1.6 Ma Guaje tephra, both of which are mapped in the erosive badland landscape between the two samples (Koning et al., 2004).

Santa Fe Group Provenance

In addition to analyzing fluvial sediment associated with the development of the Rio Grande valley, we analyzed detrital zircon from Santa Fe Group sediment in the Española Basin to investigate grain recycling and reworking into the Rio Grande–Rio Chama fluvial system. Sample 8 is a medium-coarse sand collected from the Ojo Caliente Sandstone Member of the Tesuque Formation. This cross-bedded eolianite was deposited by prevailing westerly winds in the late Miocene and is up to 300-350 m thick (Koning, 2004). Based on the wind direction, this eolianite represents sand sourced in the Colorado Plateau. The youngest zircon in this sample was dated at 10.8 ±0.2 Ma, which we interpret to be the maximum depositional age of the Ojo Caliente Sandstone. The peak of 11.2 Ma correlates well with interpretations by Koning et al. (2011b) that an 11.3 Ma tuff (Cougar Point XI ash) is interbedded within the upper Ojo Caliente Sandstone 65 m below its upper contact. Furthermore, our zircon age of 10.8 ±0.2 Ma is consistent with interpretations that the upper Ojo Caliente Sandstone contact is 9-10 Ma in the northernmost Española Basin (Koning et al., 2013). Age-probability peaks in the detrital zircon age spectrum of sample 8 are at 11.2, 23, 35, 47.6, 74, 214, 1140, 1440, and 1687 Ma, which encompass the known rock ages in New Mexico older than 10 Ma. Fifty-two percent of the sample consists of Precambrian-aged zircon, whereas 29% of the sample is Mesozoic and 5% of the zircon may be derived from the San Juan Volcanic Field. The presence of a San Juan Volcanic Field-aged peak at 35 Ma in this sediment indicates that San Juan Mountain-derived sand was blown into the Española Basin around 11 Ma and incorporated into the Santa Fe Group. Thus, Rio Grande sediment can include 28-35 Ma zircon through reworking of Santa Fe Group sediment without having a direct fluvial connection to the San Juan Mountains.

DISCUSSION

Late Pleistocene Rio Grande–Rio Chama Drainage Evolution

Here we discuss our interpretations of the detrital zircon age distributions in each of the samples, which are normalized with respect to sample size in Figure 5. Samples 1 and 2 are essentially unimodal and of similar age, but because of the modern drainage configuration, the 28.6 Ma peak in sample 1 represents a greater contribution of San Juan Volcanic Field detritus and the 27.2 Ma peak in sample 2 reflects a Latir Volcanic Field source. The lack of >28 Ma peaks in sample 1 may be attributed to a higher proportion of FCT grains compared to older lithologies in the eastern San Juan Mountains. Rio Chama sediment (samples 3 and 7) has pronounced 28-38 Ma peaks and this difference may be a good way of discriminating a San Juan Volcanic source area.

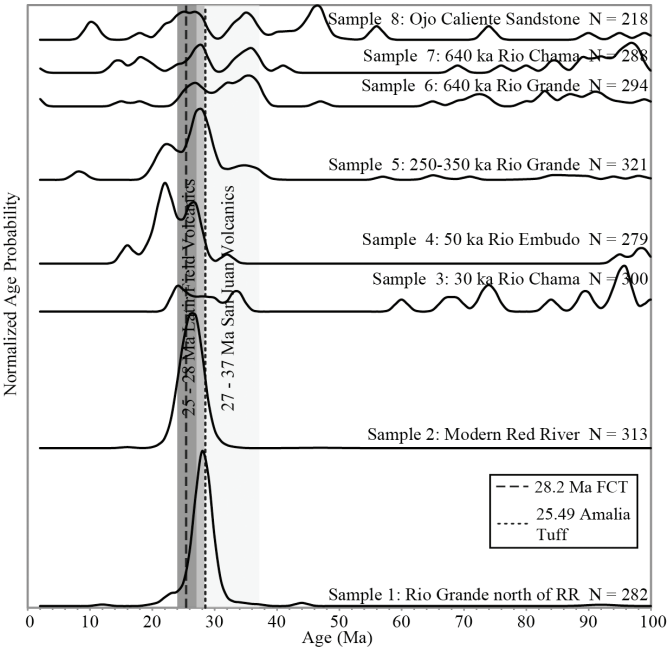


FIGURE 5. Normalized detrital zircon age probability plot comparing the detrital zircon populations in the 250-350 ka Espanola Basin Rio Grande sample to the combined detrital zircon populations in the modern Rio Grande upstream of the Red River confluence, modern Red River, and Rio Embudo samples. The differences in the two datasets reflect recycling of zircon from the Santa Fe Group into the Espanola Basin Rio Grande terrace deposit.

Populations of 20-40 Ma detrital zircon, including a peak at 28 Ma, are found in the 250-350 ka Rio Grande sample near Española (sample 5). This distribution reflects input from both the upper San Luis Basin and central Taos Range (drained by the Red River), consistent with its inferred age that postdates the proposed ~430 ka upper San Luis Basin drainage capture. Sample 5 shares many of the same age peaks with sample 8, indicating that much of the detritus in this sample has been recycled out of upper Santa Fe Group sediment into which the Rio Grande has been incising.

Samples 6 and 7 represent detritus carried by the Rio Grande-Rio Chama system and Rio Chama at 640 ka, respectively. Their detrital zircon age probability curves are very similar, sharing young LCB- and Bandelier Tuff-aged peaks, as well as both San Juan and Latir Volcanic Field peaks. The only notable difference is the lack of 0.64 and 1.2 Ma peaks and the dominance of a 1.6 Ma peak in sample 7 on the Rio Chama, which can be explained by a high abundance of 1.2 Ma tuff in the eastern and southern Jemez Mountains and the presence of eroding 1.6 Ma terraces in the vicinity of sample 7. This suggests that the Rio Chama was the dominant source of sediment in this system prior to integration of the upper San Luis Basin, an inference we test below using statistical comparison.

The Kolmogorov-Smirnov (K-S) test is useful for statistically comparing two detrital zircon age distributions because it generates a probability value (p-value) that indicates the probability that two samples could have been derived from the same population. A p-value lower than 0.05 indicates with 95% confidence that there is a statistically significant difference between the two samples and they could not have been derived from the same population. A p-value exceeding 0.05 suggests that two samples could have been derived from the same population, but does not necessarily indicate that the samples are the same (Guynn and Gehrels, 2010).

Comparison of sample 6 with samples 3 and 7 generates p-values of 0.139 and 0.154, respectively, indicating that these samples could be part of the same population. This is consistent with our interpretation that Rio Grande sediment delivery to the Albuquerque Basin at 640 ka was sourced mainly by the Rio Chama based on its detrital zircon spectra. Results of a K-S test on samples 5 and 6 yields a p-value of 0.014, indicating with 95% confidence that the 640 ka Rio Grande in the Albuquerque Basin does not have the same zircon distribution as the Rio Grande north of the Rio Chama confluence. Applying this test to the remaining samples gives results that do not exceed 0.05, indicating that there is a statistically significant difference among the remaining terraces. Thus, the K-S test strengthens our interpretations that the Rio Chama was the main provider of sediment to the Rio Grande–Rio Chama fluvial system prior to the ~430 ka integration with the upper San Luis Basin.

Figure 6 shows a comparison between the young detrital zircon age spectrum of sample 5 and that of the combined zircon age spectrum of samples 1, 2, and 4. The combination of sediment from the modern Rio Grande upstream of the Red River confluence, the modern Red River, and the young Rio Embudo should produce a similar detrital zircon age spectrum to that of the 250-350 ka Rio Grande terrace in the Española

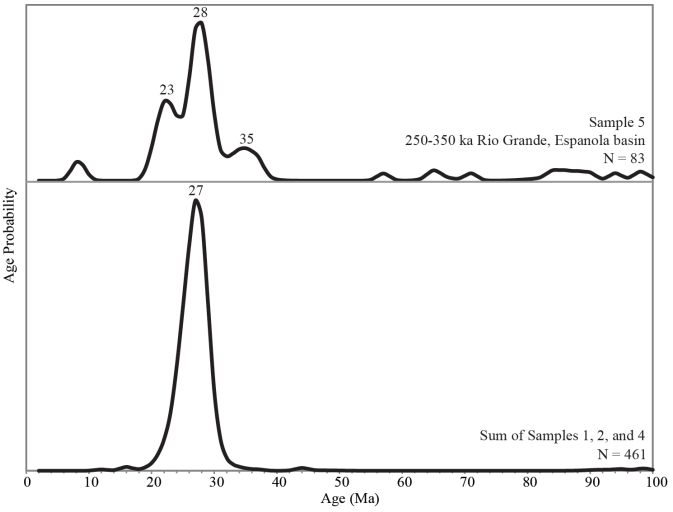


FIGURE 6. Red River detrital sanidine age probability curve (black) transposed on an age-frequency histogram and age probability curve (gray) for modern Red River detrital zircon. The high precision of the 40Ar/39Ar sanidine ages helps to identify age peaks that are smoothed out of the detrital zircon probability plot.

Basin because of its position downstream of these tributaries. Both show the 23 Ma age peak in the detrital zircon distribution of sample 5 corresponds to the 23 Ma peak observed in the Rio Embudo age spectrum, reflecting grains derived from the Latir Volcanic Field. The age peaks observed in sample 5 that are not observed in the combined spectrum (i.e., 35 Ma and Cretaceous peaks) may reflect recycling of sediment from the Santa Fe Group, including the Ojo Caliente Sandstone (sample 8) and the aforementioned Los Pinos Formation. The combined spectrum suggests that 35 Ma grains were not transported downstream from the Rio Grande headwaters, but appear to only be recycled into the river sediment from the Santa Fe Group and the Los Pinos Formation.

Detrital Zircon-Sanidine Study

Measurement uncertainties associated with U-Pb dating make it impossible to distinguish the 28.2 ±0.05 Ma FCT of the San Juan Volcanic Field from the 28.22 ±0.05 Ma Tetilla Peak Tuff of the Latir Volcanic Field. Both of these felsic volcanic rocks are rich in sanidine (a high-temperature potassium feldspar) that can be precisely (up to ±0.01 Ma uncertainty) dated using the $^{40}Ar/^{39}Ar$ method. We present pilot age distribution data for detrital sanidine separated from modern Red River sand (sample 2) in order to distinguish grains derived from the Red River drainage from those transported directly from the San Juan Mountains by the Rio Grande. Figure 4 compares the Eocene-Oligocene volcanic sanidine and zircon in the Red River sediment and shows that 25-27 Ma sanidine is twice as abundant as the 27-29 Ma sanidine. The absence of a peak at 28.2 Ma suggests that very few grains from the Tetilla Peak Tuff made their way downstream in the Red River and into the Rio Grande. Therefore, the 28 Ma peaks observed in the detrital zircon age distributions of downstream Rio Grande

terraces are dominated by FCT grains derived from the San Juan Mountains.

CONCLUSIONS

This pilot detrital zircon and sanidine study of the Rio Grande–Rio Chama system shows promise for understanding the evolution of this river system by distinguishing Rio Grande from Rio Chama sediment sources using detrital mineral geochronology. At the time of the LCB eruption (640 ka), the Rio Grande in the Albuquerque Basin carried nearly the same sediment as the Rio Chama and we infer that the Rio Chama dominated the fluvial system at this time. The Española Basin Rio Grande sample (sample 5) is key to distinguishing the Rio Grande from the Rio Chama because this location has no fluvial or sediment connectivity to the Rio Chama. The presence of 35 and 28 Ma zircon in sample 5 is consistent with direct fluvial connection of the Rio Grande with the San Juan Mountains, as predicted by the models of Wells et al. (1987) and Machette (2007; 2013), however, this zircon could also be derived from reworking of the Santa Fe Group.

The detrital zircon signatures of the modern Rio Chama, Rio Grande, Red River, and Rio Embudo are distinct from each other. The Rio Chama sediment reflects detritus from rocks of every age known in northern New Mexico. The northern Rio Grande and its tributaries are much more restricted in terms of the origin of their sediment. The Red River is dominated by detritus from the Latir Volcanic Field, as expected, and has minimal (<10%) San Juan-aged grains, which suggests that any 28-35 Ma age peak in the Rio Grande reflects detritus sourced in the San Juan Mountains. The detrital zircon age signature of another tributary, the Rio Embudo reflects local basement rocks and reworking of the Picuris Formation, the latter of which contains reworked sediment from the Latir Volcanic Field. Work is underway to extend the detrital zircon and sanidine record into stratigraphically older terraces, as well as farther downstream in the Rio Grande system, to help constrain the timing of downstream integration to the Gulf of Mexico.

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Travertine dams. Photo courtesy of Bonnie Frey.