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M. Kolomaznik, J. W. Ricketts, A. Priewisch, L. J. Crossey, K. E. Karlstrom, Y. Asmerom, and V. Polyak

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U-SERIES DATING AND STABLE ISOTOPE ANALYSIS OF QUATERNARY TRAVERTINES WITH IMPLICATIONS FOR INCISION RATES IN WESTERN RIO GRANDE RIFT, CARRIZO ARROYO, NEW MEXICO

M. KOLOMAZNIK, J.W. RICKETTS, A. PRIEWISCH, L.J. CROSSEY, K.E. KARLSTROM, Y. ASMEROM, AND V. POLYAK
Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque NM, USA 87131, lcrossey@unm.edu

ABSTRACT—Travertine deposits associated with fluvial terraces in Carrizo Arroyo, central New Mexico indicate that Plio-Pleistocene incision rates in this area have fluctuated since 3.7 Ma. Carrizo Arroyo is an east-west trending intermittent tributary to the Rio Puerco on the west side of the Rio Grande rift. It has incised deeply into the Carrizo Mesa basalt (3.7 ± 0.4 Ma) and underlying Paleozoic and Mesozoic strata exposed by the Lucero uplift. Based on the age of the Carrizo Mesa basalt and its height above the modern streambed (~ 183 m), Carrizo Arroyo incised at a minimum long-term average of 50 m/my over the history of the arroyo. Since the deposition of the basalt, terraces of abandoned river deposits were deposited at different elevations above the modern stream in Carrizo Arroyo. These terraces contain travertine as both flowstone and gravel-coating cement. We used the travertine in these terrace remnants to calculate late Pliocene and Quaternary incision rates since 3.7 Ma using the U-series radiogenic method. The terraces with travertine deposits located at 2, 18, and 130 m above the present stream give U-series and model ages of 3 ka ±0.015 ka, 170-180 ka ±1 ka, and 1180 ka ±440 ka, respectively. This indicates that the drainage incised at an average rate of ~19 m/my from 3.7 Ma to 1180 ka, but subsequent incision increased dramatically to ~150 m/my. The nearby lower Rio Puerco shows a similar incision history, with increased incision rates around 1 Ma. This regional trend may reflect: (1) climatic changes, which resulted in more erosive conditions during the late Pleistocene, (2) surface uplift due to Quaternary volcanism and mantle driven uplift associated with the Jemez lineament, and/or (3) integration of the Rio Grande system through the Albuquerque Basin.

INTRODUCTION

Carrizo Arroyo is an intermittent east-west trending drainage located in central New Mexico, 50 km southwest of Albuquerque (Fig. 1). This study seeks to better constrain the incision history in this arroyo using both new and existing geochronology. By comparing the results of this study to other drainages in the region, our results add to a growing understanding of the Quaternary incision history of the Rio Grande system of central New Mexico.

Carrizo Arroyo flows east, cutting through relatively undeformed Paleozoic strata and a Pliocene basalt flow on the Colorado Plateau. It then flows across a narrow zone of deformation formed by the Comanche and Santa Fe faults, and finally enters the Rio Grande rift and drains into the Rio Puerco (Fig. 2). A Tertiary-age basalt flow tops the canyon and helps define what is known as the Ortiz Surface (Bachman and Mehnert, 1978). The basalt sits ~183 m above the arroyo and has a K-Ar age of 3.7 ± 0.4 Ma (Bachman and Mehnert, 1978). If incision were steady, this would indicate a minimum average bedrock incision rate of about 50 m/my since 3.7 Ma (Fig. 3).

Perched terraces containing travertine-coated gravels provide an opportunity to determine more recent incision rates through time in Carrizo Arroyo. These Quaternary-age terraces are found at three different elevations above the modern stream at lower elevations than the basalt flow, creating an inverted topography, which tracks the incision of Carrizo Arroyo since the formation of the oldest terraces (Fig. 3). In this study, terraces have been labeled according to their height above the modern streambed. Qt 3 is the highest terrace above the modern streambed (~130 m), Qt 2 is the middle terrace above the modern streambed (~16-17 m), and Qt 1 is the lowest terrace above the modern streambed (~2 m). Locations of specific terraces are marked in Figure 2. The characteristics of these gravel terrace deposits and the presence of travertine-coated clasts identify these as abandoned paleostream terraces. The gravel terraces contain pebble- to cobble-sized clasts of sandstone and limestone that are locally derived from the adjacent Pennsylvanian and Permian bedrock units. Some terraces are cemented with thin rims of clast-coating travertine, while other terraces are cemented with thicker (>3 cm to several meters) accumulations of flowstone travertine (Fig. 4).

URANIUM-SERIES GEOCHRONOLOGY

We used the uranium-series method to calculate the age of the samples by measuring the ratio of ^{234}U to ^{230}Th (Bourdon et al., 2003). All lab work was performed in the Radiogenic Isotope Laboratory at the University of New Mexico using powdered samples obtained by drilling small sections of the hand samples (Fig. 4). Samples were analyzed using a Thermo Neptune multicollector inductively coupled plasma mass spectrometer (MC-ICPMS). The analysis was conducted according to Asmerom et al. (2010).

Small amounts of ^{234}U (a daughter isotope of ^{238}U) are present in natural waters, and become incorporated into the crystal lattice of travertine when it precipitates, whereas ^{230}Th is insoluble and excluded. As a result, any ^{230}Th present in travertine is a daughter isotope of ^{234}U as it decays. The U-series method provides precise dating for samples up to 500 ka; samples older than this are generally out of U-series range. For samples between 0.5 and 1.5 Ma, a ^{234}U model age can be estimated using an assumed initial $\delta^{234}U$ value. Samples older than about 1.5 Ma reach secular equilibrium (where the activity of the parent isotope ^{238}U is equal to the activity ratio of the daughter isotope ^{234}U) and dating would

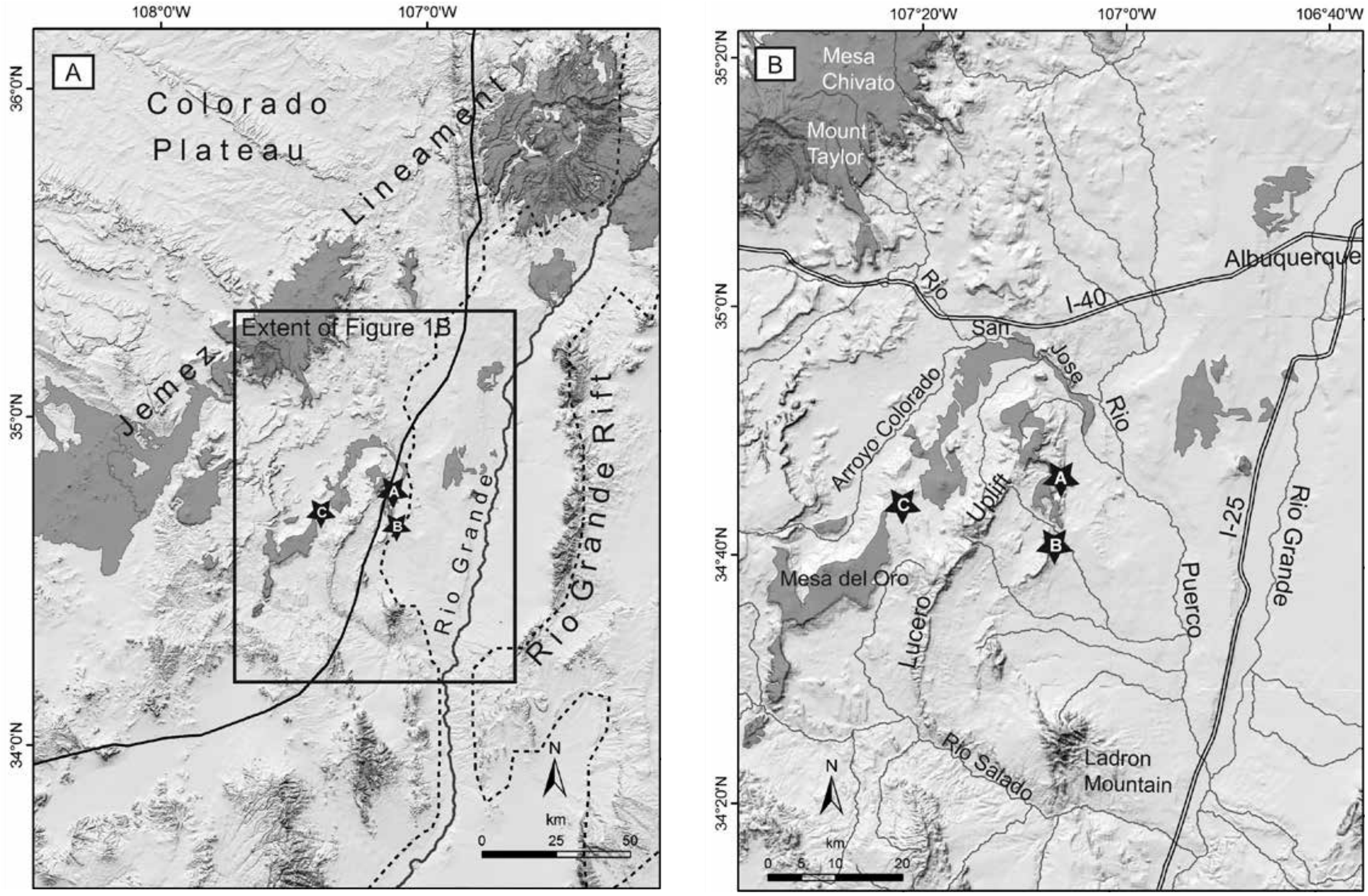

FIGURE 1. A) Shaded relief map showing central New Mexico and associated tectonic features: Colorado Plateau (outline by solid black line), Jemez Lineament, and Rio Grande Rift (outlined by dashed line). Grey shaded areas are Cenozoic volcanics. Stars indicate travertine deposits: A = Carrizo Arroyo, B = Mesa Aparejo, C = Mesa del Oro. B) Enlargement of the region south of I-40 where the travertine deposits are located: travertines at Carrizo Arroyo (Star A) and Mesa Aparejo (Star B) are located to the east of the Lucero Uplift, the travertine deposit at Mesa del Oro (Star C) is located west of the Lucero Uplift. Also shown are major rivers in the area.

require U-Pb techniques (Bourdon et al., 2003). Our model age calculations assumed an initial $\delta^{234}U$ value of 2000, based on an average of initial $\delta^{234}U$ values from the successful (younger) U-series dates (894-984 $\delta^{234}U$ and 3586 $\delta^{234}U$ for Qt 2 and Qt 1, respectively). The model age calculation hence assumes that source water composition of the older sample was similar to the source water composition of the younger samples.

STABLE ISOTOPE GEOCHEMISTRY

We measured ratios of stable isotopes for oxygen and carbon in travertine in order to infer general source water composition at the time of travertine precipitation (Crossey et al., 2011). Lab work was performed in the Stable Isotope Laboratory at the University of New Mexico using the same powdered samples used for U-series geochronology. This powder was then flushed with He gas and reacted for 24 hours with H_3PO_4 at 50°C (Spotl and Vennemann, 2003). The resulting CO_2 was measured by a continuous flow mass spectrometer with universal CNOS collectors connected to elemental analyzer, GasBench and CombiPAL autosampler.

Stable isotope results from Carrizo Arroyo indicate values similar to analyses from nearby large-volume travertine deposits Mesa Aparejo and Mesa del Oro (Fig. 5; Priewisch et al., 2012). $\delta^{13}C$ values at Carrizo Arroyo range widely from +0.17‰ to +7.16 ‰ (PDB), while $\delta^{18}O$ values vary relatively little between -5.49‰ and -8.95‰ (PDB). Stable isotope values for travertines characteristically exhibit broad ranges (Sharp, 2007). Carbon isotopic signatures reflect kinetic effects related to high rates of degassing CO_2 during travertine formation (Zhang et al., 2001), while the oxygen isotopic values are controlled by the source water composition and temperature (Kele et al., 2011). The similarity in stable isotope results between Carrizo Arroyo, Mesa Aparejo and Mesa del Oro travertines (Fig. 5) potentially suggests similar source waters. The relatively small range of $\delta^{18}O$ values in Carrizo Arroyo samples indicates that the source water composition for the travertine likely did not change dramatically between the deposition of Qt 3 and the younger terraces (Fig. 5). This is consistent with the assumed similarity of initial $\delta^{234}U$ values used for the model age estimate for Qt 3.

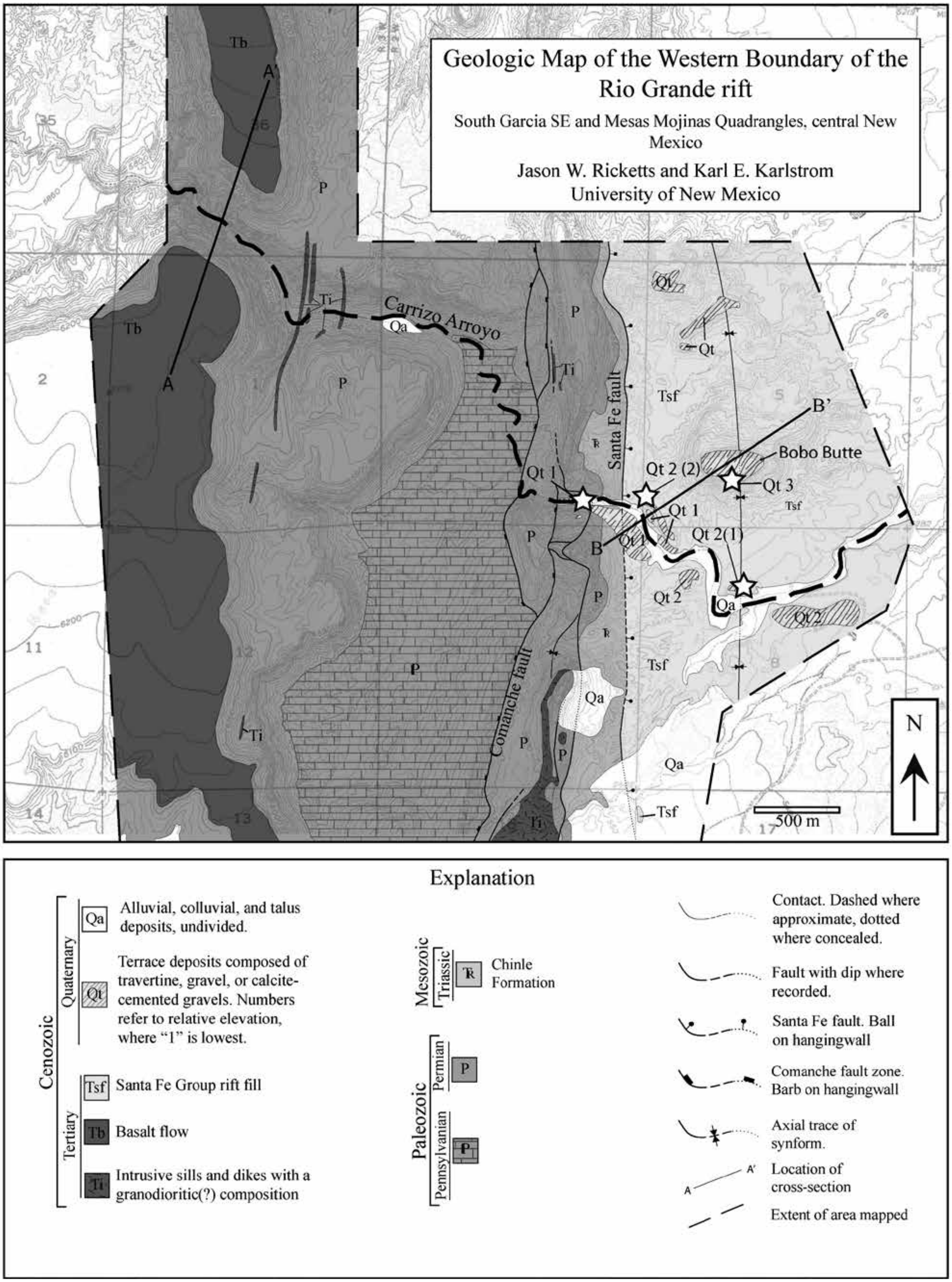

FIGURE 2. Geological setting of Carrizo Arroyo. Carrizo Arroyo drains eastward towards the Rio Grande and flows across the Comanche fault and Santa Fe fault. Carrizo Arroyo cross-cuts a basalt flow near the head of the arroyo (cross-section A-A'), while travertine deposits associated with perched terrace remnants are located farther down the drainage (cross-section B-B').

U-SERIES RESULTS AND INCISION RATES

Terrace heights and U-series ages are summarized in Table 1. Local incision rates for the three perched terraces at different heights above the modern stream were calculated from their present-day strath heights and U-series ages, shown in Figure 6. The oldest travertine terrace, Qt 3, was outside U-series range (> 500 ka), and therefore we calculated a model age and an error estimate using a reasonable range of initial $\delta^{234}U$ values. Error bars for other samples are included in Table 1. Between the formation of the canyon (after 3.7 Ma as constrained by the basalt occurrence described above) and the deposition of Qt 3 (about 1 Ma), there was little erosion and the canyon likely incised at a relatively low rate of 19 m/my. After 1 Ma, the incision rate in Carrizo Arroyo increased to a much higher rate of about 150 m/my. After about 170 ka, the incision rate perhaps slowed slightly to a rate of 124 m/my (Fig. 6).

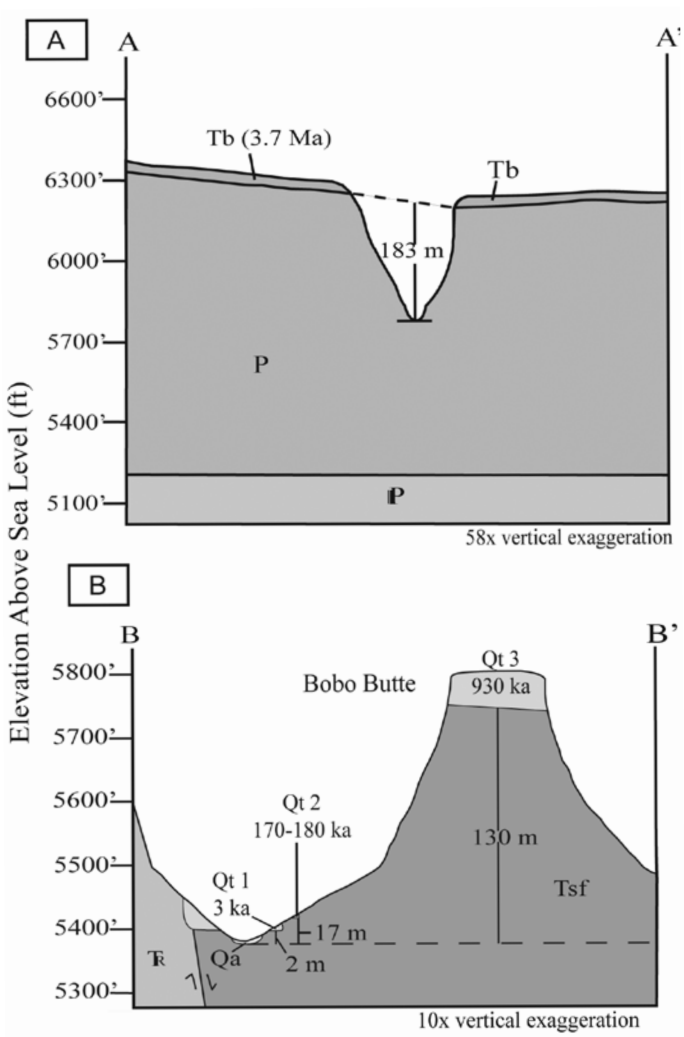

FIGURE 3. A) Cross-section A-A' (Fig. 2) through the Carrizo Arroyo Basalt (Tb) showing incision of Carrizo Arroyo. Stratigraphic units are the same as in Figure 2. B) Cross-section B-B' (Fig. 2) showing travertine-cemented terraces (Qt1, Qt2, Qt3) and their heights above stream. Also shown are the U-series ages of the travertine cement. Stratigraphic units are the same as in Figure 2.

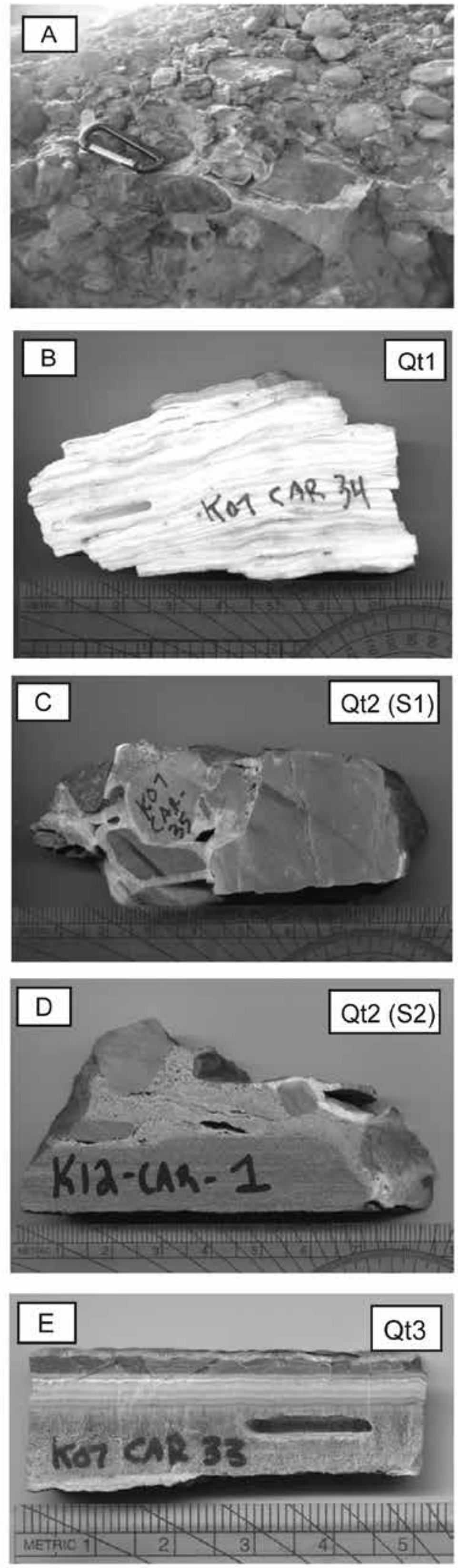

FIGURE 4. Travertine samples. A) Travertine-cemented perched gravel-terraces. B) Travertine hand sample consisting of pure white calcite layers. C) and D) Travertine-cemented river gravels. E) Massive and laminated travertine hand sample. For more detailed descriptions of the samples see Table 1.

TABLE 1. Geochronology and Heights of Travertine Terraces.

Terrace	Sample ID	Method	Age (ka)	± Error (ka)	Height above stream (m)
Basalt	Bachman and Mehnert, 1978	K-Ar	3700	400	183.0
Qt 3 (Bobo Butte)	K07 Car 33	Model age calculation	930	440	130.0
Qt 2 (Sample 1/S1)	K07 Car 35	U-series	179	1.2	17.0
Qt 2 (Sample 2/S2)	K07 Car 1	U-series	169	0.9	16.4
Qt 1	K07 Car 34	U-series	3	0.02	2.0

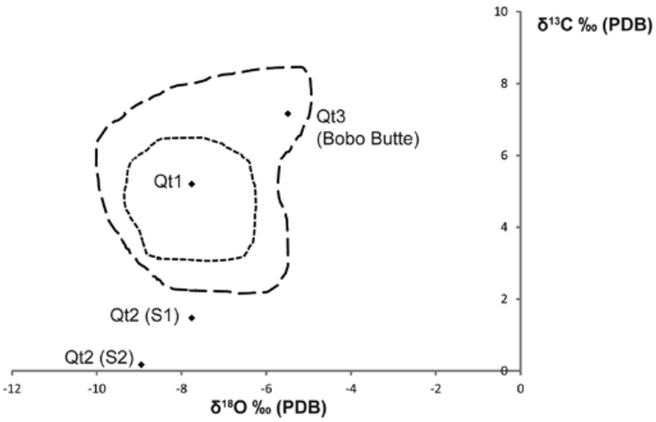

FIGURE 5. Stable isotope results of Carrizo Arroyo travertine samples (black diamonds). Dashed lines delineate the range of stable isotopes from travertine at Mesa del Oro (large dashes) and Mesa Aparejo (small dashes; Priewisch et al., 2012) $\delta^{13}C$ values of Carrizo Arroyo samples range from 0.17 to 7.16‰, while $\delta^{18}O$ are more consistent, with values ranging from -5.49 to -8.95‰. These $\delta^{18}O$ values indicate that source water composition was relatively consistent over the time of deposition of the Carrizo Arroyo travertine.

DISCUSSION

Geochronology of travertine terraces in Carrizo Arroyo indicates that incision rates in the area have changed over time, shifting from lower incision rates to higher incision rates at around 1 Ma. The nearby lower Rio Puerco has a similar incision rate history (Love and Connell, 2005), changing from low incision rates to high incision rates around 1 Ma (Fig. 6). This indicates that the change in incision rates at Carrizo Arroyo is likely a result of regional processes. Changing incision rates seen in Carrizo Arroyo and the Rio Puerco may be explained by a combination of climatic changes, tectonic activity, and/or drainage reorganization over this region.

Potential climatic factors driving changing incision rates may be a global shift toward more frequent and more dramatic climate changes in the past ~2 Ma due to global increase in amplitude and frequency of climate change (Molnar, 2004). This may explain increased incision rates and widespread terrace development in a number of New Mexico rivers and their tributaries (Connell et al., 2005).

Alternatively, Quaternary volcanism along the Jemez lineament and Rio Grande rift may have led to increased incision rates in both Carrizo Arroyo and the Rio Puerco by changing local base level (Dunbar, 2005). Surface uplift associated with volcanism and low-velocity mantle of the Jemez lineament has been proposed to affect Quaternary drainages in northeastern New Mexico (Nereson et al., 2013). Similarly, volcanism related to the Mount Taylor and Zuni-Bandera volcanic fields in central New Mexico may have resulted in uplift of the headwater areas of Carrizo Arroyo, effectively inducing the increased incision rates seen over this region. Another

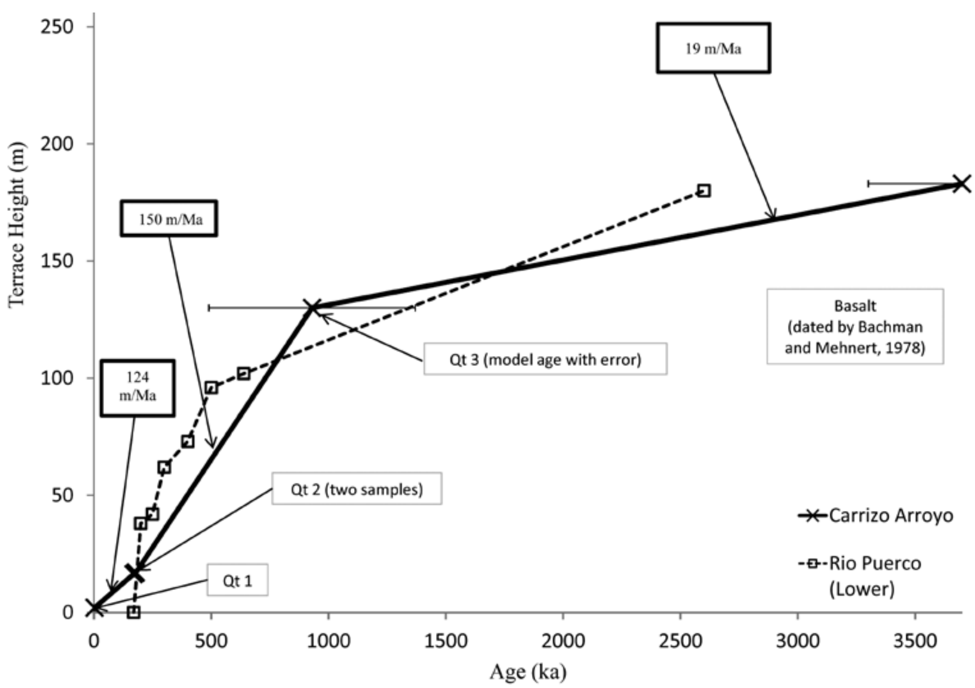

FIGURE 6. Incision rates determined for Carrizo Arroyo. Bedrock incision rate began at a rate of ~19 m/Ma, and then at about 1 Ma increased to ~150 m/Ma. Samples from Qt 1 and Qt 2 were dated precisely with U-series methods, while Qt 3 age is a calculated model age with error bar. The basalt was dated by Bachman and Mehnert (1978) with the K-Ar method. Note similar incision history determined from the Rio Puerco (Love & Connell, 2005) with changes from low incision rates to high incision rates starting at about 1 Ma.

potential driver is inflation of the Socorro Magma body, resulting in surface uplift over the magma body (Fialko and Simons, 2001) which may also have affected drainages. Although this is an intriguing possibility, the Socorro Magma body is downstream of the study area and would require very broad surface doming to affect the Carrizo Arroyo region.

Geomorphologic drivers of changing incision rates may include drainage reorganization events related to integration of separate sub-basins within the Rio Grande drainage system. Connell et al. (2005) suggested that the upper Rio Grande system was integrated by about 5 Ma to form an ancestral Rio Grande which flowed into playa lakes of the Albuquerque basin. By late Pliocene time, this ancestral Rio Grande probably flowed to the Gulf of Mexico. However, major eruptions of the Valles Caldera system at 1.6 and 1.25 Ma may have caused renewed internal or intermittent drainage and promoted establishment of inset fluvial terraces beginning between 1.2 Ma and 0.67 Ma (Connell et al., 2005).

CONCLUSIONS

Geochronologic and stable isotope data indicate that incision rates in Carrizo Arroyo have changed over time, from a slower average rate of about 19 m/my (from 3.7 Ma to 1 Ma) to higher average rates of about 150-124 m/my since 1 Ma. This onset of more rapid incision is also observed in the nearby lower Rio Puerco. Increased incision rates potentially have multiple drivers, including (1) a global shift in climate behavior, (2) local tectonics and surface uplift related to basaltic volcanism and magmatism, and/or (3) by drainage basin integration of the Rio Grande river system. However, until more studies are conducted, it is reasonable to assume that more extreme Quaternary climate changes, neotectonics, and geomorphic evolution may all have played a role in explaining the increased incision rates of Carrizo Arroyo at about 1 Ma.

Using both new and existing geochronology, this study has better constrained the incision history of this central New Mexico drainage. This study adds to a growing compilation of data that help improve our understanding of Pliocene and Pleistocene history in central New Mexico and the use of travertine deposits for dating aspects of Quaternary landscape evolution.

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