U-series dating and stable isotope analysis of Quaternary travertines with implications for incision rates in western Rio Grande rift, Carrizo Arroyo, New Mexico

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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 234U to 230Th (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 234U (a daughter isotope of 238U) are present in natural waters, and become incorporated into the crystal lattice of travertine when it precipitates, whereas 230Th is insoluble and excluded. As a result, any 230Th present in travertine is a daughter isotope of 234U 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 234U model age can be estimated using an assumed initial δ234U value. Samples older than about 1.5 Ma reach secular equilibrium (where the activity of the parent isotope 238U is equal to the activity ratio of the daughter isotope 234U) and dating would
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 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$_3$PO$_4$ 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 $^{234}\text{U}$ 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.
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
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 subbasins 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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