Appendix A. Supplementary Information for: MIDDLE PLEISTOCENE FORMATION OF THE RIO GRANDE GORGE, SAN LUIS VALLEY, SOUTH-CENTRAL COLORADO AND NORTH-CENTRAL NEW MEXICO, USA: PROCESS, TIMING, AND DOWNSTREAM IMPLICATIONS

Ruleman and others

³He surface exposure dating methods

Basalt samples were collected in situ using sledge hammer and chisel. Samples were oriented, their dimensions measured, and photographed. Topography for cosmic ray shielding was approximated using a hand-held sighting inclinometer and compass, making measurements at even increments of 15° azimuth. Samples for all bedrock surfaces were collected as large blocks of rock and brought back to the laboratory and cut using a diamond saw to obtain precise sample thicknesses.

Basalt samples contained varying abundances of fine to coarse grained (355µm – 106µm) olivine and pyroxene phenocrysts. Samples were crushed, sieved, washed with cold tap water, and dried in an oven at 99°C or air dried. Once dry, the desired size ranges were selected for optimal separations. Each mineral fraction was put through a magnetic separator to obtain concentrated fractions of each mineral phase. After magnetic separation, some samples were further concentrated using Methylene Iodide (MeI) with a density of 3.32 g/cm³, and then ultrasonically cleaned for 1 hr. Olivines and pyroxenes extracted from the samples exhibited a range of weathering alteration ranging from none to intense alteration. Due to this alteration, acid leaching was performed on all mineral separates (Bromley et al., 2014). The olivine and pyroxene separates were first treated in dilute HCl (<10%) in an ultrasonic bath for 15-30 minutes to dissolve any primary and secondary calcite present, as well as clays and iddingsite. Once the samples were rinsed thoroughly with distilled water they were treated with a dilute solution of HF (15%) in an ultrasonic bath for 15-20 minutes to dissolve any remaining
iddingsite and adhering basaltic matrix. The samples were then rinsed with distilled water and
dried at 99°C. Final olivine and pyroxene separates were handpicked using a binocular
microscope to a purity of >99%.

Prior to analysis, 150-300 mg of sample phenocrysts were encapsulated in aluminum foil.
The samples were loaded into a high vacuum-loading arm, attached to a low-blank resistance
furnace, which was connected to the extraction line and air pipets. The air pipets consisted of two
RAS (Riverside Air Standard) tanks. Once the samples were loaded and under vacuum they
were baked overnight at 150°C. Air shots of RAS and SMA (Scott Marin Air) were measured
during the same measurement session. Furnace blanks of 1400°C were done to determine
background He concentrations. Furnace blanks and samples were heated for 30 minutes
following the same method. Heated samples and blanks were treated with various getters for
purifying gases by removing active gases prior to inleting into the mass spectrometer. Getters in
the manifold system were STS-707 operated at 350°C, SAES GP-50, and several charcoal
fingers chilled with liquid nitrogen to remove argon isotopes.

\(^{3}\text{He}\) measurements were made using a Mass Analyzer Product MAP 215–50 mass
spectrometer with a Nier-type source that runs with a trap current of 400 microamperes,
equipped with an inline Faraday detector mounted on the high mass side of the optic axis and an
off-axis channeltron multiplier run in digital pulse counting mode. \(^{3}\text{He}\) is measured using the
multiplier and \(^{4}\text{He}\) is measured using the Faraday detector. \(^{3}\text{He}\) and \(^{4}\text{He}\) measurements were
corrected for blanks and calibrated against RAS and SMA air shots. Results for all sample and
standard analyses are given in Supplemental Table S1.

\textit{U-Th series disequilibria dating of pedogenic carbonates}
Multiple clasts with carbonate rinds were collected from single calcic soil horizons exposed in outcrops or quarry walls. Individual clasts were cut into slabs and polished to best expose rind microstratification and internal structure. Layers were relatively free of obvious detrital material (sand and silt) were targeted to minimize contributions from detrital components containing common Th (\(^{232}\)Th) and associated \(^{230}\)Th not derived from situ decay of \(^{234}\)U. More highly cemented layers were preferentially targeted as they are less likely to be affected by post-depositional modification of U-Th compositions compared to more porous material. Prior to collecting material for analysis, target layers were cleaned by removing softer or dirtier material using carbide dental burs. Layers thus prepared were sampled by prying off fragments or sequential milling to produce a powder. To gain confidence that resulting age estimates have geological significance, samples of rinds from multiple clasts within the same soil horizon were obtained. Ideally, dates should be concordant if they formed during the same pedogenic episode.

Aliquots of clast rinds were weighed into Teflon™ PFA vials and spiked with known amounts of a highly purified mixed-isotope tracer with known \(^{235}\)U-\(^{233}\)U-\(^{229}\)Th concentrations. Samples were digested in nitric acid under atmospheric pressure at 90-125°C. Carbonate cement was dissolved in this step; however, insoluble residue (authigenic opal or detrital silicate) was present in most samples. To avoid laboratory fraction of U and Th, residues were separated from solutions, digested using concentrated HF, and then recombined with the original digestates. U and Th in acid digestions were separated and purified by ion chromatography using Biorad™ AG1\times8 (200-400 mesh) resin in nitric and hydrochloric acid media.

Resulting U salts were loaded on the evaporation side of rhenium double-filament assemblies. Th salts were loaded onto single rhenium filament assemblies as a sandwich between layers of graphite suspension. Isotope ratios were obtained on a Thermo Finnigan Triton™
thermal ionization mass spectrometer using a single discrete dynode electron multiplier operating in peak-jumping mode. Activity ratios were determined from measured atomic ratios using decay constants for $^{234}$U and $^{230}$Th from Cheng and others (2013) and for $^{238}$U and $^{232}$Th from Steiger and Jäger (1977). Quality control was monitored using the NIST SRM 4321B U-isotope standard and two in-house materials of known age and isotopic composition run along with unknowns.

U isotopic compositions of NIST SRM 4321B U-isotope standard determined during the measurement period (April, 2015 to December, 2017) yielded an average $^{234}$U/$^{235}$U atomic ratio of 0.0073042±0.18% (±2σ, n=25), which is within analytical uncertainty of the certified value of 0.007294±0.000028. Isotope ratios for unknown materials were normalized by the factor required to correct the $^{234}$U/$^{235}$U values for the NIST standard measured during the same run.

Results for solutions of uranium ore from the Schwartzwalder mine yielded an average $^{234}$U/$^{238}$U activity ratio (activity ratios hereafter designated using square brackets, i.e., [${}^{234}$U/$^{238}$U]) of 0.9994±0.00025 and an average [${}^{230}$Th/$^{238}$U] of 0.9998±0.0045 (±2σ, n=34), which are within analytical uncertainty of the secular equilibrium values of 1.000 expected for the 69.3-Ma ore (Ludwig et al., 1985). Results for an in-house late Pleistocene Acropora coral dating standard (age of 119.6±1.9 ka; Watanabe and Nakai, 2006) yielded an average age of 119.7±1.6 ka (±2σ, n=30) and an average initial [${}^{234}$U/$^{238}$U] of 1.153±0.006 (±2σ), which is within uncertainty of accepted values for seawater (1.150±0.006; Delanghe et al., 2002).

To avoid calculating erroneously old $^{230}$Th/U ages, any $^{230}$Th (and $^{234}$U) present in detritus at the time of rind formation must be identified and excluded. Because of its very low solubility in aqueous solutions, any $^{232}$Th present in the rind analyses is assumed to reside in solid phases. We used a detritus correction approach described elsewhere (Ludwig and Titterington, 1994; Ludwig and Paces, 2002) that assumed a uniform detritus composition with a
Th/U ratio equivalent to average continental crust (Th/U = 4±2; Shaw and others, 1976; Taylor and McLennan, 1985; Rudnick and Gao, 2003; i.e., $^{232}\text{Th}/^{238}\text{U} = 1.276±0.638$) and U-series isotopes in secular equilibrium ($^{234}\text{U}/^{238}\text{U} = 1.00±0.10$, $^{230}\text{Th}/^{238}\text{U} = 1.00±0.25$). Sample $^{230}\text{Th}/\text{U}$ ages and initial $^{234}\text{U}/^{238}\text{U}$ were calculated from detritus-corrected isotope ratios using Isoplot (Ludwig, 2012). Uncertainties are propagated through the age calculations so that errors for the detritus-corrected compositions are only slightly larger than analytical uncertainties if the measured $^{232}\text{Th}/^{238}\text{U}$ is negligible (say <0.1), but may be very large if substantial amounts of $^{232}\text{Th}$ are present (that is, $^{232}\text{Th}/^{238}\text{U} > 0.2$)

All uncertainties are given at 2σ and include errors from within-run counting statistics, external errors based on reproducibility of standards, and errors propagated from uncertainties assigned to the assumed detrital component and the amount of detrital material present in a given sample. Results for all sample and standard analyses are given in Supplemental Table S2.

**Sampling site details**

This section provides additional specific details about sampling locations used to determine the geomorphic history of the Rio Grande Gorge. They are organized by geochronometer ($^3\text{He}$ and U-Th series) and then from north to south within the study area.

Samples collected at each site can be identified by respective site names for each analysis shown in Tables 2, and 3.

**$^3\text{He Sampling Sites}**

**Saddleback Mountain and Sierro del Ojito Spits, CO**

The northernmost site is located at Saddleback Mountain within the northern SLB on lacustrine landforms related to middle Pleistocene Lake Alamosa. At this location, shoreline
features are preserved around the San Luis Hills proximal to the outlet of Lake Alamosa. These
shoreline spits were formed during periods of elevated longshore drift associated with the Lake
Alamosa highstand and maximum SLB fill/aggradation level at ~2340 m asl. We replicate
analyses from Machette et al. (2007) using the same mineral separates obtained from a boulder
on the highest lake Alamosa shoreline. Our replicate analysis yielded ages of 418.8 ± 5.6 and
410.6 ± 5.6 ka, similar to exposures ages of 439 ± 6 and 431 ± 6 ka presented in Machette et al.
(2007, 2013). Two additional boulders were sampled further east and several meters lower at an
elevation of ~2332 m asl, more distal from the basaltic source outcrop for this spit (Fig. 4A).
The first boulder yielded an age of 386.4 ± 4.3 ka (RG-10-16; 2332 m asl) and three subsamples
from the second yielded ages of 325.4 ± 3.7, 322.1 ± 3.6, and 298.2 ± 3.1 ka (RG-10-17; Table
2). Additionally, we sampled a lower elevation spit, approximately 4 m below the upper spit at
an elevation of ~2328 m asl. A large basalt boulder on this surface yielded a surface exposure
age of 397.2 ± 2.2 ka (RG-10-18; Table 2).

Next, we sampled a spit at Sierro del Ojito, located to the east of Saddleback Mountain,
more proximal to the outlet of Lake Alamosa through the San Luis Hills. The spit surface occurs
at an elevation of ~2325 meters asl, and consists of a sandy-pebble gravel with basalt boulders
protruding from the surface. The elevation of this spit is ~10 meters below the elevation of the
lower spit at Saddleback Mountain. A basalt boulder on this surface yielded an age of 216.9 ±
12.2 ka (RG-11-59; Table 2).

One-Lane Bridge, CO

The first sampling location south of the San Luis Hills and along the Rio Grande Gorge is
at the “One-Lane Bridge” across the Rio Grande at an elevation of 2,280 m asl. Here, the Rio
Grande Gorge is approximately 10 m deep (Fig. 6). The surfaces at this location are comprised of tabular Servilleta Basalt with a smooth, fluvial-scoured surface. Residual lag pebble gravels can be found in scour pits forming >1-meter-wide swales in the tabular basalt, indicating substantial fluvial erosion and scouring of the basalt surface prior to incision and abandonment. Due to the fine-grained, highly weathered mafic mineralogy of the Servilleta Basalt at this location, two subsamples of olivine from a single sample slab of ~0.7 m by 0.7 m were analyzed. Two ages from this surface are 166.7 ± 1.8 and 156.6 ± 1.7 ka (RG-10-11; Fig. 3; Table 2).

Northwest flank of Ute Mountain

Servilleta Basalt was sampled at 2303 m asl where the Rio Grande Gorge cuts to approximately 40 m in depth across the northwest flank of Ute Mountain (Fig. 3, 4B, 6). This volcanic edifice is the first topographic barrier along the path of the RG across the southern SLB. It is composed of ~3.9 Ma dacitic volcanics with younger Servilleta Basalt aggraded around its base (Thompson et al., 2014a). Projections of fluvially-trimmed, fan surfaces on the west-southwest flank of Ute Mountain demonstrate two pre-gorge intervals of major fan progradation and aggradation across the present position of the gorge (Ruleman et al., 2007; 2013; 2016). The Servilleta Basalt surface along the gorge rim is fluvially scoured and pitted, and is topped with abundant well-rounded basaltic cobbles remaining as a lag deposit (Fig. 4B). Columnar jointing in the Servilleta Basalt is well expressed by fluvial erosion and abandonment of the surface, and subsequent eolian infilling of joints. A ~0.7 m by 0.7 m basaltic slab was sampled and five subsamples of either olivine or pyroxene were processed yielding ages of 278.8 ± 3.1, 300.0 ± 3.3, 268.1 ± 3.0, 258.6 ± 2.8, and 261.9 ± 2.9 ka (RG-10-6; Table 2).
Southwest flank of Ute Mountain

Samples from both sides of the Rio Grande Gorge were collected at ~2278-2280 m asl from the southwest flank of Ute Mountain (Thompson et al., 2014a, 2014b; Ruleman et al., 2013; 2016). Here, the gorge is approximately 50 m in depth. Three samples from the west side of the gorge were collected within a slightly inset (~2 m) paleochannel formed prior to canyon incision. These samples yielded ages of 193.3 ± 2.1 ka (UMPC-01), 284.3 ± 3.1 ka (UMPC-03), 306.5 ± 3.4 ka (UMPC-03R), 261.7 ± 3.3 ka (UMPC-03R), and 301.9 ± 3.3 ka (UMPC-04; Table 2). One large slab of Servilleta Basalt approximately 0.4 m by 0.4 m was sampled on the eastern gorge rim with two subsamples yielding ages of 341.9 ± 3.8 and 266.9 ± 2.9 ka (RG-10-5; Table 2).

Sunshine Valley

South of Ute Mountain the Rio Grande Gorge cuts through Sunshine Valley, a shallow structural basin between Ute Mountain and the Red River Fault Zone (Winograd, 1959; Ruleman et al., 2013). The northernmost site in Sunshine Valley is a pair of strath terraces along the gorge rim and inset into the uppermost Servilleta Basalt flow (Thompson et al., 2014b). Elevations of the two strath benches scoured on Servilleta Basalt are ~2273 and ~2260 m asl. Ages for the upper and lower straths are 226.4 ± 12.7 ka (RG-11-51) and 158.6 ± 8.9 ka (RG-11-50), respectively (Fig. 3, 6; Table 2).

The next sample site is located approximately ~3.5 km down river at the mouth of the incised meander of Latir Creek. At this location Servilleta Basalt is faulted along an east-dipping fault strand of the Gorge fault zone (Fig. 3, 4C, and 6). Here, we sampled fluvially scoured Servilleta Basalt on the footwall of the east-dipping intrabasin fault at an elevation of approximately 2270 m asl, to compliment the sample on the upper strath discussed above. Here,
the Rio Grande Gorge is approximately 50 meters in depth. This sample yielded an exposure age of 228.1 ± 2.5 ka (RG-10-4; Table 2).

The Lone Tree site is another ~1.5 km down river, at an elevation of 2260 m asl, complementing the lower strath erosional surface of the pair discussed above. A ~0.2 m by 0.2 m, fluvially scoured basalt slab here yielded an age of 155.9 ± 1.7 ka (Fig. 3, 6; RG-10-3A, Table 2). Here the RG gorge is approximately 50 m in depth as well. We also collected a shielded sample (RG-10-3B) from the underside of the uppermost basalt flow to constrain the primary $^3$He component in the Servilleta Basalt.

The southernmost sampling site within Sunshine Valley is at the Cerro Chiflo overlook. Here, the RG gorge is approximately 100 m in depth, exposing late Miocene silicic to intermediate volcanics of the Cerro Chiflo volcano, with Servilleta Basalt onlapping the older edifice. We sampled along the gorge rim at an elevation of ~2274 m asl, which yielded an exposure age of 132.7 ± 7.4 ka (Fig. 3, 6, RG-11-41; Table 2).

Footwall of Red River fault zone

The next sample location to the south is on the footwall of the RRFZ at the “Pay Station” site (Fig. 3, 4D, 6; Table 2). The samples were taken from a ~0.7 m by 0.7 m basalt slab at an elevation of 2295 m asl. Four subsamples from the one slab yielded ages of 551.3 ± 6.1, 575.9 ± 6.3, 464.5 ± 5.1, and 457.3 ± 5.0 ka (RG-10-2; Table 2). Two additional samples were collected from two adjacent slabs of fluvially scoured basalt yielding ages of 234.6 ± 13.1 ka (RG-11-19) and 245.9 ± 13.7 ka (RG-11-20; Table 2). The gorge is approximately 180 m deep at this location.
Further south along the Rio Grande Gorge rim, we sampled Servilleta Basalt at La Junta Point, the bedrock promontory above the confluence of the Rio Grande and Red River (Figs. 3 and 6). At the confluence, the gorge is approximately 250 m deep. Here, the basalt is capped by approximately 3-5 meters of coarse, clast-supported, rounded, pebble-cobble gravel. We sampled the fluvial scoured surface of the uppermost basalt flow below the mesa-capping fluvial gravel. Two subsamples from a ~0.3 m by 0.3 m basalt slab yielded exposure ages of 612.1 ± 6.7 ka and 549.1 ± 6.0 ka (RG-10-1A; Table 2). Shielded samples were collected on the underside of this uppermost basalt flow (RG-10-1B), as well as the top (RG-10-1C) and bottom (RG-10-1D) of the next lowest basalt flow, stratigraphically below a fluvial pebble-cobble gravel, to constrain contributions from inherited and primary $^3$He.

Taos Plateau

South of the RRFZ, the southern SLB broadens into the relatively flat, dissected, volcanic Taos Plateau, capped by three fluvial gravels deposited prior to gorge incision. These gravels have been previously mapped and interpreted as pre-gorge, axial RG fluvial deposits of probable Plio-Pleistocene age (Kelson, 1986; Wells et al., 1987; Pazzaglia and Wells, 1990). In order to constrain timing of regional incision on the Taos Plateau, we sampled Servilleta Basalt south of the confluence of the Rio Grande and Red River on the east side of the gorge at Cebolla Mesa and further south at the confluence of the Rio Grande and Arroyo Hondo on both sides of the gorge.

At the gorge rim at the Cebolla Mesa campground, we sampled a ~0.2 m by 0.2 m slab from the surface of fluvially scoured uppermost Servilleta Basalt flow (RG-10-7A; Fig. 3, 6; Table 2). To the east of the exhumed and incised basaltic gorge rim at this sample location lies a
broad alluvial plain reaching up to the base of the Sangre de Cristo Mountains. This alluvial plain is composed of medium to coarse, pebble-cobble gravels with abundant evidence for late Pleistocene to recent fluvial modification and dissection of the surface. The surface exposure sample along the gorge rim yielded an age of 51.4 ± 1.0 ka (RG-10-7A; Table 2). We collected a shielded sample from the underside of this uppermost basalt flow (RG-10-7B; Table 4) to constrain primary \(^3\)He production.

Lastly, we sampled in the vicinity of the confluence of the Rio Grande and Arroyo Hondo at four locations and elevations below all three pre-gorge gravels (Fig. 3, 4E, 4F, 6). At 2122 m asl, we sampled a large slab of the uppermost Servilleta Basalt flow surface yielding two subsample ages of 265.6 ± 2.9 ka and 277.9 ± 3.1 ka (Fig. 3, 6; RG-10-9; Table 2). Unusually coarse, subangular to rounded, polymictic gravels overlie the sample location and characterize the maximum aggradation surface. Lower in elevation at 2115 m asl, we sampled an inset fluvial scoured surface yielding an age of 246.6 ± 2.7 ka (Fig. 4E; RG-10-10; Table 2).

In order to constrain RG lateral constriction, fluvial/alluvial abandonment of the Taos Plateau, and Rio Grande Gorge incision initiation, we compliment gorge rim sample locations with a sample location along the westernmost fluve of the pre-gorge Rio Grande floodplain west of Arroyo Hondo (DAN-01; Fig. 3; Table 2). Here, Servilleta Basalt yields a \(^3\)He surface exposure age of 225.0 ± 2.5 ka.

Along the gorge rim directly above the John Dunn Bridge crossing at an elevation of approximately 2085 m asl, fluvially scoured basalt yielded an age of 199.8 ± 2.2 ka (RG-10-8A; Table 2), and two subsamples from an adjacent basalt surface yielded ages of 192.6 ± 2.1 ka, and 192.9 ± 2.1 ka (RG-10-8B; Fig. 3, 4F, 6; Table 2).
Directly across the Rio Grande Gorge and up the Arroyo Hondo canyon (Fig. 3, 4G), two fluvial gravels overlie the uppermost Servilleta Basalt flow. We sampled the northern Arroyo Hondo canyon rim to compare tributary stream versus Rio Grande axial incision timing and headward erosion rates. At an elevation of approximately 2085 m asl and approximately 80 m above Arroyo Hondo, Sample RG-10-13 yields an exposure age of 108.7 ± 1.2 ka (Table 2).

**U-series Site Descriptions**

**Saddleback Mountain, CO**

In addition to sampling boulders on the shorelines of Lake Alamosa, we analyzed soil carbonate rinds developed on clasts within the shoreline gravel deposits from the upper (2339 m asl) and lower (2329 m asl) spits at Saddleback Mountain. Clasts were collected from material originally excavated from two soil trenches described by Machette et al. (2013), which were backfilled following this previous investigation. Although not collected in situ, these clasts clearly came from the original soil profiles. Original pits excavated on upper and lower spits exposed approximately 2.5 meters of sandy, basaltic gravels with stage IV pedogenic carbonate development (Machette et al., 2007). The strong calcic soil profile is interpreted to represent continuous eolian influx and pedogenic carbonate development following abandonment of lacustrine constructional processes. Abundant spoil remains directly adjacent to the pits, of which clasts containing the strongest carbonate cementation and thick carbonate rinds were selected. We presume with backhoe disturbance of the complete soil profile, a representative sample suite would be available within the spoil piles. 12 clasts from the upper spit yielded ages ranging 21.0 ± 0.5 to 281.2 ± 49.3 ka, with one sample yielding an incalculable age. 12 clasts from the lower spit yielded ages ranging 19.5 ± 0.8 to 132.3 ± 1.1 ka.
Guadalupe Mountain Quarry, NM

The northernmost site on the Taos Plateau is located north of the RRFZ, to the north of Guadalupe Mountain. It is located at 2292 m asl, approximately 3 km from the east rim of the Rio Grande Gorge, where the gorge is approximately 90 m deep. At this location, a ~2 m deep profile consisting of 80 cm of carbonate-cemented alluvial gravels overlain by a 1.2 m-thick loess unit is exposed in the south and east walls of a large gravel quarry. Sample clast rinds were collected from a Stage III+-IV pedogenic calcic horizon developed within this lower gravel deposit, which is correlated to the youngest of the three pre-gorge gravels identified by previous mapping (Ruleman et al., 2007; 2013; 2016). Clast lithologies of the ~25-19 Ma Questa caldera complex (Lipman and Read, 1989; Zimmerer and McIntosh, 2012), previously described by Ruleman et al. (2007, 2013, 2016), indicate this gravel was sourced from the Cabresto Creek-Red River drainage flowing northwestward into Sunshine Valley to the north of Guadalupe Mountain (Fig. 3). Cabresto Creek currently flows southwest into the Red River gorge, and was likely captured by the incising Red River during Rio Grande Gorge incision, abandoning the alluvial deposits sampled here. The soil carbonate ages provide a minimum-limiting constraint on capture of Cabresto Creek by headward incision of the Rio Grande Gorge. 20 clast rinds collected from the lower gravel horizon range 14.4 ± 1.1 to 302.5 ± 26.2 ka.

Montosa Road Quarry and John Dunn Bridge sites, NM

Two sites are located near each other on the west side of the gorge, across from where Arroyo Hondo enters the Rio Grande Gorge. The gorge is approximately 140 m deep at this location. These sites are south of the RRFZ, on the southern Taos Plateau. The Montosa Road
Quarry is located ~1 km west of the Rio Grande Gorge at 2158 m asl, on the flat basalt plateau making up the gorge rim. Medium- to coarse-grained cobble gravels are abundant on the surface of the uppermost tread and the deposit is characterized as a clast-supported, pebble-cobble gravel with discontinuous sandy lenses. This uppermost gravel surface is capped by a discontinuous mantle of loess varying from ~0.1-1.0 meters in thickness. Eight clast rinds were collected in situ from this gravel pit exposure of pre-gorge alluvium, yielding ages ranging 73.5 ± 1.0 to 198.9 ± 5.3 ka. Three samples yielded incalculable ages.

The John Dunn Bridge site is located at the Rio Grande-Arroyo Hondo confluence, approximately 7 kilometers north of the Highway 64 bridge across the gorge. At this location, the Rio Grande gorge is approximately 120 meters deep, half of the 240-meter depth occurring to the south at the Highway 64 bridge. This location is also on the hangingwall of the Dunn fault of the Gorge fault zone (Ruleman et al., 2016), permitting aggradation of gravels within this tectonically subsided region, while incision was occurring to the north and south at the bounding Red River and Los Cordovas fault zones, respectively. Two localities within this site were sampled. The first is located adjacent to the main parking area to the west across the road, where coarse cobble clasts were collected from a recent roadcut exposure revealing a strong calcic soil (Bk stage III-IV, Machette, 1985) formed in gravels onlapping the footwall of the Dunn fault and Servilleta Basalt. Six clast rinds yielded ages ranging 83.8 ± 0.7 to 319.5 ± 87.3 ka were obtained. The second site is adjacent to the main parking area atop the Dunn Bridge crossing at the level of the parking lot, within gravels overlying the Rio Grande gorge rim on the hangingwall of the Dunn fault. Four clast rinds yielded ages ranging 58.5 ± 0.4 to 168.7 ± 2.9 ka. ³He surface exposure dating on the gorge rim adjacent to this second site indicates fluvial
scouring of the Sevilleta Basalt and initiation of gorge incision ~190 ka, further demonstrating the lag time from gravel deposition to incision, abandonment, and pedogenesis.

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*Earthship Quarry, NM*

The Earthship Quarry site is located on the Servilleta Basalt plateau 3 km west of the gorge at 2150 m asl. It is located on an interfluve just east of a prominent incised drainage connected downstream to the gorge, where the gorge is approximately 150 m deep. The northwest quarry wall exposes a Stage III+ carbonate-cemented fluvial gravel overlain by 2 m of interbedded channel lag gravels, cross-bedded sands, and loess with Stage II-III soil carbonate development (Fig. 5). Cross-bedding relationships show accretionary crossbeds indicative of a south-southwest migrating meander belt. The lower gravel contains clasts of quartz latite from the Latir Peaks volcanic field, and various Proterozoic metamorphic rocks that outcrop only in the Sangre de Cristo Mountains on the opposite side of the Rio Grande Gorge. This deposit is overlain by sediments indicative of episodic local alluvial/colluvial and eolian deposition on the abandoned broad, alluvial plain following gorge incision. Soil carbonate ages therefore provide minimum limiting constraints on the age of abandonment of the axial channel, and incision of the gorge. 14 clast rinds were analyzed from the lower gravel unit, yielding ages ranging 44.6 ± 28.0 to 153.1 ± 3.0 ka. Two of these yielded incalculable ages. Three rinds on pebbles within an upper channel lag deposit yielded ages ranging 67.4 ± 0.9 to 184.6 ± 3.1 ka (ES-2A to 2C; Table 3).

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*Dead Cholla Trailhead, NM*
The southernmost site in the SLB is located near the Dead Cholla Trailhead, 0.4 km west of the Rio Grande Gorge rim, which is approximately 190 m deep. At this location, Servilleta Basalt is overlain by ~4 m of interbedded fluvial gravels and thickly bedded loess. Clasts in the gravels have similar composition to those at the Earthship Quarry, consistent with an axial pre-gorge river. Quartzite clasts are also common, likely sourced from the Picuris Mountains across the gorge to the southeast. Clast rinds were collected in a natural arroyo exposure from a fluvial gravel bed with Stage III+ carbonate development. Nine clast rinds yield ages ranging 22.2 ± 3.0 to 177.6 ± 3.8 ka (Table 3).

Supplement References


Delanghe, Doriane, Bard, Edouard, and Hamelin, Bruno, 2002, New TIMS constraints on the uranium-238 and uranium-234 in seawaters from the main ocean basins and Mediterranean Sea: Marine Chemistry, v. 80, no. 1, p. 79–93.


