Geochemistry and microbial diversity of CO_2-rich springs and U-series dating of travertine from the Tierra Amarilla anticline, New Mexico

Brandi Cron, Laura J. Crossey, Karl E. Karlstrom, Victor J. Polyak, Asmerom, Yemane, and Chris McGibbon, [eds.]

2024, pp. 225-235. https://doi.org/10.56577/FFC-74.225

Supplemental data: https://nmgs.nmt.edu/repository/index.cfml?rid=2024007

in:

Geology of the Nacimiento Mountains and Rio Puerco Valley, Karlstrom, Karl E.;Koning, Daniel J.;Lucas, Spencer G.;Iverson, Nels A.;Crumpler, Larry S.;Aubele, Jayne C.;Blake, Johanna M.;Goff, Fraser;Kelley, Shari A., New Mexico Geological Society 74 th Annual Fall Field Conference Guidebook, 334 p.

This page is intentionally left blank to maintain order of facing pages.

New Mexico Geological Society Guidebook, 74th Fall Field Conference, 2024, p. 225–235, https://doi.org/10.56577/FFC-74.225

GEOCHEMISTRY AND MICROBIAL DIVERSITY OF CO_2-RICH SPRINGS AND U-SERIES DATING OF TRAVERTINE FROM THE TIERRA AMARILLA ANTICLINE, NEW MEXICO

BRANDI CRON[1], LAURA J. CROSSEY[1], KARL E. KARLSTROM[1],
VICTOR J. POLYAK[1], YEMANE ASMEROM[1], AND CHRIS MCGIBBON[1]

[1]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87106; kek1@unm.edu

Abstract—This paper explores the water geochemistry, microbial heterogeneity, and paleohydrological longevity of a set of desert springs in north-central New Mexico. This series of CO_2-rich springs is aligned along a southern extension of the Nacimiento fault at the Tierra Amarilla anticline in the boundary zone between the Colorado Plateau and Rio Grande rift. The springs are warm (24±1°C) year around and sustained by artesian head. Geochemical data show $^3He/^4He$ ratios of 0.17–0.20 R_A, which indicates the presence of mantle-derived helium in the groundwater. Carbon isotope values range from -4.6 to -8.1 per mil, and water chemistry modeling of eight samples indicates that most of the CO_2 is endogenic and derived from deep (magmatic) sources (C_{endo} = 89%); the rest of the CO_2 is from dissolution of carbonate in the aquifer (C_{carb} = ~6%) and from organic sources such as soil gas (C_{org} = ~5%). Stable isotopes of the water plot to the right of the Global Meteoric Water Line, suggesting geothermal influence from the Valles Caldera. The combination of new water chemistry and spring monitoring reported here illustrates the unique character of these carbonic, travertine-depositing warm springs. These high-CO_2, low-dissolved oxygen (DO) waters host unique microbial ecosystems. DNA and 454-sequencing analyses revealed native microbiological communities including Zetaproteobacteria. The Zetaproteobacteria had previously only been known from submarine seamount communities, such that the Tierra Amarilla springs host the first published occurrence of chemolithotrophic iron-oxidizing Zetaproteobacteria in a continental setting. These communities are interpreted to be structured to inhabit ambient-temperature terrestrial springs via metabolic processes similar to chemolithotrophic communities found in deep-sea vents with inferred metabolic reactions including oxidation of hydrogen, manganese, and hydrogen sulfide. We report 17 new U-series dates from travertine deposited by the springs to evaluate the longevity of the Tierra Amarilla spring system. Highest-elevation extinct mounds give ages from 269 to 212 ka; lower mound systems range in age from 105 to 70 ka; youngest travertines return ages from 9 ka to 630 years. Travertine mound springs north of Highway 550 are actively cementing Rio Salado gravels in the modern floodplain and provide an analog for travertine cements and caps on Rio Salado terrace gravels that extend ~200 m up the dip slope of the southern nose of the Nacimiento Mountains. These terrace travertines range in age from 534 to 31 ka and provide a good incision record for the Rio Salado. The data presented in this paper show artesian spring alignment along a southern continuation of the Nacimiento fault, multi-year-consistent water temperature and conductance (lack of seasonality), deep sources for the high CO_2 and He, unique chemolithoautotrophic microbiology, and >500 ka longevity of the spring system as recorded by travertine. These findings are consistent with models for geothermal influences from the Valles Caldera, neotectonically active southern Nacimiento Mountains fault systems, and episodicity in deposition of travertine that may be facilitated during wetter climate intervals.

INTRODUCTION

A major breakthrough in the late 1970s was the discovery of unique biological ecosystems that flourish in anoxic conditions at hydrothermal vents along mid-ocean ridges (Corliss et al., 1979). These have been called "smokers" due to plumes of mineralized hot water visibly emanating from the vents. Black smokers are characterized by carbon dioxide and hydrogen sulfide (dominant volatile species) due to seawater interactions with basalt. White smokers are characterized by lower-temperature fluids (40°C to 90°C), are rich in hydrogen from serpentinization-influenced systems, and precipitate calcite (Kelley et al., 2005). In both systems, unique chemo-litho-trophic communities flourish on energy derived from upwelling hot fluids via chemical reactions enabled by these fluids.

Similar systems exist on continents and have been called continental smokers (Crossey et al., 2006, 2009, 2016). They include both hydrothermal and CO_2-rich cool spring vents that carry deeply-circulated (endogenic) fluids with evidence for mantle-derived magmatic components. These fluids ascend along extensional and transtensional faults, are commonly associated with extensive travertine deposits, and provide the setting for chemo-litho-autotrophic microbial communities (Colman et al., 2015). Mixing of these systems in groundwater also has an underappreciated influence on groundwater quality (Newell et al., 2005).

Active warm springs and travertine mounds along the crest of the Tierra Amarilla anticline in New Mexico provide an important field laboratory to characterize continental smokers. These springs are aligned along a mile-long ridge south of the Nacimiento uplift that appears to be a southern continuation of the Nacimiento fault (Fig. 1). The travertine mounds are actively forming as CO_2-charged artesian groundwater ascends along fault systems that are acting as semiconfined conduits (McGibbon et al., 2018). The San Ysidro springs were the first location where Zetaproteobacteria (specialists in microbial iron oxidation) were found in a continental setting (Cron, 2011; Colman et al., 2015; Crossey et al., 2016; Vander Roost et al., 2018). Since then, they have also been described in geothermal continental settings (see compilation in Hribovsek et al., 2024).

The goals of this paper are to summarize data from Cron

(2011) in the context of a summary of more recent papers by Coleman et al. (2015), Crossey et al. (2016), McGibbon et al. (2018), McGibbon (2021), and Reed et al. (2024). This paper reports key results from: (1) monitoring of spring temperature, pH, and conductance; (2) cation and anion hydrochemistry of springs; (3) stable isotope data; (4) modeling of the source of the CO_2; (4) microbial results; and (5) U-series dating of travertine.

METHODS AND RESULTS

Continuous Monitoring

Cron (2011) applied a YSI Sonde model 6920V2-S autonomous sensor to measure temperature, pH, conductivity, and dissolved oxygen. Cron (2011) and McGibbon (2021) reported several deployments at different depths and in different springs that provided a continuous sensor record over about 2.5 years from 2012 to 2015. Figure 2 shows results from one year of monitoring of Twin Mound East from January 2013 to January 2014, with the sensor at ~6±0.1 m depth. The jumps in recorded depth reflect probe downloads. The several-centimeter depth fluctuation is interpreted to reflect diurnal spring level fluctuation due to earth tides (McGibbon, 2021). Temperature remained near constant at 24°C with ±1°C variation reflecting annual summer-winter seasonal fluctuation. Conductance is ~13±1 mS/cm, and the occasional freshening episodes are interpreted to reflect snowmelt and rain events; this value is one-fourth the conductance of seawater but is due mainly to sulfate rather than chloride. Records from multiple springs that vary in elevation by about 100 m show parallel behavior and similar geochemistry, indicating the aligned springs are connected parts of an artesian groundwater system within a semiconfined aquifer. McGibbon (2021) applied a fault zone hydrologic system model to explain a system where groundwater has substantial storage while traveling through the fault damage zone and can respond to increases in barometric pressure.

Water Chemistry

A total of ten springs were sampled in and around the Tierra Amarilla anticline since 2003. Figure 1 shows sample locations. Twin Mound East (TME) was sampled at the surface and also from 6 m below the surface with a battery-driven peristaltic pump. Grassy Spring was also sampled at 2 m depth below the surface. The samples were analyzed for major and minor element chemistry, stable isotopes, and gas analyses. For each sampling event, two water samples were taken from spring sources. From the two samples that were collected, one sample was filtered and acidified with HNO_3. This sample was analyzed for major cations using inductively coupled plasma spectrometry optical emission spectroscopy (ICP-OES).The other sample (unfiltered and unacidified) was used for anion, alkalinity, and stable isotope determinations. Anions were filtered in the lab and analyzed using ion exchange chromatography (IC). Alkalinity was determined by titration with dilute sulfuric acid. Oxygen and hydrogen stable isotopes were analyzed in the Stable Isotope Laboratory at the University of New Mexico using an induction module cavity ring-down spectroscopy (IM-CRDS) water isotope analysis system from Picarro. Field parameters were also catalogued, and temperature, pH, dissolved oxygen, and conductivity were measured with handheld meters.

Water composition was characterized by pH values from 5.38 to 8.27. The temperature range was 11–26.7°C, and the average temperature was 22.8°C. Major and minor ion concentrations are displayed in Figure 3, where cation and anion concentrations are projected onto a Piper diagram (Piper, 1944; Drever, 1997). The water samples were sodium- and chloride-rich, and most were Na-K type waters with salinity of 4,000–10,000 mg/L. In contrast, the Rio Salado (bright green dot) was a Cl + SO_4, HCO_3 type water (salinity 7,060 mg/L). Figure 3 suggests that Tierra Amarilla springs plot along a mixing trend between geothermal waters of the Valles Caldera, Soda Dam, Jemez Springs, and other springs near the Jemez River that are considered part of the outflow plume of the Valles geothermal system (McGibbon et al., 2018 and references therein), and a meteoric end member represented by the Guadalupe River tributary to the Jemez River.

Oxygen and Hydrogen Stable Isotopes

For stable oxygen and carbon isotopic analysis, approximately 1 mg of travertine powders were loaded into vials (12 mL borosilicate exetainers), then the vials were flushed with He gas and the samples were reacted for 24 hours with H_3PO_4 at 50ºC. The evolved CO_2 was measured by continuous flow isotope ratio mass spectrometry using a GasBench device coupled to a Finnigan Mat Delta Plus Isotope Ratio Mass Spectrometer (model Picarro L11O2-i). The results are reported using the delta notation, versus PDB. Reproducibility was better than 0.15‰ for both $\delta^{13}C$ and $\delta^{18}O$ based on repeats of a laboratory standard (Carrara Marble). The standards were calibrated versus NBS 19, for which the $\delta^{13}C$ is 1.95‰ and $\delta^{18}O$ is 2.2‰.

Whereas cations and anions reflect dissolved solutes, oxygen and hydrogen stable isotopes reflect the composition and evolution of the water molecules themselves and can be used to determine the source of the waters and effects of mixing, evaporation, and water-rock interaction on groundwater. Figure 4 shows stable isotopes of deuterium and oxygen (Cron, 2013). The global meteoric water line (GMWL) line represents the global average variation in the isotopic composition of precipitation. The values of $\delta^{18}O$ of -12 to -14‰ for the Jemez River (shown as dark blue dots) are consistent with derivation from high elevations in the Jemez Mountains. The spread of Jemez River compositions (shown as orange dots) reflects mixing of meteoric waters (e.g., snowmelt or precipitation) with geothermal waters. Geothermal waters themselves show a wide range of compositions to the right of the GMWL, which are interpreted to primarily reflect water-rock interaction in the geothermal system plus some evaporation in the flow path. Tierra Amarilla springs plot in between and are interpreted to reflect mixing of meteoric water and geothermal water from the Jemez Mountains that reaches the spring system via fault conduits (McGib-

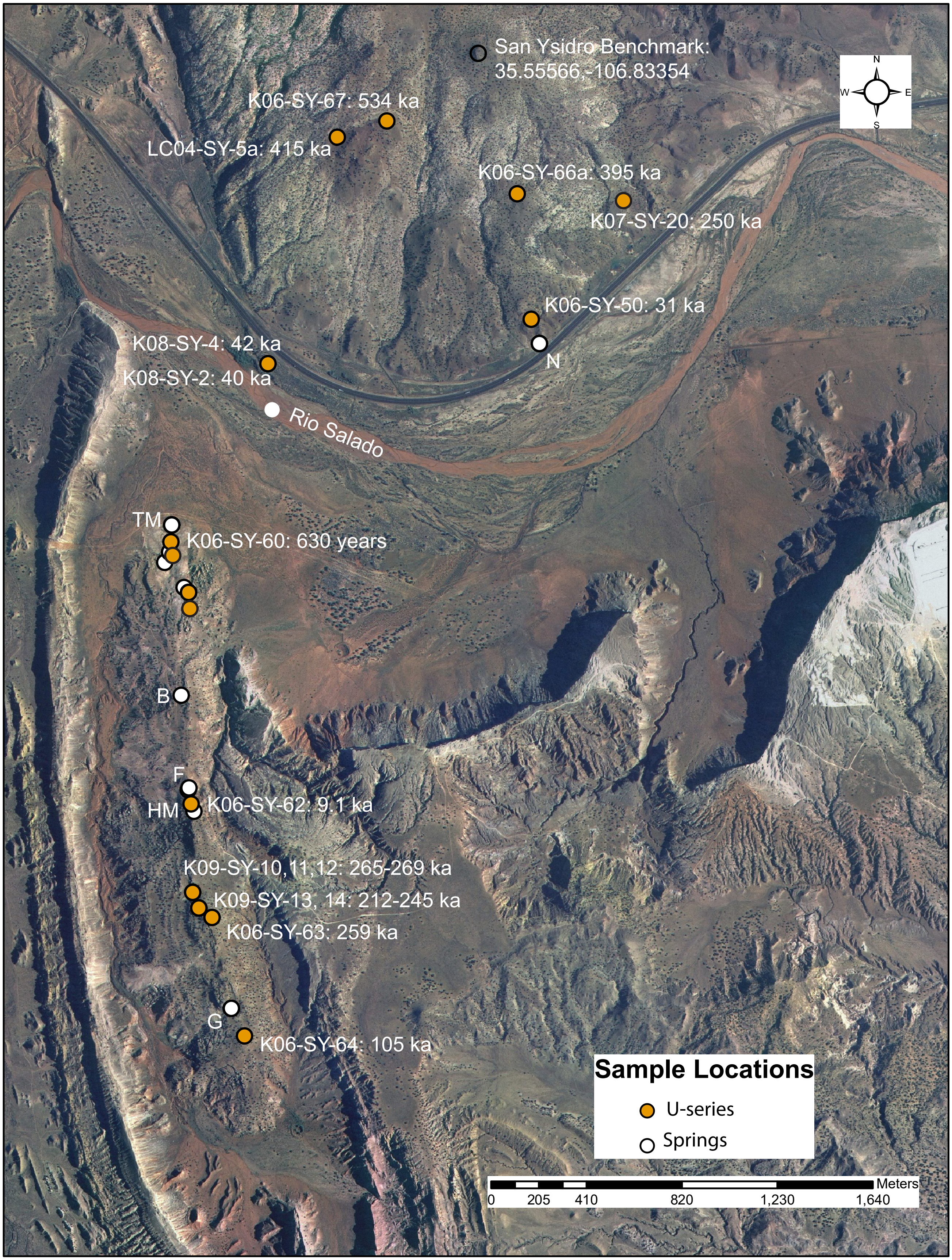

FIGURE 1. Distribution of travertine-depositing springs along a concealed strand of the Nacimiento fault in the core of the Tierra Amarilla anticline. Springs (white) include: N = North Highway, TM = Twin Mounds, B = Bathtub spring, HM = High Mound spring, F = Fissure Ridge, G = Grassy spring. Dated travertine locations from both north and south of the Rio Salado (orange) are listed in Table 1.

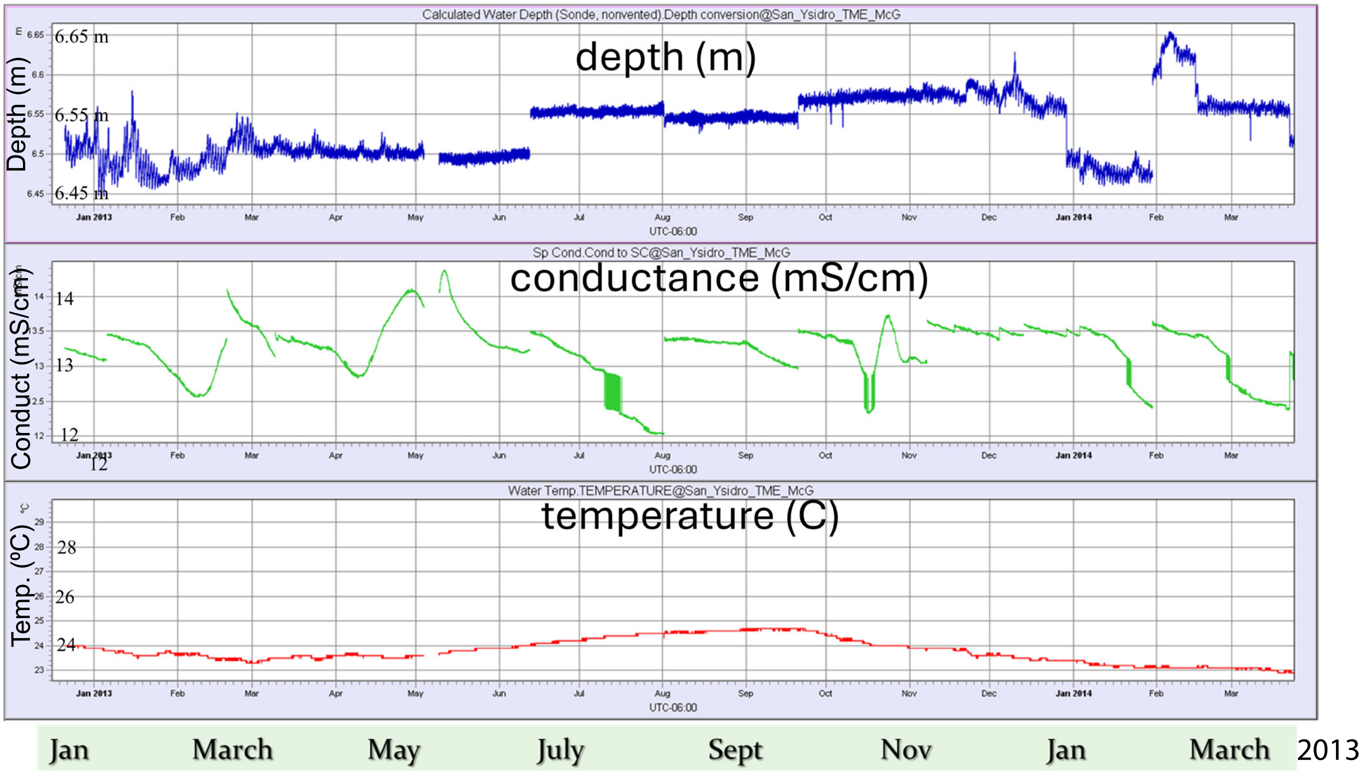

FIGURE 2. Continuous sensor monitoring of Twin Mound east from January 2013 to January 2014 with CDT sensor positioned about 6.5 m depth below the surface. The jumps in recorded depth reflect probe downloads, but centimeter-scale fluctuation reflects diurnal earth tides (McGibbon, 2021). Temperature was near constant at 24±1°C with variation following annual winter-summer fluctuation. Conductance of ~13 mS/cm shows occasional freshening episodes interpreted to reflect snowmelt and rain events.

bon et al., 2018).

Carbon Isotopes

The CO_2 carbon isotopic composition reflects mixing of external CO_2 (e.g., from soil gas and magmatic inputs) plus CO_2 from carbonate rocks dissolved along the hydrologic flow path. To parse the sources of CO_2 in the gas and fluids of the springs we utilized carbon isotope data, chemical speciation models, and carbon balance equations with methods similar to Karlstrom et al. (2013). The total dissolved inorganic carbon, DIC_{tot} is calculated with the aqueous speciation model Phreeqc Interactive 2.17.4799. Then the external carbon is computed on an equi-molar basis by subtracting the C derived from dissolution of carbonate (Ca + Mg) and removing the Ca derived from gypsum via $C_{carb} = (Ca + Mg) - SO_4$. The external carbon is then $C_{ext} = DIC_{total} - C_{carb}$. We then remove the carbon isotope contribution from the C_{carb} and estimate the carbon isotope contribution from the external carbon via the equation: $(DIC_{tot} \cdot \delta^{13}C_{tot}) = (C_{carb} \cdot \delta^{13}C_{carb}) + (C_{ext} \cdot \delta^{13}C_{ext})$, assuming a value for $\delta^{13}C$ of local marine carbonate of 0‰ versus PDB.

The external carbon (C_{ext}) can include deeply sourced CO_2 of magmatic origin and CO_2 from soil gas. Figure 5 shows an analysis of C_{ext} in the Tierra Amarilla anticline compared to groundwaters of the Rio Grande rift. Model mixing curves are shown in Figure 5 that encompass most of the Rio Grande rift waters and connect empirically derived end members for organic CO_2 ($\delta^{13}C_{org}$ = -28‰) and deeply sourced CO_2 ($\delta^{13}C_{endo}$ = -5‰). Tierra Amarilla waters all fall above the 75% proportion line for C_{endo}, and most Rio Grande rift waters also show >50% C_{endo}. The position of the Tierra Amarilla waters above the model curves may suggest that CO_2 was degassed (removing the lighter carbon) before the samples were collected. Alternatively, the inset to Figure 5 shows a similar model field drawn for an Italian magmatic system by Chiodini et al. (2004) that used a wider range of end member values of endogenic fluids to $\delta^{13}C$ = 0, which could also explain Tierra Amarilla points. We infer from this analysis that most of the CO_2 in the Tierra Amarilla travertine- depositing springs is of endogenic (deep) origin, which is compatible with derivation of CO_2 from the Valles Caldera geothermal system and other Quaternary magmatic sources in the region.

Helium Isotopes

Helium isotopes can be used to detect the presence of mantle-derived fluids. ^4He accumulates from radioactive decay of U and Th and is most enriched in the continental crust. Most ^3He is primordial and was acquired during Earth formation (e.g., Clarke et al., 1969). $^3He/^4He$ ratios are generally reported relative to air, where the $^3He/^4He$ ratio in air (R_A) is used as a reference value, with $R_A = {\sim}1.4 \times 10^{-6}$. Mantle-derived fluids at oceanic spreading centers (mid-ocean ridge basalts [MORB]) from asthenospheric sources are 8±1 R_A (Graham, 2002) and subcontinental lithospheric mantle (SCLM) has values of 3–7

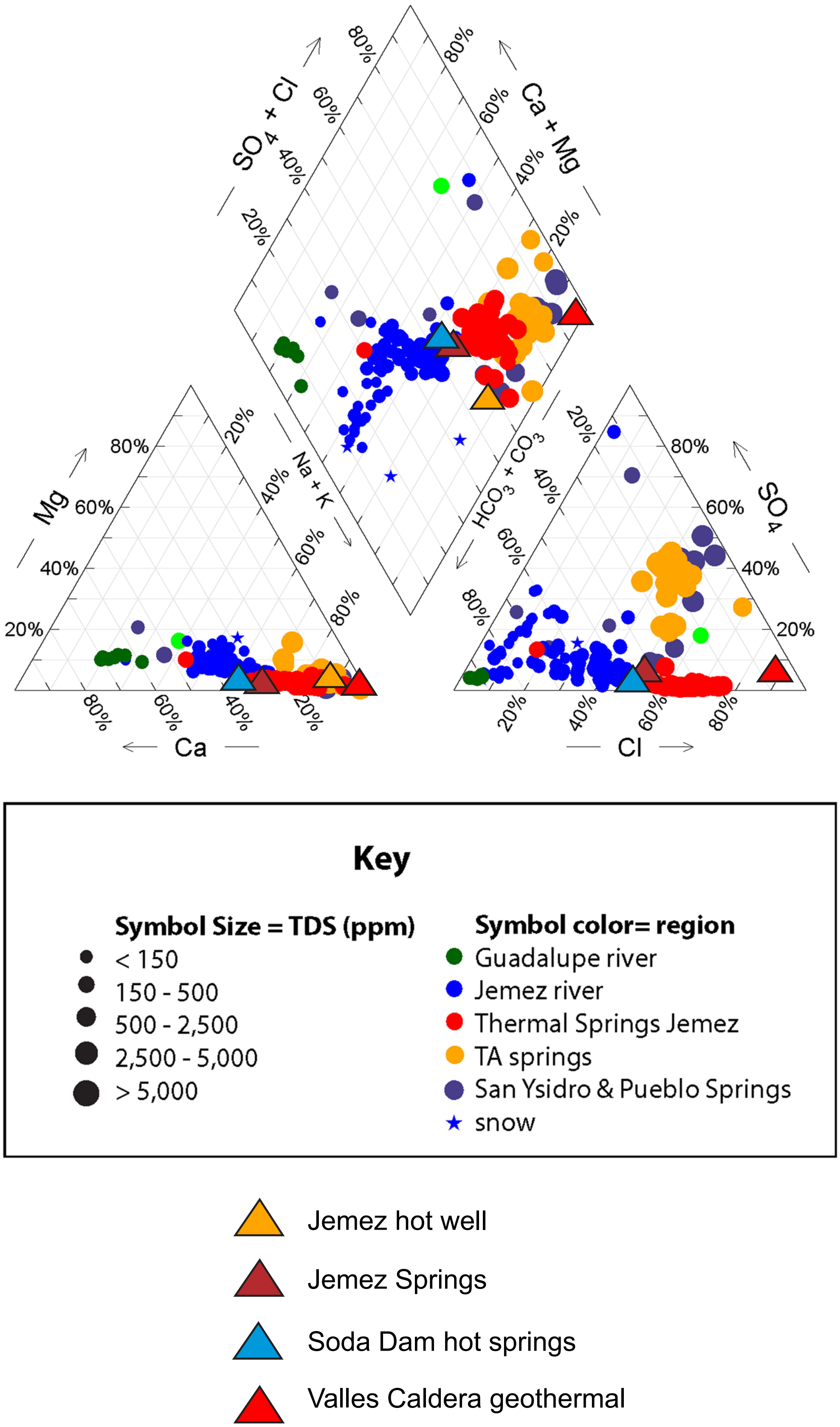

FIGURE 3. Piper diagram displaying the normalized concentrations of major cations and anions projected graphically into the quadrilateral (Piper, 1944). The Tierra Amarilla springs (orange dots) overlap with the Jemez Pueblo springs (red dots). Triangles are geothermal waters of the Jemez Mountains (means from McGibbon et al., 2018). Jemez River waters mix with geothermal waters at Soda Dam. Guadalupe River water (dark green) provides the meteoric end member for the observed mixing trend with Jemez Mountains geothermal waters. Light green dot is the Rio Salado.

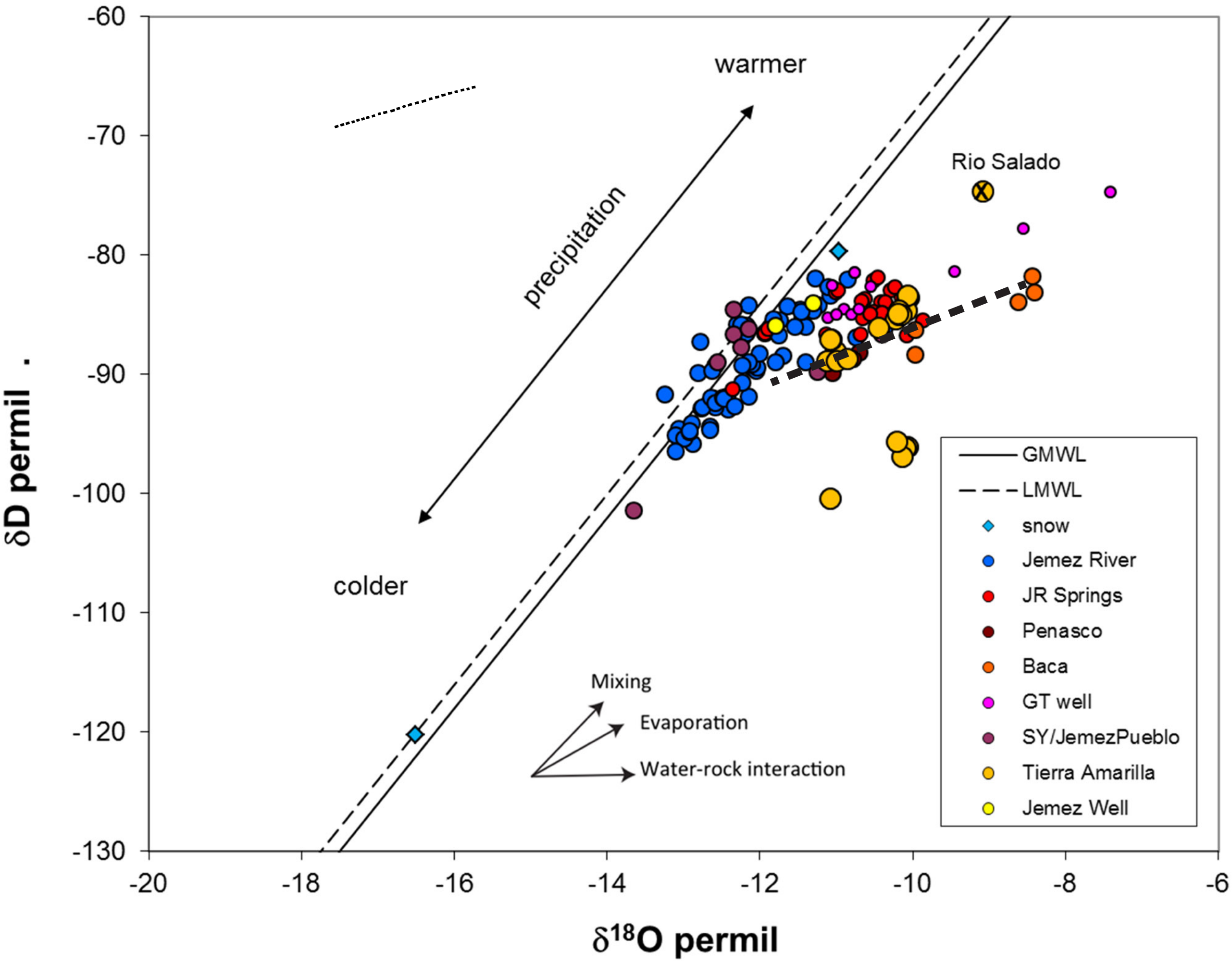

FIGURE 4. Stable isotopes of deuterium and oxygen (Cron, 2013). Solid line is GMWL = global meteoric water line. Tierra Amarilla springs (orange dots) fall to the right of the GMWL on a mixing trend (heavy dashed line) between a meteoric end member represented by the Jemez River and geothermal waters of the Baca wells in the Jemez Mountains geothermal system (Goff and Janek, 2002).

R_A (Gautheron and Moreira, 2002). Stable continental shield areas have values of ~0.02 R_A (Andrews, 1985), indicating most continental groundwaters do not have significant mantle inputs. Air-corrected $^3He/^4He$ ratios (R_C/R_A) are computed using He/Ne ratios, and if these ratios are significantly greater than 0.02 R_A, they are taken as evidence for the presence of mantle-derived fluids entrained in the hydrologic system (Ballentine et al., 2002; Klemperer et al., 2022).

Tierra Amarilla springs have air-corrected $^3He/^4He$ values that indicate the presence of mantle-derived helium (Karlstrom et al., 2013, table DR-1). These include: Twin Mounds = 0.17 R_A, Grassy Spring = 0.2 R_A, and North Spring (the spring north of U.S. Route 550) = 0.39 R_A. These values suggest that 2–5% of the total helium is likely of asthenospheric (MORB) origin. The Jemez geothermal system has values up to 6.16 R_A (77% of MORB) at Sulfur Spring in the Valles Caldera, and $^3He/^4He$ values get variably lowered by ^4He input along the outflow of the geothermal system to values of 0.84 (10.5% of MORB) at Soda Dam, 1.27 R_A (16% of MORB) at Jemez Springs, and 0.38 R_A (5% of MORB) at upper Owl Springs on the Jemez Pueblo. These data as well the $CO_2/^3He$ ratio in the same springs decrease progressively with distance away from the Valles Caldera, suggesting that Valles geothermal fluids contribute to groundwater hydrochemistry at Tierra Amarilla springs and other travertine-depositing springs in between (McGibbon et al., 2018; Blomgren et al., 2018).

Microbial Analyses

DNA was extracted from four springs in the Tierra Amarilla spring group: North Highway Spring, Twin Mound East, High Mound, and Grassy Spring. 454 pyrosequencing was performed on planktonic communities that were collected by filtering ~1 L of spring water with a 0.22 µm Sterivex filter (Millipore, Bedford, MA), and DNA was extracted as described by Colman et al. (2014). 454 pyrosequencing was performed at Research and Testing Laboratories (Lubbock, TX) using universal bacterial PCR primers, quality-filtering steps, and analytical steps described elsewhere (Van Horn et al., 2014; Crossey et al., 2016). Further phylogenetic analysis at Twin Mound East spring was conducted using nearly full-length bacterial 16S rRNA gene sequences generated with universal bacterial PCR primers as

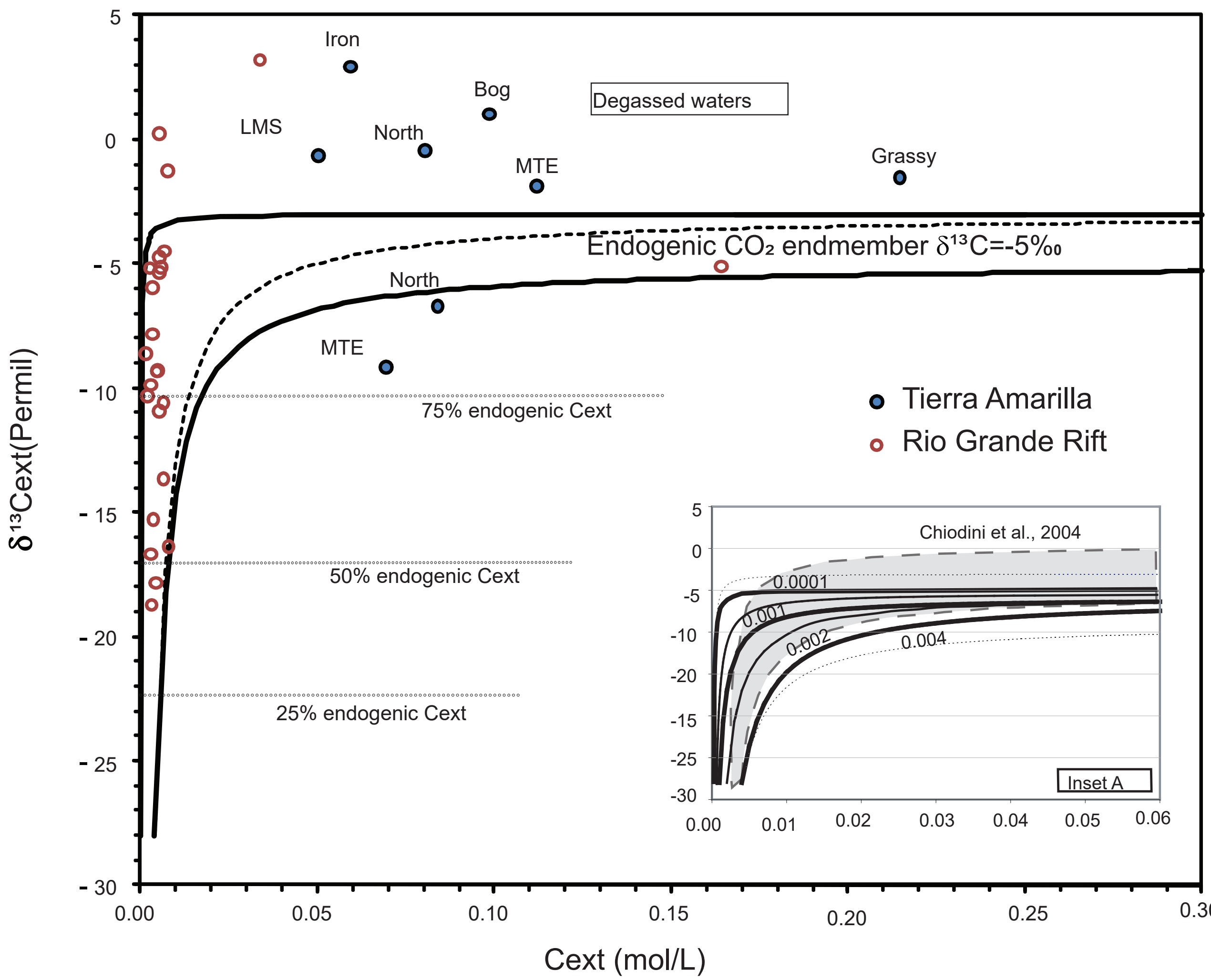

FIGURE 5. Diagram of $\delta^{13}C_{ext}$ ‰ versus C_{ext} of springs located in the Tierra Amarilla anticline and the Rio Grande rift that parses external carbon (C_{ext}) sources in terms of the percentage of the C_{ext} derived from deep sources (C_{endo}) versus organic sources (C_{org}). Tierra Amarilla springs (blue) have high C_{ext} and a high percent C_{endo} compared to lower C_{ext} and more variable C_{endo} in Rio Grande rift waters (red). Endogenic end members for the model curves (heavy lines) are similar to mantle $\delta^{13}C$ values of −6‰±2‰ (Sano and Marty, 1995). Points above these curves suggest degassing. Alternatively, the inset shows end members used for Italian magmatic systems (Chiodini et al., 2004) that could encompass Tierra Amarilla points. Regardless of mixing end members, this diagram suggests that most of CO_2 in Tierra Amarilla springs is from magmatic sources.

described in Northup et al. (2010) at the Washington University Genome Sequencing Facility. Sequences were edited and assembled into contigs using Sequencher (v.4.8, Gene Codes, Ann Arbor, MI).

Bacterial communities varied considerably among Tierra Amarilla springs, as summarized in Crossey et al. (2016). *Mariprofundus*-like taxa dominated the Twin Mound East spring, whereas the other three springs were dominated by other Proteobacteria taxa including Betaproteobacteria, putatively photosynthesizing Cyanobacteria, and putatively heterotrophic taxa of the Gammaproteobacteria. The Twin Mounds samples containing *Mariprofundus*-like populations harbored Zetaproteobacteria belonging to two monophyletic clades with and distantly related to marine-vent associated uncultured clones in addition to *Mariprofundus* isolates. These springs contain the first Zetaproteobacteria published in a continental setting and may potentially represent new terrestrial-associated genera within the Zetaproteobacteria that are distinct from marine-associated relatives.

The Tierra Amarilla spring system has high endogenic fluid input: $^3He/^4He$ up to $0.4R_A$, P_{CO2} up to 0.93 (nearly pure CO_2), and moderately high values of geothermal Br, Li, and B. These waters provide a distinct hydrogeochemical environment that is necessary for the microaerobic chemo-litho-autotrophic niches employed by both the iron-oxidizing (FeOB) Zeta-and Betaproteobacteria found in these springs (Emerson and Moyer, 2010). Further investigation of these populations is needed to evaluate potential physiological adaptations to continental settings.

U-Series Analyses

The mounds are generated by aggradation of travertine deposits around spring orifices as well as outflow aprons. In order to date the travertine accumulation over time and hence the longevity of the spring system, we sampled: (1) a ~10-m-thick

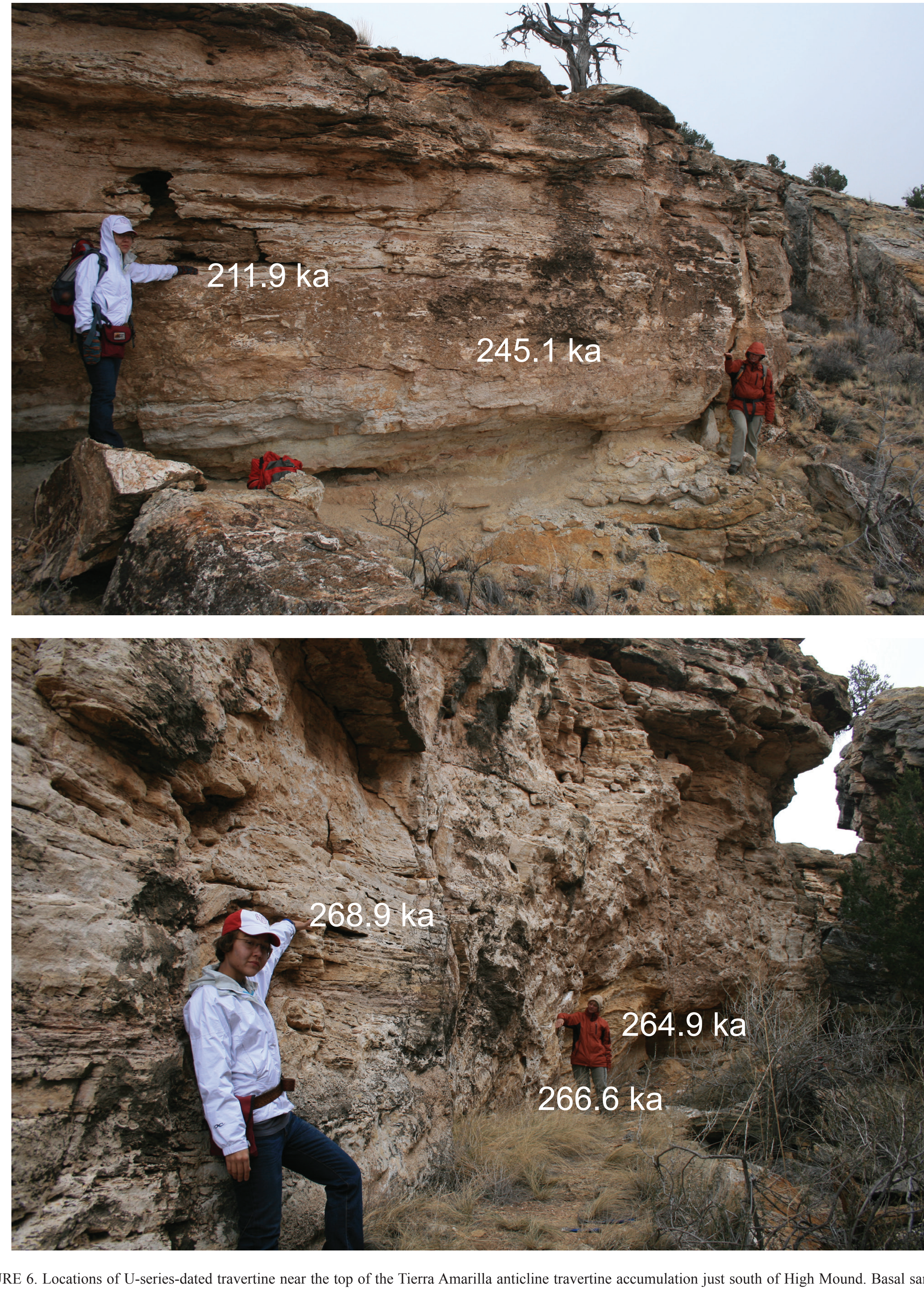

FIGURE 6. Locations of U-series-dated travertine near the top of the Tierra Amarilla anticline travertine accumulation just south of High Mound. Basal samples are 269–265 ka and are all within analytical error (Table 1); upper samples are 245–212 ka. Duration of accumulation of this ~10-m-thick section was about 57 ka.

travertine accumulation from near the top of the deposit where travertine lies unconformably on the Petrified Forest Formation (Fig. 6); (2) locations lower on the anticline including near the actively travertine- depositing Twin Mounds (Fig. 1); and (3) travertine-cemented gravel terraces of the Rio Salado on the north side of U.S. Route 550 (Fig. 7; Table 1). We cut and drilled individual growth bands with an automated drill. The resulting powder, typically around 200 mg, was dissolved in HNO_3 and spiked with ^{229}Th-^{233}U-^{236}U, which eliminates the propagation of weighing errors into the age uncertainties. Sample aliquots were powdered and dissolved using 3N HNO_3. After samples were spiked with a known concentration, they were run through a 200 μL Teflon column with resin. Thorium was collected using 6N HCl, uranium using H_2O. The samples were then dried and redissolved with 3% HNO_3 and analyzed on a Neptune Multicollector Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS) in the Radiogenic Isotope Laboratory at the University of New Mexico.

The U-series dates from the highest part of the accumulation on top of the Tierra Amarilla anticline span a time period of ~57 ka. Samples K09-SY-10 (266.6±3.3 ka), K09-SY-11 (264.9±3.3 ka), and K09-SY-12 (268.9±3 ka) were the lowest in elevation and have overlapping error bars such that all are ~ 265 ka. The next higher sample, about 4 m higher stratigraphically, was K09-SY-13 (245.1±2.8 ka). Sample K09-SY-14 (211.8±2.1 ka) was ~2 m higher than K09-SY-13.

Figure 7 and Table 1 also show U-series dates from travertines in terrace remnants north of U.S. Route 550 on the south-plunging nose of the Nacimiento uplift. In about eight terrace remnants at different levels above the modern floodplain, horizontally bedded travertines overlie and cement thin (1–5-m-thick) Rio Salado River gravels that rest on a strath cut onto Petrified Forest Formation shales within a few meters above their contact with the more resistant Triassic Agua Zarca Sandstone. The thin skim of Petrified Forest Shale preserved on the gravels suggests the then-active springs were able to break through their upper confining layer from the underlying Agua Zarca to deposit the travertines. This is similar to the modern floodplain, where active travertine mound springs including North Highway Spring are currently cementing Rio Salado gravels. Thus, by analogy, the ages of the travertine from the elevated terraces are considered to approximately date the terraces. Not all terrace levels were dated, but the increase in age upward is consistent with this interpretation.

U-series dates of Table 1 and their utility for incision and landscape evolution studies are described in more detail in Reed et al. (2024) and Bailey et al. (2024). Figure 7 shows that the highest gravels are near the San Ysidro benchmark at an elevation of ~195 m (6120 ft) above modern river level (ARL). The highest dated terrace, with its strath 164 m ARL, was outside of U-series range (hence >~500 ka) and gave a ^{234}U model age of age of 534±148 ka (see Appendix 1). Terrace ages decrease downwards as follows: the 130 m ARL terrace is 415 ka, the 114 ARL terrace is 394 ka, the 95 m ARL terrace is undat-

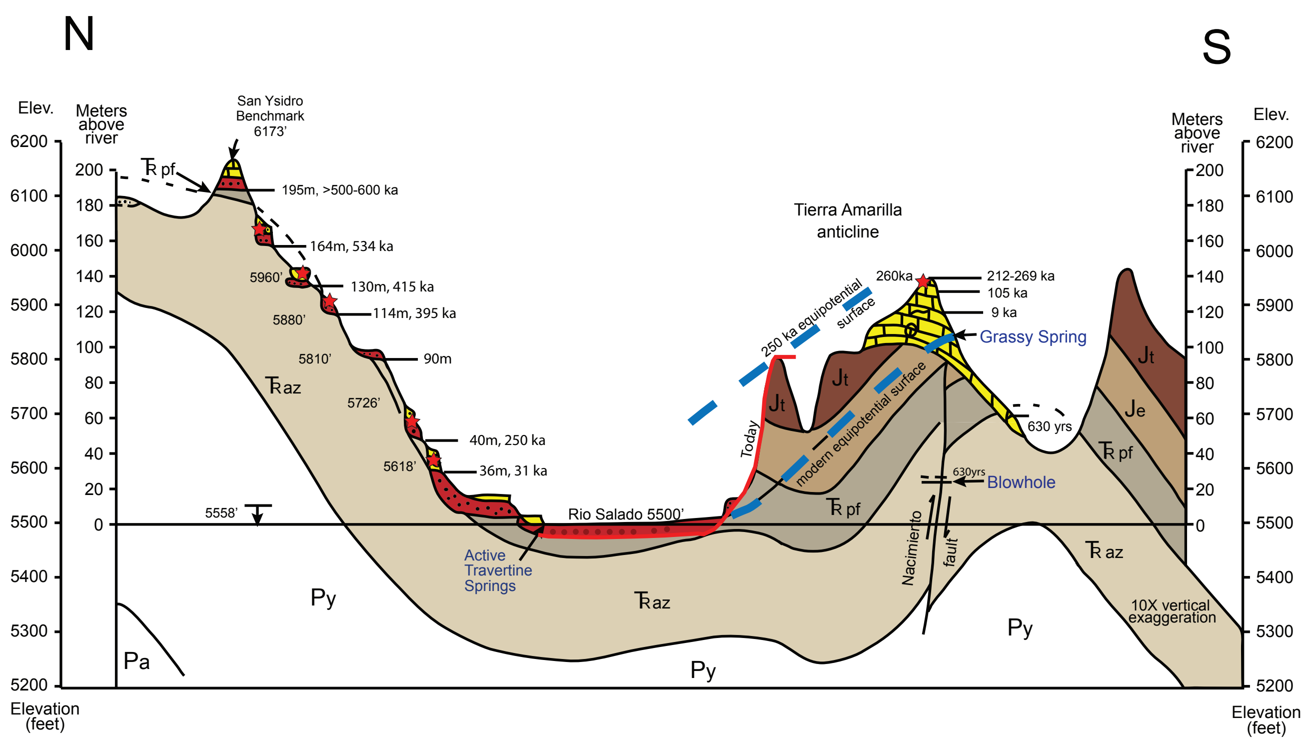

FIGURE 7. Locations of U-series-dated travertine in the Tierra Amarilla anticline (at S, right side) and in terrace gravels of Rio Salado (at N, left side). Py = Permian Yeso Group, Traz = Triassic Aqua Zarca Sandstone of Chinle Group. Trpf = Triassic Petrified Forest Formation of the Chinle Group, Je = Jurassic Entrada Sandstone, Jt = Jurassic Todilto Formation. Yellow = travertine; red = Rio Salado gravel and paleogravel. The U-series dates from the highest part of the accumulation on top of the Tierra Amarilla anticline span a time period of ~57 ka, from 269 to 212 ka. Terrace gravels north of the Rio Salado extend ~200 m up the dip slope of the southern nose of the Nacimiento Mountains and range in age from 31 ka to outside of U-series range (>500 ka), with the 164-m terrace giving a model age of 534±148 ka. The highest gravels and undated overlying travertine are near the San Ysidro benchmark.

TABLE 1. U-series dates from travertines of the Tierra Amarilla anticline (white) and Rio Salado terraces (orange)

Field Sample #	U-series age in years BP (corrected) (ka)	error (ka)	Remarks	Latitude	Longitude	Elevation (m)
SY Benchmark	undated		USGS benchmark in travertine above 195 m strath	35.555658	-106.833539	1882
K06-SY-67	534	148	$\delta^{234}U$ age on travertine above 164 m strath	35.552664	-106.837919	1834
LC04-SY-5a	415.23	15.64	travertine cap on ~130 m strath	35.551805	-106.839503	1822
K06-SY-66	394.75	17.04	fine-grained calcite in thin veins	35.549936	-106.831656	1797
K06-SY-63a	259.49	3.28	south end of TA antiform ~3 m below surface	35.521833	-106.845542	1807
K07-SY-20	250.44	4.46	east of Towa structure, calcite veins in micrite	35.551361	-106.826328	1740
K09-SY-12	268.87	3.42	8 m below top of travertine deposit	35.522009	-106.846139	1802
K09-SY-10	266.57	3.9	10 m below top of travertine deposit	35.522022	-106.846131	1800
K09-SY-11	264.94	3.27	9 m below top of travertine deposit	35.52263	-106.84643	1801
K09-SY-13	245.12	2.77	4 m below dead tree, Alexandra for scale	35.522631	-106.846431	1787
K09-SY-14	211.94	2.06	2 m below dead tree, Brandy for scale	35.522631	-106.846431	1789
K06-SY-64	105.32	7.19	from "bridge" between double vents	35.517117	-106.8439	1798
K08-SY-4	42.06	0.34	trench below paleovent south of highway	35.54309	-106.843474	1694
K08-SY-2	39.71	0.248	trench below paleovent south of highway	35.544234	-106.84432	1694
K04-SY-50	30.58	0.34	base of travertine on gravel of ~20 m ARL strath	35.544908	-106.831153	1698
K06-SY-62	9.12	0.057	High Mound, 1 m below south rim	35.525736	-106.846667	1791
K09-SY-60	630	4	banded flowstone from Pipeline trench	35.536034	-106.847737	1695
Rio Salado River level			~base level at nose of Nacimiento dip slope	35.539796	-106.836982	1681

ed, the 44 m ARL terrace is 250 ka, and the 36 m terrace is 31 ka. The 250 ka 44 m ARL terrace is similar in age to the base of the travertine accumulation near the top of the Tierra Amaria anticline, implying there was ~100 m of artesian head above the 250 ka river level, which is similar to the modern artesian head supplying High Mound and Grassy Spring today (Fig. 7).

CONCLUSIONS

Travertine has been forming along the central fault of the Tierra Amarilla anticline episodically for at least the past 270 ka, and the Tierra Amarilla area travertine-depositing system goes back >500 ka. Existing data suggest that deposition and evolution of individual mound spring vents may have lasted tens of thousands of years, whereas the overall system has been active for hundreds of thousands of years. Dates from the ~8-m-thick accumulation near the highest springs reveal that these springs were most active for about 57 ka, from 69 to 212 ka. Lower elevation samples were deposited ~100 ka and <10 ka. These data demonstrate that "continental smoker" microbial communities have evolved due to persistent flux of deeply sourced, warm, anoxic fluids through the Tierra Amarilla fault system over hundreds of thousands of years, with water flux (and episodic deposition of travertine) likely mediated by changing climate. The artesian spring alignment along a southern continuation of the Nacimiento fault, the consistent water temperature and conductance in all the springs and the lack of seasonality, hydrochemical data for deep sources for the high CO_2 and He, and the unique chemo-litho-autotrophic microbiology are consistent with models for geothermal influences from the Valles Caldera (McGibbon et al., 2018) and neotectonically active southern Nacimiento Mountains fault systems (Reed et al., 2024; Karlstrom et al., 2024).

ACKNOWLEDGMENTS

This work was funded by NSF EAR-0538304 (to L. Crossey), EAR 0838575 (to Crossey and Karlstrom), and NS-FOCE 0728391 to A.L. Reysenbach, and by student research funding to B. Cron from the Geological Society of America, the New Mexico Geological Society, UNM's Research Opportunity Programs, the Ronald E. McNair Program, New Mexico Alliance for Minority Participation (LSAMP), and LSAMP-Bridge to the Doctorate Fellowship (NSF HRD0832497). Amy Williams and Abdul Mehdi Ali helped with the water analyses. Jennifer Hathaway and Dave Van Horn helped with molecular laboratory work. This paper benefitted from reviews by Jayne Aubele, Dan Colman, and Johanna Blake.

REFERENCES

Andrews, J.N., 1985, The isotopic composition of radiogenic helium and its use to study groundwater movements in confined aquifers: Chemical Geology, v. 49, p. 339–351.

Ballentine, C.J., and P.G. Burnard, 2002, Production, release and transport of noble gases in the continental crust, *in* Porcelli, D., Ballentine, C.J., and Weiler, R., eds., Reviews in Mineralogy and Cosmochemistry, v. 47: Washington, D.C., Mineralogical Society of America, p. 481–538.

Blomgren, V.J., Crossey, L.J., Karlstrom, K.E., Fischer, T.O., and Darrah, T.H., 2019, Hot spring hydrochemistry of the Rio Grande rift in northern New Mexico reveals a distal geochemical connection between Valles Caldera and Ojo Caliente: Journal of Volcanology and Geothermal Research, v. 387, https://doi.org/10.1016/j.jvolgeores.2019.106663

Chiodini, G., Cardellini, C., Amato, A., Boschi, E., Caliro, S., Frondinin, F., and Ventura, G., 2004, Carbon dioxide Earth degassing and seismogenesis in central and southern Italy: Geophysical Research Letters, v. 31, p. 1–4.

Clarke, W.B., Beg, M.A., and Craig, H., 1969, Excess ^{3}He in the sea: Evidence for terrestrial primordial helium: Earth and Planetary Science Letters, v. 6, p. 213–220, https://doi.org/10.1016/0012-821X(69)90093-4

Colman, D.R., Garcia, J.R., Crossey, L.J., Karlstrom, K.E., Jackson□Weaver, O., and Takacs- Vesbach, T., 2015, An analysis of geothermal and carbonic springs in the western United States sustained by deep fluid inputs: Geobiology, v. 12, no. 1, p. 83–98.

Corliss, J.B., Dymond, J. Gordon, L.I., Edmond, J.M., von Herzen, R.P., Ballard, R.D., Green, K., Williams, D., Bainbridge, A., Crane, K., and van Andel, T.H., 1979, Submarine thermal springs on the Galápagos Rift: Science, v. 203, p. 1073–1083, https://doi.org/10.1126/science.203.4385.1073

Cron, B., 2011, Geochemical characteristics and microbial diversity of CO_2-rich mounds springs of the Tierra Amarilla anticline, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 42 p.

Crossey, L.J., Fischer, T.P., Patchett, P.J., Karlstrom, K.E., Hilton, D.R., Newell, D.L., Huntoon, P., Reynolds, A.C., and de Leeuw, G.A.M., 2006, Dissected hydrologic system at the Grand Canyon: Interaction between deeply derived fluids and plateau aquifer waters in modern springs and travertine: Geology, v. 34, p. 25–28.

Crossey, L.J., Karlstrom, K.E., Springer, A., Newell, D., Hilton, D., and Fischer, T., 2009, Degassing of mantle-derived CO_2 and ^{3}He from springs in the southern Colorado Plateau region—Flux rates, neotectonics connections, and implications for understanding the groundwater system: Geological Society of America Bulletin, v. 121, no. 7–8; p. 1034–1053, https://doi.org/10.1130/B26394.1

Crossey, L.J., et al., 2016, Continental smokers couple mantle degassing and unique microbiology within continents: Earth and Planetary Science Letters, v. 435, p. 22–30, https://doi.org/10.1016/j.epsl.2015.11.039

Drever, J.I., 1997, The Geochemistry of Natural Waters: Surface and Groundwater Environments (third edition): Prentice Hall, 345 p.

Emerson, D., and Moyer, C.L., 2010, Microbiology of seamounts: Common patterns observed in community structure, Oceanography, v. 23, no. 1, p. 148–163.

Gautheron, C., and Moreira, M., 2002, Helium signature of the subcontinental lithospheric mantle: Earth and Planetary Science Letters, v. 199, p. 39–47, https://doi.org/10.1016/S0012-821X(02)00563-0

Goff, F., and Janek, C.J., 2002, Gas geochemistry of the Valles caldera region, New Mexico and comparisons with gases at Yellowstone, Long Valley and other geothermal systems: Journal of Volcanology and Geothermal Research, v. 116, p. 299–323

Graham, D.W., 2002, Noble gas isotope geochemistry of mid-ocean ridge and ocean island basalts: Characterization of mantle source reservoirs: Reviews of Mineralogy and geochemistry, v. 47, p. 481–538.

Karlstrom, K.E., Crossey, L.C., Hilton, D.R., Barry, P.H., 2013, Active mantle degassing above the Aspen Anomaly of Colorado: Mantle to surface interconnections and implications for neotectonics of the Rocky Mountains: Geology, v. 41, p. 495–498.

Kelley D.S., et al., 2005, A serpentinite-hosted ecosystem: The Lost City hydrothermal field: Science, v. 307, p. 1428–1434.

Klemperer, S.L., Zhao, P., Whyte C.J., Darrah, T.H., Crossey, L.J., Karlstrom, K.E., Liu, T., Winn, C., Hilton, D.R., and Ding, L., 2022, Limited underthrusting of India below Tibet: ^{3}He/^{4}He analysis of thermal springs locates the mantle suture in continental collision: Proceedings of the National Academy of Sciences, v. 119, no. 12, https://doi.org/10.1073/pnas.2113877119

McGibbon, C., 2013, Carbonic springs as distal manifestations of the Jemez geothermal system, San Ysidro, New Mexico, highlighting the importance of fault pathways and hydrochemical mixing [M.S. thesis]: Albuquerque, University of New Mexico, 116 p.

McGibbon, C., 2021, Geochemical and sensor-based monitoring of fault-associated carbonic springs in Grand Canyon and northern New Mexico: Identifying hydrologic pathways and establishing baselines [Ph.D. dissertation]: Albuquerque, University of New Mexico, 157 p.

McGibbon, C., Crossey, L.C., Karlstrom, K.E., and Grulke, T., 2018, Carbonic springs as distal manifestations of geothermal systems, highlighting the importance of fault pathways and hydrochemical mixing: Example from the Jemez Mountains, New Mexico: Applied Geochemistry, v. 98, p. 45–57.

Newell, D., Crossey, L.J., Karlstrom, K.E., Fischer, T., and Hilton, D., 2005, Continental-scale links between the mantle and groundwater systems of Western United States: Evidence from travertine springs and regional He isotope data: GSA Today, v. 15, no. 12, p. 4–10.

Piper A.M., 1944, A graphic procedure in the geochemical interpretation of water-analyses: Eos v. 25, p. 914–928, https://doi.org/10.1029/TR025i006p00914

Reed, C., Karlstrom K.E., Rodriguez, B., Iverson, N., Heizler, M., Rose-Coss, D., Crossey, L.J., Cox, C., Jean, A., Polyak, V., and Asmerom, Y., 2024, Differential river incision due to Quaternary faulting on the Río Salado-Jemez system at the million-year timescale, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Río Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 237–256.

Sano, Y., and Marty, B., 1995, Origin of carbon in fumarolic gas from island arcs: Chemical Geology, v. 119, p. 265–274, https://doi.org/10.1016/0009-2541(94)00097-R

Van Horn, D.J., Okie, J.G., Buelow, H.N., Gooseff, M.N., Barret, J.E., and Takacs-Vesbach, C.D., 2014, Soil microbial responses to increased moisture and organic resources along a salinity gradient in a polar desert: Applied Environmental Microbiology: v. 80, p. 3034–3043.

Appendices can be found at
https://nmgs.nmt.edu/repository/index.cfml?rid=2024007

CO_2-rich spring waters from Twin Mounds seep down the sides of the mounds. Small irregularities cause turbulence that increases CO_2 degassing—a feedback mechanism that causes travertine terracettes and small pools to form and grow. *Photo by Laura Crossey*