U-series ages and morphology of a Quaternary large-volume travertine deposit at Mesa del Oro, NM: Implications for paleohydrology, paleoclimate, and neotectonic proceses

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U-SERIES AGES AND MORPHOLOGY OF A QUATERNARY LARGE-VOLUME TRAVERTINE DEPOSIT AT MESA DEL ORO, NM: IMPLICATIONS FOR PALEOHYDROLOGY, PALEOCLIMATE, AND NEOTECTONIC PROCESSES

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ABSTRACT—This paper describes a large-volume travertine deposit that formed at the northeastern end of Mesa del Oro, a basalt mesa located at the southwestern edge of the Colorado Plateau and along the Jemez lineament. The travertine deposit forms two topographically elevated platforms that cover an area of 27 km^2, are up to 63 m thick, and have a calculated volume of 0.7 km^3. We report six new dates for the Mesa del Oro accumulation and show that travertine formation occurred in two main intervals, 360-250 ka and 760-560 ka. The intervals overlap with episodes of basaltic volcanism in the area. The northern platform was deposited along a fissure ridge and an associated marsh as shown by both travertine morphology and facies. Large-volume travertine formation requires both high CO_2 influx and significant groundwater discharge. The high CO_2 influx is interpreted to be related to the episodic volcanic activity that produced over-pressuring of the CO_2/groundwater system with magmatic gasses. Intervals of high groundwater discharge are attributed to high head in a confined aquifer achieved through increased recharge and thus, episodes of travertine formation at Mesa del Oro are interpreted to record wet paleoclimate periods.

INTRODUCTION

Travertines are groundwater discharge deposits made of calcite or aragonite that precipitate from CO_2-rich groundwater. Travertine deposits are common throughout New Mexico (Fig. 1; Barker et al., 1996) and are generally well-preserved due to the resistance of carbonate to erosion in the arid climate. They predominantly occur along the Rio Grande rift flanks and on the Colorado Plateau along the Jemez lineament (Fig. 1). Here we describe a large-volume travertine deposit at Mesa del Oro, a Tertiary basalt-capped mesa located near the southeastern boundary of the Colorado Plateau and along the Jemez lineament, about 30 km south of I-40 and to the west of the Lucero uplift (Fig. 2). The travertine deposit formed between two basalt flows, at the northeastern end of the Mesa del Oro basalts (Jicha, 1958) and south of a second basalt flow that flowed north from Volcano Hill vent (Fig. 2). The travertine occurs in two connected platforms, herein called the northern and southern platforms (Fig. 3). The travertine overlies Triassic Chinle Formation and, at the northwestern edge, Cenozoic basalt (Fig. 3). The travertine at Mesa del Oro was mentioned and mapped by Wright (1946), and discussed in detail by Jicha (1958) who also mapped the southern platform. The northern platform has been quarried to a minor extent by NZ Legacy LLC and is well-known among cavers for its Pronoun Caves (Forbes and Stephens, 1994). The travertine-precipitating groundwater at Mesa del Oro, although no longer active, is inferred to have issued from springs along fault-related fissures which lead to the formation of a fissure ridge on the northern platform (Fig. 3; Chafetz and Folk, 1984; Pentecost, 2005; Brogi

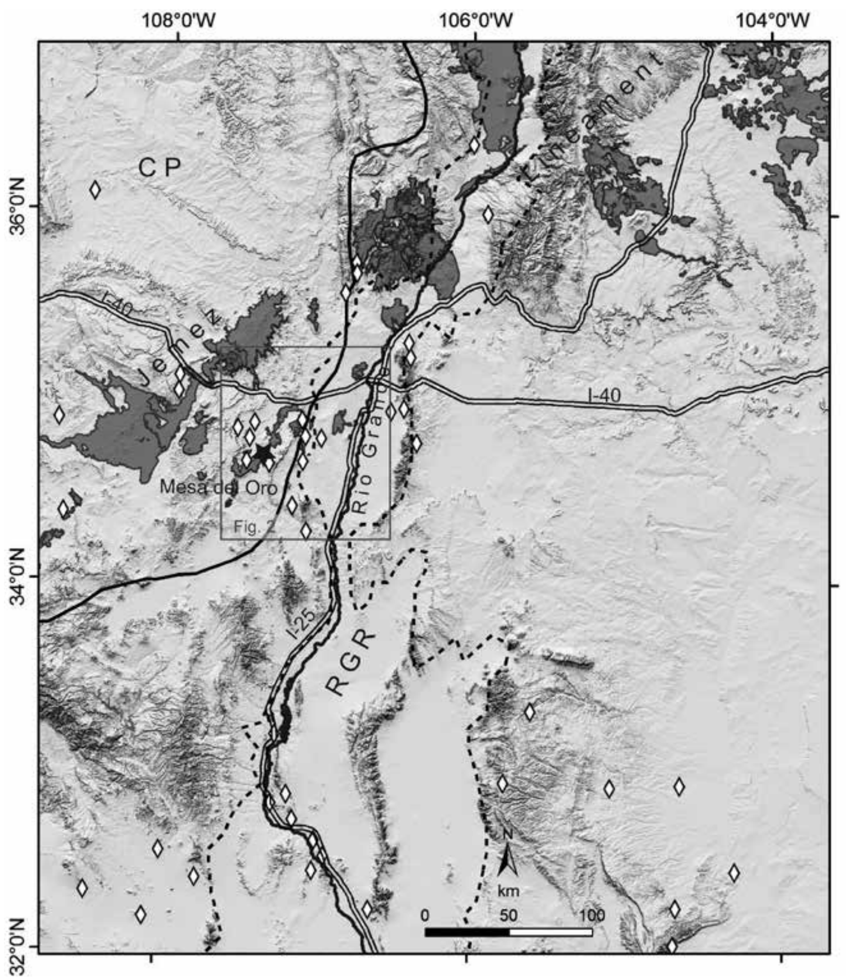

FIGURE 1. Shaded relief map of New Mexico showing locations of travertine accumulations (white diamonds; Barker et al., 1996), the large-volume travertine deposit at Mesa del Oro (black star; this study), late Cenozoic volcanics (dark grey areas outlined in black), and associated tectonic features such as the Rio Grande rift (RGR, dashed black line), Colorado Plateau (CP, solid black line), and Jemez lineament. The box indicates the area of interest.

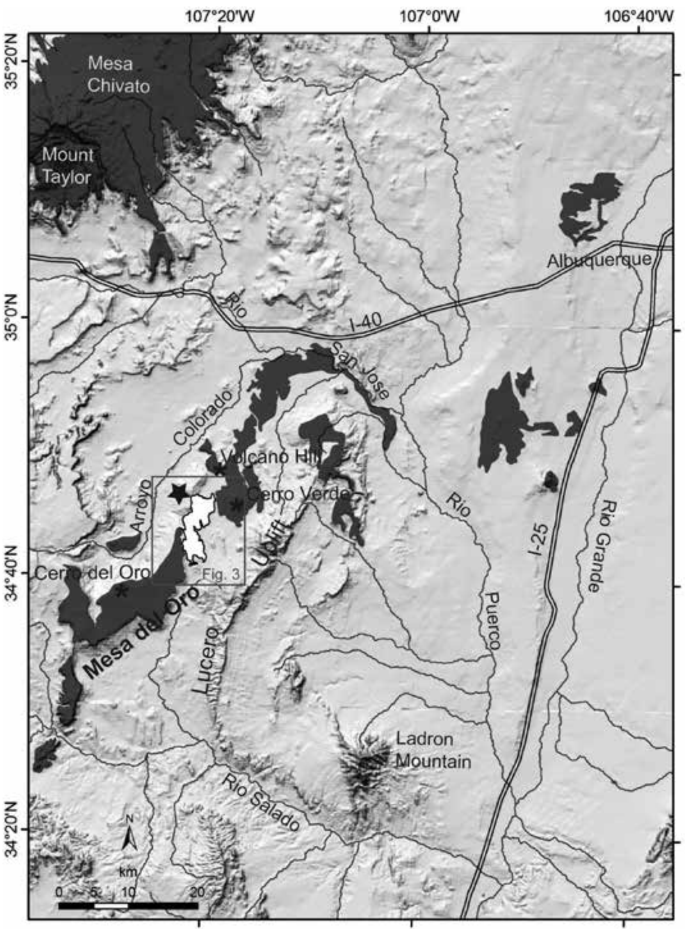

FIGURE 2. Shaded relief map showing the large-volume travertine deposit at Mesa del Oro (black star, outlined in black). Also shown are late Cenozoic volcanics (dark grey areas outlined in black), and volcanic vents (black asterisks). The box indicates the study area.

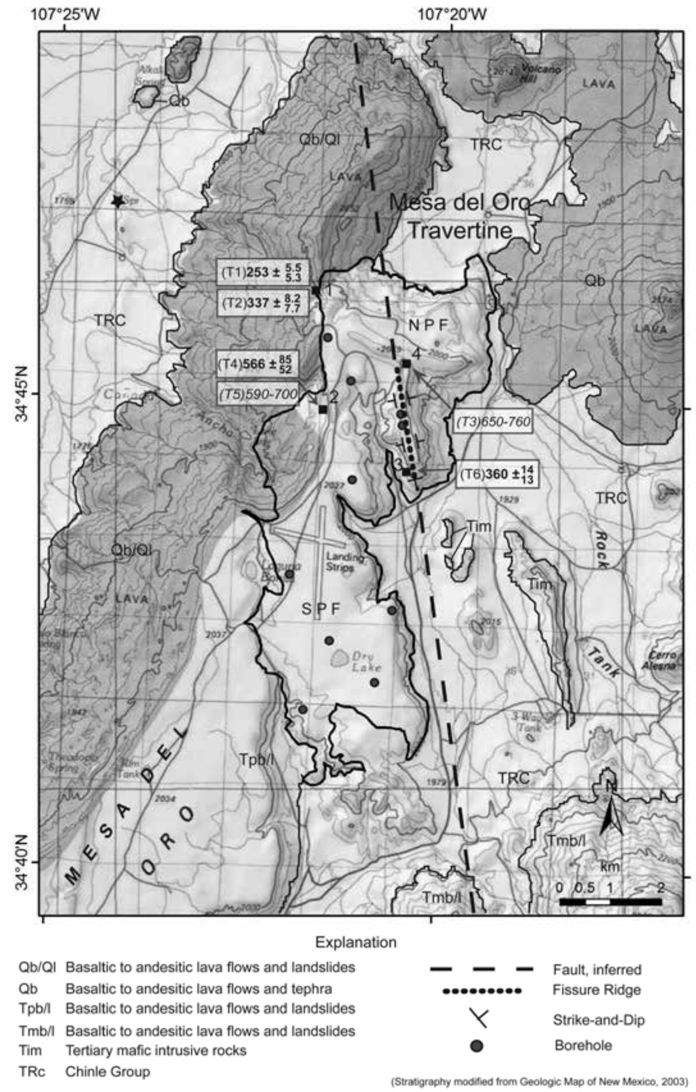

FIGURE 3. Topographic map showing the extent of the large-volume travertine deposit at Mesa del Oro (outlined in black), with its two platforms: northern platform (NPF) and southern platform (SPF). Also shown are ages of the travertine: ages in bold print are stratigraphic ages (ka), and ages in italics are model ages (ka). Numbered black squares are locations of measured sections (1-3), and a sampling location (4). The location of the modern travertine-precipitating Eddleman Spring is marked by a black star. Geographic coordinates of the samples can be found in Table 1. Geologic contacts and information are modified from the Geologic Map of New Mexico (NMBGMR, 2003).

and Capezzuoli, 2009). Travertine can be dated with the precise U-series method and because the deposits are well-preserved in the landscape they provide a powerful tool for understanding paleohydrology, paleoclimate, and neotectonic processes (Glover and Robertson, 2003; Faccenna et al., 2008; Crossey et al., 2011; De Filippis et al., 2012; Kampman et al., 2012). In this paper, we report new results for travertine morphologies and facies at Mesa del Oro, six new travertine ages and associated volumes, and implications for paleohydrology, paleoclimate, and neotectonics.

BACKGROUND ON TRAVERTINE AND TRAVERTINE FORMATION

Travertines are fresh-water carbonates that precipitate at springs and along streams due to the degassing of CO_2 from groundwater that is supersaturated with respect to calcium carbonate (Pentecost, 2005; Crossey et al., 2006):

$$CO_{2(g)} + H_2O + CaCO_{3(limestone)} \rightarrow Ca_2{}^{+}{}_{(aq)} + 2HCO_3{}^{-}{}_{(aq)}$$
$$Ca_2{}^{+}{}_{(aq)} + 2HCO_3{}^{-}{}_{(aq)} \rightarrow CO_{2(g)}\uparrow + H_2O + CaCO_{3(travertine)}$$

Travertine deposits usually occur along faults that are conduits for CO_2-charged groundwater (Hancock et al., 1999), and the ascent of the groundwater along faults requires high hydraulic head in a confined aquifer (Crossey et al., 2011; Priewisch et al., 2013). Modern studies show that a significant component of the CO_2 in travertine-depositing springs is derived from deep geological sources (Crossey et al., 2009; Williams et al., 2009). CO_2 is considered to be the carrier gas of helium and helium isotopes provide a tracer of potential mantle contributions (Ballentine and Sherwood Lollar, 2002). The water chemistry of modern travertine-depositing springs shows complex mixing of shallow meteoric recharge and deeply-derived fluids (Newell et al., 2005; Crossey et al., 2006; Williams et al., 2009). Travertines can be dated with the precise U-series method (Uysal et al., 2007; Embid, 2009; Sierralta et al., 2010) because uranium, which is soluble in natural waters, becomes incorporated in the crystal lattice of calcite during travertine precipitation (Hillaire-Marcel, 2009). Travertine deposits are often associated with Cenozoic basaltic volcanism which indicates over-pressuring of the CO_2/groundwater system with magmatic gasses (Gilfillan et al., 2008).

METHODS

Mapping of the travertine platforms was conducted on RGIS digital orthophotos (1 m) and USGS 7.5' topographic maps in the field, using additional information from geologic maps compiled by Jicha (1958) and the New Mexico Bureau of Geology and Mineral Resources (NMBGMR, 2003). The travertine extent was digitized on digital orthophotos in ArcMap GIS in order to assess the volume of the deposit. The area was multiplied by an average thickness of the two platforms, which was determined through field mapping and available borehole reports provided by the NMBGMR. Measured sections at the northern platform were sampled for U-series and petrographic analysis to assess travertine ages and facies, respectively. The samples were cut into slabs and micro-drilled to obtain powder from dense travertine layers for U-series analysis. Cut hand samples and slabs were used to analyze travertine facies macroscopically. The powdered samples were dated at the Radiogenic Isotope Laboratory at the University of New Mexico with the U-series method as described in Asmerom et al. (2010). This is a reliable dating method for measuring geologic age of about 500-600 ka (Edwards et al., 1987) because the ^{234}U-^{230}Th system returns to secular equilibrium within analytical resolution after about 6-8 half-lives of the daughter isotope, ^{230}Th, which has a half-life of 75,700 years (Cheng et al., 2000). We calculated ^{234}U model ages for two samples that were out of U-series range (Table 1) by assuming the initial ^{234}U for these samples based on the initial ^{234}U of successfully dated samples (Priewisch et al., 2013).

TRAVERTINE MORPHOLOGIES AND FACIES

The travertine of the northern platform was mapped in detail and dated. Its eastern part is a fissure ridge in terms of classic travertine morphology (Chafetz and Folk, 1984; Pentecost, 2005) that formed along an approximately NNW-SSE trending fault (Fig. 3). The fault is now concealed by travertine but we infer its trace from a fault mapped by Jicha (1958) to the south of the deposit. The central fissure is not well-preserved, but evidence for it is given by the bedding orientation of the travertine; along the central part of the fissure ridge the beds dip away from each other (Fig. 3). Fault-related fissure ridges like at Mesa del Oro form on tensional fissures where travertine precipitates from spring orifices along a central fracture (Chafetz and Folk, 1984; Hancock et al., 1999; Pentecost, 2005; Brogi and Capezzuoli, 2009). The fissure ridge is cross-cut by horizontal and vertical feeder veins (Figs. 4a and 5) that conveyed travertine-precipitating fluids to the surface, similar to those

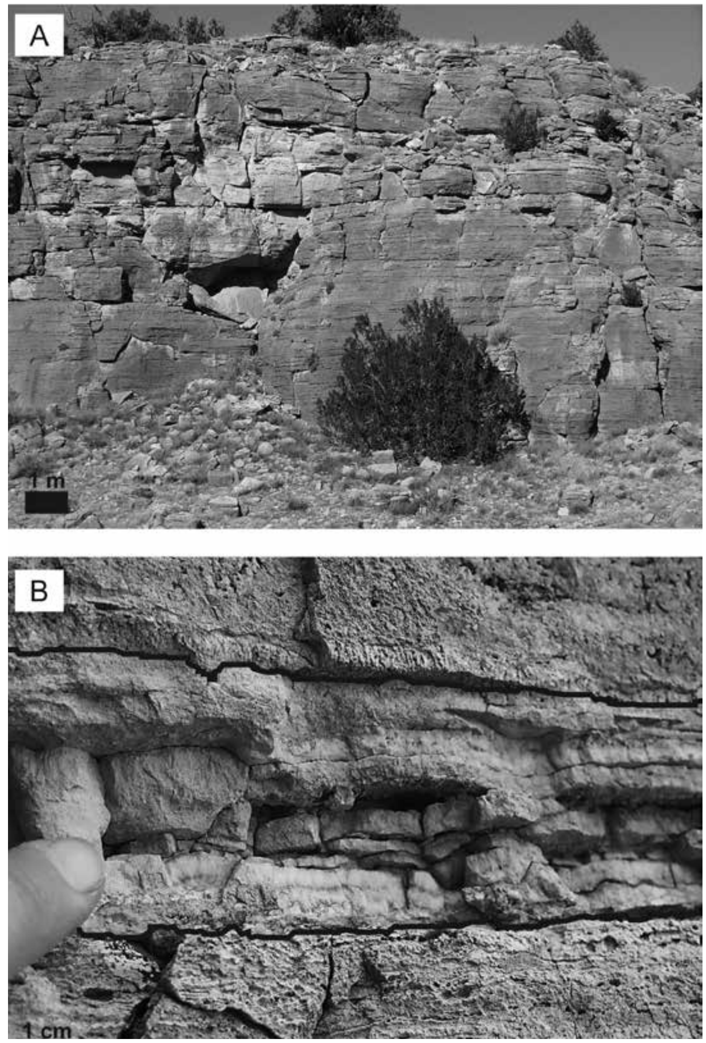

FIGURE 4. A) Fractured beds of horizontally bedded travertine at the southern end of the fissure ridge. B) E-W striking horizontal feeder vein (outlined in black) cutting across bedded travertine. The vein formed when travertine-precipitating groundwater was pushed into fractures in the existing travertine deposit during times of high hydraulic head. The vein is filled with sparry calcite.

TABLE 1 Locations, U-Series and Model Ages of Travertine Samples.

Sample No.	Sample ID	Easting	Northing	U-Series Age	+ Error	- Error	Model Age*
		NAD 83		(ka)	(ka)	(ka)	(ka)
T1	AP10-MDO4a	284164	3849773	252,750	5,500	5,275	
T2	AP10-MDO13-b1	284132	3849805	337,163	8,241	7,728	
T3	AP10_MDO12C-a	285719	3848485				650-760
T4	AP10-MDO30	284181	3847946	565,700	84,917	52,105	
T5	AP10-MDO46A-b	284171	3847946				590-700
T6	AP10-MDO53B-a	285808	3846487	360,581	13,800	12,628	

*(Priewisch et al., 2013)

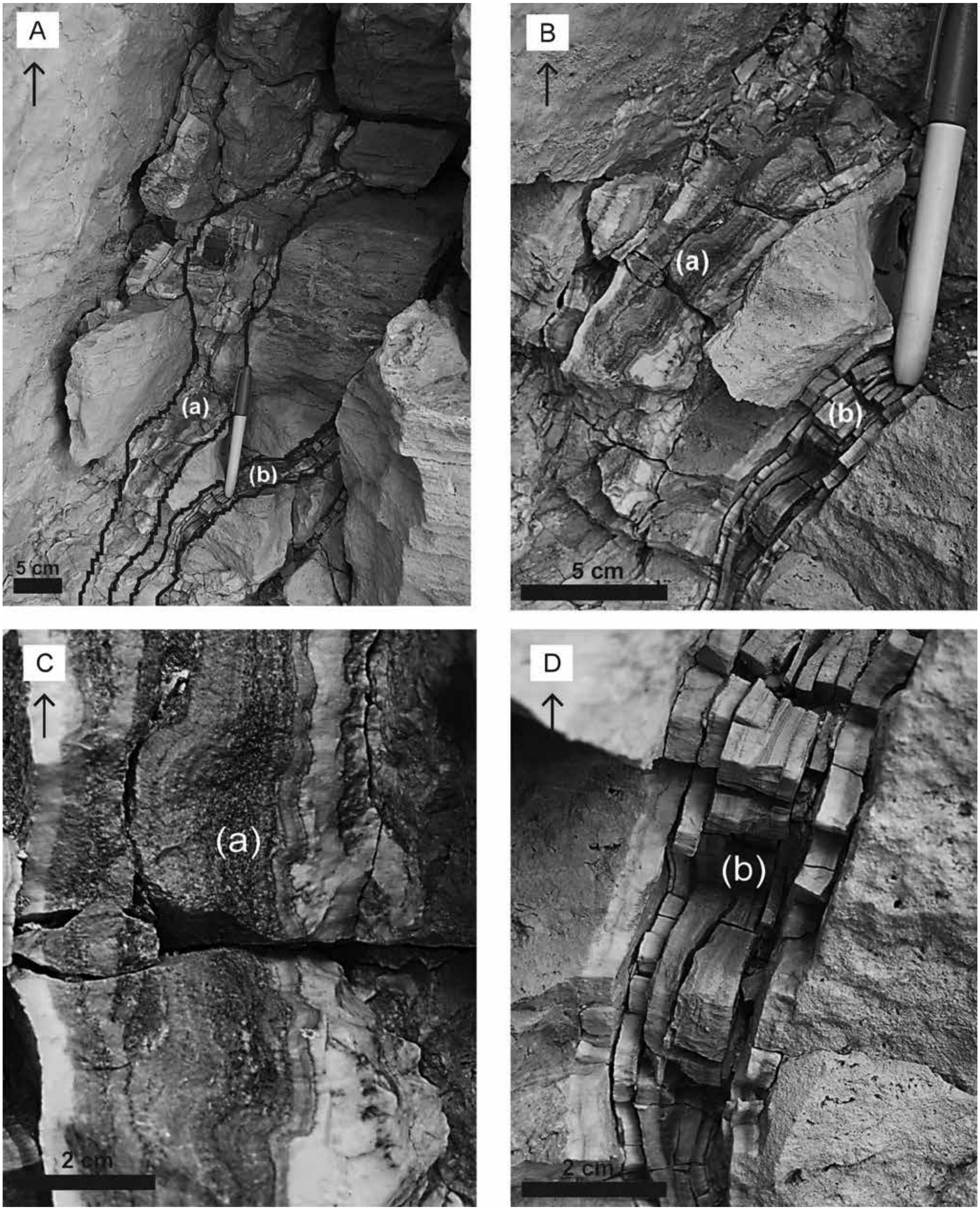

FIGURE 5. A) N-S striking vertical feeder veins (outlined in black) cutting across bedded travertine that is highly fractured. The veins formed when travertine-precipitating groundwater was pushed into fractures in the existing travertine deposit during times of high hydraulic head. B) Close-up view of the two central veins, (a) and (b). C) Close-up view of vein (a) showing intricate sparry calcite layers in different colors filling the vein. D) Close-up view of vein (b) showing parallel sparry calcite layers filling the vein. Black arrows in the photos are pointing upwards.

described in Italy (Brogi and Capezzuoli, 2009; De Filippis et al., 2012).

We identified two travertine facies for the northern platform at Mesa del Oro, which are described below. Our classifications are influenced by Chafetz and Folk (1984) and Alonso-Zarza and Tanner (2010) who give excellent overviews of travertine facies and morphologies. However, their facies classifications are based on modern, still active travertine systems, which are very different from ancient travertine deposits like the one at Mesa del Oro. It is often difficult to interpret the depositional environment of an ancient deposit based only on travertine types shown in the rock record because the same travertine type may form in different environments. Therefore, we modified the existing facies classifications to describe our ancient deposit. The northern platform at Mesa del Oro is dominated by two travertine facies: a step-pool facies along the fissure ridge (Fig. 3, locations 3 and 4), and a palustrine facies to the northwest and to the west of the fissure ridge (Fig. 3, locations 1 and 2, respectively).

The fissure ridge is characterized by the step-pool facies that formed when water emanating from the central fissure flowed down the flanks of the growing fissure ridge. Figure 6 shows a stratigraphic column of the different travertine types that represent the step-pool facies: peloidal travertine and horizontally bedded travertine that form in pools behind travertine dams, travertine drapes (Fig. 6a) that represent the overflow of travertine dams, and microterracettes (Fig. 6b) that form on steeply sloped dams and drapes (Fouke et al., 2000; Pentecost, 2005). An additional travertine type of the step-pool facies, also observed at Mesa del Oro, is travertine that formed by calcification of microbial mats that grew in pools behind travertine dams (Fig. 7; Fouke et al., 2000; Pentecost, 2005). The step-pool facies is an important travertine facies for interpreting the carbonates as spring deposits, as opposed, for example, to lake carbonates.

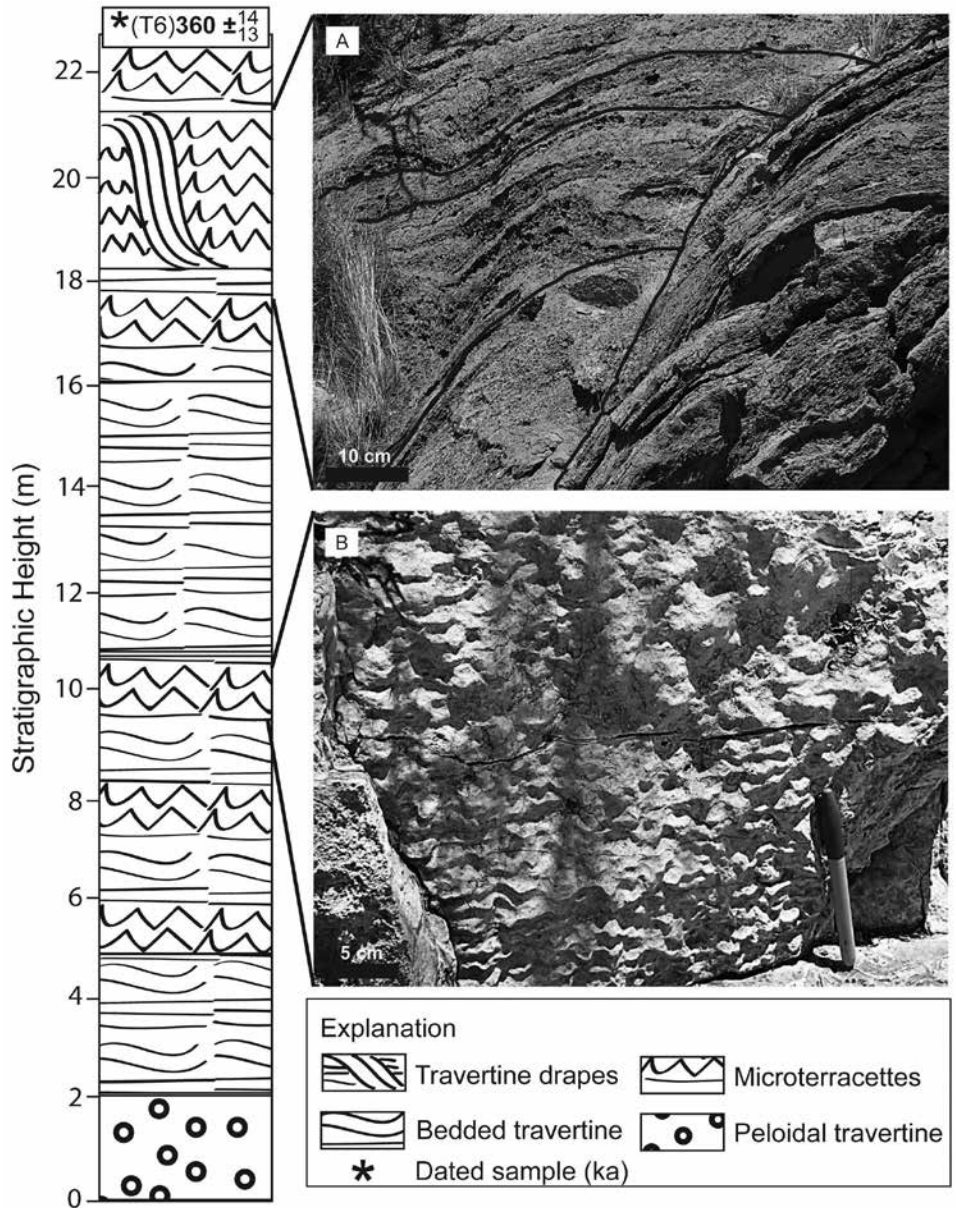

FIGURE 6. Stratigraphic column of the step-pool travertine facies from the west slope of the fissure ridge (see Fig. 3, location 3) showing travertine types that are indicative of this facies. A) Cross-sectional view of drapes that formed at large dams where the water flowed over the edge of one pool and down into the next pool. Some of the drapes are outlined in black. Flow direction of the water was down the slope of the fissure ridge to the west (left). B) Microterracettes that formed on the surface of a steeply sloping drape. Flow direction of the water was down the slope of the fissure ridge to the west (toward the viewer). Note that the spacing of the microterracettes indicates the surface steepness (steeper toward the base of the outcrop).

The northwestern and western edge of the platform are characterized by a marsh-related or palustrine travertine facies that formed when water flowing off the fissure ridge collected on surrounding flats and in depressions where standing bodies of water promoted development of vegetated areas in wetlands, similar to occurrences elsewhere (Guo and Riding, 1999; Glover and Robertson, 2003; Pentecost, 2005). Figure 8 shows a stratigraphic column of the different travertine types that represent the palustrine facies: bedded travertine (Fig. 8a), peloidal travertine with phytoclasts (Fig. 8b) and peloidal travertine that form in shallow ponds in the marsh, and travertine breccia that form when travertine crusts break up during flood events and get deposited in nearby areas.

According to drilling reports provided by the New Mexico Bureau of Geology and Mineral Resources the travertine is thickest

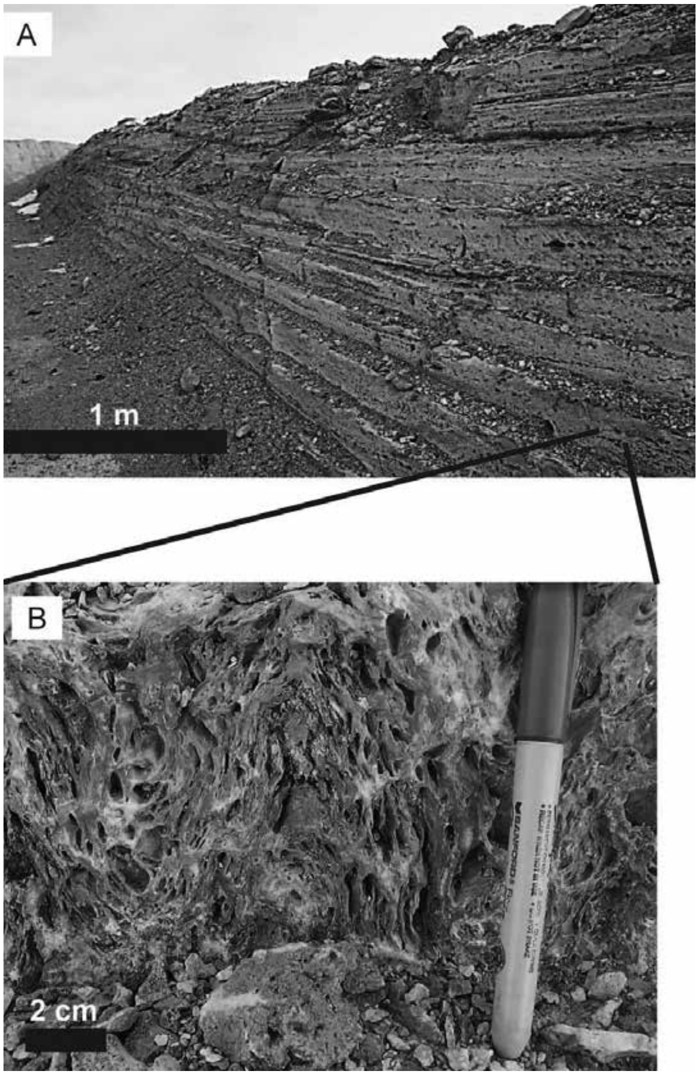

FIGURE 7. Step-pool travertine facies at the northern end of the fissure ridge (see Fig. 3, location 4). A) E-W striking bedded travertine exposed in a quarry on top of the northern platform. B) Close-up view of travertine fabric formed by calcification of microbial mats that grew in the step-pools.

(up to 63 m) in the central part of the fissure ridge, while the thickness decreases (~8 m to 11 m) to the northwest and to the west of the northern platform which was determined by field mapping. The drilling reports provided by the New Mexico Bureau of Geology and Mineral Resources also show that at the southern platform the travertine is thickest (up to 48 m) in the southern central part of the deposit where we infer the location of the primary spring vents.

TRAVERTINE VOLUMES AND AGES

The two travertine platforms at Mesa del Oro cover an area of 27 km^2 and have an estimated travertine volume of 0.7 km^3. The calculated volume is a minimum volume because we do not know how much of the travertine has been eroded. New U-series ages are 566 ± 68.5 ka, 360 ± 13.5 ka, 337 ± 8.0 ka, and 253 ± 5.4 ka (Fig. 3; Table 1). We calculated model ages (Priewisch et al., 2013) for two samples that were out of U-series range (> 500 ka) and these model ages are slightly older, 590-700 ka and 650-760 ka (Table 1). Based on these results we infer that travertine formation at Mesa del Oro occurred in two intervals, from 360 ka to 250 ka and from ~560 ka to 760 ka. Two samples from the northwestern edge of the northern platform gave ages of 337 ka at the bottom of the section and 253 ka at the top (Figs. 3 and 8), in agreement with their stratigraphic position. The two measured ages suggest travertine deposition may have taken place over 84 ky, resulting in a long-term average deposition rate of 10 cm/ky which we interpret to be a maximum accumulation rate given the likelihood of unconformities in the section.

DISCUSSION

Travertine morphology and facies as well as the volume and ages of the travertine deposit have implications for understanding neotectonic processes, paleohydrology, and paleoclimate.

The NNW-SSE trending fissure ridge at the northern platform (Fig. 3) likely formed due to the E-W extension of the Rio Grande rift and attests to repeated fault activity (Brogi et al., 2010; Ricketts et al., 2012) as shown by vertical and horizontal veins that cross-cut the deposit (Figs. 4b and 5). These veins suggest that CO_2-rich groundwater ascended along the fault and was precipitated in extensional veins. We infer that part of the CO_2 was derived from the mantle by analogy to the nearby active Eddleman Spring (Fig. 3), which may be similar to the springs responsible for depositing the travertine. The geochemistry of this spring is characterized by a high amount of CO_2 and the presence of primordial ^{3}He that suggests the input of mantle volatiles (Newell et al., 2005). Volcanic activity that might have led to an over-pressuring of the CO_2/groundwater system with magmatic gasses (Baldridge et al., 1987; Gilfillan et al., 2008; Embid, 2009) is recorded by the Mesa del Oro basalt flows which were dated by Baldridge et al. (1987) between 3.4 Ma and 1.1 Ma. Younger flows to the northeast of Mesa del Oro have ages between 800 ka and 300 ka (Baldridge et al., 1987), and the two intervals of travertine formation from 360 ka to 250 ka and from ~560 ka to 760 ka (Fig. 3; Table 1) overlap this period of Quaternary basaltic volcanism.

Although there are no active springs on the travertine platforms, the existence of the Pronoun Caves, which are dissolution caves in the travertine, provide evidence for past groundwater activity (Forbes and Stephens, 1994). The feeder veins (Figs. 4b and 5) cutting horizontally and vertically across the fissure ridge show that the hydraulic head was episodically high enough to push groundwater up and through the existing travertine deposit and we infer that groundwater originating from a confined aquifer system had significant artesian head to ascend along faults and fractures at these times. Modern hydrologic studies have identified the Permian San Andres-Glorieta (SAG) aquifer and Pennsylvanian Madera limestone as the regional aquifers at Mesa del Oro (Goff et al., 1983; Baldwin and Anderholm, 1992; Rauzi, 1999; Rawling, 2005). They also show groundwater mixing and complex flow paths because of two different recharge areas for these aquifers, the Lucero uplift to the east and the Zuni Mountains to the west (Baldwin and Anderholm, 1992). We assume that aquifers, recharge areas, and groundwater flow paths were similar at the time of travertine formation, and that the recharge areas received enough precipitation during extended wet times to increase the hydraulic head of the aquifers and facilitate travertine precipitation at Mesa del Oro during both glacial and interglacial paleoclimate periods (Priewisch et al., 2013).

Paleohydrologic conditions, topography, and the amount of CO_2 degassing affected travertine precipitation and facies at Mesa del Oro. Although fissure ridges are related to normal faulting (Brogi and Capezzuoli, 2009; De Filippis et al., 2012), the flow rate of the water flowing out of the central fissure can influence its height and width (Hancock et al., 1999), and thus slope gradient. The peloidal and bedded travertine of the palustrine travertine facies to the northwest and west of the fissure ridge reflect the presence of adjacent wetlands, ponds or lakes, and hence the availability of significant amounts of water that collected in the marsh. Windblown clastic material accumulated in these water bodies and led to the formation of marly sediment. The availability of water also led to the growth of abundant vegetation represented by travertine layers that contain plant casts and fibrous material.

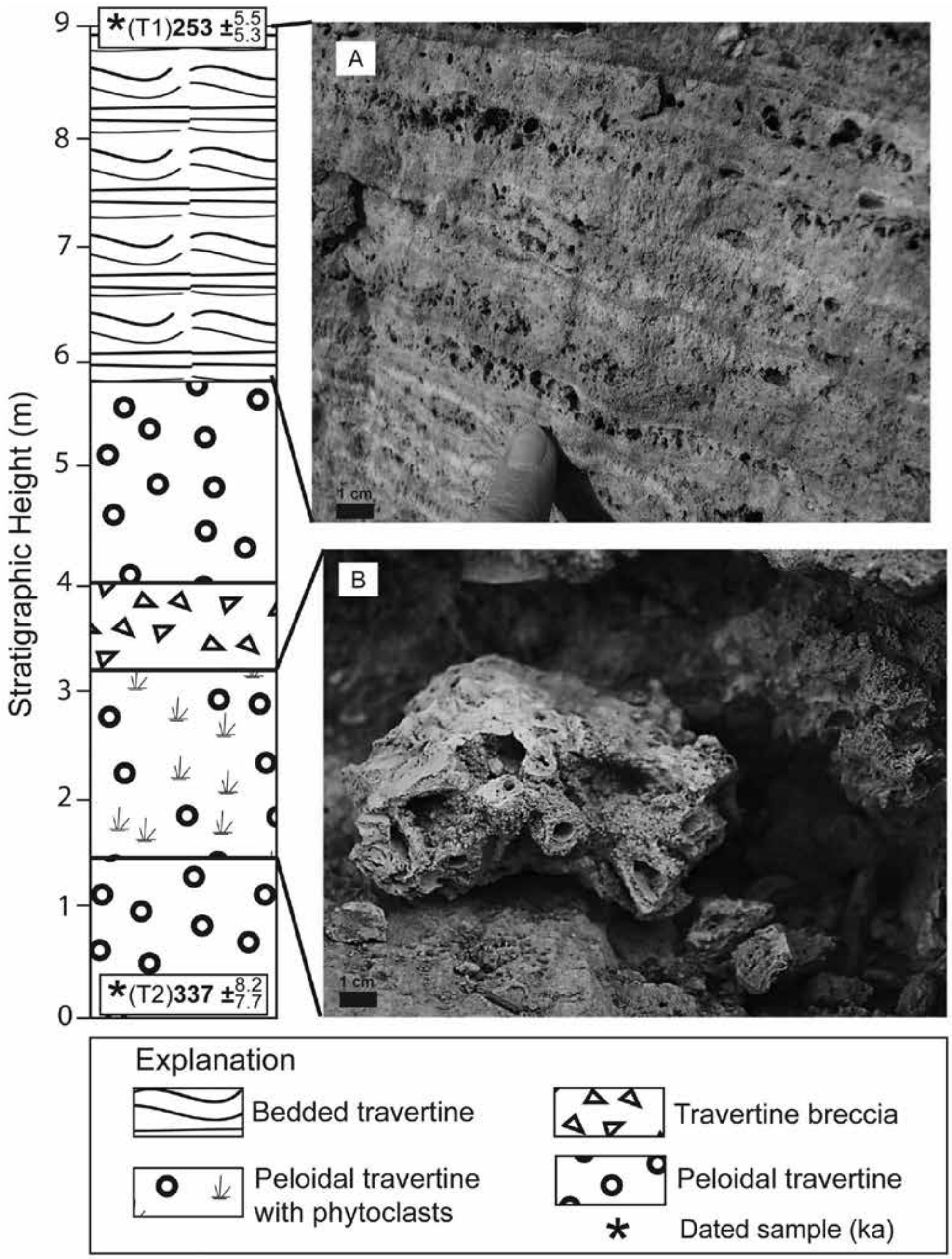

FIGURE 8. Stratigraphic column of the palustrine travertine facies to the northwest of the northern platform (see Fig. 3, location 2) showing travertine types that are indicative of this facies. A) Example of bedded travertine with alternating irregular layers of different colors and porosity. B) Peloidal travertine with phytoclasts: the micritic travertine contains calcite-encrusted stems and plant casts.

CONCLUSION

New ages show that large-volume travertine formation at Mesa del Oro occurred in two intervals, from 360 ka to 250 ka, and from ~560 ka to 760 ka. These intervals coincide with local basaltic volcanism between 300 ka and 800 ka that we infer led to high CO_2 influx to the groundwater system. Increased recharge during wet climate periods are interpreted to have caused high hydraulic head in a confined aquifer leading to artesian springs and facilitating travertine precipitation. The formation of a fissure ridge and associated marsh reflect the availability of significant amounts of water and hence, we conclude that travertine formation at Mesa del Oro represents extended wet times during paleoclimate periods.

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The southern tip of the northern platform at Mesa del Oro, showing 22 m of travertine (view to the east). *Photo courtesy of Alexandra Priewisch.*