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QUATERNARY PALEOSPRING DEPOSITS AT SAN DIEGO MOUNTAIN IN SOUTH-CENTRAL NEW MEXICO

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Abstract—Quaternary paleospring deposits at San Diego Mountain in southern New Mexico are associated with the West Tonuco fault and are related to a hydrothermal system in the Tonuco uplift. In this study, preliminary models explaining the depositional environment and relative timing of paleospring activity at San Diego Mountain are presented. Paleospring facies were determined from field descriptions and classified according to White et al. (1964) and Chafetz and Folk (1984). Paleospring facies include bedded opaline sinter, opaline-cemented alluvium, thin-bedded opaline sinter, travertine proximal mound, travertine fan, and travertine cascade deposits. Opaline deposits are the result of precipitation from cooling paleospring waters. The travertine deposits result from CO_2 degassing. Two end-models are presented to explain the depositional sequences at San Diego Mountain: (1) Degassing of CO_2 at the paleospring source results in the precipitation of proximal calcium carbonate (travertine), followed by the cooling and synchronous precipitation of distal amorphous silica (sinter) and (2) changes in temperature and chemistry through time result in diachronous opaline sinter and travertine deposits. Three separate periods of spring activity, determined by geomorphic position, have been identified along the West Tonuco fault.

INTRODUCTION

The Rio Grande rift in New Mexico is characterized by high heat flow (Reiter et al., 1978; Reiter et al., 1986). Hydrothermal spring deposits associated with geothermal systems along the Rio Grande rift are found at Soda Dam near the Jemez caldera in northern New Mexico, as well as to the south at Rincon (Goff and Shevenell, 1987; Witcher, 1991). Temperature gradient studies of the geothermal system at Rincon reveal high heat flow (>800 $\mathrm{mW/m^2}$) in association with paleospring deposits of opal (Witcher, 1991). Heat-flow measurements at San Diego Mountain are greater than 600 $\mathrm{mW/m^2}$ and indicate potential for another geothermal system at depth in the Tonuco uplift (Reiter et al., 1978).

San Diego Mountain is a horst, the Tonuco uplift, formed of Precambrian granite, Paleozoic carbonate rocks, and Tertiary volcaniclastic rocks (Seager et al., 1971). This study describes post-Camp Rice Formation paleospring deposits on the northwest lower slopes of San Diego Mountain along the West Tonuco fault (Fig. 1). San Diego Mountain is also known as Tonuco Mountain.

Facies mapping of spring deposits are used to determine depositional environments and relative timing of paleospring activity. Results of this study provide preliminary data to understand the hydrothermal system at San Diego Mountain, paleohydrogeology, and tectonic activity along the West Tonuco fault.

PALEOSPRING FACIES

Two main types of paleospring deposits are found at San Diego Mountain: sinter and travertine. Sinter refers to deposits consisting predominantly of opaline silica that initially formed at the surface through precipitation. The classification of White et al. (1964) is used with some modification. Travertine is a rock, consisting dominantly of one or more of the carbonate minerals. Descriptive morphology of Chafetz and Folk (1984) and White et al. (1964) is used. Sinter and travertine deposits are commonly associated with thermal spring discharges and suggest a geothermal system beneath San Diego Mountain or associated with the West Tonuco fault. The siliceous materials found at San Diego Mountain can be separated into bedded opaline sinter, opaline-cemented alluvium, and thin-bedded opaline sinters. Travertine deposits are subdivided into proximal mound, fan, and cascade deposits (Table 1).

Bedded opaline sinter facies

The bedded opaline sinter facies occurs approximately 100 m from the paleospring source above the opaline-cemented alluvium facies (Fig. 2). This facies consists of planar, nearly pure opaline beds 3–18 cm thick with abundant plant fossils that can occur in both growth position and flow direction. The beds are pale yellow (2.5Y8/2), to pale gray (5Y7/2), to light greenish gray (5GY7/1).

Opaline-cemented alluvium facies

Opaline-cemented alluvium is the most common sinter deposit. This facies is characterized by alluvial deposits, generally debris flows, which have undergone various degrees of opaline cementation. Most deposits are less than 1.5 m thick with pale red (10R6/3; 5R7/2) to reddish brown (2.5YR4/3) color and beds ranging in thickness from 2 to 30 cm. Occasionally, beds 2–3 cm thick of the thin-bedded opaline sinter facies are interbedded. Clasts include quartz, orthoclase, limestone, siltstone, and sandstone that are poorly sorted and angular. Plant fossils are common and generally in growth position.

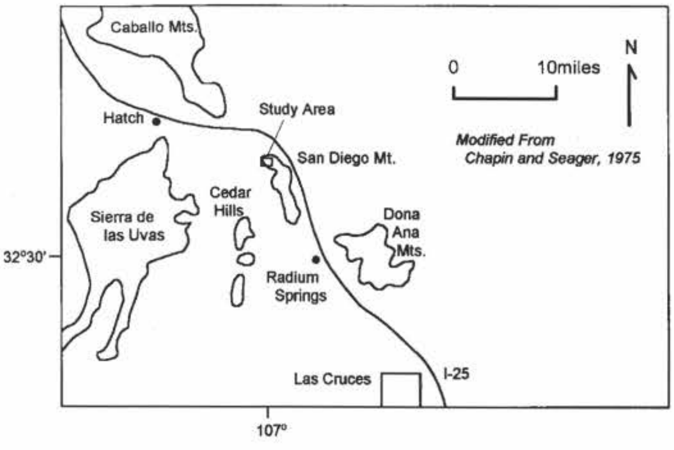

FIGURE 1. Location of study area on northwest side of San Diego Mountain in south-central New Mexico.

TABLE 1. Opaline and travertine facies with their identifying characteristics at San Diego Mountain.

	Bedded Opaline Sinter	Opaline-Cemented Alluvium	Thin-Bedded Opaline Sinter
Sinter	Casts and molds of plant roots and stems	Opal cements clasts of sand to boulder size	Silica deposits in discharge arroyos (1-3 cm thick)
	Plant fossils are parallel and perpendicular to bedding	Fossil root and stem tubules and petrifactions	Evidence of high dissolved silica
	Diatoms are present	Evidence of penetration of water into the substrate	High rates of evaporation and rapid cooling of waters

Modified from White et al., 1964

	Proximal Mound	Fan	Cascade
Travertine	Interlocking carbonate spar	Large-scale sloping deposits	Fibrous structures from plant encrustation
	No fossil plants	Deposits dip radially away from high regions	Form in regions of increased water turbulence
	No inclusions	Intraclasts integrated from higher on slope	Structures from algae and mosses, not bacteria
		Fossil root and stem molds, tubules and petrifactions	Possible nonbedded or massive structures

Modified from Chafetz and Folk, 1984

Thin-bedded opaline sinter facies

The thin-bedded opaline sinter facies is occasionally interbedded within the opaline-cemented alluvium facies closest to the paleospring source. The nearly pure opal beds are 1–3 cm thick, planar, and white (5Y8/1).

Travertine proximal mound facies

The travertine proximal mound facies occurs above hydrothermally altered bedrock, indicating that these are the apparent paleospring sources. At least three distinct paleospring sources occur within the study area: Carson paleospring, Tonuco paleospring and Diablo paleospring (Fig. 2). The proximal travertine mound facies are up to 2.5 m thick and rest unconformably on Tertiary volcaniclastic sediments. The mounds are composed of 0.5–4 cm thick, wavy layers of spar calcite. Individual layers consist of interlocking calcite crystals 0.5–3 cm long and 1–5 mm wide that are oriented perpendicular to bedding. When fresh, the proximal mound travertine is white (5Y8/1) and contains no inclusions or fossils.

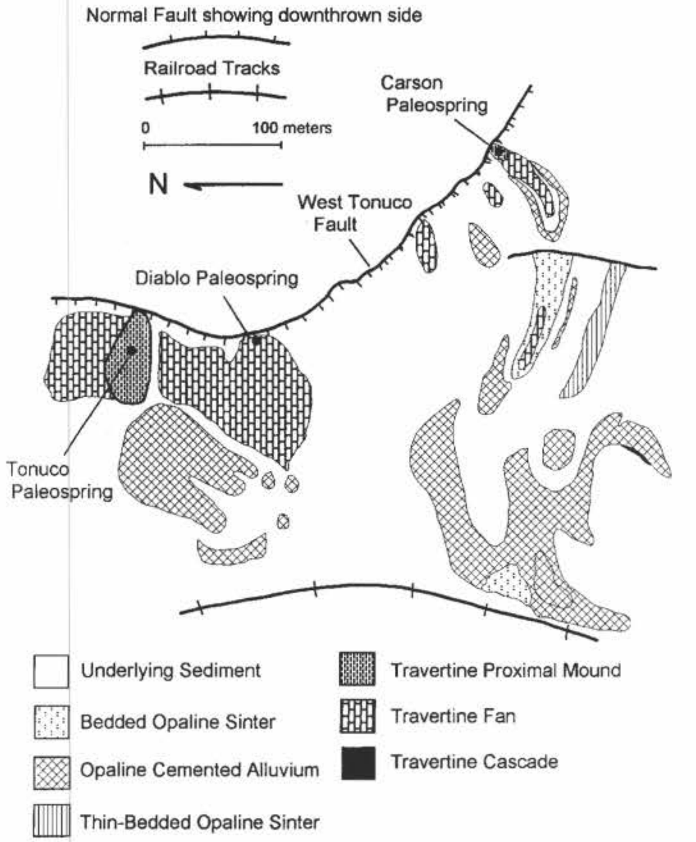

FIGURE 2. Distribution of travertine and opaline paleospring facies at San Diego Mountain. Three paleospring sources are located along the West Tonuco fault. Notice the facies shift from travertine near the source to opaline sinter away from the source.

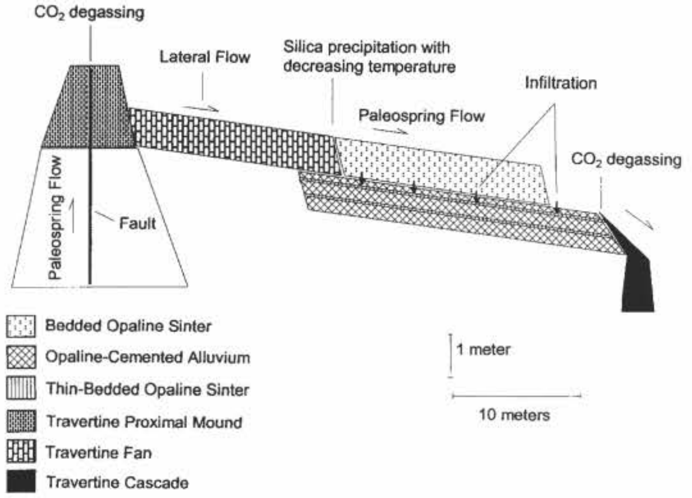

FIGURE 3. Model of Depositional Environment. Source waters upwelling along the West Tonuco fault degas CO_2 at the surface causing travertine deposition. Water cooling away from the source stimulates amorphous silica precipitation. Turbulence (waterfall) away from the source can cause renewed travertine deposition.

Travertine fan facies

The travertine fan facies is a distal paleospring deposit that is downslope of the proximal mound travertine facies (Fig. 2). Beds in this facies are 0.5–3 cm thick and wavy, sometimes containing 2–3 mm thick, contorted laminae of probable algal origin. The fan facies is characterized by micrite containing sand and gravel. Plant fossils are common and can occur in growth position or as clasts oriented in flow direction.

Travertine cascade facies

The travertine cascade facies is characterized by 2–8 cm thick vertical beds composed of 1–2 mm thick, wavy and crenulated, laminated micrite. The laminae appear to be of algal and/or bacterial origin (Chafetz and Folk, 1984; Ferris, 1995). This facies occurs as an outcrop 1.5 m high and 1 m wide approximately 200 m down gradient from the nearest paleospring source (Fig. 2).

FOSSILS

Fossil plants are found in all of the facies with the exception of the travertine cascade and the travertine proximal mound facies. The fossils occur as root molds, root tubules, root petrifactions, and stems (Klappa, 1980).

Root molds occur as tubular voids in the bedded opaline deposits and sometimes in the opaline-cemented alluvium (Klappa, 1980). The molds are 1–3 mm thick and usually 1–6 cm in length with no preferred orientation.

The root tubules are opaline encasements of root molds (Klappa, 1980). The tubules are only abundant in the opaline-cemented alluvium. The tubules consist of opaline-cemented sands and weather to form anastomosing or downward branching networks. The cemented tubules are about 1 cm thick.

The root petrifactions described by Klappa (1980) are created by mineral replacement of the organic matrix through filling of cellular voids. The petrifactions are found in the fan travertine, bedded-opaline deposits, and opaline-cemented alluvium. The roots are silicified with their original cellular texture preserved and are 1–3 mm wide and up to 10 cm long.

Stems are distinguished from the root fossils by their lack of tapering at the ends. The stems can be found in the bedded opaline sinter, opaline-cemented alluvium, and travertine fan facies. They are generally silicified with the cellular structure preserved and are indicative of paleoflow direction because of parallel, horizontal orientation.

GEOMORPHIC HISTORY, DEPOSITIONAL MODELS, AND RELATIVE TIMING

Geomorphic history

Deposition of the Camp Rice Formation began approximately 3.4 Ma (Mack et al., 1993). The Camp Rice fluvial (ancestral Rio Grande) and piedmont (alluvial fan) deposits alternate to create an interfingering sequence adjacent to San Diego Mountain. Deposition continued until the onset of Rio Grande entrenchment after 0.78 Ma. Several generations of post-La Mesa surface entrenchment straths and backfill terraces characterize the Rio Grande valley above the modern Rio Grande floodplain (Gile et al., 1981).

Paleospring activity along the West Tonuco fault during this time resulted in deposits of sinter and travertine within arroyos because (1) they occur in narrow, sinuous beds that emanate from sources along the fault and (2) they are located in geomorphic positions below the Camp Rice deposits. Consequent differential erosion has resulted in the inversion of these arroyos to form sinuous ridges and other topographic highs. The facies of the paleospring deposits indicate chemical, temperature, biological, and possibly discharge rate factors for the paleosprings. We present two possible models to explain the relationships between the sinter and travertine facies in the study area.

Contemporaneous deposition model

Contemporaneous deposition describes synchronous precipitation of travertine and silica by the same spring discharge water at different locations along the flow path (Fig. 3). As the water nears the surface at the paleospring vent, travertine is deposited because of CO_2 degassing as the waters equilibrate with the atmosphere (Herman and Lorah, 1987). Degassing causes a decrease in acidity, which decreases carbonate solubility. The autochthonous layers of spar in the travertine mound facies are evidence of a physio-chemical or non-biologic origin (Julia, 1983; Pedley, 1990). A lack of fossils supports this hypothesis as well.

Downstream of the travertine mound facies, decreases in temperature and increases in biological activity promote additional travertine deposition in the travertine fan facies. Also, as cooling and evaporation occur, the waters become supersaturated with respect to amorphous silica (opal). These silica-saturated waters infiltrate underlying alluvium and precipitate, forming the opaline-cemented alluvium facies. As the alluvium becomes cemented, water is forced to flow over the surface. Surface flow and precipitation forms the thin-bedded opaline sinter facies.

In this model, formation of the travertine cascade facies would occur at any waterfall, where increased turbulence triggers CO_2 degassing, which increases pH and stimulates carbonate precipitation (Amundson and Kelly, 1987; Herman and Lorah, 1987).

Diachronous deposition mode

Geochemically distinct facies of travertine and silica may also be explained by deposition from paleospring chemistry variations through time. Higher temperatures are required to concentrate silica in solution compared to travertine. Opal deposition requires geothermal reservoir temperatures much greater than 100°C (Rimstidt and Cole, 1983). At San Diego Mountain, discharge from a high-temperature (>100°C) reservoir would result in the paleospring sinter facies. Aragonite in the travertine would be another indicator of higher temperatures (Barker et al., 1996). Also, high-temperature geothermal systems tend to be self-sealing from mineralization of shallow vertical permeability to confine or cap the system. In this case, shallow groundwater discharges precipitate travertine conformably on early sinter (Fig. 3). This relationship is not observed in the study area. However, travertine appears much less resistant to erosion than sinter; therefore, the travertine deposits may have been more extensive than at present.

Discussion

The mapped depositional relationships favor the contemporaneous deposition of travertine and sinter deposits. Overall, the travertine is always proximal to paleospring vents and sinter is found in distal outflow locations. Inverted arroyo sequences held up by paleospring deposits and deposits in younger and lower elevation drainages attest to the fact that several generations of spring depo-

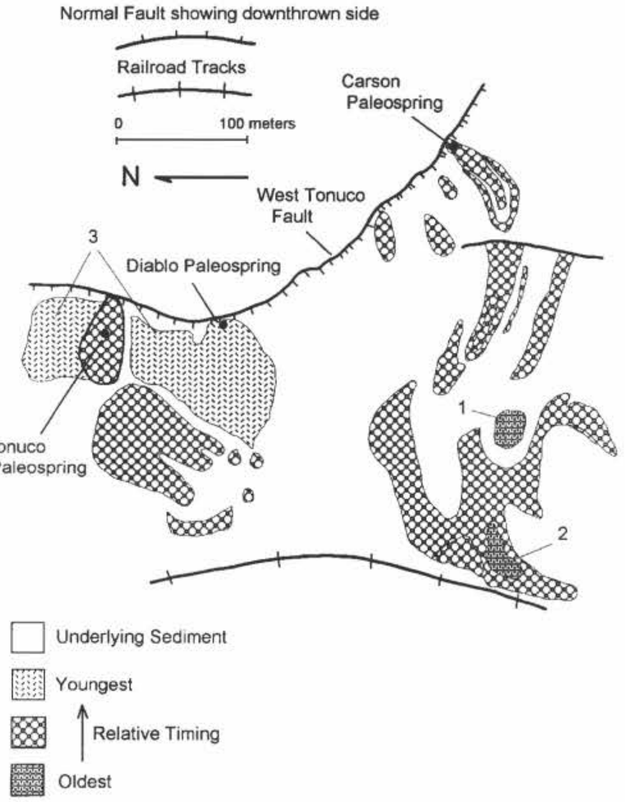

FIGURE 4. Relative geomorphic position of paleospring deposits at San Diego Mountain. Deposits at locations 1 and 2 are at the highest topographical positions and therefore interpreted to be the oldest deposits. The next youngest deposits surround sites 1 and 2 and occur at topographically lower positions. Deposits of similar elevation are found associated with Tonuco paleospring and are probably similar in age. The youngest deposits are indicated at site 3 and appear to be related to Diablo paleospring.

sition may exist. Reservoir self-sealing, drops and rises in the regional groundwater head as a result of Rio Grande entrenchment and backfilling events or climate, migration of the depocenter over short time frames, tectonic reactivation of subsurface permeability, and episodic heating and cooling of shallow geothermal reservoirs may all play roles individually or in concert.

Relative timing

The paleospring deposits are grouped into three relative age categories. The oldest deposits are found at the highest elevations, while the youngest are found at the lowest. The highest group of deposits includes two opaline-cemented alluvium outcrops approximately 200 m west of Carson paleospring (Fig. 4, locations 1 and 2). The intermediate elevation of these beds along with their advanced weathering suggest that they are older than other opaline deposits in the area. These two outcrops appear to be "inverted valley" arroyo fill and are similar in age based upon similarity of facies and elevations.

The next apparently younger group of deposits include travertine facies at both Carson and Tonuco paleosprings with associated down slope sinter facies. These deposits form "inverted valley" arroyo topography. The Carson paleospring deposits are higher in elevation than the Tonuco deposits and are believed to be older.

The youngest paleospring deposit is the travertine fan deposit west of Diablo paleospring (Fig. 4, location 3). The deposits associated with Diablo paleospring occur at the lowest elevation. The travertine deposit fills a paleo-arroyo being cut by modern arroyos grading to the Rio Grande floodplain.

CONCLUSIONS

The paleospring deposits at San Diego Mountain originate from vents associated with the West Tonuco fault. Paleospring deposits in the study area are mapped as six facies: bedded opaline sinter, opaline-cemented alluvium, thin-bedded opaline sinter, travertine mound, travertine fan and travertine cascade. Presence of opaline spring deposits infers a geothermal system with reservoir temperatures in excess of 100°C. Two models were constructed to explain the paleospring deposition. In the first model, degassing of CO_2 at the paleospring vent results in proximal travertine deposition, followed by distal amorphous silica (sinter) deposition as water cools during outflow. The second model is diachronous deposition from paleosprings discharges with different chemistry. Both models could have been viable throughout paleospring deposition either separately or simultaneously. The paleospring discharges have been grouped into three relative ages, but all of the paleospring deposits are post-Rio Grande entrenchment. Apparent periodicity of paleospring activity may be related to regional groundwater head changes in response to Rio Grande entrenching and backfilling, tectonism, climate, geothermal system self-sealing, or episodic heating and cooling of a shallow geothermal reservoir.

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