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POST-RESURGENCE LAKES IN THE VALLES CALDERA, NEW MEXICO

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Abstract — Valles caldera has contained multiple lakes since resurgence at ≥1.2 Ma. Many details of the history of these lakes are yet to be defined, but a partial framework has been developed from recent mapping and other studies. Three large lakes, each >20 km^2 in area, formed as a result of damming of drainages during the three youngest episodes of volcanism, and earlier volcanism also likely blocked drainages and impounded lakes. Much of Valle Grande was inundated at ca. 50-60 ka following burial of the East Fork Jemez River canyon by thick El Cajete pumice deposits. This lake was ~10 km long and up to 5 km wide; beach ridges, spits, and wave-cut shorelines mark its extent. The El Cajete lake was probably short-lived, draining rapidly once an outlet was established. An older, somewhat larger lake, ~11 km long, also occupied much of Valle Grande, formed by damming of the East Fork by ca. 521-552 ka South Mountain rhyolite flows. Drilling logs indicate at least 90 m of clayey diatom-rich sediment are associated with this lake, and recent studies suggest it persisted for at least 170 ky. A third lake occupied much of the northern moat of the caldera, extending ~20 km eastward from a ca. 557 ka San Antonio Mountain rhyolite dam into Valle San Antonio, Valle San Luis, Valle Santa Rosa, and Valle Toledo. The part of the lake in Valle Toledo filled with diatom-rich sediment that is conformably overlain by fluvial deposits, and an inferred delta front is preserved downstream in eastern Valle San Antonio. Farther west, fluvial terraces unconformably overlie lacustrine sediment and indicate draining before the lake filled with sediment, caused by incision of the outlet. Preliminary OSL analyses, supported by a ^{14}C date, suggest that upper Valle Toledo lake beds have an age of ca. 40-50 ka, indicating either a very long-lived lake or a younger damming event, although a younger dam has not been identified. Surface and subsurface data indicate the presence of additional post-resurgence lakes in the caldera, although their age and characteristics are less well constrained.

INTRODUCTION

The Valles caldera, in the Jemez Mountains of northern New Mexico (Fig. 1), was formed at ca. 1.25 Ma following eruption of voluminous ignimbrites of the Tshirege, or upper, Member of the Bandelier Tuff (Smith and Bailey, 1968; age from Phillips, 2004). The caldera includes a large resurgent dome (Redondo Peak), multiple post-resurgence rhyolite domes that erupted along ring fractures, and broad sediment-filled valleys (Smith et al., 1970). Lacustrine deposits are present in many of the valleys, and first attracted interest after they were described in drill cuttings in 1948 as part of water-supply investigations (H. T. Stearns, 1948, unpubl. report to U.S. Atomic Energy Commission [AEC]). In one of the earliest applications of palynology to paleoclimatic studies in the Southwest, examination of pollen from the 1948 cuttings and a short core suggested that several wet-dry (glacial-interglacial) cycles were recorded in Valle Grande lake sediments (Sears and Clisby, 1952). However, the lake deposits subsequently received little attention and were not well described, leading to conflicting interpretations.

References to “a lake” by Conover et al. (1963) and Griggs (1964) suggests that they envisioned deposits penetrated in drill holes in different valleys were from a single lake created following caldera formation. Smith and Bailey (1968) proposed that overflow of the initial caldera lake or lakes and breach of the caldera rim occurred during late stages of resurgence (>1 Ma), and that lake drainage resulted in incision of San Diego Canyon. Smith et al. (1970) mapped lacustrine deposits in Valle San Antonio and Valle Toledo that they reported were interbedded with tuffs of the Valle Grande Member of the Valles Rhyolite, documenting the occurrence of one or more post-resurgence lakes in the caldera. In contrast to the early breach proposal of Smith and Bailey (1968), other workers inferred that breach of the caldera rim occurred much later, at ca. 0.5-0.43 Ma, and that the initial caldera lake therefore persisted for >700 ky (Goff and Shevenell, 1987; Goff et al., 1992; Goff and Gardner, 1994). Rogers (1996) and Rogers et al. (1996) later supported the early breach proposal, and in addition they proposed that lacustrine deposits along San Antonio Creek in Valle San Antonio and Valle Toledo recorded drainage disruption by ring fracture domes. In his unpublished 1948 report to the AEC, Stearns also proposed that lacustrine deposits along San Antonio Creek and in Valle Grande recorded impoundments behind lava dams, although this report (classified until 1965) has received little notice.

In this paper we present additional information on post-resurgence lakes in the Valles caldera obtained during 1:24:000 scale mapping for the New Mexico STATEMAP program (Reneau et al., 2004; Goff et al., 2005b, 2006a, b; Gardner et al. 2006) and from other studies. Resurgence is now believed to have been complete by 1.2 Ma, within 54 ky of caldera collapse (Phillips, 2004), and the post-resurgence period therefore spans over 95% of the time since eruption of the Bandelier Tuff. Although many details of the history of lakes within the caldera remain unresolved, our work supports the basic interpretation of Rogers and colleagues that the lacustrine deposits along San Antonio Creek record post-resurgence damming events within the caldera, subsequent to breaching of the caldera rim, and similarly documents lakes in Valle Grande formed by damming of the East Fork Jemez River. Some insights into post-lake evolution of the valleys are also provided.

VALLE GRANDE

Valle Grande is the largest valley in the Valles caldera, extending for >10 km along the East Fork Jemez River and having a maximum width of >5 km. It is bordered by the caldera wall on

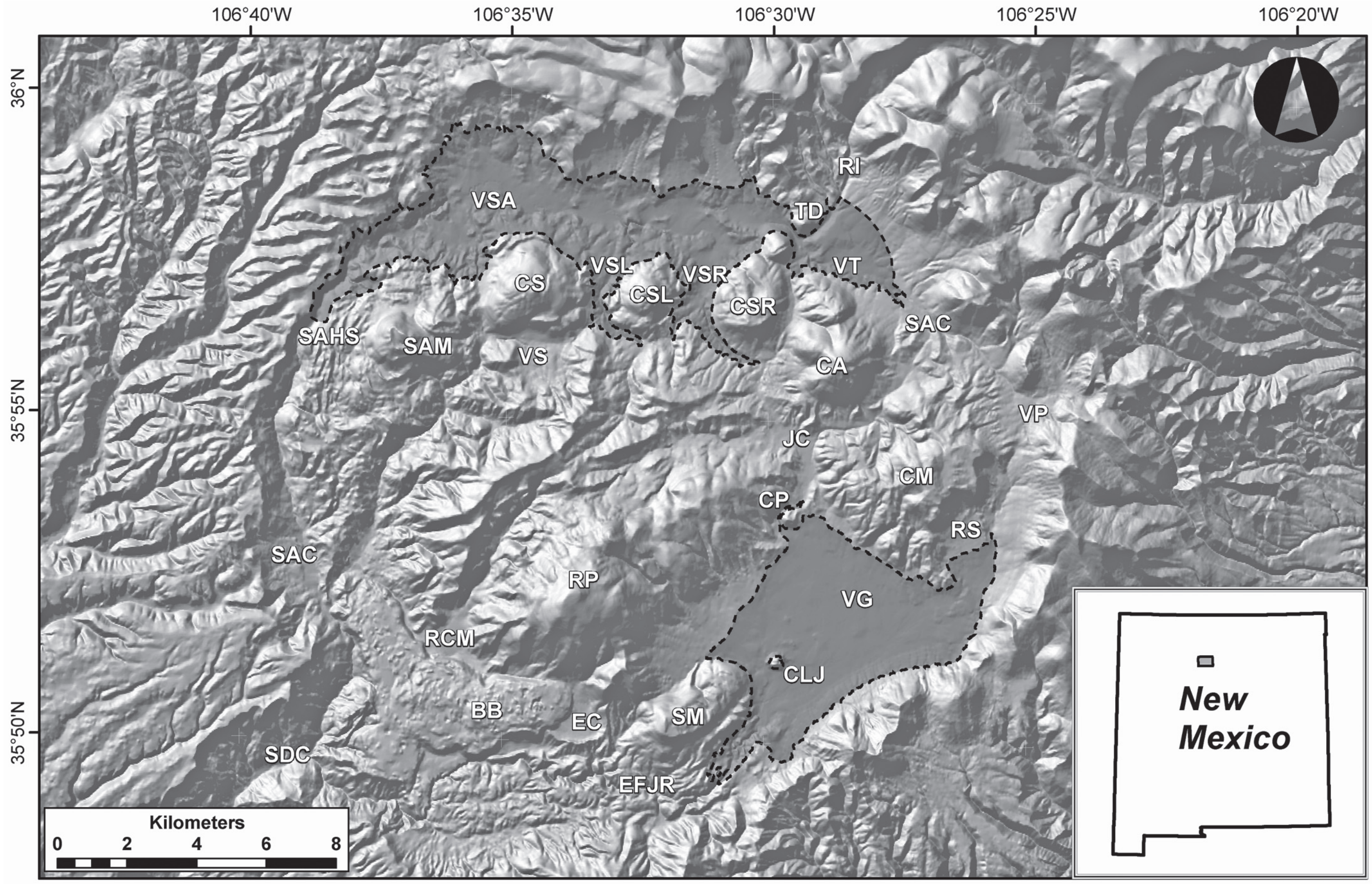

FIGURE 1. Digital elevation model (DEM) map of the Valles caldera showing estimated maximum lake extent in Valle Grande (South Mountain lake) and along San Antonio Creek (San Antonio lake), and other locations mentioned in text. Lake extent may have been greater where younger fans have buried shorelines. BB = Banco Bonito; CA = Cerros del Abrigo; CLJ = Cerro La Jara; CM = Cerro del Medio; CP = Cerro Piñon; CS = Cerro Seco; CSL = Cerro San Luis; CSR = Cerro Santa Rosa; EC = El Cajete; EFJR = East Fork Jemez River; JC = Jaramillo Creek; RCM = Redondo Creek meadows; RI = Rito de los Indios; RP = Redondo Peak; RS = Rincon de los Soldados; SAC = San Antonio Creek; SAHS = San Antonio Hot Springs; SM = South Mountain; SAM = San Antonio Mountain; SDC = San Diego Canyon; TD = Trasquilar Dome; VG = Valle Grande; VP = Valle de los Posos; VS = Valle Seco; VSA = Valle San Antonio; VSL = Valle San Luis; VSR = Valle Santa Rosa; VT = Valle Toledo.

the southeast, the resurgent dome on the northwest, and the ring fracture domes of Cerro del Medio and South Mountain on the northeast and southwest, respectively (Fig. 1). Jaramillo Creek is a major tributary that enters Valle Grande from the north. Geologic mapping (Fig. 2) and subsurface exploration provide clear evidence for large lakes at two separate times in this basin, one associated with the South Mountain eruptions and a second associated with eruptions from El Cajete farther west (Reneau et al., 2004).

South Mountain lake

Deposits of the older Valle Grande lake were completely penetrated by exploratory drilling in 1949, revealing up to 90 m of clayey, partly diatomaceous, lacustrine sediment beneath alluvium in the valley bottom (Conover et al., 1963; Griggs, 1964). Drilling extended to a total depth of 360 m without encountering deeper, fine-grained lacustrine deposits; instead, a thick section of gravel and sand, often pumice-rich, was encountered, interpreted to at least partly represent pyroclastic deposits. Based on pollen, the upper lacustrine sediments were originally interpreted "to have been deposited in the last 25,000 years" (Griggs, 1964, p. 72), although this interpretation is not supported by more recent evidence (discussed below).

Surface exposures of deposits from this lake are poor, but are consistent with a lake formed when massive flows of rhyolite from South Mountain buried and dammed the East Fork Jemez River at ca. 521-552 ka, completely spanning the 3 km-wide gap between the resurgent dome and the southern caldera wall (Reneau et al., 2004; ages from Spell and Harrison, 1993, and Fawcett et al., 2006). Outcrops of fine-grained lacustrine deposits were found in four areas in Valle Grande (unit Qlsm, Fig. 2), and the upper elevations at two of them (along the main Valle Grande access road and in Rincon de los Soldados), ~2630 m, are essentially the same as the low point between pressure ridges of the South Mountain lava flows where the East Fork subsequently re-established a channel. Deposits of clay-rich lacustrine sediment at the entrance to Rincon de los Soldados are also overlain by dipping gravelly sediments interpreted as nearshore washover fan deposits behind a small ridge of Cerro del Medio lava (Fig.

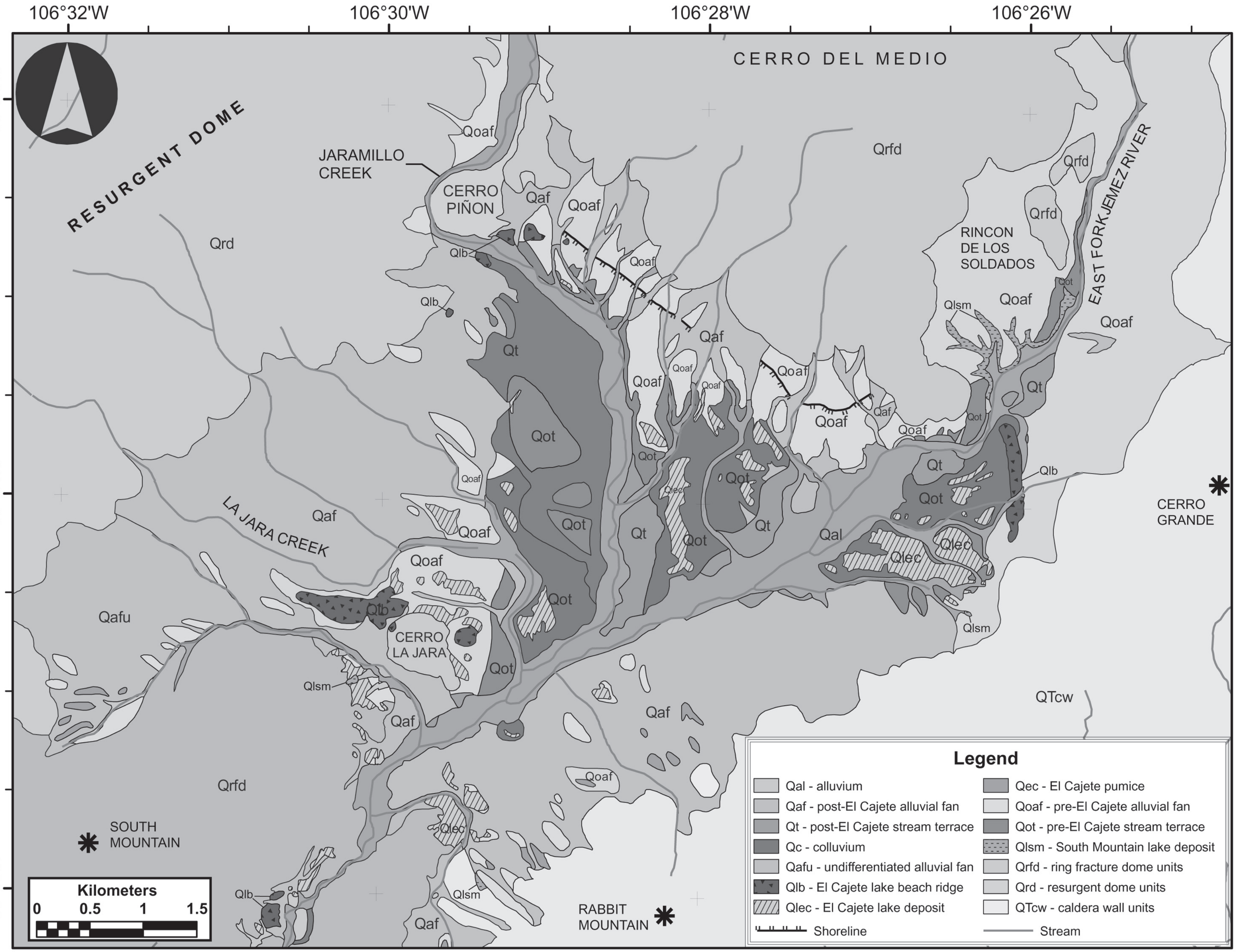

FIGURE 2. Geologic map of sedimentary units in Valle Grande. Mapping by S. L. Reneau, P. G. Drakos, and D. Katzman. Modified from Goff et al. (2005b, 2006a, b), and Gardner et al. (2006), combining units associated with the resurgent dome (Qrd), ring fracture domes (Qrfd), and the caldera wall (QTcw). See Plate 16 on p. 126 for a color version of this map.

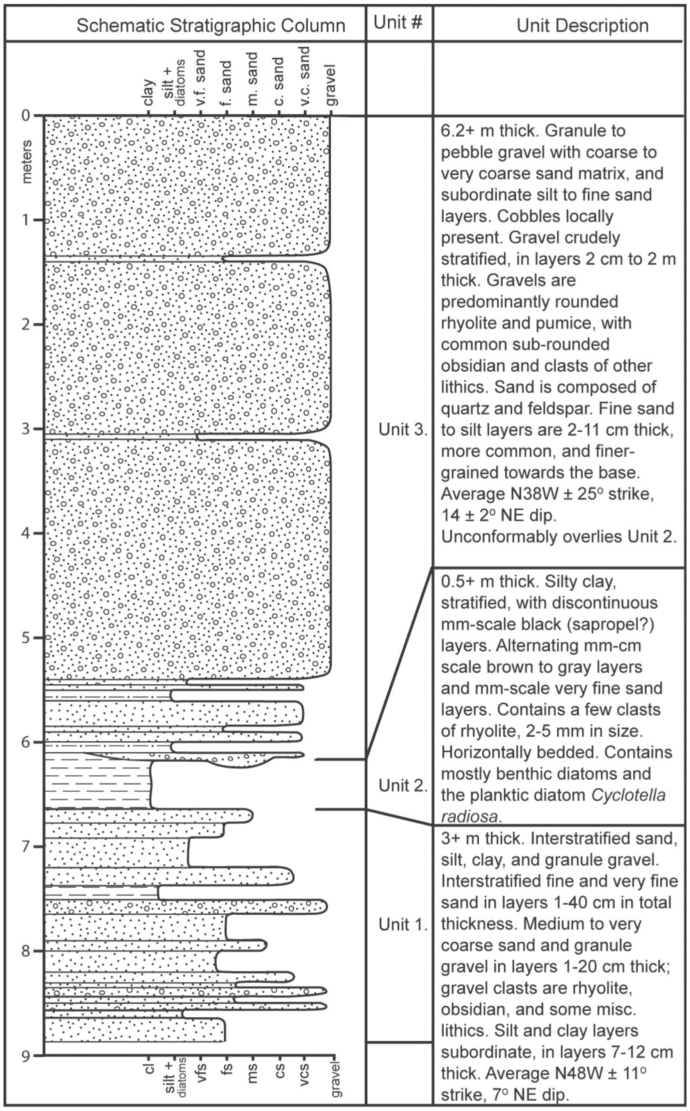

FIGURE 3. Stratigraphic section of nearshore lacustrine deposits at entrance to Rincon de los Soldados, northeastern Valle Grande, capped by inferred washover fan deposits (unit 3); upper elevation ~2620 m.

3). A third outcrop that is slightly lower in elevation (~2610 m), consists of >5 m of light gray clay interbedded with very fine to medium sand that overlies the east flank of South Mountain, confirming a post-South Mountain age. More recent analyses of tephra from the bottom of the lacustrine sequence in core hole VC-3, located in the eastern part of Valle Grande, yielded an age of ca. 552 ka and geochemically confirmed a South Mountain source (Fawcett et al., 2006; WoldeGabriel et al., 2007). Studies of VC-3 core suggest that ~170 ky are recorded in the ~75 m lacustrine section, including low-water periods when mud cracks formed (Fawcett et al., 2005, 2006). The top of the lacustrine section in VC-3 is ~35-40 m below the estimated high stand, below a young alluvial fan deposit, and an unknown amount of section has been removed by erosion.

Field mapping and topographic relations indicate a total lake length of ~11 km and an area of ~30 km^2 (Figs. 1, 4), and combined with drilling indicate a maximum depth of the closed basin of ≥125 m. Maximum lake depth may have been less as an unknown amount of sediment was deposited before initial overflow. The highest stream terraces in Valle Grande are below the elevation of the highest lacustrine sediments (Fig. 4), and suggest that the lake basin did not completely fill with sediment before the East Fork Jemez River and Jaramillo Creek were re-established as through-flowing streams. This in turn suggests that the lake's outlet was being eroded and lowered by the East Fork after its high stand was reached, resulting in partial drainage. Although early post-lake fluvial deposits may have been extensively eroded, we expect that some remnants would be preserved at higher levels in this low-gradient basin, recording former stream levels, and the field relations therefore indicate that complete filling of the lake basin with sediment did not occur.

El Cajete lake

Deposits that include well-rounded El Cajete pumice clasts are present along the sides of Valle Grande and also overlie stream terraces and alluvial fans within the valley, and document the existence of a large lake following the El Cajete eruptions at ca. 50-60 ka (age from Toyoda et al., 1995, and Reneau et al., 1996). Well-preserved constructional landforms are present in four areas (unit Qlb, Fig. 2), and, combined with wave-cut shorelines on older fans on the southwest side of Cerro del Medio (Fig. 2), document a lake high stand at ~2615 m, or ~15 m lower than the South Mountain lake. The lake had a length of ~10 km, a maximum width of ~5 km, and an area of ~23 km^2. Despite its youth and size, the existence of this lake was apparently not recognized before the recent mapping effort, presumably because of access restrictions and a focus on volcanic units by prior researchers.

Although deposits of pumice aren't obvious candidates for dams, the size of the El Cajete eruptions and the proximity of the narrow East Fork Jemez River canyon to the vent provided favorable conditions for effectively blocking the drainage. The vent is located only 1 km north of the river and the primary dispersal plumes were towards the river and Valle Grande. Just south of the East Fork canyon, El Cajete deposits were 20 m thick at the Copar mine (Reneau et al., 1996; Wolff et al., 1996), and the elevation of the high lake stand indicates that ~30-35 m of pumice buried the East Fork just west of Valle Grande. We expect that the dam was initially quite porous but eventually become less permeable as pores were plugged with fines, causing water to gradually back up into Valle Grande. No clay-rich lacustrine sediments associated with this lake have been found, suggesting it was very short-lived. Instead, deposits consist of sand and pumice gravel that mantle pre-El Cajete surfaces, also locally burying primary fallout deposits, consistent with transgressive beach and associated nearshore deposits. We expect that once the lake overflowed, the river would have rapidly incised through the pumice dam, potentially resulting in a catastrophic outburst flood, although no deposits from such a flood have yet been recognized downriver.

The most easily accessible deposits and constructional landforms occur next to Cerro La Jara, a small outlying dome of South Mountain rhyolite in western Valle Grande (unit Qlb, Fig.

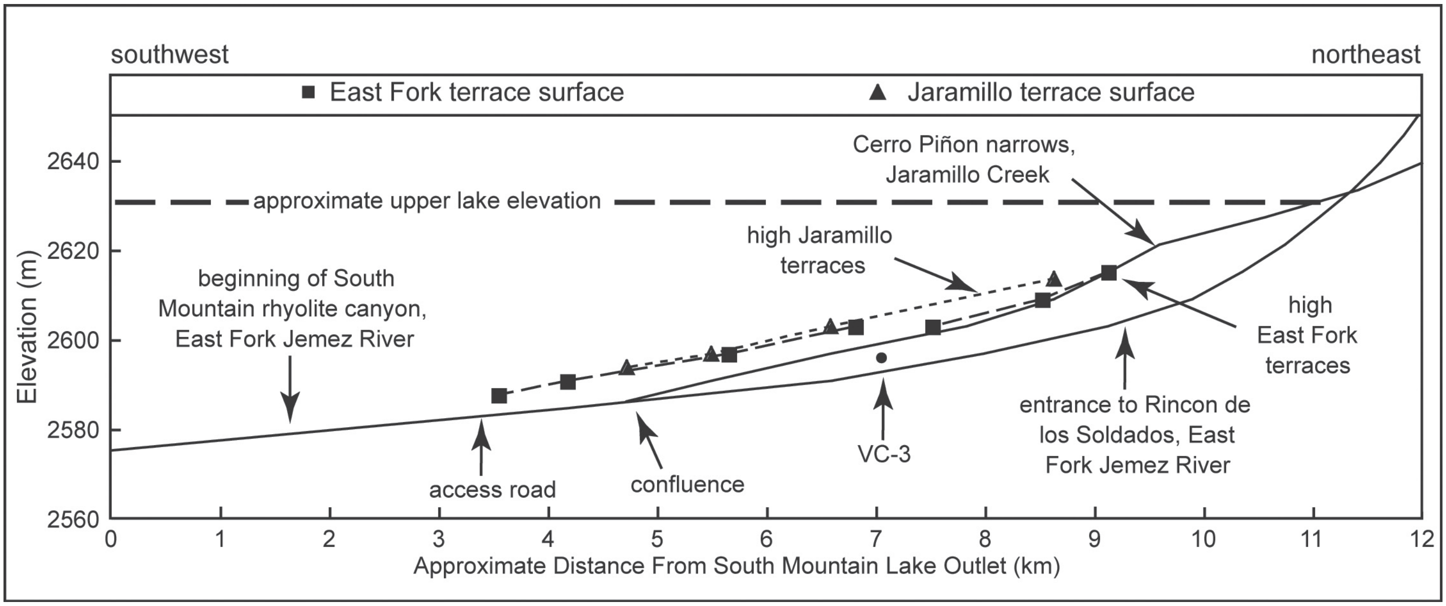

FIGURE 4. Longitudinal profile of East Fork Jemez River and Jaramillo Creek in Valle Grande, showing estimated upper elevation of South Mountain lake and post-lake stream terraces. Profiles are of valley bottoms, smoothing out meanders, and are not true stream profiles. Field relations suggest that the extensive terraces north of the East Fork largely represent sediment derived from Jaramillo Creek.

2). An abandoned borrow pit on the east side of the dome exposed stratified sands and pumice that extend to at least 12 m below the upper constructional surface, although the lower exposures have been buried due to development of a parking area. The borrow pit exposes a shore face or spit, where lower steeply-sloping beds transition abruptly to near-horizontal beds at the top of the section (Fig. 5). Nearby, northwest of Cerro La Jara, the main access road follows the adjoining crests of a pair of beach ridges or shoals for ~1 km (Fig. 2). The lower ridge is ~8 m below the upper one, and presumably was first formed and then submerged as the lake level rose. Stratified sands and pumice were described in shallow gullies along the road, and the same materials can be found in animal burrow mounds on the nearby slopes. The higher western crest is underlain by ~7 m of beach sediment, in turn overlying an older alluvial fan derived from La Jara Creek.

Another 1 km-long beach ridge or spit is located on the east side of Valle Grande next to the entrance to Rincon de los Soldados, overlying an alluvial fan to the south and an East Fork stream terrace to the north (Figs. 2, 6). It rises ~4 m above the adjacent terrace and the top has abundant rounded clasts of Tschicoma dacite, up to 5 cm (B-axis), reworked from the terrace. The largest area of lake-bottom sediment from the El Cajete lake occurs southwest of this ridge, burying another East Fork stream terrace (unit Qlec, Fig. 2). A hand auger hole here reached the underlying terrace at a depth of 4.3 m. The lower 1 m appeared to be weathered primary El Cajete pumice, and the upper 3.3 m stratified very fine to coarse sand and rounded pumice, capped by a dark silty soil.

Smaller constructional shoreline features occur in two other areas: 1) in the northern embayment of Valle Grande next to Cerro Piñon, where Jaramillo Creek enters Valle Grande; and 2) near the lake's outlet over South Mountain lava flows (Fig. 2). The Cerro Piñon ridges rise ~2-3 m above adjacent alluvial fans and also have rounded clasts to 5 cm on their crests. The ridges near the outlet rise ~10 m above adjacent surfaces and are composed of sand and reworked pumice. A gully below the larger beach ridge near the outlet exposes a thick section of primary El Cajete pumice underlying stratified sandy shoreline deposits. A weathered ash layer in the transition zone between primary pumice and overlying shoreline deposits suggests fallout from a late-stage El Cajete eruption into the lake, consistent with evidence for numerous small eruptions following the major plinian eruptions responsible for the main pumice deposits (Wolff et al., 1996).

SAN ANTONIO CREEK

San Antonio Creek heads in Valle de los Posos in the northeastern part of the Valles caldera, follows the northern moat through Valle Toledo and Valle San Antonio, and then wraps around the west side of the caldera past San Antonio Hot Springs (Fig. 1). Major tributaries include the drainages of Rito de los Indios, Valle Santa Rosa, and Valle San Luis. Geologic mapping and subsurface exploration support the existence of several separate post-resurgence lakes in this basin, with the largest associated with eruptions from San Antonio Mountain at ca. 557 ka (age from Spell and Harrison, 1993), as previously proposed by Rogers (1996) and Rogers et al. (1996).

San Antonio lake

The most extensive outcrops of lacustrine sediment in the Valles caldera occur in the northern moat along San Antonio Creek and its tributaries, as first mapped by Smith et al. (1970). Downstream from these outcrops, thick flows of rhyolite from San Antonio Mountain abutted the west wall of the caldera, and San Antonio Creek was forced to cut a course between the lava

FIGURE 5. Photograph of upper shoreline deposits of El Cajete lake in borrow pit on east side of Cerro La Jara. Gravel layers consist of pumice clasts (e.g., below knife), and remaining layers are very fine to very coarse sand.

and weaker Bandelier Tuff. The topographic relations are consistent with damming by San Antonio Mountain lava flows, as proposed by Rogers (1996) and Rogers et al. (1996), and the distribution of lacustrine deposits supports this interpretation. However, although Rogers and colleagues proposed that the outcrops in Valle San Antonio and Valle Toledo were from two separate lakes, the latter dammed by older Cerro Santa Rosa lavas, our mapping supports the inference of Gardner and Goff (1996) that most of the outcrops in both valleys are from the same lake.

The topography along the San Antonio Creek canyon rims near San Antonio Hot Springs, where the rims are highest, suggests a possible low point on a dam at ~2650 m elevation. Stratified deposits of silt to fine sand on top of San Antonio Mountain rhyolite ~2 km northeast of the hot springs, also at ~2650 m, are consistent with shallow water, nearshore lacustrine sediment. The highest lacustrine deposits we located in Valle Toledo, 15-18 km upvalley, are also at ~2650 m and are consistent with a single lake, ~40 km^2 in area, that extended for ~20 km between San Antonio Hot Springs and the east part of Valle Toledo (Figs. 1, 7). Lacustrine deposits at similar elevations are also present in Valle San Luis and Valle Santa Rosa, representing major arms of the San Antonio lake. Maximum depth of the closed basin exceeded 100 m, although actual lake depth at any time is uncertain. Clays, silty clays, and clayey silts, often diatomaceous, dominate many outcrops, and sand layers are common in nearshore settings, including the upper and lower parts of some sections (e.g., Figs. 8, 9).

Stream terraces are prominent features along San Antonio Creek and its tributaries, and the relation of the terraces and associated fluvial deposits to the lacustrine deposits varies from east to west (Fig. 7). In Valle Toledo, clay-rich, diatomaceous lacustrine sediment is conformably overlain by fluvial sands and a buried soil that indicate filling of this part of the lake with sediment (Fig. 8). The buried soil is in turn overlain by gravelly alluvium, ~4-6 m thick, which constitutes the main terrace deposit. A radiocarbon (^{14}C) date of 38,940 ± 440 yr B.P. (Beta-208305) has been obtained from charcoal in the buried soil, and preliminary optically stimulated luminescence (OSL) ages of either ca. 14 and 16 ka (quartz sand, single-aliquot regeneration [SAR] method) or ca. 38 and 43 ka (fine silt, infra-red multi-aliquot additive dose [IR-MAAD] method) have been obtained from the fluvial deposits above and below the buried soil, respectively (Thorstad et al., 2004; K. Lepper, unpubl., 2007; see Fig. 8 for sample locations). Although the reason for the disparity in OSL age estimates is not yet understood and additional work is warranted, both ^{14}C and OSL methods indicate a late Pleistocene age for the overlying fluvial deposit. Compared to the age of the San Antonio Mountain

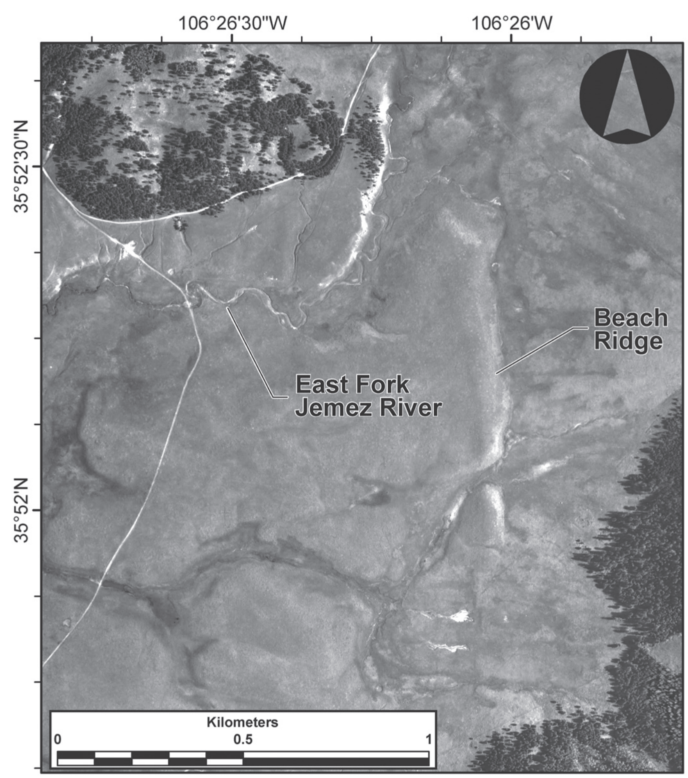

FIGURE 6. Orthophotograph of east side of Valle Grande showing beach ridge from El Cajete lake.

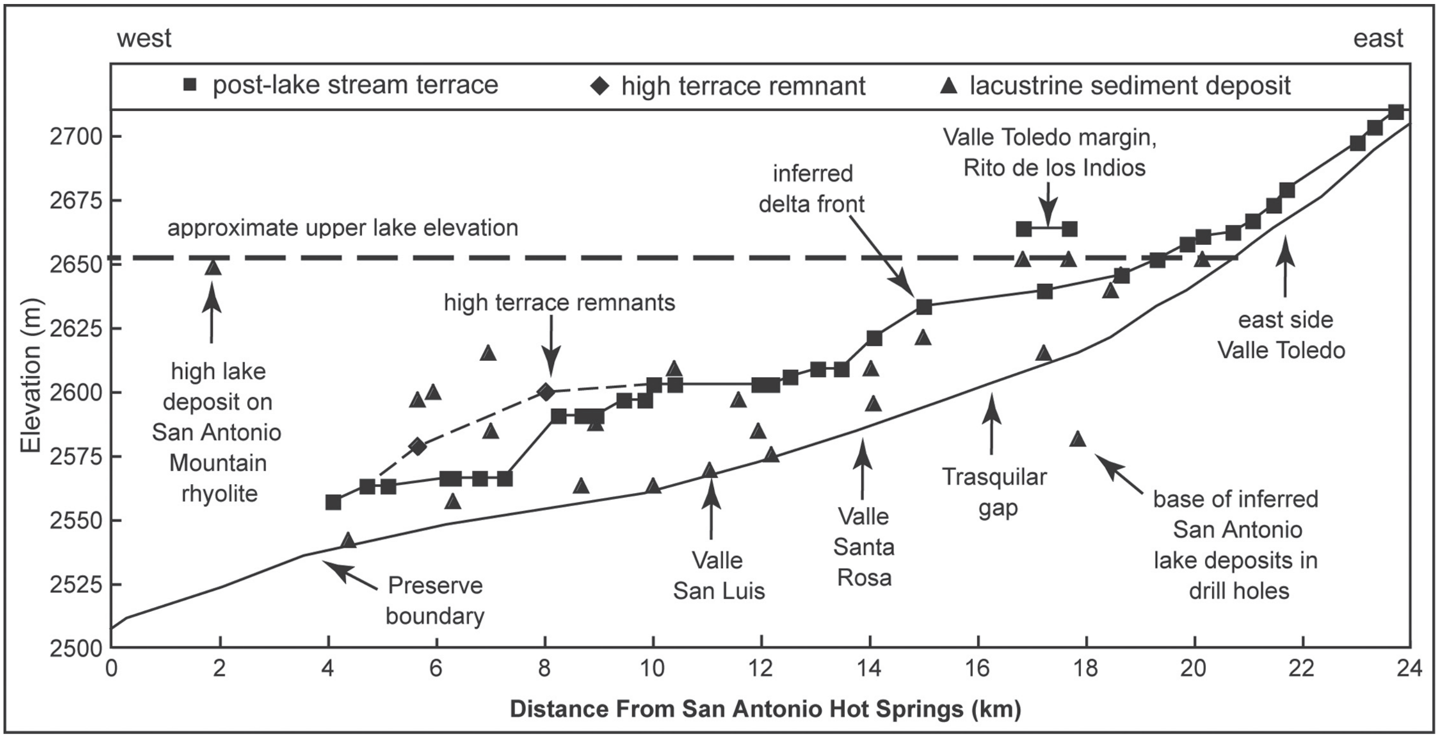

FIGURE 7. Longitudinal profile of San Antonio Creek, showing estimated upper elevation of San Antonio lake, post-lake stream terraces and terrace remnants, and deposits of lacustrine sediment. Profile is of valley bottom, smoothing out meanders, and is not a true stream profile. Except for two high terrace remnants in eastern Valle San Antonio, only the upper limit of the main stream terraces are shown, and these terraces are probably not all the same age. Terraces along Rito de los Indios are contiguous with San Antonio Creek terraces in Valle Toledo. Not all lacustrine deposits are shown.

dam, the Valle Toledo terraces may therefore be very young features, consistent with their youthful appearance and with a relatively weakly developed soil with an A-Bw-C (Inceptisol) profile. Soil properties are similar to those on late Pleistocene (Pinedale) glacial till in the southern Sangre de Cristo mountains (Shroba, 1987; Wesling, 1987), supporting a late Pleistocene age.

In the eastern part of Valle San Antonio, east of Valle Santa Rosa, gently dipping laminated silt and clay beds are overlain by ~9 m of sand and gravel, the lower part of which dips up to 30°. The steeply dipping beds exhibit a wide range of orientations and are inferred to represent a delta front at the head of the lake as San Antonio Creek prograded westward (Fig. 7). Similar relations are also present up Valle Santa Rosa, with basinward-dipping sands and gravels overlying more flat-lying lacustrine silts and clays.

West of Valle Santa Rosa, all San Antonio Creek terraces appear to be strath terraces, with relatively thin (0.5-2 m) deposits of sand and gravel overlying beveled surfaces on the lake beds or older rock units, as previously reported by Gardner and Goff (1996) (although they also interpreted the Valle Toledo surfaces as strath terraces). A stratigraphic section below a prominent terrace on the west side of lower Valle Santa Rosa (Fig. 9), shows the unconformable contact between lacustrine and overlying fluvial deposits. The highest terraces are commonly lower than nearby lacustrine deposits (Fig. 7). These relations indicate incision of the outlet and drainage of the lake before it could completely fill with sediment, with perhaps relatively rapid incision after the delta front reached Valle Santa Rosa. Multiple terrace levels are commonly present in Valle San Antonio, recording episodic incision, and local base level controls were probably also created when the incising stream encountered rhyolite or other resistant units.

Elevations of the uppermost lacustrine deposits along San Antonio Creek decrease between the east part of Valle Toledo and Valle Santa Rosa (Fig. 7), suggesting that the base level at the outlet may have been slowly lowering while the eastern part of the lake filled with sediment. However, fine-grained lacustrine sediment in this area also dips towards the valley axis, with dips up to 13° measured in exposures near the valley margins, suggesting tilting induced by dewatering compaction of sediment in the center of the valleys. The amount of compaction has not been estimated, and therefore it is not certain how much lowering of the outlet may have occurred as the eastern part of the lake filled with sediment.

The best information on the total thickness of lacustrine sediments from the San Antonio lake is in Valle Toledo, where drilling in 1949 encountered a maximum of 24 m of clay-rich sediment immediately beneath the valley bottom (Conover et al., 1963; Griggs, 1964). Combined with the exposed section, this indicates a total thickness of ~34 m in the western part of Valle Toledo. The drill holes indicated that the clayey layers interfinger with sand and gravel and pinch out to the east, which is consistent with a location near the head of a lake. The upper clays are underlain by ~60 m of sand and gravel, beneath which additional clayey layers were encountered. These are inferred to have been deposited in an older lake or lakes, as discussed in the next section. Downstream, the maximum thickness of clay-rich lacustrine section examined

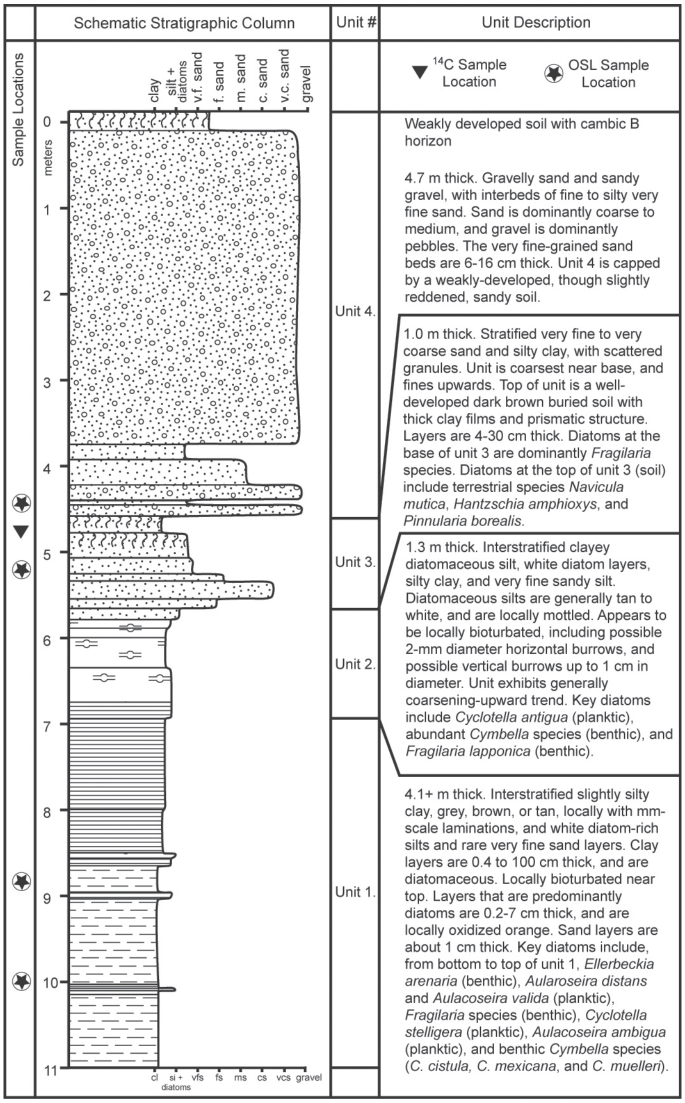

FIGURE 8. Stratigraphic section of lacustrine deposits and conformably overlying fluvial deposits on north side of Valle Toledo, showing ^{14}C and OSL sample locations; upper elevation ~2645 m. Unit 3 represents a transition from shallow-water lacustrine deposition to fluvial deposition and is capped by a buried soil with terrestrial diatoms (P. Bradbury, personal commun., 2003).

in outcrop is ~11 m, at a location in lower Valle Santa Rosa, overlying inferred beach sands (Fig. 9). The maximum thickness of lake beds in Valle San Antonio is not known.

A prominent bench that may represent a wave-cut platform associated with the San Antonio lake is present on the north side of Cerro Seco, beveling cemented, dipping sandstones that are inferred to be associated with hydromagmatic deposits. The bench is >2.5 km long, up to 0.5 km wide, and extends to >2630 m in elevation. However, the south edge is mantled with colluvium and no lacustrine or nearshore sediment has yet been found here.

OSL analyses suggest that a lake existed in Valle Toledo as recently as the late Pleistocene, with preliminary ages of ca. 45-50 ka (IR-MAAD) obtained from depths of 3-4 m below the top of the lacustrine section in Figure 8 (Thorstad et al., 2004; K. Lepper, unpubl., 2007). If accurate, these analyses indicate that either a lake persisted along San Antonio Creek for >500 ky after creation of a dam by San Antonio Mountain lava flows, longer than the duration of the South Mountain lake in Valle Grande, or that a younger lake formed after drainage of the San Antonio lake. Trasquilar gap, where San Antonio Creek exits Valle Toledo, is the only likely location for a younger dam. Although blockage of this narrow gap by landslides is possible, evidence of large landslides here has not been found. In addition, the Valle Toledo terraces appear to be continuous with those in eastern Valle San Antonio (Fig. 7), and lake deposits have been found at similar elevations east and west of the gap, arguing for a closely-related fluvial and lacustrine history in these two valleys and a single lake. Because of potential discrepancies between evidence for a

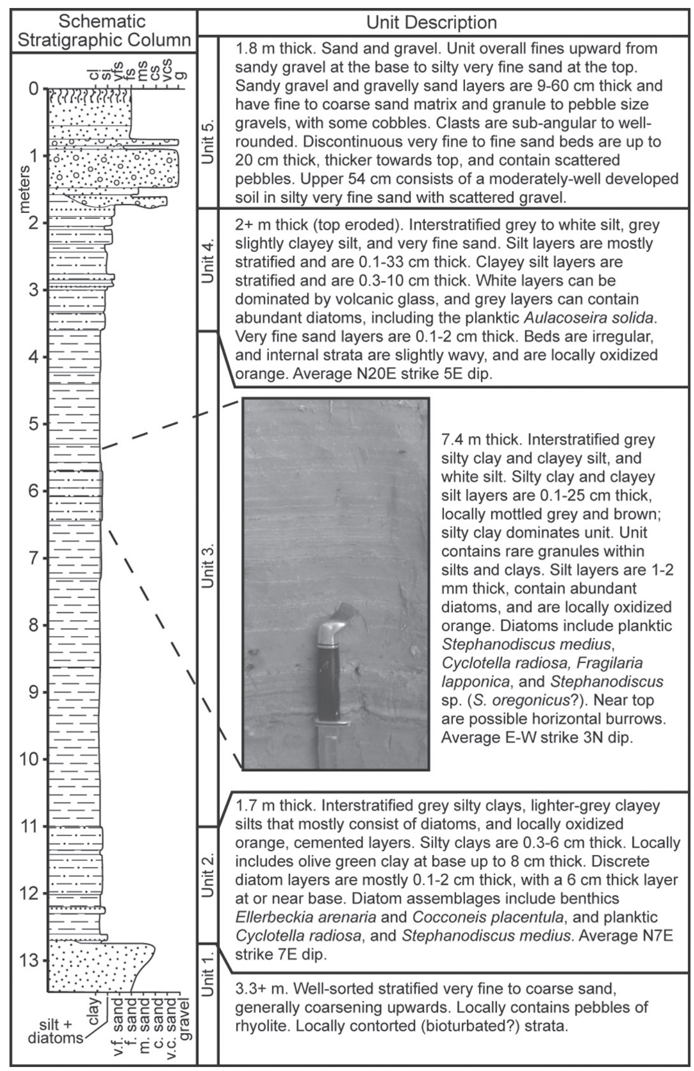

FIGURE 9. Stratigraphic section of lacustrine deposits and unconformably overlying fluvial deposits (unit 5) in lower Valle Santa Rosa; upper elevation ~2605 m. Inset photograph is of finely laminated sediments in middle part of section. Unit 1 is inferred to represent beach sands, and diatom assemblages indicate that water depth increases upsection from unit 2 to unit 3 (P. Bradbury, personal commun., 2003).

relatively old dam and a relatively young lake, additional work is warranted on the lacustrine and fluvial history in Valle Toledo and adjacent parts of Valle San Antonio.

Older lakes in the northern moat

Lacustrine sediments examined in outcrop and penetrated in the subsurface indicate additional, older post-resurgence lakes existed in the northern moat of the Valles caldera, although these are less well defined. Northwest of Cerro Seco and south of San Antonio Creek, pyroclastic deposits interpreted to be derived from Cerro Seco (ca. 800 ka; age from Spell and Harrison, 1993) directly overlie lacustrine sediment and indicate that a lake existed at that time. Nearby lacustrine sediment contains abundant plant remains and locally contains insect impressions, not observed elsewhere, indicating shallow water conditions. It is possible that early eruptions from Cerro Seco buried drainages and created a local closed depression, although evidence is inconclusive. Inferred hydromagmatic deposits near Cerro Seco also indicate the presence of a lake or a high water table, although the age of these deposits has not yet been confirmed.

An additional unusual exposure of silicified lacustrine sediment, suggestive of hydrothermal alteration, occurs northwest of Cerro Seco (Gardner et al., 1996, p. 49). The age and context of this deposit is uncertain, possibly being related to nearby hydromagmatic deposits or instead to the initial caldera lake, which is believed to have had high bottom temperatures.

As previously described, exploratory drilling in 1949 revealed clay-rich sediments at depth in Valle Toledo (Conover et al., 1963; Griggs, 1964), below the upper lacustrine sediments, that are presumably associated with an older lake or lakes. Lava erupted from the nearby northern Cerro Santa Rosa dome (ca. 787 ka; Spell and Harrison, 1993), which abutted the older Trasquilar dome to the north, is a likely candidate for creation of a dam. Eruptions from the southern Santa Rosa Dome (ca. 915 ka) or Cerros del Abrigo (ca. 973 ka) may also have locally blocked drainages in this area. To the east, drilling in Valle de los Posos also encountered lacustrine sediment at depth, and topographic relations indicate that lava flows from Cerro del Medio (ca. 1.1-1.2 Ma) may have created dams in this area.

OTHER LAKES

Because of the complex topography in the Valles caldera and the many volcanic eruptions that have occurred, it is virtually certain that other post-resurgence lakes have existed associated with local damming of drainages. Thin (<1 m) clay-rich deposits that have been examined in Valle Seco (Fig. 1) may represent a second lake impounded behind San Antonio Mountain lava flows where they abutted the resurgent dome to the east. We consider it probable that deposits from a small, young lake occur beneath the Redondo Creek meadows, impounded behind the Banco Bonito lava flows (Fig. 1). Banco Bonito is the last phase of the eruptive sequence that began with the ca. 50-60 ka El Cajete pumice (Wolff et al., 1996), and sediments here may be amenable to radiocarbon dating, making them attractive targets for paleoclimatic studies.

FOSSILS

The most striking fossils within Valles caldera lacustrine deposits are diatoms, which locally form nearly pure diatomaceous beds. The late Platt Bradbury (personal commun., 2003) provided diatom identification for samples from Valle Grande (Rincon de los Soldados; Fig. 3), Valle Santa Rosa (Fig. 9), and Valle Toledo (Fig. 8), revealing diverse diatom assemblages that contain information on varied paleoenvironments in the lakes. One species, *Ellerbeckia arenaria*, is discernable in the field with a hand lens and is highly abundant in many layers. It is a large benthic species that lives in the trophic zone and records shallow water conditions. Other identified benthic diatoms include *Cocconeis placentula*, *Epithemia turgida*, *Fragilaria lapponica* and several species of *Cymbella* (*C. cistula*, *C. mexicana*, and *C. muelleri*). Planktic species include *Aularoseira ambigua, A. distans*, *A. solida*, *A. valida*, *Cyclotella radiosa, C. stelligera*, and *Stephanodiscus medius*. Terrestrial diatoms identified in the buried soil overlying the lacustrine sediments in Valle Toledo include *Hantzschia amphioxys*, *Navicula mutica*, and *Pinnularia borealis*.

We observed abundant plant fragments and rarer insect impressions in lacustrine sediments in one part of Valle San Antonio, and other workers have reported leaf impressions (Smith et al., 1970) and possible fossil reeds (F. Goff, personal commun., 2006). These all suggest shallow water conditions. We also observed possible horizontal and vertical burrows and other evidence of bioturbation in some lacustrine beds. Interestingly, no fish bones or mammal bones have been found yet, and examination of samples from Valle Santa Rosa failed to reveal ostracodes (B. Allen, personal commun., 2004). Carbonate fossils appear to have been geochemically unstable and not preserved in this silica-rich carbonate-poor environment, in contrast to the well-preserved siliceous fossils.

SOFT-SEDIMENT DEFORMATION

Soft-sediment deformation was observed in fine-grained lacustrine sediment in several areas that is indicative of underwater landslides, possibly associated with seismic shaking. As one example, a 1.2 m-long, 0.6 m-thick block of finely-bedded diatomaceous sediment in the southwestern part of Valle San Antonio is back-tilted 30° towards the valley margin (Fig. 10). The upper part includes an overturned fold created as the block slid into soft sediments to the north. Evidence for sand boils also occur in this exposure. Also notable is an area of complex folding with widely divergent strikes and dips that extends for at least 70 m along a gully in lower Valle Santa Rosa. Beds here dip up to at least 34°. Other deformation may be associated with loading, including flame structures that were observed in Rincon de los Soldados near the head of the South Mountain lake.

EVIDENCE FOR A LATE BREACH?

Since the proposal by Smith and Bailey (1968, p. 620-621) for an early overflow of the initial caldera lake or lakes associ-

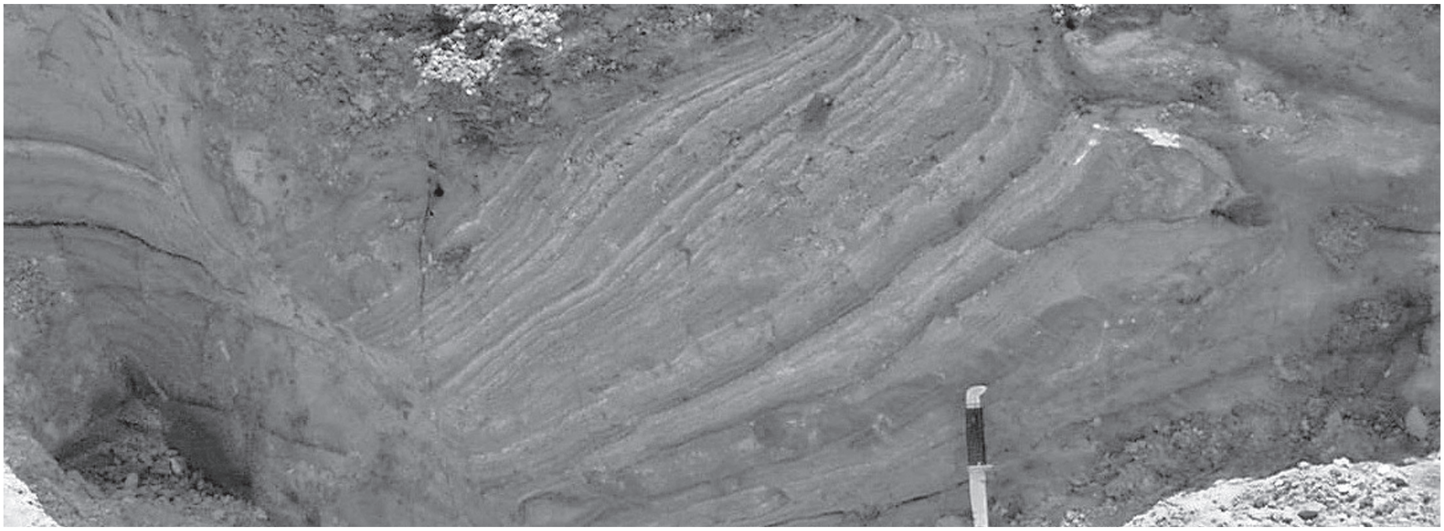

FIGURE 10. Photograph of deformed diatomaceous lake sediments in southwestern Valle San Antonio.

ated with resurgence, causing breaching of the caldera rim at >1 Ma and resultant incision of San Diego Canyon (later supported by Rogers, 1996, and Rogers et al., 1996), several workers have instead proposed a much later breach. Goff and Shevenell (1987) proposed breaching as late as 0.5 to 0.43 Ma, although they incorrectly attributed this hypothesis to earlier workers (e.g., Doell et al., 1968). Goff et al. (1992) and Goff and Gardner (1994) further illustrated the hypothesis of breaching and rapid canyon cutting at ca. 0.5 Ma, and Gardner and Goff (1996) interpreted the stream terraces along San Antonio Creek as forming during post-breach incision. More recently, Goff et al. (2005a) proposed that a "lake may have filled much of the caldera at around 800 ka," based on possible beach deposits on Cerro San Luis and Cerro Seco as high as 2780 m (unit Qos of Goff et al., 2006b). Benches on Cerro del Medio as high as 2805 m have also been interpreted as wave-cut erosional surfaces (J. N. Gardner, personal commun., 2002; unit Qog of Gardner et al., 2006).

Several lines of evidence argue against a long-lived post-resurgence lake as high as 2780-2805 m. First, the caldera rim in Bandelier Tuff adjacent to the head of San Diego Canyon is ~150 m lower than the hypothesized lake high stand of ~2805 m, and the western and southern rims are below 2805 m for a distance of ~30 km. It seems improbable that this much Bandelier Tuff would have been eroded from the upper mesas, and that significant lowering of the rim would have extended over such a wide area. Second, thick fine-grained lacustrine deposits that would have been deposited in such a deep and long-lived lake have not been found. For example, after penetrating up to 90 m of clayey sediment associated with the South Mountain lake, drilling in Valle Grande reported only sand and gravel to a total depth of 360 m (Conover et al., 1963; Griggs, 1964), although Valle Grande would seem to be an ideal location for preservation of old lacustrine deposits. Third, pillow breccias, evidence of relatively deep water, have only been reported in the ca. 1.25 Ma Deer Canyon Rhyolite (Goff et al., 2006a), and not in younger post-resurgence lavas. In addition, field checking indicates that the features on Cerro del Medio, Cerro San Luis, and Cerro Seco are all inconclusive as to the presence of high lake stands, and alternative explanations for these features are more likely (e.g., *in situ* weathering and colluvial deposition). Finally, as pointed out by Rogers (1996) and Rogers et al. (1996), the evidence of Goff and Shevenell (1987) for at least 300 m of incision by the Jemez River at Soda Dam by 1.1 Ma is best explained by an early breach. The weight of evidence therefore supports the original hypothesis of Smith and Bailey (1968) that overflow and breaching occurred during resurgence. Although remnants of the initial lake likely persisted for some time in low areas within the caldera, there is no clear evidence that an extensive caldera-wide lake existed after resurgence.

DISCUSSION

Valles caldera has contained multiple lakes since resurgence at ca. 1.2-1.25 Ma, and these lakes were probably largely or entirely created as volcanic eruptions from ring fracture vents buried and dammed drainages within the caldera. Two large, post-resurgence lakes may have existed at the same time, one in the northern moat, dammed by ca. 557 ka rhyolite flows from San Antonio Mountain, and the other in Valle Grande, dammed by ca. 521-552 ka rhyolite flows from South Mountain. The erodibility of rocks at the outlets has probably had a strong influence on the longevity of lakes and on subsequent valley evolution. A large lake in Valle Grande at ca. 50-60 ka, impounded behind an easily eroded El Cajete pumice dam, was probably short lived, draining rapidly after initial overflow and leaving relatively thin and patchy deposits in the lake basin. In contrast, the South Mountain dam apparently impounded water for >170 ky and is still largely intact today, with relatively little incision having occurred through the lava flows and with most of the thick sequence of lake deposits remaining buried beneath the valley floor. The San Antonio lake also had a resistant dam at first, although it apparently drained before most of the basin filled with sediment after San Antonio

Creek cut a deep channel through less-resistant Bandelier Tuff on the margin of the lava flows. Progressive incision has left a series of post-lake stream terraces along San Antonio Creek up to 45 m above the modern channel, whereas incision has been less in Valle Grande and terraces are generally within 5-15 m of the East Fork Jemez River and Jaramillo Creek.

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