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LATE PLIOCENE DEPOSITION IN CULEBRA LAKE AND PLEISTOCENE EROSION OF LAKE SEDIMENT, NORTHEASTERN PAJARITO PLATEAU, NEW MEXICO

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Abstract —Thick exposures of lacustrine sediment and interlayered tephra deposited in Culebra Lake record late Pliocene damming of the Rio Grande in White Rock Canyon and coeval dacitic and basaltic volcanism along the northeastern flank of the Jemez Mountains, New Mexico. Culebra Lake was impounded by basalt flows near White Rock at about 2.35 Ma, reached depths ≥ 80 m, covered an area of ~1000 km^2 and probably extended upstream along both the Rio Grande and Rio Chama. Dacitic tephra mixed with mafic cinders and hydroclastic shards record coeval silicic and basaltic eruptions as Culebra Lake began to fill. Basal Culebra clay is as much as 12 m thick, contains pollen typical of climate cooler than the Holocene, and is composed of illite/smectite intergrade and kaolinite, both likely derived from the Colorado Plateau. Silt, sand and sandy diamict overlie the clay, thickening and coarsening to the west and north near a paleoshoreline at an elevation of ~1950 m. After the lake began to drain in late Pliocene time, aggradation predominated north of White Rock Canyon until after eruption of the lower Bandelier Tuff at 1.6 Ma. Downcutting by Rio Grande tributaries after early Pleistocene time eroded lacustrine deposits from much of the Española basin. On the Pajarito Plateau, however, slower rates of incision and denudation preserved shoreline-to-offshore facies of Culebra Lake in east-draining canyons. The Bandelier Tuff helped to preserve Culebra deposits, but failed as massive slumps where headward erosion removed lateral support from the clay layer, probably in the middle Pleistocene. Evolution from blockage to downcutting along the margin of the Pajarito Plateau records incision through the volcanic dam, but circumstantial evidence suggests a role for Pliocene climate change as well.

INTRODUCTION

Lacustrine sediment mantles paleotopography, records geological processes that led to lake formation and filling, and preserves information about past climate (Talbot and Allen, 1996). Fine lacustrine sediments, however, are eroded easily by sheetwash and their low shear strength and impermeability destabilize overlying rock materials. Preservation potential for lacustrine sediment thus is limited, particularly in semiarid environments subject to intense rainfall.

The southern Española basin is an ideal location for formation and preservation of late Cenozoic lakes (Fig. 1). The Rio Grande has flowed south in the Española basin since Miocene time (Broxton and Vaniman, 2005). Downstream from the study area, White Rock Canyon, a narrow, ~300 m-deep corridor, cuts into late Cenozoic volcanic rocks and underlying Miocene sediment susceptible to mass movement. Basaltic and silicic eruptions and massive slumps have blocked drainage repeatedly since about 3 Ma, but preservation of lacustrine sediment in the canyon is limited (Reneau and Dethier, 1996a).

Extensive lakes formed as east-flowing tholeiitic lavas dammed the Rio Grande near White Rock between about 2.5 and 2.3 (?) Ma (Reneau and Dethier, 1996b). Kelley (1948, p. 6) informally named the "Culebra lake clay and gravel", suggesting that it accumulated when a Cerros del Rio flow dammed the Rio Grande south of Los Alamos Canyon. In this paper we use "Culebra Lake" only for the youngest, deepest late Pliocene lake, modifying the usage of Kelley and that of Waresback and Turbeville (1990), who suggested including the Pliocene lake sediment in a "Totavi formation". Our mapping shows that Culebra Lake filled with tens of meters of fine to coarse sediment and disappeared prior to eruption of the 1.6 Ma lower Bandelier Tuff, which blanketed the landscape, covering and preserving the lake deposits (Griggs, 1964; Smith et al., 1970; Dethier, 2003). Since middle (?) Pleistocene time, downcutting by Rio Grande tributaries has eroded Culebra Lake deposits from much of the Española basin. Our study characterizes the extent, sedimentology, and physical characteristics of the preserved lacustrine deposits to aid our understanding of local Plio-Pleistocene geomorphic evolution and to help provide a record of a poorly documented, climatically significant interval of late Pliocene time.

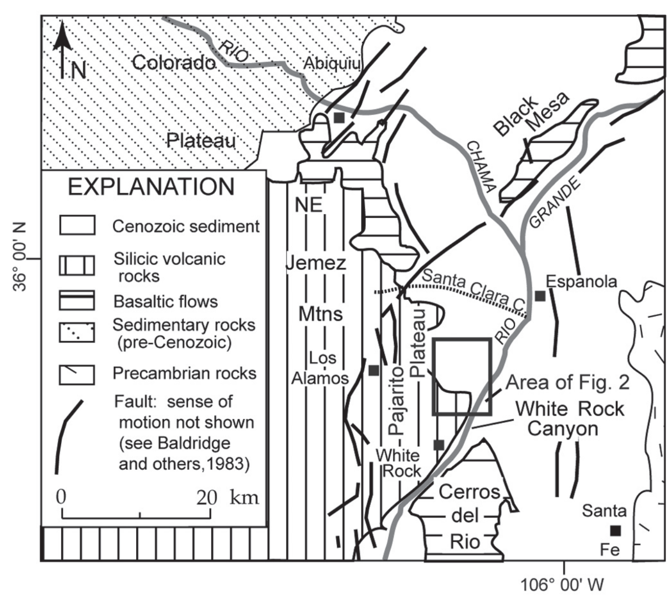

FIGURE 1. Location map showing generalized geology of the Española basin and locations noted in text (modified from Reneau and Dethier, 1996a). Study area is outlined.

SETTING

The northeastern Pajarito Plateau forms a SE-dipping tableland dissected by the 200 m-deep Los Alamos, Guaje, and Garcia Canyons, which drain east into the Rio Grande. We mapped lacustrine sediment along the eastern margin of the northern Pajarito Plateau, in portions of the Puye and White Rock 7.5-minute quadrangles (Fig. 1; Dethier, 1997, 2003). Elevations range from ~1600 m along the Rio Grande to >2000 m on nearby mesas. Surfaces of several mesas display hummocky local topography underlain by extensive slumps composed of coherent to disrupted blocks of Bandelier Tuff.

Climate and paleoclimate

Modern climate in the Española basin is warm and semi-arid; areas near Española receive only ~30 cm of annual precipitation whereas the western margin of the Pajarito Plateau receives 40 to 50 cm (Broxton and Vaniman, 2005). Precipitation occurs seasonally, distributed between summer convective storms and frontal storms during late fall and winter. Surface flow in the canyons is unusual and generally of short duration except for prolonged snowmelt runoff in some years.

Global climate cooled and fluctuated during late Pliocene and early Pleistocene time, but is not well known for northern New Mexico and the southwestern United States. Climate reconstructions for the southwestern United States suggests that, compared to the present, climate was: (1) more moist and less seasonal until about 2.5 Ma; (2) drier and episodically colder from ~2.5 until ~2.0; and (3) wetter, with higher amplitude alternation between wet and dry beginning sometime after about 1.0 Ma (Thompson, 1991). A sedimentary record from the San Luis Valley of southern Colorado indicates summer-monsoonal and possibly arid conditions after 1.6 Ma (Rogers et al., 1992). Near White Rock, stage IV soil carbonate and local silica-carbonate layers accumulated on 2.4 Ma basalt before eruption of the Bandelier Tuff, indicating climate at least as arid as that of the late Holocene.

GEOLOGIC HISTORY

Late Pliocene volcanism and development of the Puye fan

Paleotopography mantled by late Pliocene lacustrine deposits records late Cenozoic upland erosion and basin filling along the Rio Grande rift, volcanism in the Jemez Mountains and adjacent Cerros del Rio, and basin incision that began in Pliocene time. Between ~7 and 4 Ma, growth of Tschicoma dacitic domes dominated activity along the northern Jemez Mountains (Broxton and Vaniman, 2005). Deposition of upper Santa Fe sediments slowed in the Española basin and the Puye Formation fan expanded north and east (Manley, 1976; Waresback and Turbeville, 1990), forcing the Rio Grande east. Cerros del Rio volcanic centers were most active along the Rio Grande after about 2.8 Ma (WoldeGabriel et al., 2006), locally blocking and diverting the river to the west.

The Puye fan originally contained >15 km^3 of mainly dacitic debris that was transported by a variety of fluvial, mass-movement and volcanic processes on relatively low gradients (Waresback and Turbeville, 1990). Growth of the Puye fan records volcanic construction and erosion in Tschicoma source areas upstream of an episodically dammed White Rock Canyon (Reneau and Dethier, 1996b). Basal Puye Fm, at least one interval exposed upsection, and subsurface deposits locally are rich in cobbles of quartzite and other resistant rock types, the axial river gravel that Griggs (1964) termed the Totavi Lentil. Near the Rio Grande, Puye fanglomerates were deposited in marginal lake environments and are interlayered with fine-grained lacustrine deposits, facies of the Puye Formation (Dethier, 2003), over a stratigraphic thickness of tens of meters. Slightly older, silt-rich lake deposits are exposed locally beneath Culebra Lake sediment in the southwestern study area. After the older lakes filled, the Rio Grande prograded over the lacustrine sediment, depositing sand and fine gravel as far south as Los Alamos Canyon (Waresback and Turbeville, 1990). A local, dacitic tephra and distinctive gray, clay-rich Culebra Lake deposits conformably overlie the gravel and interlayered Puye fanglomerate.

Culebra Lake and late Pliocene and Pleistocene landscape evolution

Culebra Lake formed during a period of rapid aggradation induced by basalt flows that filled canyons incised as much as 180 m into the Miocene Santa Fe Group near White Rock Canyon. The youngest, highest-level tholeiites flowed from sources to the west, damming the Rio Grande near White Rock at progressively higher elevations between about 2.48 and 2.33 Ma (Reneau and Dethier, 1996b; WoldeGabriel et al., 2006). Topset/foreset contacts in deltas composed of pillow basalt record one stable lake level at ~1875 m and a final stage that reached ~1950 m. After Culebra Lake filled or drained in latest Pliocene time, the Rio Grande recut a canyon through the western Cerros del Rio, dropping base-level in southern White Rock Canyon more than 170 m between ~2.3 and 1.6 Ma (Dethier and Reneau, 1995). Aggradation on the western Pajarito Plateau continued until after early Pleistocene time, but the distal Puye fan did not grow significantly after Culebra Lake disappeared (Waresback and Turbeville, 1990). The modern landscape records middle to late Pleistocene base-level lowering along the Rio Grande and dissection of the northern Pajarito Plateau driven by headward-cutting tributaries.

METHODS

To help document Culebra Lake and Pio-Pleistocene geomorphic evolution of the northeastern Pajarito Plateau, we mapped and sampled lake deposits and overlying slump complexes. We recognized Culebra Lake deposits by the distinctive gray color of a widespread basal clay unit and by the occurrence of a ledge-forming tephra below the basal clay (Fig. 2). In the laboratory, we used wet-sieving and sedimentation-chamber techniques to measure the size distribution of selected samples and separated cinders and clay-sized material for binocular and X-ray diffraction (XRD) analysis. Rick Warren (Los Alamos National Laboratory) characterized the tephra and provided an x-ray fluorescence

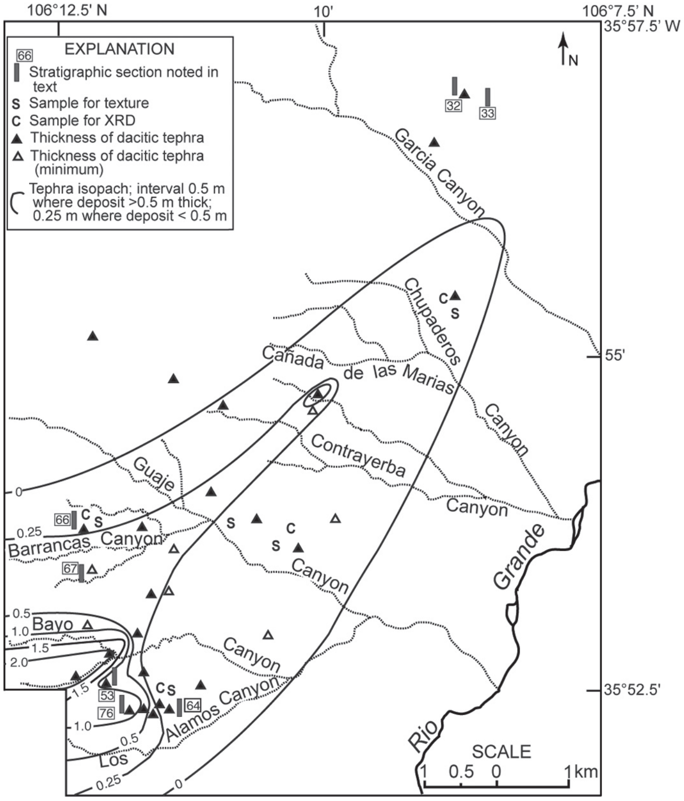

FIGURE 2. Map showing isopachs of the dacitic tephra and locations of stratigraphic sections and sample sites noted in the text, eastern Puye and northeastern White Rock quadrangles, New Mexico.

(XRF) analysis for one clay sample; Robert Newton (Smith College) conducted the XRD analysis using methods described by Drever (1973). Debra Willard (U. S. Geological Survey) recovered and identified pollen assemblages from four of six samples of Culebra Lake clay using standard techniques.

RESULTS

Culebra Lake deposits north of Los Alamos Canyon consist of dacitic tephra, clay, silt, sand, and sandy diamict that overlie fanglomerate, axial gravel and older lacustrine facies of the Puye Formation (Fig. 3). Erosion has stripped Pliocene sediment to the east of the Rio Grande, but headward incision of tributaries to the west has exposed lacustrine deposits in canyon walls and along mesa edges. Piedmont alluvium rich in dacitic pebbles, the Guaje Pumice bed of the Bandelier Tuff, or slump blocks of the Tshirege Member of the Bandelier Tuff unconformably overlie Culebra lacustrine deposits and local subaerial facies.

Stratigraphic relationships near the base of Culebra Lake deposits

Depositional environments in Culebra Lake varied spatially and temporally, but most exposures consist of a thin dacite-rich tephra overlain by 2 to 10 m of massive to thinly laminated gray clay, covered by coarser deposits. Sections along Los Alamos Canyon (Figs. 2, 3) also expose underlying coarse axial deposits and older lacustrine facies. The ~12 m thickness of clay exposed at section A76 locally is interlayered with altered, subaqueously emplaced pillow basalt. The subaerial part of a nearby correlative flow has an $^{40}Ar/^{39}Ar$ age of 2.33 ± 0.08 Ma (WoldeGabriel et al., 2006), which approximates the beginning of clay deposition in Culebra Lake. Older lacustrine deposits, interbedded with volcanic fanglomerate, extend tens of meters below the axial alluvium.

Dacitic tephra fines and thins to the east (Fig. 2), forming a mappable horizon in >14 km^2 of the study area. Dacitic material is mixed with basaltic cinders and preserved in deposits that display mud cracks, wave ripples, and other evidence of nearshore sedimentation (Waresback and Turbeville, 1990).

Clay thickness and paleotopography

Measured thicknesses of basal Culebra clay increase from northwest to southeast, attaining values as great as 12 m (Fig. 4). The clay locally is >4 m thick near Santa Clara Canyon, some 5 km north of the northern border of Figure 4. The shoreline of the highest lake stage probably stood at an elevation of ≤1950 m,

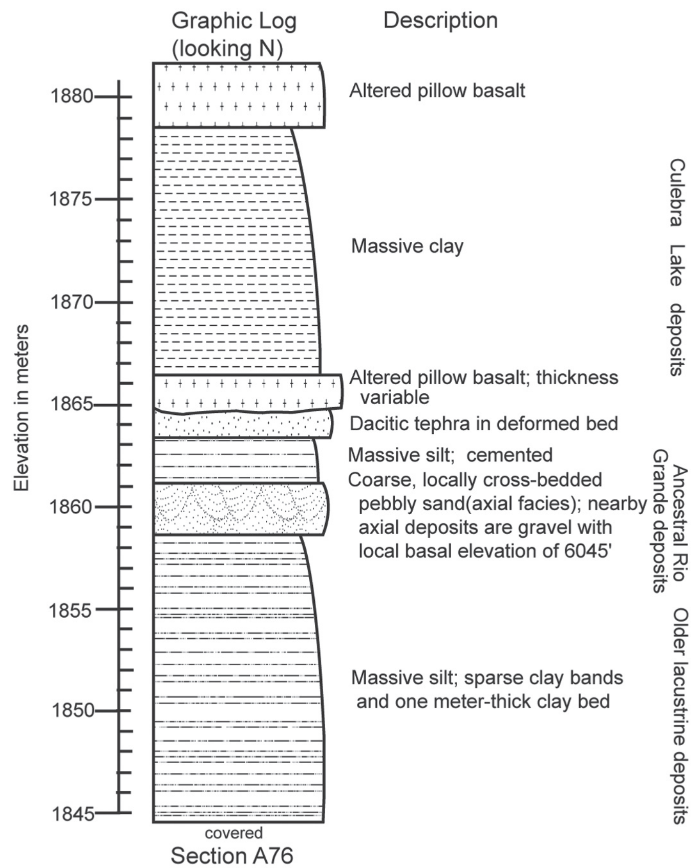

FIGURE 3. Stratigraphic section exposed at site A76 (see Fig. 2), Los Alamos Canyon (comparable to the upper part of section LA-01 of Waresback and Turbeville, 1990).

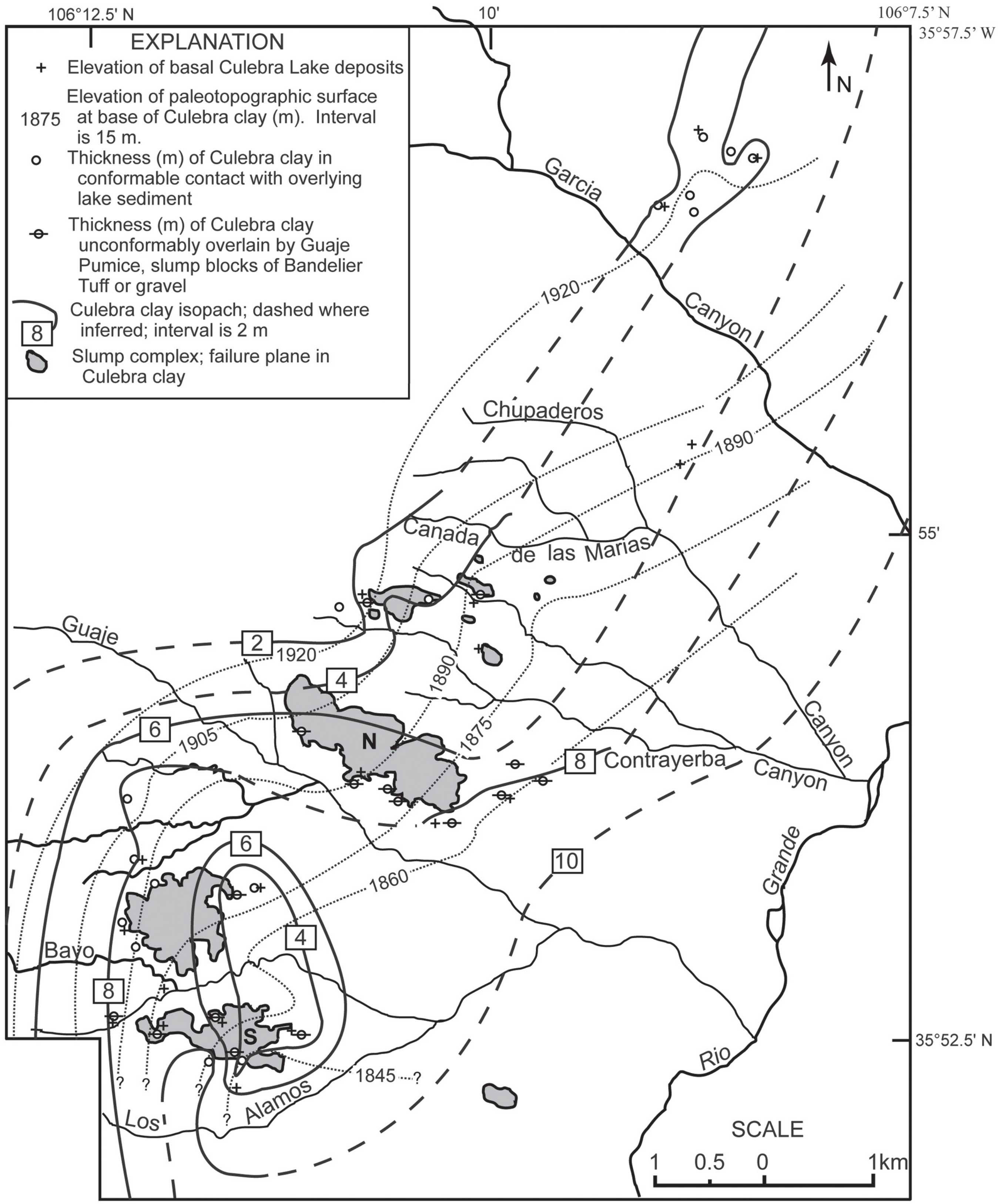

FIGURE 4. Map showing thickness of Culebra Lake clay, the paleotopographic surface beneath the clay and slump complexes ("N" and "S" identify slumps shown in detail in Fig. 8). Elevations not corrected for postdepositional tilting or displacement. Map base Puye and White Rock 7.5' quadrangles.

several kilometers west of the 2 m clay isopach. The area of relatively thin clay near lower Bayo Canyon and the slightly higher elevation of basal contacts suggest that the area was a paleotopographic high. Extensive slump complexes that crop out in a zone 3 to 5 km west of the Rio Grande overlie the basal clay.

The landscape buried by Culebra deposits had relief >80 m, sloped east-southeast at an average gradient of 2 to 3%, but was not as deeply dissected as the modern Pajarito Plateau. Relief was greatest in the southeastern study area near the ancestral Rio Grande. Our data do not clearly define the location of paleovalleys, but subsurface studies (R. Warren, unpubl. data, 1998) suggest that a canyon ≥85 m deep coincided with the modern position of Los Alamos Canyon southwest of the map area. Isopachs of clay thickness and inferred paleotopography suggest that Guaje Canyon was not a major late Pliocene drainage. Between Contrayerba Canyon and Guaje Canyon paleosurfaces sloped ~3% to the southeast.

Composition of the basal clay and underlying layer of dacitic tephra

Field observations, and textural and XRD analyses show that the Culebra clay is remarkably uniform in texture and composition over an area of tens of square kilometers. Five samples collected at intervals of 1.85 m from a 9.5 m-thick section (A64; Fig. 2), for example, contain >90% <5-µm material; the basal sample contains <0.8% fine sand and the section fines upward. Representative samples collected from the gray clay at four additional sites (see Fig. 2) mainly contain >90% clay and very fine silt and <<1% fine sand (Fagenholz, 1998). Diffractograms of the <2-µm fraction of six samples are nearly identical. Samples are rich in random illite/smectite intergrade and contain abundant kaolinite and minor amounts of quartz. A single XRF analysis (sample A64e) shows that the clay contains 62.17% SiO_2, 17.75% Al_2O_3, 6.01% Fe_2O_3, 2.56% MgO, and 1.67% CaO (R. Warren, written commun., 1998).

The coarse fraction separated from nine samples of basal clay contains clear, colorless, angular glass and angular quartz grains in all samples. Accessory grains include metamorphic quartzite, dacite, biotite, and dark vesicular glass. Calcite and gypsum (which occurs as blades) may be either primary or secondary. Several samples also include charred woody fragments.

Samples of the dacitic layer contain tephra fragments as large as 11 mm and consist of ~60% dacite, 35 to 40% mafic or hydroclastic shards, and minor amounts of other debris. Dacitic lithics in all samples are generally slightly larger than mafic and hydroclastic shards. "The light gray, moderately well sorted medium ash matrix in these samples consists of pumice, black vitric hydroclastic shards, very pale red devitrified lava, and feldspar. Clasts in all samples are mainly brownish black vitric dacitic pumice with feldspars locally >1.3 mm, quartz, sanidine, and sparse hornblende and biotite grains. Mafic clasts are vitric and sparsely to well vesiculated with local olivines. Hydroclasts occur as both dark gray, vitric, vesicular shards and very pale red, devitrified, vesicular grains" (R. Warren, written commun., 1998).

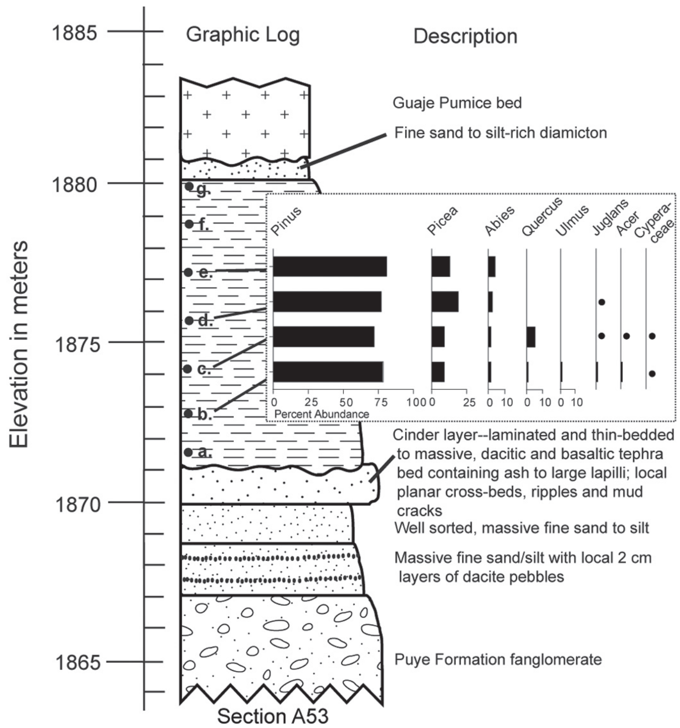

FIGURE 5. Stratigraphic section exposed at site A53 (see Fig. 2), showing location of samples collected for pollen analysis. Culebra clay here consists of massive to finely laminated clay and silty clay with local fine sand partings. Inset shows pollen diagram for samples b-e, which contained significant amounts of pollen (D. Willard, U. S. Geological Survey, written commun., 2004).

Palynology

The fossil pollen assemblage from Culebra clay samples at measured section 53 (Figs. 2, 5) is dominated by *Pinus* (pine) pollen with subdominance of *Picea* (spruce). *Abies* (fir) pollen is present in low percentages; *Quercus* (oak) is common in sample 53c. Herbaceous pollen is relatively rare, comprising 1 to 8% of assemblages and consisting primarily of Poaceae (grasses) and Asteraceae (Aster family) pollen. In samples b-c, pollen from the deciduous hardwoods *Acer* (maple), *Juglans* (walnut), and *Ulmus* (elm) is present, although sparsely represented. Pollen of the herbaceous Cyperaceae (sedges) also is present in samples b-c. We do not know how this local pollen assemblage reflects eolian transport or fluvial dispersal, so: "… only qualitative paleoclimatic interpretations may be made from these data. Although the lowest two samples are codominated by *Pinus* and *Picea* pollen, the presence of deciduous taxa is suggestive that relatively warmer, moister conditions predominated…. In the upper two samples, the increased abundance of *Picea* and *Abies* pollen and loss of deciduous elements indicate the presence of spruce-fir forests in the area and a shift to cooler, drier conditions…" (D. Willard, written commun., 2004). Willard noted a relative abundance of diatoms in sample b.

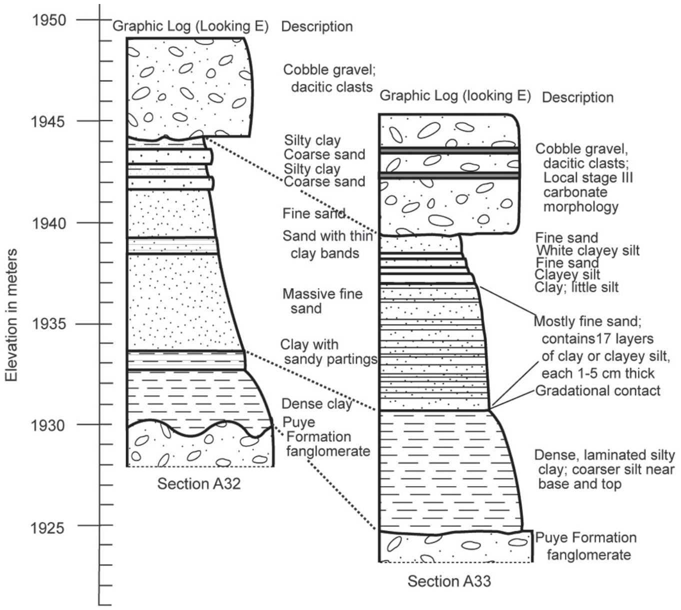

FIGURE 6. Stratigraphic sections A32 and A33, Garcia Canyon (see Fig. 2).

Nearshore and subaerial facies

Two stratigraphic sections separated by ~ 500 m expose the highest lake deposits that we mapped and reflect facies relationships on a gradient away from the sediment source (Figs. 2, 6). Basal clay in sections A33 and A32 shows that both areas initially were distant from the lakeshore in water >15 m deep. Above the clay, deposition at the proximal A32 section consisted of coarser sediment while the more distal A33 site accumulated fines. Interstratification of sand and clay-rich sediment near the top of both lacustrine sections suggests fluctuations in lake level or sediment input. Subaerially deposited cobble gravel that truncates lacustrine deposits at both sites is of unknown age, but has the same apparent slope (1%) as the underlying contact between Puye fanglomerate and the basal clay.

Sections A66 and A67 flank Barrancas Canyon (Figs. 2, 7) and are typical of thick, relatively coarse sequences deposited near the western margin of Culebra Lake. At both sites, ~8 m of massive lacustrine clay is capped by sandy deposits that coarsen up into dacitic, fluvial gravel and gravel-rich diamicts, separated by a series of buried soils. Both sections demonstrate that considerable subaerial deposition occurred west of the eastward-migrating lakeshore. Subaerial sequences as thick as ~20 m are preserved in the area from Bayo to Garcia Canyon; deposit geometry suggests deposition in relatively wide channels.

Extent of Culebra Lake

By tracing the present 1950 m contour in this area, we were able to estimate the maximum potential extent of Culebra Lake in the western portion of the Española basin as about 1000 km^2. Where we have mapped lake deposits along the eastern Pajarito Plateau, the 1950 m contour gives a reasonable approximation for the lake shoreline. Faulting may make this elevation locally incorrect, but more significant errors arise from our imperfect knowledge of late Pliocene paleotopography. Culebra Lake extended up the modern course of the Rio Grande and inundated lower reaches of the Rio Chama (Manley, 1976) at least as far north as the vicinity of Black Mesa on both drainages. We cannot constrain lake extent to the northeast and east because all Pliocene deposits have been removed and Miocene deposits are deeply eroded.

If Culebra Lake had a maximum area of ~1000 km^2 and a maximum depth >80 m, we estimate that the average depth was between 10 and 30 m, assuming that the paleogradient of the late Pliocene Rio Grande was similar to that of the modern river. Using these estimates, Culebra Lake contained a maximum volume of 10 to 30 km^3 of water. If average discharge of the late Pliocene Rio Grande was ~50 m^{3}s^{-1} (approximate modern Rio Grande discharge before regulation and diversions), Culebra Lake would have filled in a few decades, assuming that leakage and evaporative losses were relatively small.

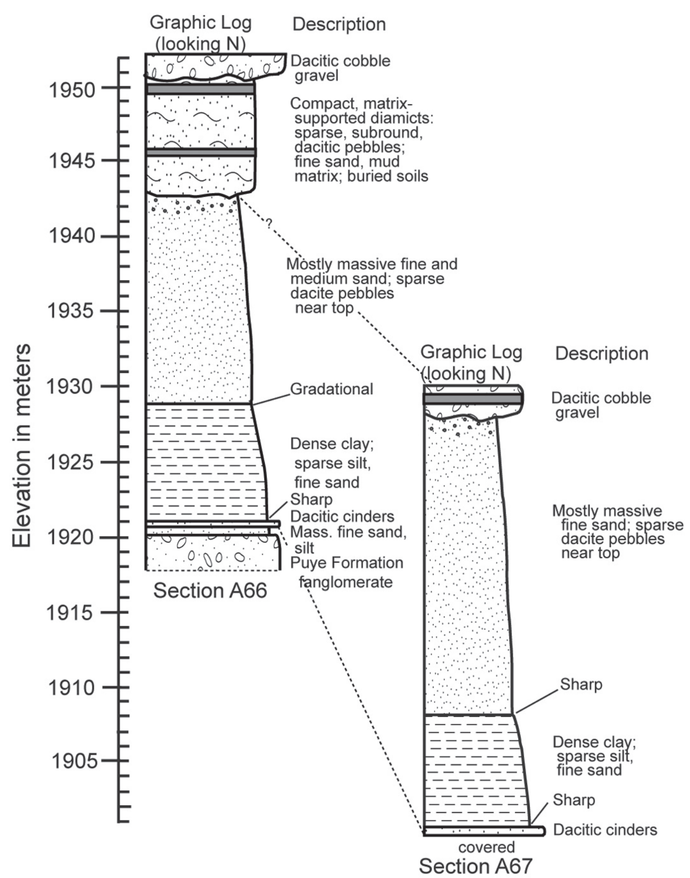

FIGURE 7. Stratigraphic sections A66 and A67 Barrancas Canyon area (see Fig. 2).

Slumps involving Bandelier Tuff overlying Culebra clay

Culebra Lake deposits are overlain locally by massive, coherent to highly disrupted slumps composed of Bandelier Tuff (Figs. 4, 8a). We mapped three large complexes and several smaller, isolated slumps to the north. Deposits of reworked Bandelier Tuff that overlie clay in adjacent areas show that slumping affected a wider area than that exposed at present: e.g., an extensive surface south of lower Los Alamos Canyon (Fig. 4). Slump blocks of Bandelier Tuff as long as several hundred meters generally are elongate perpendicular to their direction of motion. Block dips range from <10 to ~55° (Fig. 8b), steepening progressively away from intact outcrops of tuff or from ESE-trending axes. Slump blocks with dips of 45 to 55° generally are smaller and less coherent than blocks with shallow dips. At tilt angles steeper than ~50°, the tuff disintegrates. Although slumps dip steeply, they must have failed on subhorizontal planes within the Culebra clay. In slump complexes where nearby undeformed exposures indicate that the clay was originally 8 to 10 m thick, the remaining clay is 2 to 4 m thick, indicating that failure planes formed in the zone of finest clay and fewest partings.

The slump complex north of Guaje Canyon (“Northern”) displays the most clearly ordered morphology of the three extensive slides in the area (Fig. 8). It covers approximately 0.8 km^2 and has a SE-trending deformation axis, which we infer records the axis of a Bandelier Tuff mesa prior to slumping. In the center of this complex a small, elongate block of in situ Bandelier Tuff is riddled with tension features and marks the early Pleistocene paleodrainage. The smallest, yet perhaps best exposed of the large complexes (“Southern”) occurs south of Bayo Canyon and adjacent to N.M. State Road 4 (Fig. 8). This slump area covers 0.5 km^2 and has a local relief of 70 m. The deformation axis of this complex does not correspond with the present topographic ridge, but is closer to the southern perimeter and Los Alamos Canyon.

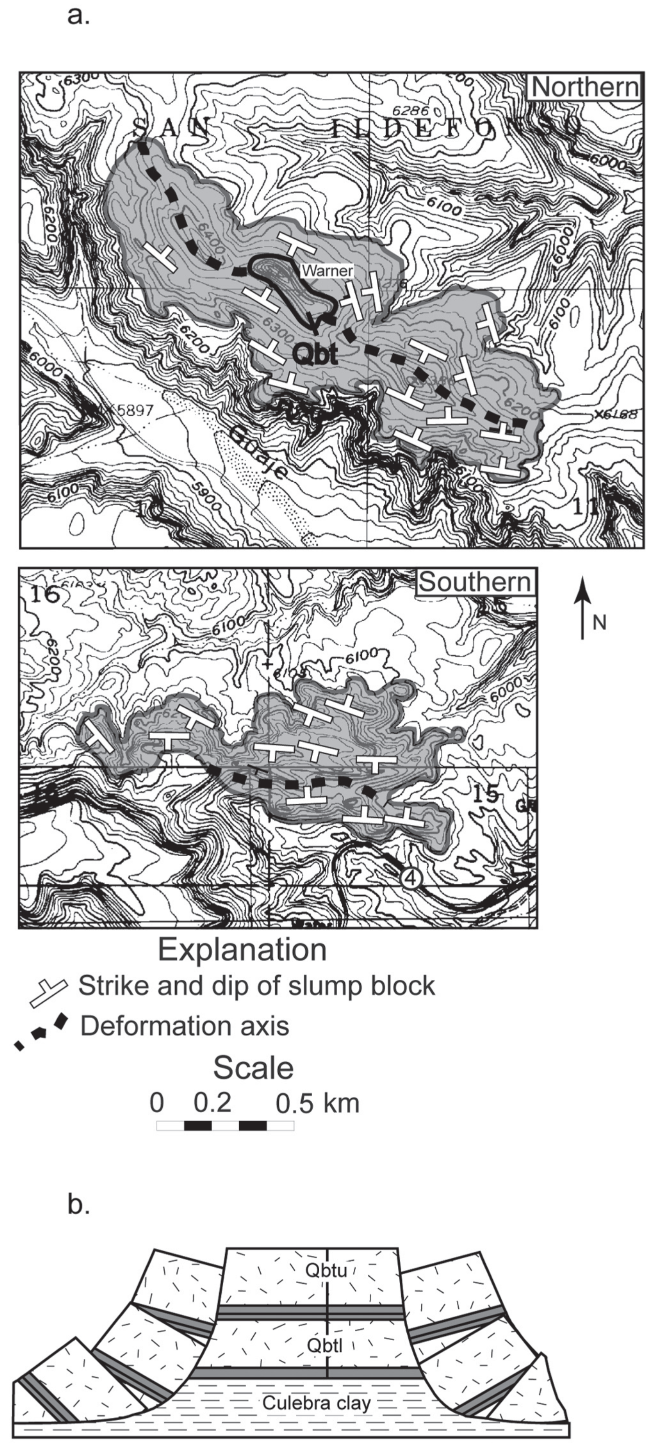

FIGURE 8. **a**. Maps showing the “Northern” and “Southern” slump complexes, southeastern Puye 7.5-minute quadrangle (see Fig. 4). “Warner” is fractured, in situ Bandelier Tuff. **b**. Sketch section across the Northern slump complex

DISCUSSION

Culebra Lake sediment preserves information about late Pliocene topography, volcanism, and climate, and serves as an unstable platform for overlying rock materials exposed along the margin of the Pajarito Plateau. In this section, we discuss the sedimentary record preserved in different lacustrine facies in Culebra Lake, estimate the duration of the lake and note how these deposits and overlying Bandelier Tuff allow us to reconstruct middle to late Quaternary geomorphic evolution of the eastern Pajarito Plateau area. We then speculate about the role of climate change in this evolution.

Culebra Lake sedimentation

Exposures of Culebra Lake sediment along the eastern margin of the Pajarito Plateau record successive deposition of: (1) dacitic tephra; (2) gray clay; (3) silty fine sand, sand, and coarser deposits; and (4) gravelly dacitic alluvium, most of it deposited subaerially. Mafic cinders and hydroclastic shards mixed with the dacitic tephra record coeval basaltic eruptions. Coarse tephra probably was ballistically transported from a nearby post-Tschicoma (?) dome, whereas finer grains found in thin, distal exposures may have been transported by southwest winds. Reworking of tephra by shoreline processes probably contributed to thickness patterns in the western part of the study area.

The basal gray clay is the signature unit of Culebra Lake, but overlying coarser deposits also are widely preserved. The clay overlies dacitic tephra deposited in shallow water, recording rapid deepening of Culebra Lake and an extended period of late Pliocene lake stability. Clay thickness increases to the south and east where the lake was deeper and coarse sediment sources more distant. Nearly identical texture and similar mixtures of random illite/smectite intergrade and kaolinite on vertical and lateral transects suggests that clay originated as suspended load from a single area, most likely the Colorado Plateau drained by the ancestral Rio Chama. Modern canyons draining the Jemez Mountains do not carry much clay-size material, nor is there evidence for much fine material in the Puye Formation. Exposed rocks of the Jemez volcanic field and the Santa Fe Group are not clay-rich and mica and illite dominate their fine mineralogy. Mesozoic mudstones of the Colorado Plateau, however, are rich in illite/smectite and kaolinite (Keller, 1962) and are highly erodible, strongly coloring the modern Rio Chama with washload during the summer and fall thunderstorm season.

How long did a deep Culebra Lake persist? We use several approximations below to help constrain sedimentation rates. Sediment transport at the north end of White Rock Canyon by the Rio Grande is ~10^6 tonnes(t)yr^{-1} and 86% of the modern load is suspended (Graf, 1994). During one moderate summer flow Nordin and Beverage (1965) determined that 27% of Rio Grande suspended load was <4 μm. We use these values and a lacustrine sediment density of 1.7 tm^{-3} to estimate that ~150,000 m^3yr^{-1} of <4 μm material entered Culebra Lake. If significant amounts of clay accumulated on ~200 km^2 of the lakebed, deposition rates would have been ~75 $cmky^{-1}$, or ~15 $cmky^{-1}$ if deposition occurred over the entire 1000 km^2 lake area. Contemporary rates of silt, clay and fine sand accumulation in lower Rio Grande reservoirs are 1000 to 5000 $cmky^{-1}$ (Calender and Van Metre, 1997). Such values likely overestimate presettlement rates and the < 5 μm fraction probably is < 30% of the total. Tulelake and Summer Lake, in California, accumulated mud at a rates from 6 to >30 $cmky^{-1}$ during Pliocene and Pleistocene time, comparable to the deep-water phases of Lake Bonneville (Adam et al., 1989; Thompson et al., 1995; Cohen et al., 2000). Given the substantial uncertainties in these values, we estimate that Culebra clay accumulated at 15-150 $cmky^{-1}$, equivalent to 8000 to 80,000 yrs for a 12 m thickness of clay.

Culebra Lake filled on the north with axial sediment transported by the Rio Chama and Rio Grande and on the west and east with piedmont-slope sediment. Lake filling, depth fluctuations, and net eastward migration of the western shoreline are recorded in the study area by coarsening-upward sequences of nearshore, shoreline, and subaerial deposits. In several areas near Santa Clara Canyon, for example, nearly continuous exposures suggest that fan-deltas migrated ≥3 km to the east before drainage of Culebra Lake. Thick subaerial deposits that cover lacustrine sediment near and north of Barrancas Canyon (Fig. 3) demonstrate that aggradation continued locally after Culebra Lake began to drain. Buried soils and diamicts rich in soil material in subaerial deposits suggest that the style of sediment production and erosion upstream had changed and that transport rates were lower than those on the pre-Culebra Puye fan. Infilling from the north should be recorded by relatively thick sequences of comparable coarse deposits, but they have not been recognized in the stratigraphic record (Manley, 1976).

Lake drainage, incision of the Pajarito Plateau, and landslides

The distribution of Culebra Lake deposits and associated slump complexes suggests that tributary drainages evolved slowly and that significant headcutting did not occur until after eruption of the upper Bandelier Tuff. Culebra Lake probably persisted as an extensive, deep-water body for ≥10, 000 yrs, impounded by basalt that was eroded only slowly by the Rio Grande. Hamblin (1994) has shown that along the Colorado River in Grand Canyon, backcutting dominated erosion of numerous basaltic dams, which persisted for only tens of thousands of years. Even allowing for slower backcutting by the smaller Rio Grande, it seems likely that in <100,000 yrs, erosion would have incised through the basalt dam in White Rock Canyon or that the lake basin would have filled with sediment. Extensive upstream incision, however, was delayed until after early Pleistocene time.

Culebra Lake deposits were exposed to subaerial processes for ~0.6-0.7 m.y. before eruption of the lower Bandelier Tuff at 1.61 Ma, but little erosion occurred on the northern Pajarito Plateau. The Rio Grande probably cut down through the highest lacustrine deposits soon after Culebra Lake drained, leaving thin deposits of axial gravel stranded locally on upland surfaces above elevations of ~1920 m (Dethier, 2003). If either tributary downcutting or surface erosion had been substantial, there would be no record of lacustrine deposits. However, aggradation continued locally near Guaje Canyon until after eruption of the San Diego Canyon pumice at ~ 1.85 Ma (Waresback and Turbeville, 1990). Preservation of lacustrine sediment north of White Rock Canyon suggests that a deep paleocanyon did not extend north of Los Alamos Canyon before 1.6 Ma and that deep tributary incision and valley widening along modern canyons were minimal on the northern Pajarito Plateau.

Slumping of the Bandelier Tuff in the Guaje Canyon area probably started after early Pleistocene time. Mapping in the Puye quadrangle (Dethier, 2003) and in nearby areas shows some upland drainages cut down 20 to 45 m between 1.6 and 1.2 Ma, locally removing the lower Bandelier Tuff. Many of these channels, however, had backfilled before eruption of the upper Bandelier Tuff at 1.22 Ma. Since that eruption, backcutting of deep tributary canyons and failure of large areas of tuff were triggered as tributary drainages cut down through the tuff and exposed Culebra Lake clay. Morphology of the largest slump complexes (Fig. 8) appears to be dictated by the orientation and size of nearby drainages and their distance from the slump. For instance, the southern complex, flanked by Bayo Canyon on the north and the wider and deeper Los Alamos Canyon on the south, is asymmetric to the south, apparently because a large tributary eroded headward into the complex. Headward migration of slumping appears to be almost complete at present; where Bandelier Tuff overlies Culebra Lake clay, only small areas remain intact.

Climatic influences?

Late Pliocene and early Pleistocene time included periods of rapid climate change, and resulting variations in stream power and sediment yield likely affected Culebra Lake and subsequent geomorphic evolution of the area. Relatively moist middle Pliocene climates in the southwestern United States gave way to drier and episodically colder periods after ~2.5 Ma and to higher amplitude alternation between wet and dry intervals beginning sometime after 1.0 Ma (Smith, 1994). Deposition of the coarse Totavi "Lentil" (Griggs, 1964) and coarse axial deposits south of White Rock Canyon indicate that a vigorous Rio Grande was established before ~2.8 Ma, probably in late Miocene time. Episodic blockage and damming of the Rio Grande in the period 2.8 to 2.2 (?) Ma was driven by volcanic activity. The persistence of volcanic dams, longevity of Culebra Lake, and the relatively slow incision by the Rio Grande after ~2.2 Ma, however, may signal that the Rio Grande had relatively low flow in this period. Stage IV soil carbonate on late Pliocene basalt near White Rock requires a climate at least as dry as that of the late Holocene. Relatively rapid downcutting during middle Pleistocene time (Reneau and Dethier, 1996b) and headcutting by tributaries through the Pajarito Plateau suggest high stream power in the Rio Grande, consistent with high amplitude alternation of pluvial and interpluvial climates that began during this period. Evolution from blockage to downcutting along the margin of the Pajarito Plateau undoubtedly reflects removal of the volcanic dam, but circumstantial evidence suggests a role for Pliocene climate change as well.

CONCLUSIONS

The deposits of Culebra Lake record late Pliocene sedimentation in a deep lake formed by damming of the Rio Grande by basalt flows near White Rock. A thick basal clay derived from erosion of the Colorado Plateau records sedimentation over thousands of years. Local aggradation continued north of White Rock Canyon after Culebra Lake began to drain and significant incision began only after eruption of the Bandelier Tuff. The tuff helped to protect Culebra deposits, but failed in massive slumps when headward-cutting drainages removed lateral support from the clay layer after early Pleistocene time. Our preliminary work suggests that fossil pollen and other microfossils in the lacustrine sediments offer a potentially detailed record of climate change during late Pliocene time.

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