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David P. Dethier and Stephanie K. Kampe

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RECONSTRUCTING PYROCLASTIC FLOW DYNAMICS AND LANDSCAPE EVOLUTION USING THE UPPER BANDELIER TUFF, PUYE QUADRANGLE, NEW MEXICO

DAVID P. DETHIER[1] AND STEPHANIE K. KAMPF[2]
[1]Department of Geosciences, Williams College, Williamstown, Massachusetts 01267, ddethier@williams.edu
[2]Department of Forest, Rangeland & Watershed Stewardship, Colorado State University, Fort Collins, CO 80523-1472

Abstract — Exposures of the upper unit (Tshirege Member) of the Bandelier Tuff on the northeastern Pajarito Plateau, preserve information about the dynamics of distal pyroclastic flows, the landscape buried by the tuff, and post-Bandelier geomorphic evolution. Our analysis reflects mapping of upper Bandelier units on the Pajarito Plateau in the Puye 7.5-minute quadrangle, 15 to 20 km from their eruptive source, and synthesis of research from adjacent areas of Los Alamos National Laboratory (LANL). Understanding the present distribution and internal boundaries within the upper Bandelier Tuff aids in paleoseismic studies and analysis of groundwater and contaminant transport in the Los Alamos area. Tshirege tuff crops out beneath narrow mesas in the western and central portion of the Puye quadrangle. Tuff classification systems developed in the LANL area apply reasonably well in the study area. Unit 1g, the basal Tshirege tuff, is mainly covered and protected by unit 1v. Unit 2 is thinner than the underlying tuff units and forms only a thin, resistant cap on some mesas. At a few locations, thin remnants of unit 3 cap the Tshirege section. In the LANL area to the west, Tshirege units are slightly thicker, less deeply eroded and more continuous. Isopach maps of unit 1g display thickness variations that highlight paleotopography, delineate an easterly flow path from the rim of the Valles caldera into the Puye quadrangle and indicate lobate flow morphology. Where lobes overlap, unit 1 contains abundant pumice concentrations and surge deposits. Exposures of units 2 to 4 indicate deposition as pyroclastic fans that spilled out across the western Pajarito Plateau little affected by topography, leaving a relatively smooth surface. Structural contours on the base of unit 1g show that two broad, Tshirege-filled paleodrainages underlie the study area; the largest can be considered a “paleo-Guaje Canyon”. South of modern Guaje Canyon, buried canyons trend southeast, bending south in the southern LANL area. Flow thickness and the degree of welding in Tshirege units, base-level changes along the Rio Grande and pre-Bandelier stratigraphy influenced Pleistocene landscape evolution. Tshirege outcrops overlying Pliocene lacustrine deposits failed in massive slumps as headward incision by tributaries removed lateral support. Canyon cutting initiated erosion of the Tshirege, but in most areas upstream from the slumps, weathering processes, block-failure and surface erosion drove cliff retreat.

INTRODUCTION

The northeastern Pajarito Plateau exposes deep canyons that separate narrow mesas capped by the multicolored Bandelier Tuff in a landscape transitional between the main plateau to the south and west and alluvial fans and deeply eroded Miocene rocks near the Rio Grande (Fig. 1). The tuff records the most recent caldera-forming events in the Jemez volcanic field, paleotopography, emplacement mechanics of upper Bandelier pyroclastic flows and Pleistocene erosion. The texture and cooling characteristics of distal outcrops suggest local pyroclastic flow mechanisms and provide an “end-member” useful in evaluating criteria for tuff classification. Understanding the internal boundaries of the upper Bandelier Tuff also aids in paleoseismic studies and analysis of groundwater and contaminant transport in the Los Alamos area.

Volcanic processes

Pyroclastic material ejected by eruptions is dispersed by fall, surge, and flow mechanisms (Fisher et al, 1997) as the eruption column collapses, producing significant thicknesses of tuff where volcanic debris falls and flows downslope away from the volcanic center. Surge deposits associated with pyroclastic flows mark the base of flow units and are commonly thin, crystal-rich beds cross-stratified to form dunes, or in massive to planar beds (Sparks and Walker, 1973; Carey, 1991). As the magma chamber empties, successive pyroclastic flows tap material from deeper in the magma chamber and are typically smaller, hotter and volatile-poor compared to the initial eruption. Flow directions and thickness of pyroclastic deposits are strongly influenced by underlying topography and by eruption volume; flows tend to smooth or bury paleolandscapes.

Cooling processes begin during flow emplacement and create both sharp and gradational changes in composition and physical structure within grossly homogeneous, unstratified deposits. Dominant cooling features include welding, compaction, secondary crystallization, and jointing. Welding intensity may vary both vertically and laterally, depending on distance from cooling surfaces and eruptive source (Broxton et al., 1995). Devitrification and vapor phase crystallization attack the initial glassy structure of tuffs, converting it to crystalline material (Ross and Smith, 1960). Boundaries within a sequence of rapidly emplaced pyroclastic flows may represent flow, cooling or mineralogic boundaries.

Weathering and erosion of pyroclastic flows

In a semi-arid climate such as that of northern New Mexico, rapid downcutting into and erosion of consolidated materials produces deeply incised mesa-canyon landforms. Thick, complex sheets of tuff are chemically altered during and after cooling, dissected by fluvial erosion, and modified by sheetwash and mass movements. Fluvial activity begins in braided stream channels (Reneau, 1995), whereas fluvial incision is controlled by headward cutting that migrates from a major drainage. Incision progresses headward, gradually deepening canyons and leaving tuff mesas exposed to additional erosion. The mixture of materials in

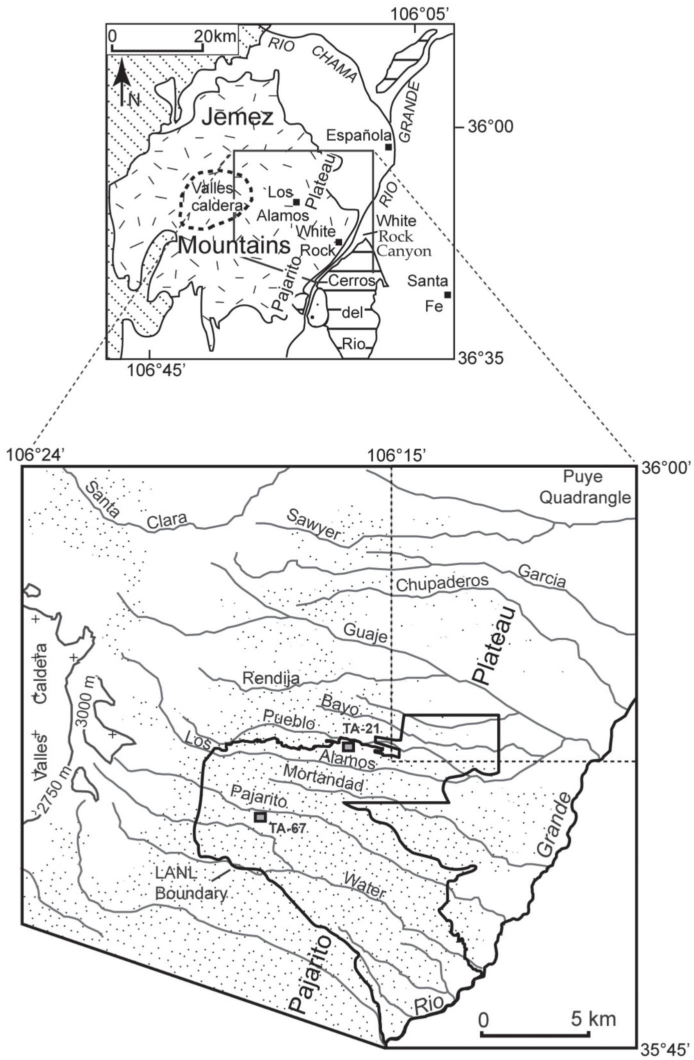

FIGURE 1. Map showing location of the Valles caldera, the Pajarito Plateau, the western Puye quadrangle, and Los Alamos National Laboratory (LANL); stipple outlines areas of Bandelier Tuff. Inset shows the Jemez Mountains and nearby features noted in the text.

tuffs promotes selective weathering that produces pitted surfaces in nonwelded units (Ross and Smith, 1960). More highly welded tuff tends to form vertical cliffs in outcrop and remains relatively unmarred by large cavities. In relatively dry climates, weathering and erosion are localized along fractures in welded tuffs, producing gradual cliff retreat as a result of rockfall and landslides (Reneau, 1995).

Mass movements, surface erosion and weathering processes differentially remove individual tuff units. Nonwelded units typically erode into broad, gentle slopes, whereas slightly to moderately welded units stand vertically. Rubble from rockfalls often obscures less welded sections, creating a dramatic contrast between vertical cliffs of welded units and talus-covered slopes of nonwelded units.

SETTING

Location

The upper Bandelier Tuff is exposed best along canyons that dissect the Pajarito Plateau, a broad area of mesas that slope eastward from elevations over 3100 m near the Jemez Mountains (Fig. 1) to 1900 m along White Rock Canyon (Reneau et al, 1996). This study focuses on distal outcrops of Tshirege Member tuff along the northeastern margin of the Pajarito Plateau within and adjacent to the Puye 7.5-minute quadrangle. In this area the plateau is fragmented into narrow canyons and elongate mesas by Pueblo, Guaje, and Garcia Canyons and by other ephemeral drainages. We also synthesize published work about more proximal outcrops of Bandelier Tuff preserved south and west of the quadrangle on the Los Alamos National Laboratory (LANL).

Climate

Modern climate in the Puye quadrangle is temperate, continental with strongly seasonal precipitation. The eastern portion of the Pajarito Plateau receives about 30 cm of precipitation each year; 40% of this precipitation falls during the months of May through October. Rainfall is most intense during convective storms of July and August, which cause the most extensive surface erosion (Reneau et al, 1996). Details of early and middle Pleistocene paleoclimate are not well known, but conditions must have been colder and at times wetter than those of the late Holocene. Modern vegetation is predominantly mixed Ponderosa-piñon/juniper woodland (McFadden et al, 1996). Ponderosa pines tend to cover north-facing slopes of mesas whereas piñon/juniper woodlands dominate in most other areas below 2100 m. North-facing slopes of the mesas generally are moister and more densely vegetated; colluvial deposits cover the bedrock in many places.

GEOLOGIC HISTORY

The Bandelier magma, lower Bandelier Tuff and Cerro Toledo deposits

The upper Bandelier Tuff is the youngest widespread unit produced by recent volcanism in the Valles caldera, which formed in early Pleistocene time over a large body of silicic magma (Self et al., 1986; Gardner et al., 1996). San Diego Canyon tuff units (Spell et al, 1996) erupted at about 1.85 Ma followed by the lower Bandelier Tuff at about 1.61 Ma (Self et al., 1986; Izett and Obradovich, 1994). Pyroclastic flows (the Otowi Member) 20 to 100 m thick cooled to form a broad ignimbrite sheet dipping gently east and southeast, obscuring a deeply dissected Pliocene landscape. Local erosion of the nonwelded Otowi Member, followed by deposition of pumice fall units and dacitic alluvium (Cerro Toledo deposits) in channels locally as deep as 50 m occurred between 1.6 and ~1.2 Ma (Heiken et al., 1986; Spell et al., 1996; Broxton and Reneau, 1996). Base level controlled by the Rio Grande was relatively constant in the early Pleistocene and the non-welded Otowi Member probably eroded into a landscape of gently rolling hills.

The upper Bandelier Tuff: eruption and products

Eruption of 300 km^3 of upper Bandelier Tuff at 1.22 Ma (Izett and Obradovich, 1994) buried the Toledo landscape with tens of meters of pyroclastic flows derived from a compositionally zoned magma chamber (Broxton and Reneau, 1995). In the study area, decimeter-thick plinian deposits (Tsankawi Pumice) were covered rapidly by pyroclastic flows (Tshirege Member tuffs) that display distinct thickness, welding, geochemical, and mineralogical characteristics. Although the Tshirege is distributed symmetrically around the caldera, individual units have different flow axes (Self et al., 1986). The earliest pyroclastic flows likely were confined by paleodrainages, leaving thickest deposits in paleocanyons. Once these canyons filled, subsequent pyroclastic pulses traveled freely over a relatively smooth landscape. By the time pyroclastic flows reached the Puye quadrangle, some 20 km from the caldera, they had cooled, were more irregular in their flow pattern and likely to reflect diverse travel paths and complex local deposition (Ross and Smith, 1960).

Subdivision of the Tshirege Member

The upper Bandelier Tuff is a compound, complex unit (Ross and Smith, 1960; Caress, 1996) that encompasses multiple flow units and cooling boundaries. In this paper we follow criteria suggested by Broxton and Reneau (1995), who subdivided the Tshirege Member based on welding, crystallization and mineralogical features (Fig. 2). Unit 1 is subdivided into three subunits based on a boundary (the vapor-phase notch) that separates basal glass-rich tuff (1g) from overlying devitrified tuff (1v) within the same cooling unit. Welding and weathering characteristics distinguish units 2, 3 and 4, which are separated by surge deposits and pumice concentrations in the LANL area. The Broxton and Reneau classification has been applied to studies of Tshirege outcrops on the central and eastern Pajarito Plateau.

METHODS

Our field studies of the upper Bandelier Tuff involved measuring sections and mapping contacts using the Broxton and Reneau (1995) criteria and sampling selected outcrops on mesas, which we numbered informally. We plotted contacts, relying primarily on measured data, but using field estimates of thicknesses and contact elevations where sections could not be measured. At many locations where the Tsankawi Pumice was hidden by talus or vegetation, we calculated a maximum limiting elevation for the base of 1g. After combining measured and estimated elevations, we created structure contour maps for the base of 1 and 2 and isopach maps showing thicknesses of 1g, 1v, and a composite 2 and 3 unit (Kampf, 1998).

We analyzed maps that show individual Tshirege units in the LANL area (Rogers, 1995), following the procedures used with our field data to extend our maps of structure contours and isopach thicknesses for units A, B, and C (equivalent to units 1g, 1v, and 2; see Fig. 2). We also incorporated maps of pre-Tshirege topography based on subsurface data for the LANL area (Broxton and Reneau, 1996).

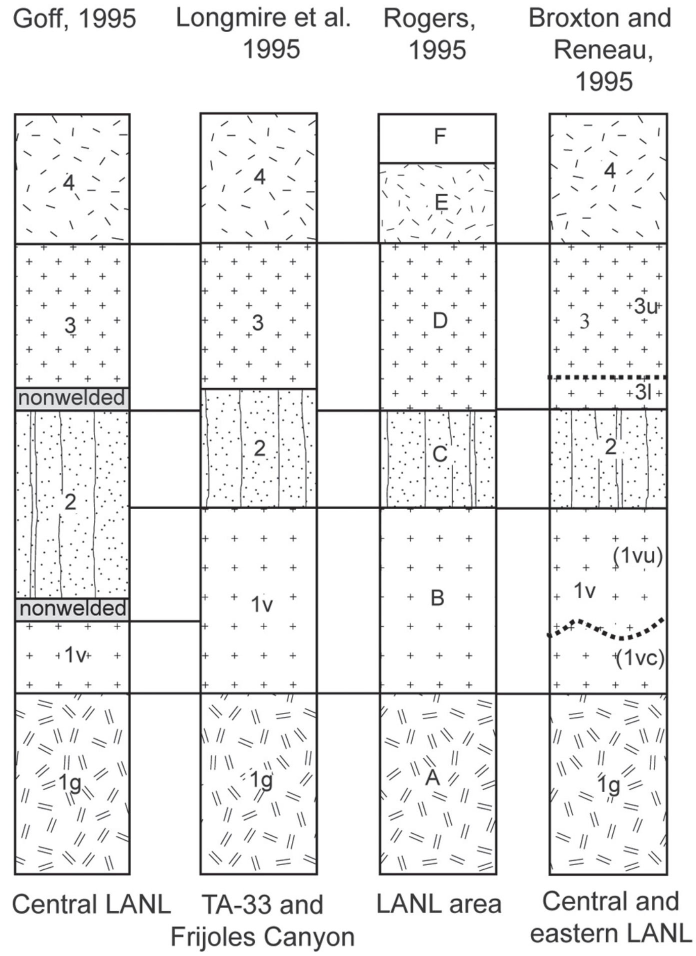

FIGURE 2. Correlation of stratigraphic subunits proposed for the Tshirege Member of the Bandelier Tuff (after Broxton and Reneau, 1995; Rogers, 1995). Our subunits follow those of Broxton and Reneau; we informally subdivide subunit 3 into upper and lower parts.

RESULTS

Distribution of the Tshirege Member on the northeastern Pajarito Plateau

The outcrop pattern of the Tshirege tuffs (Fig. 3) highlights the narrow mesas found in much of the northeastern Pajarito Plateau. The map and cross-sections suggest spatial relations of the tuff outcrops; map scale prevents detailed portrayal of the contacts between tuff units. In most locations, unit 1g is covered by 1v (composite of Broxton and Reneau's 1vc and 1vu), which slows erosion of the basal tuff. Unit 2 forms a thin, resistant cap on many of the smaller mesas and is more extensively exposed to the south and west. At a few locations, a thin cover of unit 3, distinguished by pumice concentrations or significant changes in welding, caps the upper Bandelier section.

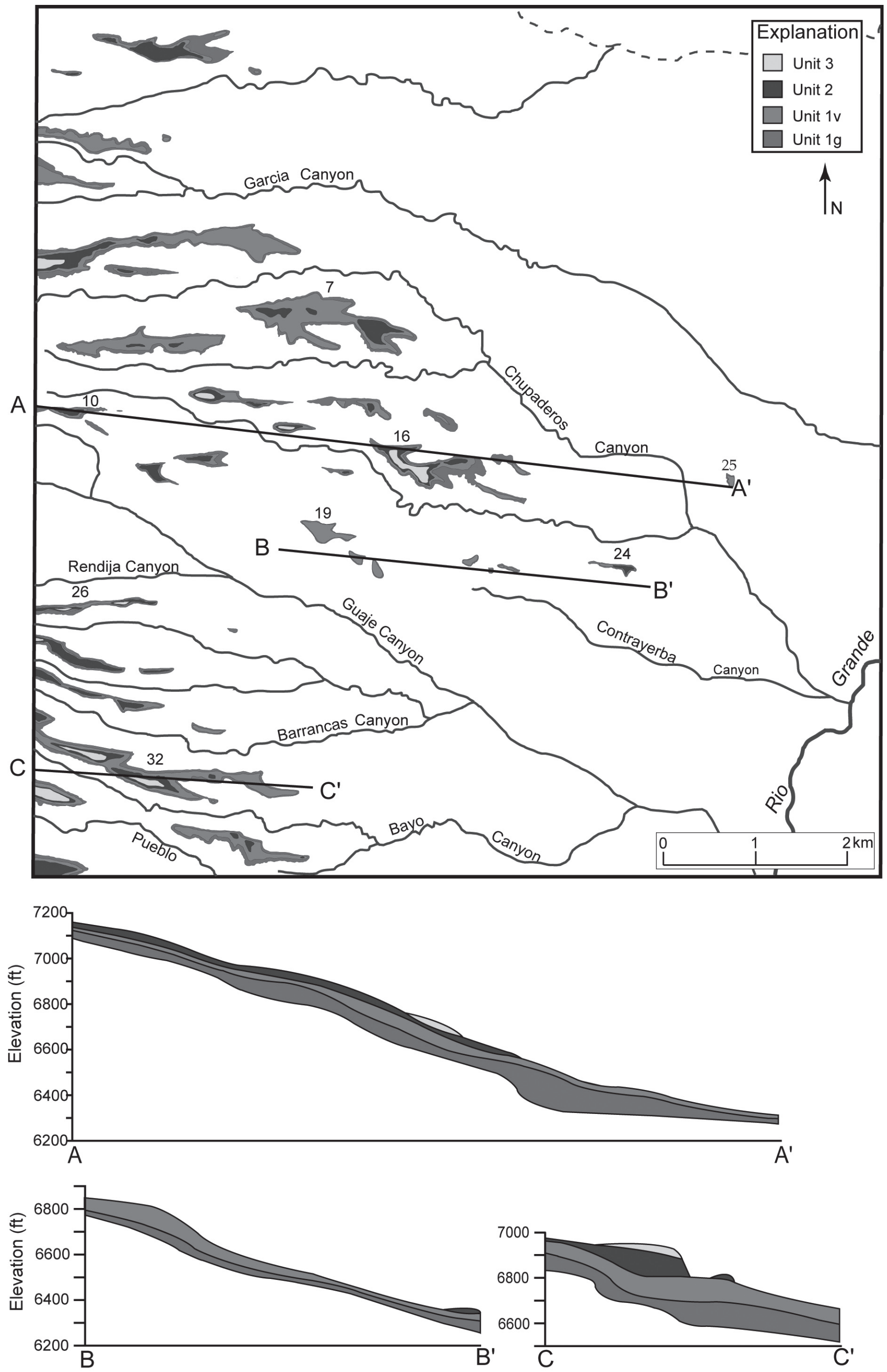

FIGURE 3. Map showing the distribution of Tshirege units in the Puye quadrangle on informally numbered mesas. Sketch cross sections A-A', B-B' and C-C' reflect thicknesses within 400 m of the section line.

The basal contact of unit 1 varies in elevation (Fig. 3; Section A-A'), but subsequent units flowed over a relatively smooth surface that sloped ~ 3% to the east. Local changes in thickness of 1g are small except in one place where the basal contact drops more than 16 m. Thickness variations within the other units are relatively minor. Along and near section A-A', preserved sections of unit 2 are similar in thickness to sections where unit 2 is covered by unit 3. Section B-B' portrays patterns of thickness in a zone of thin flows that buried a surface sloping at about 3%. Unit 1g is about 16 m thick, whereas 1v tapers from more than 30 m in the west to about 6 m in the east. Unit 2 is preserved only on the most distal mesa. In the vicinity of section C-C', western exposures of 1g and 1v slope at ~ 3.5%, but flatten locally to ~ 1%. Slope changes are less prominent for units 2 and 3, which apparently flowed over a surface sloping at ~ 1 to 2%. Where unit 2 is exposed at the surface, it is substantially thinner than in areas where it is covered by unit 3.

Tshirege descriptions and distinctive outcrops

The expression of distal Tshirege units in the Puye area varies from vertical cliffs broken only by changes in color or welding to alternating ledges and benches. Here we summarize characteristics of outcrop and cooling units from four illustrative areas, indicated by numbers (Fig. 3) in more detail on Figures 4 and 5. Otowi Mesa (#32) exposes a sequence of Tshirege tuff units similar to those described by Broxton and Reneau beneath large, intact mesas at LANL. Exposures on three adjacent mesas that represent the Tshirege remnants closest to Guaje Canyon (Fig. 4) show anomalous relations. On all three mesas, our basal glassy unit (1g?) is extremely thin, generally less than 6 m. In areas on mesa 19, a pumice concentration zone and surge bed separates unit 1g and an overlying unit (1vc?). The overlying tuff on mesa 19 has trace-element chemistry (Dethier et al., this volume) typical of unit 2 or 3, but we have not recognized other areas where a thick unit 2 or 3 overlies 1g. On mesas 20 and 21, surge beds and pumice concentrations occur within the basal tuff (1g?). Partings above 1g disrupt the overlying unit on mesas 20 and 21, producing a double ledge on the north face of mesa 20. The tiny remnants of Tshirege tuff east of Mesa 21 (Fig. 3) also expose anomalous characteristics within the basal unit and a wide transitional zone containing high concentrations of chocolate brown and olive green-colored pumices.

Mesa 16 (Fig. 5) exposes the most distal preserved unit 3 and is probably the most distinctive Tshirege section in the Puye quadrangle. Unit 1g is as thick as 42 m in the eastern part of the mesa and its lower portion forms a prominent white-colored, southeast-facing ledge. This white section weathers as tent rocks, which are locally broken by a zone of pumice concentration. The 1g ledges and tents lie beneath a series of prominent zeolitized (?) ledges, which grade up into the typical outcrop pattern and salmon color of 1g. Similar ledges are present in the thick 1g section of adjacent mesas, but we have not mapped them elsewhere in the quadrangle.

The two most distal outcrops of upper Bandelier tuff in the Puye quadrangle are exposed on Mesas 24 and 25 (Fig. 5). All units on the two mesas are extremely thin, and the welded units, 1vc and 2, display closely spaced cooling joints. On mesa 24, these columnar structures radiate outward at their base. On mesa #25 (Battleship Mesa), unit 1vc displays thin vertical columns of variable height.

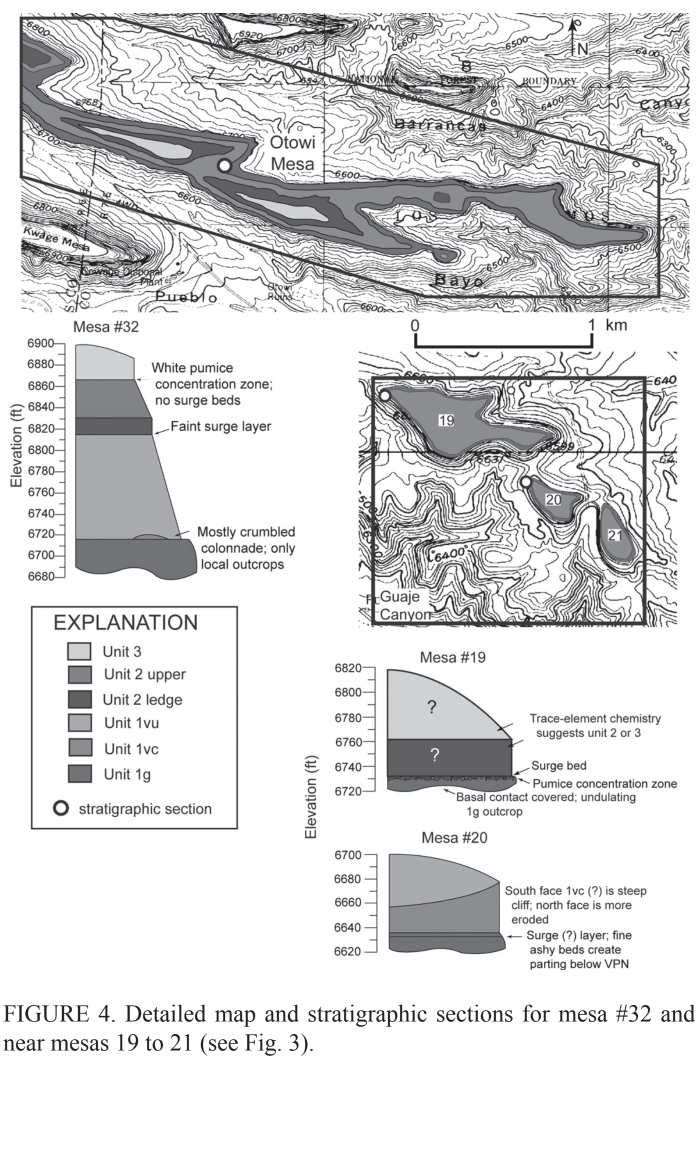

FIGURE 4. Detailed map and stratigraphic sections for mesa #32 and near mesas 19 to 21 (see Fig. 3).

Isopachs of Tshirege unit thickness

Measurements from preserved Tshirege remnants allow us to estimate the original thickness of pyroclastic flows and the shape of underlying paleotopography. For example, 1g isopachs (Fig. 6) show that the unit is thicker to the west and suggest that it flowed into the study area in three lobes. The northern and least constrained area is a broad, eastward-thinning fan centered on Garcia Canyon. A southern lobe, between Barrancas and Bayo Canyons, is narrower and also thins gradually to the east. The central lobe is elongate east and of fairly uniform thickness (~24 m), increasing locally to 43 m. Unit 1g is thin (less than 6 m) in distal areas and near Guaje Canyon. Southwest of the Puye quadrangle, basal 1g is exposed only in the northeast LANL area, and at a few points in the southeast. Maps of unit 1g thickness suggest that the fill thickens locally in two areas near modern Los Alamos Canyon (Kampf, 1998). The northern lobe trends east and the southern lobe trends toward ~135°.

Isopach maps for unit 1v are sufficiently detailed to combine observations from the Puye and LANL areas (Fig. 7). Two thick zones are preserved near the northern and southern lobes of 1g in the Puye quadrangle. However, the northern zone of 1v is significantly thicker (43 m) than that to the south (30 m). North of Guaje Canyon, where 1g is thick, the 1v cover is only 2 to 4 m thick whereas the belt near Guaje Canyon covered by thin 1g exposes up to 24 m of 1v (?) or 2. In the northern LANL area, thickness has no apparent trend. The southern portion of the LANL area exposes one 30 m-thick zone that trends south and thickens up to 90 m in the paleochannel of the early Pleistocene Rio Grande.

North of Guaje Canyon, three major fans of combined units 2 and 3 slope in from the west. The southernmost lobe is subparallel to the central thick lobe of 1g and to a depression preserved on the surface of 1v (Kampf, 1998). South of Guaje Canyon, however, units 2 and 3 give no indication of channeling effects. Unit

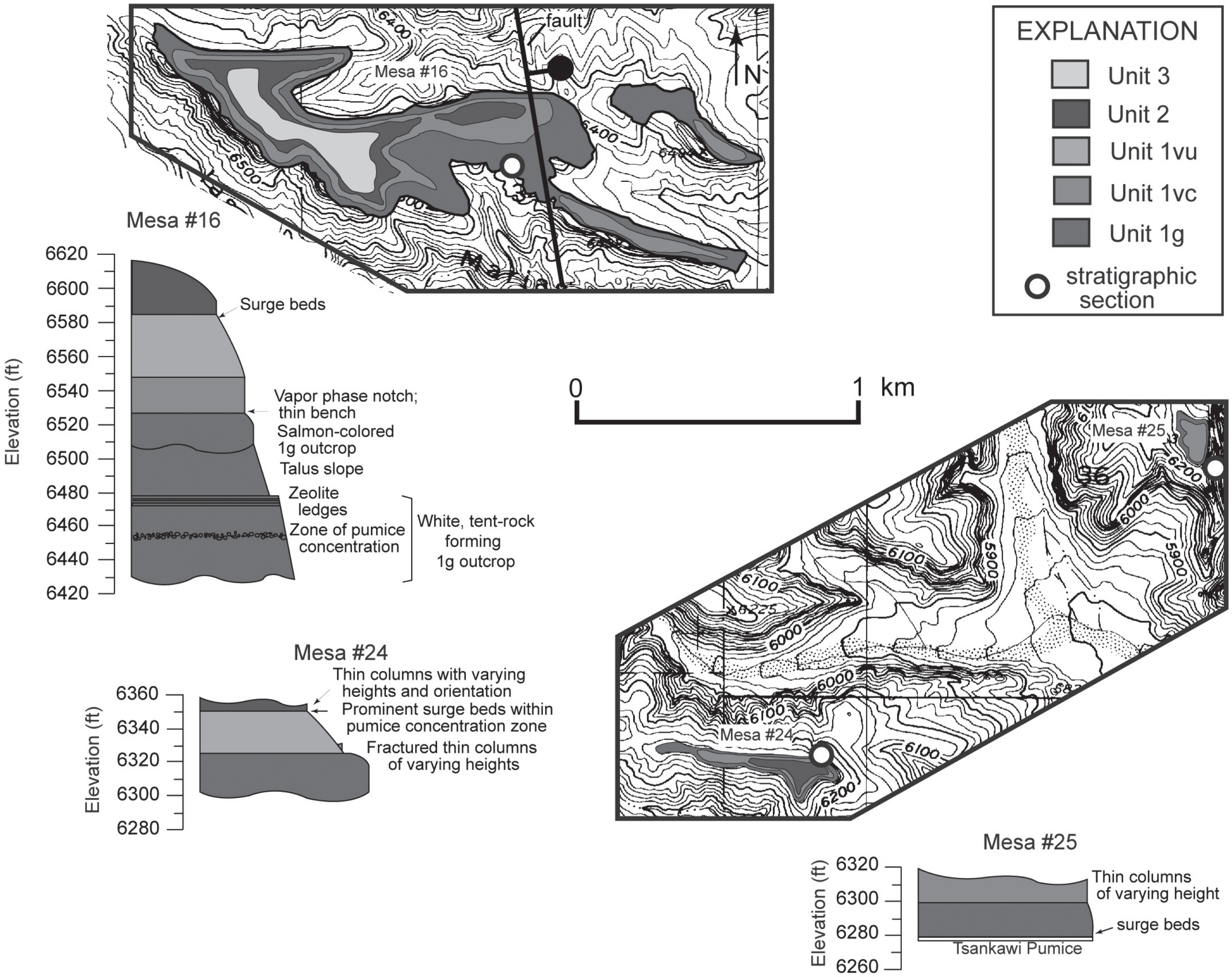

FIGURE 5. Detailed map and stratigraphic sections for mesas 16, 24 and 25 (see Fig. 3).

2 (C) is significantly thinner (average 12 to 18 m) than underlying units in most of the LANL area (Rodgers, 1995). Its isopach pattern shows that in both the northeastern and southern portions of the Lab area, unit 2 covered relatively smooth topography, except for one thick (42 m) lobe in the southwestern part of LANL. We could not resolve thicknesses for unit 3 (D) in the LANL area into a consistent isopach map, perhaps because the outcrop pattern integrates original thickness and erosion.

Structure contours in the Puye quadrangle and adjoining areas

Maps showing structure contours provide information about alteration of topography by Tshirege pyroclastic flows. Before the massive Tshirege eruptions, the eastern margin of the Pajarito Plateau was a less deeply eroded version of the present landscape. Structural contours on the pre-Tshirege surface (Fig. 8) suggest that two major drainages trended east in the northern portion of the area and another trended southeast, north of modern Guaje Canyon. South of Guaje Canyon another major drainage may have cut to the southeast. The pre-Tshirege surface is exposed only in the northeastern LANL area, where structural contours suggest several southeasterly trending drainages. To the south, subsurface data (Broxton and Reneau, 1996) indicate the location of several large south or southeast-trending channels.

One of the most distinctive paleotopographic features is a broad, east-trending canyon north of modern Guaje Canyon. Tshirege tuff 20 to >40 m thick in this channel suggests that it was a major early Pleistocene drainage --a “paleo-Guaje Canyon”. Our plotted location of “Otowi Canyon”, near Bayo Canyon, corresponds to a drainage inferred by Broxton and Reneau (1996), who identified “Lab Canyon” as the major LANL drainage in their map of pre-Bandelier topography. Local thickening portrayed near the southeastern margin of the 1v isopach map (Fig. 7) corresponds with the paleochannel of the early Pleistocene Rio Grande (Broxton and Reneau, 1996). After unit 1 had flowed out

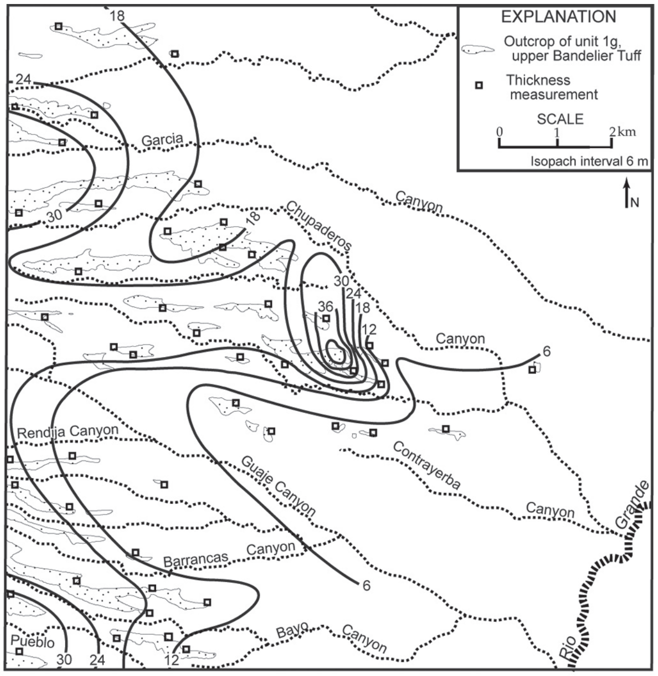

FIGURE 6. Map showing isopachs for Tshirege tuff unit 1g, Puye quadrangle.

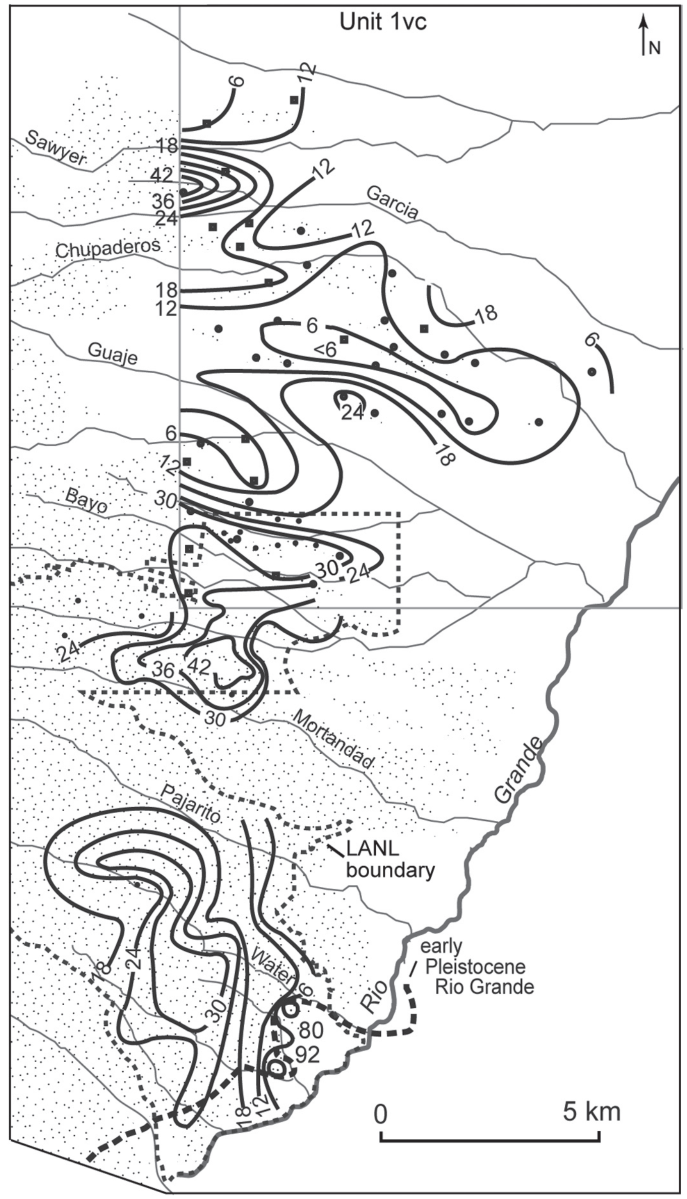

FIGURE 7. Map showing isopachs for Tshirege tuff unit 1v, Puye quadrangle and LANL area (from maps of Rogers, 1995). Values of 80 and 92 m are from early Pleistocene Rio Grande canyon filled by Tshirege tuff.

over the Pajarito Plateau, a relatively smooth topographic surface sloped at ~2% gradient to the ESE.

The orientation of thick Tshirege fill in the central Puye quadrangle (Figs. 5, 6) likely records the junction of southeast-trending drainage and paleo-Guaje Canyon along a fault scarp. Correspondence of the fault and an anomalously thick exposure of unit 1g (Figs. 3, 6) suggests that tuff buried a 15 m high scarp that broke again after Tshirege deposits had been cemented locally by zeolites. Our results provide limited information about smaller tributaries within this buried drainage network. The tiny outlying mesas, # 24 and #25 (see Figs. 3, 5) probably are casts of small tributaries. Deposit geometry and radiating columnar joints suggest that the Tshirege filled ~ 20 m-wide canyons. Both mesas have orientations appropriate for back-filled side tributaries to paleo-Guaje Canyon.

DISCUSSION

The distribution, thickness and outcrop characteristics of Tshirege tuff in the Puye quadrangle and LANL areas provide insight into flow and cooling processes for individual Tshirege units, paleotopography of the eastern Pajarito Plateau before emplacement of the tuff, and evolution of the post-Bandelier landscape.

Inferences about flow and cooling processes in the Tshirege tuff

The isopach patterns and outcrop characteristics for each of the Tshirege units record the interaction of pyroclastic flows and topography in the Puye quadrangle and LANL areas ~ 10 to 25 km from the Valles caldera. Fans of pyroclastic material flowed through gaps in the caldera rim and entered the study area from the west. Topography guided the first flows that poured over the landscape, whereas subsequent flows, traveling over a relatively smooth surface, preserve variations in thickness and cooling characteristics that reflect the dynamics of the source area and local effects.

Unit 1—Unit 1 is the thickest part of the upper Bandelier Tuff and the distribution and thickness of 1g records filling of preexisting topography. Multiple ledges and closely spaced, faint partings throughout 1v suggest that unit 1 represents a series of pyroclastic flows that poured into the Puye area in rapid succession. Flows may have been so closely spaced and similar in composition that they are indistinguishable in most exposures. In the northern and southern parts of the Puye quadrangle, unit

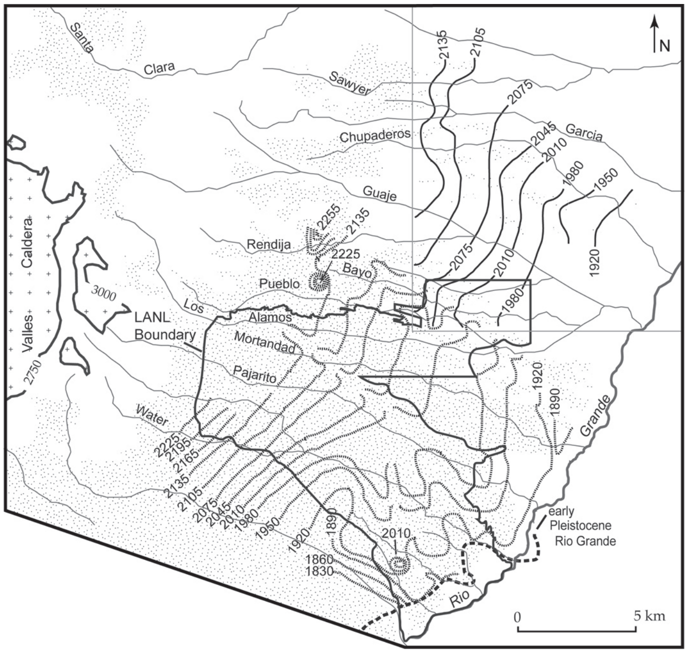

FIGURE 8. Map showing structure contours drawn on the pre-Tshirege surface, Puye quadrangle and LANL area. LANL values from Broxton and Reneau (1995) and from maps of Rogers (1995). Contour interval 30 m.

1v thickness patterns mimic those of unit 1g; thick wedges taper east. However, 1v thicknesses are variable locally and the unit thickens to the east locally in both the central Puye quadrangle and LANL areas (Figs. 3, 7). Hotter, locally thicker flows may have produced slower cooling of the distal buried tuff, lowering the elevation of the vapor phase boundary and increasing the thickness of unit 1v at the expense of unit 1g. Near Guaje Canyon unit1v is as much as 24 m thick where the 1g is only around 6 m thick; conversely, only 6 to 12 m of 1v covers the 42 m thickness of 1g at the eastern end of paleo-Guaje Canyon.

The pyroclastic flows of unit 1 traveled in and filled pre-Tshirege canyons and spilled over their rims to cover most of the Pajarito Plateau. Near Guaje Canyon, however, where 1g is thin, it is rich in pumice concentrations and anomalous surge deposits that suggest extensive flow-lobe intersection and overlap. This interpretation supports our hypothesis that the area of the modern Guaje Canyon was a topographic high where the upper portions of flow lobes from the north and south intersected.

Units 2 and 3 — After a pause in eruptive activity and brief cooling, unit 2 poured in behind an ash cloud associated with surge deposits preserved even in the most distal areas of the Puye quadrangle. Unit 2 is not widely exposed, but isopachs for units 2 + 3 are thickest along depressions that remained after emplacement of unit 1 (Kampf, 1998). Flows may have been sufficiently thin that they only followed the remaining channels and did not actually cover much of the western Puye area. Because these pyroclastic flows traveled across gentle topography, anomalously thick local sections probably reflect proximity to a gap in the caldera rim. A 42 m-thick wedge of unit 2 is preserved locally in the western LANL area, but in most places unit 2 forms a fairly uniform mantle. The most distal outcrop of unit 3 is preserved near the eastern end of paleo-Guaje Canyon; field relations suggest flows pooled in a local depression. Data for the LANL area show considerable variation in unit 3 thicknesses (Kampf, 1998), suggesting only minor topographic effects and subsequent erosion.

Distribution patterns on the Pajarito Plateau

Combining the structure contours, isopach distribution, and outcrop characteristics for upper Bandelier units allows us to infer general patterns of pyroclastic-flow transport across the Pajarito Plateau. Flow directions (Fig. 9) primarily reflect the influence of pre-Tshirege topography and paleocanyons (Broxton and Reneau, 1995). Gaps in the caldera rim that guided the thickest flow lobes apparently had little effect on the transport direction of flows in the vicinity of the eastern Pajarito Plateau.

Thicknesses of Tshirege units and their present distribution suggest that flows probably did not travel much farther east than the edge of Figure 1. The most distal preserved Tshirege outcrop is only ~ 12 m thick, which suggests that unit 1g thinned significantly over the eastern Puye quadrangle area. Unit 2 flows may not have reached the eastern margin of the quadrangle because unit 2 is < 6 m thick on the central Pajarito Plateau; unit 3 probably accumulated over an even smaller area. Units above 3 probably did not reach the Puye area, although it is difficult to assess how much material has been eroded from mesa tops. In the LANL area, Tshirege units are more laterally extensive and less eroded; ~90 m of unit 1 filled the Rio Grande paleochannel. In the same area unit 2, which covers the LANL area, is only 6 to 12 m thick.

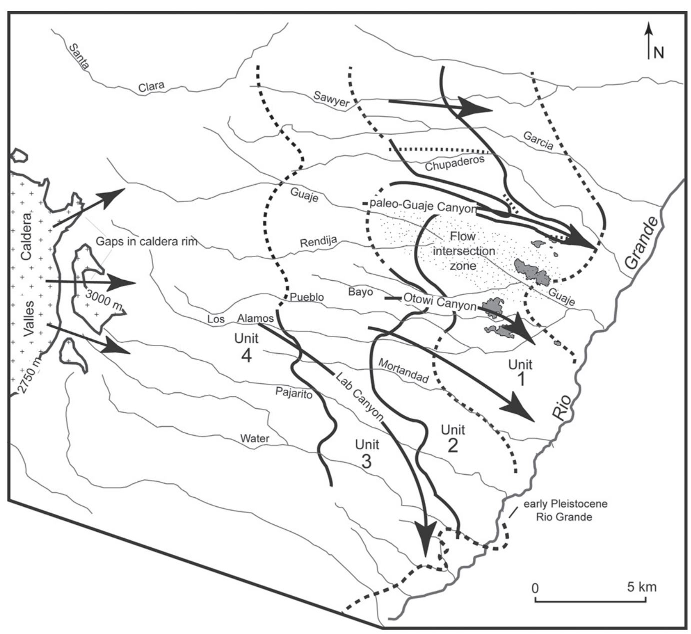

FIGURE 9. Map showing approximate surface extent of Tshirege tuff units 1-4; arrows show probable flow direction for basal pyroclastic units, reflecting influence of pre-Tshirege topography and inferred paleo-canyons. LANL values derived from maps of Rogers (1995); position of the early Pleistocene Rio Grande is from Broxton and Reneau (1995). Active slump complexes involving Tshirege units are shown in gray.

Evolution of the post-Tshirege drainage and landscape

Flow thickness and welding in Tshirege units, base-level changes along the Rio Grande, and pre-Bandelier stratigraphy influenced Pleistocene landscape evolution in the Puye area. Just as the pre-Tshirege drainage network and Tshirege flow processes affected thicknesses, the upper Bandelier Tuff influenced subsequent redevelopment of tributary drainages as a knickzone migrated north up the Rio Grande (Reneau and Dethier, 1996).

The largest modern drainage in the Puye quadrangle, Guaje Canyon, developed in post-Bandelier time through thin (12 to 36 m), nonwelded Tshirege cover. The location of Guaje Canyon was fixed where a headward-cutting Rio Grande tributary exposed underlying late Pliocene lacustrine clay (Waresback and Turbeville, 1990), producing massive slumping. Where the Bandelier failed with the clays, tuff blocks broke up, were eroded easily, and fluvial incision cut through the clay and upstream into the more consolidated Puye Formation. The present ~130° trend of Guaje Canyon follows a zone of thin pyroclastic deposits between two thicker fills of upper Bandelier Tuff (Fig. 9).

South of Guaje Canyon, closely spaced mesas trending ~ 100° are separated by deep canyons. Development of canyons through the thicker, more uniform Tshirege cover effectively rotated the dominant drainage direction east of its pre-Bandelier orientation (Fig. 9). Capture and evolution of lower Los Alamos Canyon resulted in an anomalous pattern, perhaps controlled by an initial direction of downcutting, massive slumping, or headward erosion in the softer sediment north of the basalt flows that cap the mesa south of Los Alamos Canyon.

The broad interfluve between Guaje and Chupaderos Canyons separates southeast-trending canyons from areas north of Guaje Canyon where drainages and mesas trend east, turning southeast in deep canyons where the Tshirege thins or is absent. The modern interfluve is underlain by thick tuff that may have impeded drainage development to such an extent that this area now has no major canyons. Zeolite-rich ledges developed in thick unit 1g deposits preserve a record of local ground water flow. Because this area hosted a major pre-Tshirege drainage, it continued to serve as a zone of perched groundwater transport even after the paleodrainage was filled with Tshirege flows. Older groundwater tables in this area may also reflect seepage from the fault zone (Fig. 5; Dethier, 2003). We did not observe similar zeolitized ledges elsewhere in the Puye quadrangle.

Canyon-cutting initiated erosion of the Tshirege tuff, but in most areas upstream from the massive slumps, weathering processes, block-failure and surface erosion controlled cliff retreat. In almost all locations underlain by Pliocene lake clays, the tuff is either completely removed or remains as a complex of slumped blocks. Thin deposits of Tshirege must have extended farther east, but did not remain stable over the clays in areas such as the zone southeast of lower Los Alamos Canyon. Where drainages were most deeply incised (southern Puye quadrangle), extensive erosion must have occurred as large blocks toppled off the sides of the mesas and cliffs gradually retreated (Reneau, 1995). In such areas, exposed units are mainly continuous along mesa tops. Where drainages are shallower and do not play an active role in undercutting the tuff, other erosional forces dominated. North of Guaje Canyon, fewer cliffs remain, especially along the course of paleo-Guaje Canyon. Individual cooling units tend to be more differentially weathered and outcrops are discontinuous, suggesting that modern erosion is not dominated by drainage systems incising headward. In fact, an isolated patch of unit 3 remains on one of the easternmost mesas, although little of the unit crops out to the west.

CONCLUSIONS

Our results suggest that analyses of upper Bandelier tuff unit characteristics and flow directions can be extended to the most distal preserved outcrops on the Pajarito Plateau. The few remaining exposures of tuff beneath Puye mesas and the more extensive areas preserved at LANL allow general inferences about paleotopography and flow dynamics, but a number of anomalies remain. More detailed study of tuff exposures and chemical analyses will aid in determining pyroclastic flow and cooling mechanisms among the individual units.

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