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THE TIME BETWEEN THE TUFFS: DEPOSITS OF THE CERRO TOLEDO INTERVAL IN BANDELIER NATIONAL MONUMENT, NEW MEXICO

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Abstract — The Cerro Toledo Rhyolite and associated tuffs and sediments are products of volcanic activity centered on a series of high-silica rhyolite domes located along the eastern rim of the Valles caldera. These domes were active between 1.65 and 1.21 Ma during a 380 kyr interval (Spell et al., 1996) between the caldera-forming eruptions of the upper (Tshirege) and lower (Otowi) members of the Bandelier Tuff. Volcaniclastic sequences exposed in Bandelier National Monument (BNM) record a period of dynamic geomorphologic change coupled with continued eruptive activity. Rabbit Mountain and Paseo del Norte, located 10 -15 km west of exposures in BNM, are the most likely source areas for these sequences. Outcrops in BNM consist of braided stream and hyperconcentrated flow deposits, tephras, and a pyroclastic collapse deposit. Comparison of units exposed in BNM to those exposed to the north, in the vicinity of Los Alamos, illustrates the importance of provenance in determining the nature of Cerro Toledo volcaniclastic deposits. Thick sequences of Cerro Toledo deposits fill an east-trending post-Otowi paleodrainage; these deposits, in turn, are incised by an east-trending drainage system that formed just prior to eruption of the Tshirege Member of the Bandelier Tuff.

INTRODUCTION

Bandelier National Monument (BNM) is located on the eastern flank of the Valles caldera and on the western edge of the Española Basin and the Rio Grande rift in north central New Mexico (Fig. 1). The topography is characterized by rugged terrain that includes the headwaters of the Rito de los Frijoles and the SE- to S-dipping Pajarito Plateau, a 48 km-long dissected tableland underlain by Bandelier Tuff (Smith, 1938; Broxton and Vaniman, 2005). Narrow deep canyons that incise the Bandelier Tuff provide excellent exposures of the rock units. In the western part of BNM, the Bandelier Tuff is cut by the Pajarito fault zone, a north-south trending zone of down-to-the-east normal faults that delineate the western active margin of the Española Basin. The Pajarito fault zone shows up to 180 m of displacement in BNM where it defines the boundary between the mountains and mesas. Within BNM, elevations range from 1600 m along the river to more than 3100 m at the summit of the volcanic domes that rim the caldera.

The Toledo-Valles caldera complex and associated deposits of Bandelier Tuff were formed during two major pyroclastic eruptions that occurred at 1.61 (Otowi Member) and 1.22 Ma (Tshirege Member) (ages from Izett and Obradovich, 1994; Spell et al., 1996). The combined volume of these deposits is approximately 650 km^3 (Self et al., 1996). Both eruptions were preceded by plinian fall deposits that form the Guaje Pumice Bed at the base of the Otowi Member, and the Tsankawi Pumice Bed at the base of the Tshirege Member. These pumice beds serve as useful stratigraphic markers in BNM.

Deposits between the two members of the Bandelier Tuff on the Pajarito Plateau fall into two categories, the *Cerro Toledo Rhyolite* (Griggs, 1964), and *tephras and volcaniclastic sediments of the Cerro Toledo interval* (Broxton and Reneau, 1995). The Cerro Toledo Rhyolite consists of rhyolitic lava flows and pyroclastic rocks that erupted from a group of volcanic domes in the vicinity of Cerro Toledo, located northeast of the Valles caldera, and from Rabbit Mountain and Paseo del Norte (Justet, 1996), located along the southeast rim of the Valles caldera (Fig. 1). Dates for domes and tephras range from 1.65 ± 0.03 Ma to 1.21 ± 0.01 Ma (Spell et al., 1996), and indicate continued eruptive activity throughout the interval between the Otowi and Tshirege eruptions. "Cerro Toledo interval" is an informal name for epiclastic sediments and tephras of varied provenance that lie between the two members of the Bandelier Tuff (Broxton and Reneau, 1995). These deposits show a wide but scattered distribution across the Pajarito Plateau with thicknesses ranging from 0 to 60 m. In this paper, the term Cerro Toledo deposits is used to describe these latter units.

Cerro Toledo deposits in BNM, the focus of this study, are best exposed in two major canyons, Frijoles and Alamo, in the northern part of the monument ~10-15 km east of Rabbit Mountain and Paseo del Norte. These narrow, steep walled canyons range from 60 to 180 m deep and have a northwest to southeast orientation (Fig. 1). The objectives of this paper are to 1) define a basic stratigraphy of Cerro Toledo deposits within BNM; 2) compare BNM deposits to northern deposits that crop out in the vicinity of Los Alamos; and 3) outline portions of two E-trending paleovalleys that developed on post-Otowi and pre-Tshirege landscapes.

PRIOR WORK ON ROCKS OF THE CERRO TOLEDO INTERVAL

Griggs (1964) named the rocks that form a group of volcanic domes along the northeast and southeast rim of the Valles caldera the Cerro Toledo Rhyolite, after a peak in the northeastern Jemez Mountains of the same name. Griggs (1964) postulated that the domes were extruded after eruption of the Otowi Member and before eruption of the Tshirege Member. Smith et al. (1970) differentiated the Cerro Toledo Rhyolite lavas and domes from the

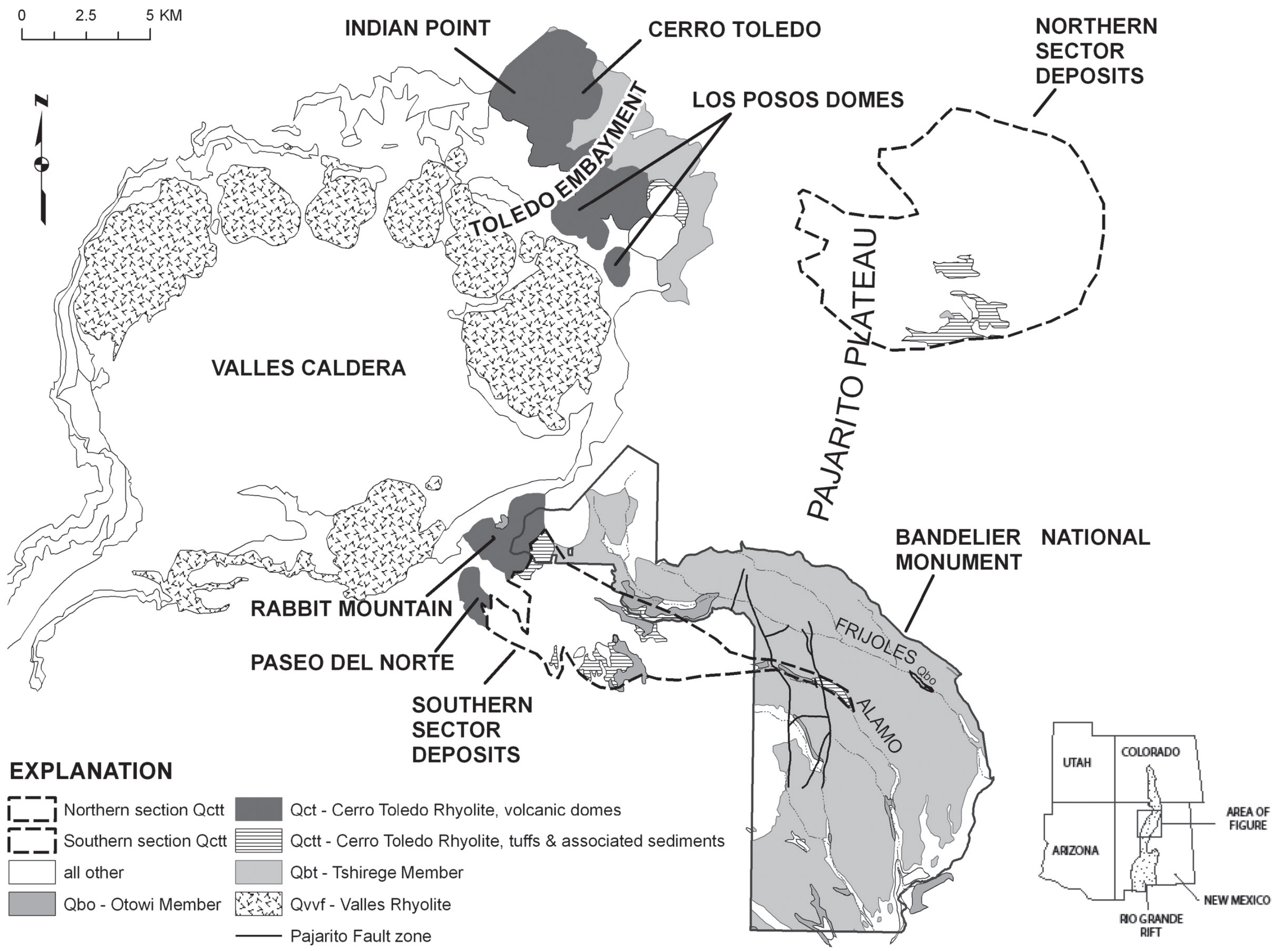

FIGURE 1. Simplified geologic map of the Valles caldera and Bandelier National Monument showing distribution of Cerro Toledo Rhyolite domes and associated Cerro Toledo deposits. Locations of Cerro Toledo deposits are from Heiken et al. (1986). Base geology modified from Smith et al. (1970).

volcaniclastic deposits by using a stippled map pattern and the symbology Qctt to delineate "rhyolite tuffs and tuff breccias". In addition, they described these volcaniclastic units as containing "hot avalanche deposits from the Rabbit Mountain center. Izett et al. (1981) used K/Ar dates to correlate domes and associated sediments of Cerro Toledo age. Heiken et al. (1986) recognized that the Cerro Toledo deposits with tephras are limited to two zones, a northern 20 km-wide sector trending E to SE from the Toledo embayment, and a southern 4 km-wide sector trending SE from Rabbit Mountain. Paseo del Norte, a small dome just south of Rabbit Mountain was also recognized as Cerro Toledo Rhyolite (Justet, 1996). Deposits within BNM are associated with the southern sector (Fig. 1). Stix et al. (1988) and Spell et al. (1996) correlated northern deposits of Cerro Toledo Rhyolite tephra with domes using stratigraphic, geochronologic, and geochemical data. Fluvial Cerro Toledo deposits are discontinuously preserved in the northeastern (Kempter et al., 2004, 2005) and southwestern Jemez Mountains (Kelley et al., 2007). Cerro Toledo deposits are generally not present in the western and northwestern Jemez Mountains (Kelley and Kelley, 2004). These studies provide a framework for understanding and correlating deposits found in BNM.

Broxton and Reneau (1996) and Broxton and Vaniman (2005) created maps of early Pleistocene landscapes on the Pajarito Plateau prior to the eruption of each member of the Bandelier Tuff, using drill hole and outcrop data from Los Alamos National Laboratory (LANL). Cole et al. (2006) compiled this information into a 3D hydrogeologic model for LANL property. The work done at LANL suggests that drainages on the Pajarito Plateau during Cerro Toledo time were oblique to modern drainages and showed a NE to SW trend. Studies by Dethier and Kampf (2007) on the Puyé quadrangle located at the northeastern edge of the Pajarito Plateau, indicate that drainages exhibited a similar orientation to the present ones (NW to SE) but were less deeply incised than modern drainages.

This study of deposits in BNM extends stratigraphic and paleotopographic trends on the Pajarito Plateau southward. The deposits in BNM differ in many respects from the northern deposits due to the influence of provenance, most notably the importance of Rabbit Mountain and Paseo del Norte as sources of sediment and possibly tephra. K/Ar dates of 1.43 ± 0.04 Ma and 1.54 ±0.06 Ma for Rabbit Mountain (Stix et al., 1988) and an $^{40}Ar/^{39}Ar$ date of 1.47 ± 0.04 Ma for Paseo del Norte (Justet, 1996) place these domes in the middle of the Cerro Toledo time period and reinforce their importance as potential sources for Cerro Toledo deposits. The most significant differences between the deposits that occur in BNM, versus the northern deposits that occur in the vicinity of Los Alamos, are the size and composition of clasts, as well as the presence of a thick volcanic breccia. The first step in understanding Cerro Toledo deposits is examine their stratigraphy in detail.

STRATIGRAPHY OF UNITS FROM THE CERRO TOLEDO INTERVAL

Frijoles Canyon

Exposures of Cerro Toledo deposits are limited to a 1.3 km reach in Frijoles Canyon where they form a continuous fluvial unit that ranges from 0.1 to 2 m in thickness (Fig. 2). These deposits are tan to brown, matrix-supported, massive volcanic lithic breccias and conglomerates that are overlain by mudstones in a fining upward trend. Clasts are angular to subrounded and range up to 10 cm in size. Lithic clasts include fine-grained andesite, basalt, pumice, and tuff that appear to be recycled from the Otowi Member. Deposits fill channels in the Otowi Member along an erosive contact and are overlain by the Tsankawi Pumice Bed throughout their exposure. Where exposed at the base of Tshirege cliffs, these poorly consolidated deposits promote cliff retreat, which negatively impacts archeological sites in BNM. This fluvial unit represents a braided stream deposit that resulted from localized erosion.

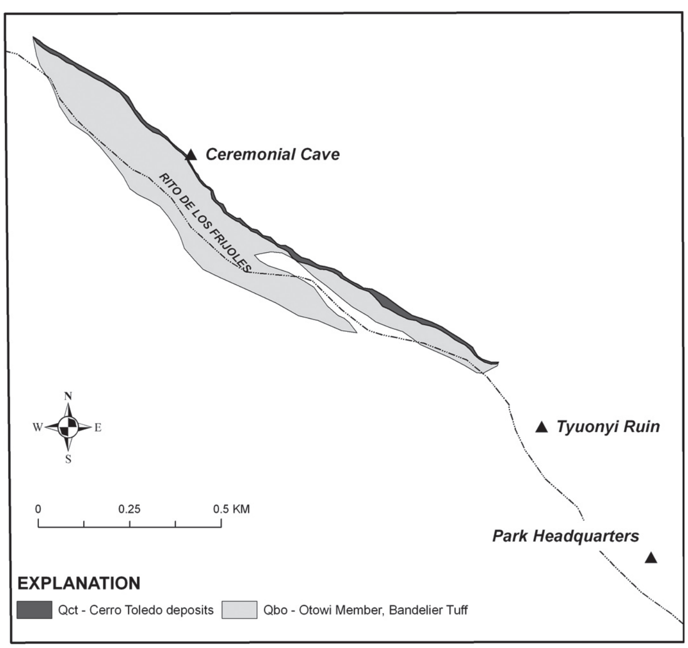

FIGURE 2. Geologic map of Cerro Toledo deposits in Frijoles Canyon.

Alamo Canyon

Cerro Toledo deposits in Alamo Canyon are exposed throughout much of its reach in BNM (Fig. 3). The thickness of these deposits ranges from 0 to 60 m. Stratigraphic relationships are complex and distinguishing between fluvial and pyroclastic deposits is often difficult. However, the following units have been identified, even if their origin remains uncertain.

Otowi Member, Bandelier Tuff

The Otowi Member occurs throughout most of Alamo Canyon within BNM to an elevation of ~1710 m. Thicknesses range from 0 to 70 m. The Guaje Pumice Bed occurs at the base of the Otowi Member and ranges from 0 to 4 m thick in the study area. The Otowi Member ranges in color from dull gray to salmon to white. Rather than appearing as a homogeneous ignimbrite, the Otowi Member is stratified, particularly in the upper part of its exposure. A ~50 cm-thick lithic-rich pumice swarm containing subangular lapilli up to 5 cm in size occurs ~3-4 m below the contact of the Otowi Member with overlying Cerro Toledo deposits. This stratified interval is overlain by a 5 cm-thick pink ash deposit. The distinctive color of this ash, together with preferential weathering of the lapilli, allows this interval to be correlated laterally throughout much of Alamo Canyon (Fig. 4). The Otowi Member tends to form distinctive banded tent rocks. The upper part of the Otowi Member forms a gradational contact where it appears to be interbedded with 2 to 3 m of Cerro Toledo fluvial deposits. Geochemical and geochronologic work in progress will help to

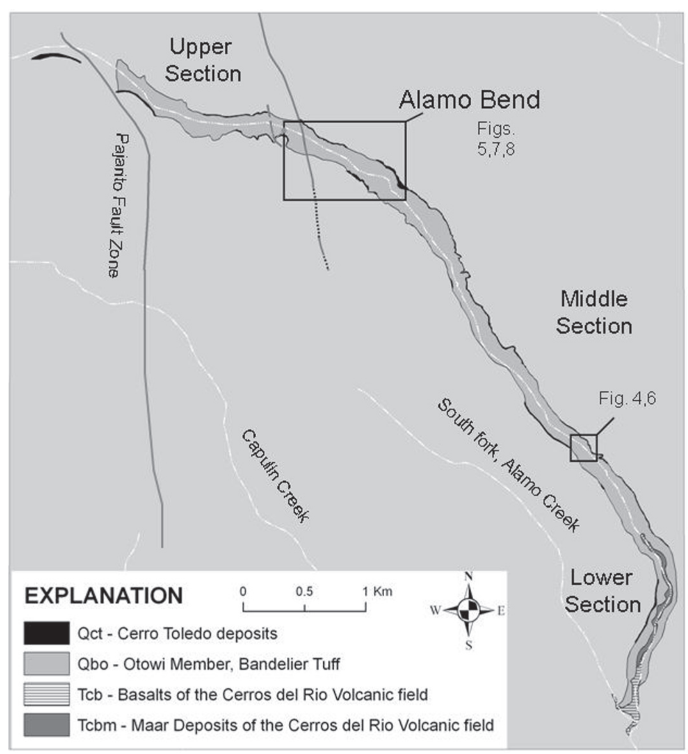

FIGURE 3. Geologic map of Cerro Toledo deposits in Alamo Canyon.

determine if this stratified interval represents a waning phase of the Otowi eruption or is a younger tephra.

Lower fluvial unit

The lower fluvial unit comprises a significant component of the Cerro Toledo deposits in Alamo Canyon (Fig. 5) and shows a varied character with location. It is exposed on the south side of Alamo Canyon west of the Pajarito fault zone and on the north side of Alamo Canyon east of the Pajarito fault zone (Fig. 6). It is discontinuously exposed on both sides of the canyon in the middle and lower reaches of the main drainage and south fork of Alamo Canyon to an elevation of ~1760 m. Thickness ranges from 0 to 30 m. This unit occurs as a buff to gray, poorly sorted, matrix- or clast-supported, subangular to subrounded silt and sand- to cobble-sized volcanic breccia that is weakly graded (Fig. 7). Maximum clast size is 55 cm. Clast size decreases distally. Clasts include distinctive brecciated obsidian, perlite, tuff, andesite, dacite, basalt, and rhyolite. The abundance of obsidian increases up section. In the upper part of the canyon, porphyritic andesite clasts are probably derived from the Paliza Canyon Andesite (~ 8.69-9.48 Ma, Goff et al., 2002), whereas dacite clasts are probably derived from Sawyer Dome (3.61±0.2 Ma, Goff et al., 2005). In the middle to lower part of the canyon, clasts of basalt and dacite may be derived from Cerros del Rio volcanic vents located both within the lowest 2 km of Alamo Canyon, as well as to the north and east. Deposits show cross-stratification together with irregular channel geometries and scour-and-fill structures. In some areas, the base of these deposits is difficult to distinguish from the Otowi Member and may represent a period of reworking of the Otowi shortly after its deposition. In other areas, the lower fluvial unit occurs as channel fill along an erosional contact with the Otowi Member. Depending on their location, these deposits may be overlain by tephra deposits, the Tsankawi Pumice Bed, or the Tshirege Member. Where they are overlain by tephra deposits, the contact is gradational. Contacts with the Tsankawi Pumice Bed and Tshirege Member are planar or shallowly dipping. The lower fluvial unit represents braided stream to hyperconcentrated flow deposits, with the latter resulting from the increased contribution and reworking of pyroclastic debris. Interbedding of the basal 2-3 m of this unit with the Otowi Member may suggest a period of waning volcanism during the transition from Otowi to Cerro Toledo time.

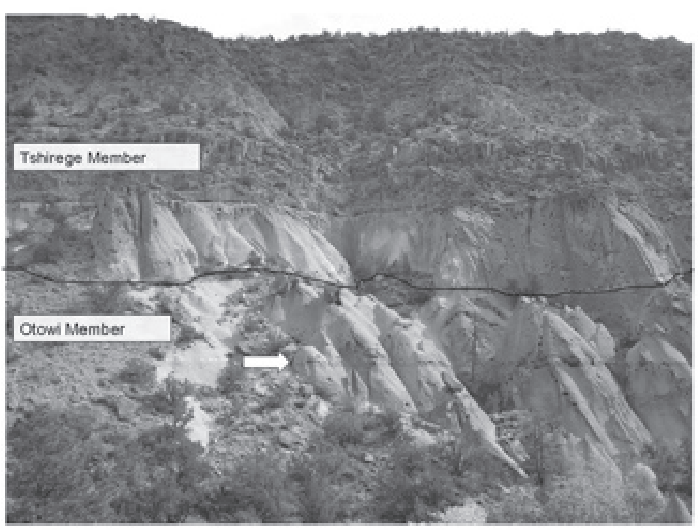

FIGURE 4. Photo of the Otowi and Tshirege Members of the Bandelier Tuff on the north side of Alamo Canyon in the vicinity of the mid-Alamo Canyon trail. The arrow marks stratification defined by a ~50 cm-thick pumice swarm overlain by pink ash.

Pyroclastic deposits

Pyroclastic deposits include the tephra sequence and the volcanic breccia (Figs. 5, 7). These deposits are restricted to a 1.6 km stretch of upper to middle Alamo Canyon (Fig. 5). Along this stretch the canyon bends to the south and changes orientation from W-E to NW-SE. Accordingly, the informal name “Alamo bend” will be used to describe the locality of these deposits. These deposits occur along an elevational range of 1970 m to 2070 m. A NW-SE-trending fault with displacement of approx 2 m crosses modern Alamo Canyon on the northwest end of these deposits.

Tephra sequence. Up to five layers of white to gray to salmon lapilli and ash tephra can be distinguished. The sequence is ~ 4 m thick with individual layers ranging from 5 to 117 cm thick. A salmon-colored seam of ash ~ 5 cm thick occurs in the middle of the sequence. The layers above this lens are stratified and show normal and reverse grading. Lithic clasts often occur in bands and include fibrous pumice, obsidian, perlite, and flow-banded rhyolite, as well as crystals of plagioclase and quartz. The base of the tephra sequence shows fluvial reworking expressed by normal grading, rounded lithics, scour beds, and pumice granules float-

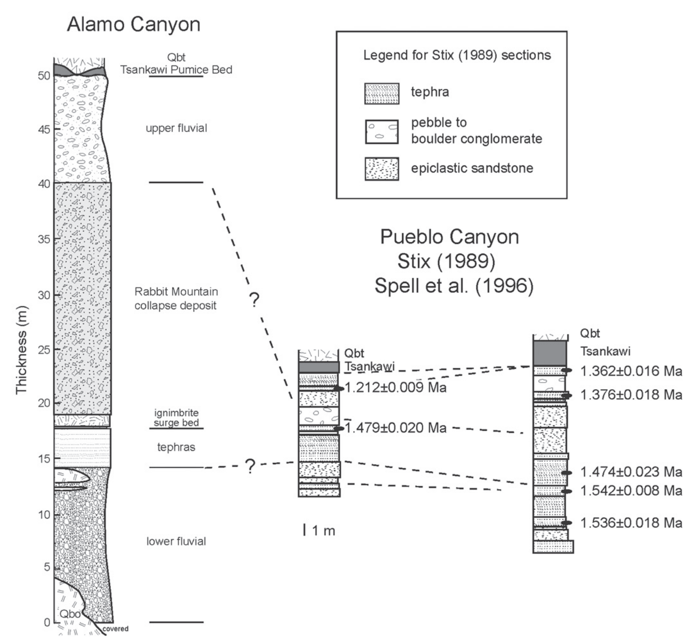

FIGURE 5. Stratigraphic column for type section of Cerro Toledo deposits at Alamo bend in Alamo Canyon compared to stratigraphic sections from Pueblo Canyon in the vicinity of Los Alamos (Spell et al. 1996).

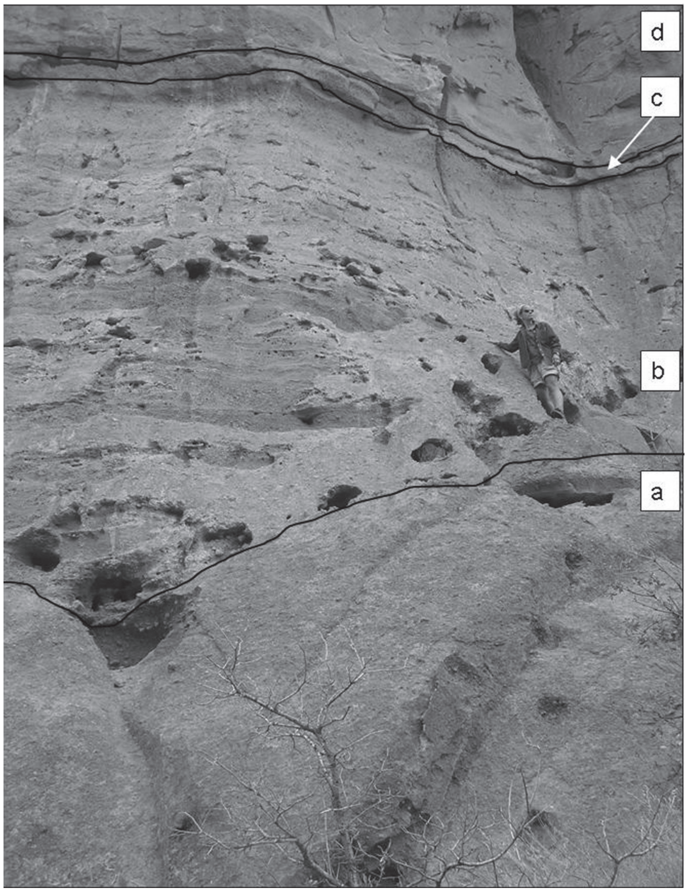

FIGURE 6. Photo of the lower fluvial unit showing a channel on the north side of Alamo Canyon in the vicinity of the mid-Alamo Canyon trail. a, Otowi Member; b, Cerro Toledo lower fluvial unit; c, Tsankawi Pumice Bed; d, Tshirege Member.

ing in a matrix of volcanic sand. At the base of the easternmost exposure, large angular clasts of red to orange tuff < 1.5 m in size appear to be inset against the Otowi Member. The tephras are overlain by a volcanic breccia deposit throughout their exposure. The layers of tephra reflect continued eruptive activity of Cerro Toledo volcanic domes in the mountains west and north of Alamo Canyon. Geochemical and geochronological analyses of individual tephra layers are currently under way to determine the source domes for these deposits.

Volcanic breccia. This striking deposit is marked by a ~6 cm-thick pale tan basal surge bed containing cross-beds (Fig. 5). The unit shows a coarsening upward sequence with the next 0-2 m consisting of a light brown apparent ignimbrite with an ash-sized matrix that contains angular to subangular lithics 1-5 mm in size (Fig. 8). The apparent ignimbrite is discontinuous in its exposure beneath the volcanic breccia and in places the breccia has scoured into the ignimbrite. The breccia is 0 to 30 m thick. It is brown to gray, poorly sorted, clast supported, with angular to subrounded clasts up to 2 m in size. Clasts include perlite, obsidian, andesite, tuff, and flow-banded rhyolite. As in the lower fluvial unit, porphyritic andesite is probably derived from the Paliza Canyon Andesite. The size and abundance of obsidian clasts increases up section. Perlite blocks are the largest (<2 m) and most abundant clast type. The volcanic breccia is overlain by discontinuous deposits of the upper fluvial unit, the Tsankawi Pumice Bed, or the Tshirege Member. The contact with the upper fluvial unit is mostly planar to shallowly dipping and contains small-amplitude scours into the breccia. The contact with the Tsankawi Pumice Bed and Tshirege Member is characterized by large swales of moderate dip, indicating that this unconsolidated deposit was very susceptible to erosion. This breccia deposit probably represents the collapse of a side of the Rabbit Mountain rhyolite dome due to seismic shaking during an eruptive cycle. The collapse deposit was constrained by and filled a broad post-Otowi valley. Close

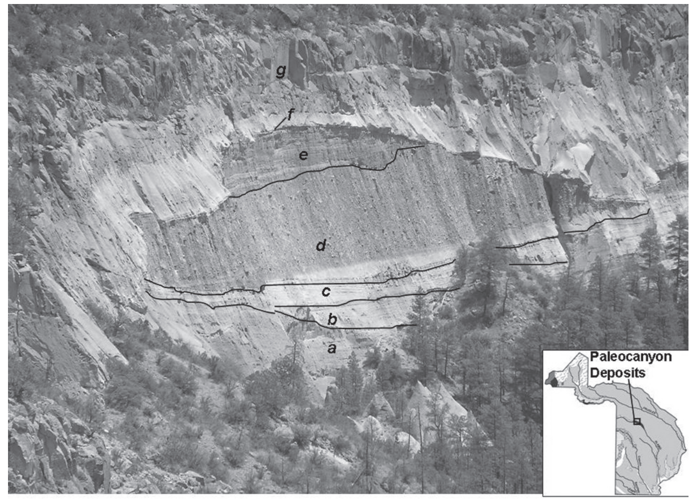

FIGURE 7. Photo of the type section of Cerro Toledo deposits in Alamo Canyon from the north side of the canyon at Alamo bend. Units are as follows: a, Otowi Member, Bandelier Tuff; b, lower fluvial unit; c, tephra sequence; d, volcanic breccia; e, upper fluvial unit; f, Tsankawi Pumice Bed; g, Tshirege Member, Bandelier Tuff. Height of exposure is ~ 120 m. For a color version of this figure, see Plate 12 on page 142.

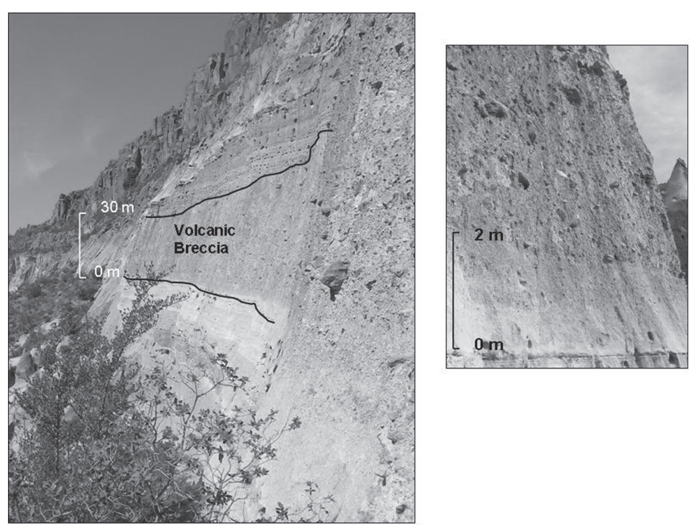

FIGURE 8. Photos of the volcanic breccia at Alamo bend. Left photo was taken on the north side of the canyon with the view to the NW (up canyon). Right photo was taken on the north side of the canyon with the view to the SE (down canyon). This photo shows coarsening upward from the apparent ignimbrite into the breccia.

inspection of thin sections will allow determination of whether the collapse deposit was hot or cold at the time of emplacement.

Upper fluvial unit

The upper fluvial unit is composed of deposits that are discontinuously preserved along Alamo bend. This unit ranges in thickness from 0 to 15 m. The deposit is a buff to purplish gray to pale salmon, matrix-supported, stratified volcanic conglomerate with a discontinuous layer (up to 15 cm thick) of red silt at the top. The clasts are angular to subrounded and include pumice, tuff, andesite (Paliza Canyon), rhyolite, obsidian, and perlite. The upper fluvial unit contains a higher percentage of glassy cobble-sized clasts than the lower fluvial unit. On the south side of Alamo bend, at the southeastern edge of this unit, orange rounded clasts of tuff < 3 m in size occur at the contact with the underlying breccia. The upper fluvial unit occurs on top of the volcanic breccia along a planar to shallowly dipping contact. The overlying Tsankawi Pumice Bed and Tshirege Member fill channels incised up to 5 m into these deposits. The upper fluvial unit probably represents a return to braided streams. The presence of a red paleosol in some areas suggests that a period of relative landscape stability occurred prior to the eruption of the Tshirege Member.

COMPARISON TO NORTHERN DEPOSITS

Stratigraphic sections for this study as well as for northern deposits in the vicinity of Los Alamos (Heiken et al., 1986; Spell et al., 1996) are presented in Figure 5. Spell et al. (1996) showed that Cerro Toledo Rhyolite tephra eruptions preserved in the northern deposits occurred in distinct pulses at 1.54, 1.48, 1.37, and 1.21 Ma. For BNM, dates that fall in the 1.48 -1.54 Ma range most closely correlate to the ages of Rabbit Mountain and Paseo del Norte. However, because the study by Spell et al. (1996) focused on northern tephra deposits, they restricted their study to domes that occur northeast of the Valles caldera. Three domes in this area, Indian Point, Los Posos East, and Los Posos West, have ages similar to those of Rabbit Mountain and Paseo del Norte (Table 1). Therefore, these domes could serve as sources of tephra deposits in BNM as well. In cases where domes and tephras show similar ages, geochemical differences may aid in correlations. Geochemical and geochronological analyses currently in progress will help with the correlation of tephra layers between these sections. However, even with correlations of tephras, it is clear that the deposits vary significantly between locations. The northern Cerro Toledo deposits are much thinner and the sediments are finer grained. These differences illustrate that Cerro Toledo deposits strongly depend upon the nature of source areas and the proximity of outcrops to these source areas. In addition, paleotopography is an important factor in the distribution of Cerro Toledo deposits.

PALEOTOPOGRAPHY

The stratigraphy and field relations of Cerro Toledo deposits exposed in Alamo Canyon show that volcanic and sedimentary

TABLE 1. Geochronology of selected Cerro Toledo Rhyolite domes.

Dome	***K/Ar (Ma ± σ)***	***$^{40}Ar/^{39}Ar$ (Ma ± σ)***
Los Posos East	1.47 ± 0.05*	1.446 ± 0.009†
Indian Point	—	1.463 ± 0.011†
Los Posos West	1.50 ± 0.05*	1.540 ± 0.012†
Rabbit Mountain	1.43 ± 0.04*	—
Rabbit Mountain	1.52 ± 0.06*	—
Paseo del Norte	—	1.47 ± 0.04‡

*Stix et al. (1988)
†Spell et al. (1996)
‡ Justet (1996)

processes during this time were dynamic and at times cataclysmic. Layers of pumice and ash record discrete pulses of explosive activity throughout the interval. Although the climate for the early to middle Pleistocene is poorly documented for the southern Rockies, it was probably cooler and wetter (Leopold, 1951; Smith, 1984; Thompson, 1991). Precipitation patterns may have been more pronounced than those of today, with strong thunderstorms occurring in the summer months and short-duration, high-volume, melt-water runoff occurring in the spring. These high intensity events created pulses of water that caused alternate incision and aggradation of channels. Inputs of colluvium were common and probably dammed streams until erosive action and high water events re-established drainage channels.

Post-Otowi landscape

The poorly welded Otowi Member was easily eroded by mountain streams into a landscape of mesas and canyons rimmed by sloping hillsides and tent rocks. Production of readily mobilized ash by continued volcanic activity in the uplands probably overwhelmed the carrying capacity of these streams, resulting in aggradation and deposition of large sediment loads. During times of abundant sediment supply, braided streams became hyperconcentrated flows. A cooler wetter climate may have supported mountain snowfields in the Sierras de los Valles, increasing the possibility of lahars accompanying eruptive activity. Fluvial deposits aggraded in a broad EW-oriented paleocanyon incised into the Otowi Member. This channel was subsequently filled by collapse deposits from Rabbit Mountain (Fig. 9). Southeast of Alamo bend, smaller grain sizes and greater rounding of fluvial deposits indicate that the post-Otowi canyons decreased in gradient away from the mountains. These distal, gentle gradients may have been controlled by basalts of the Cerros del Rio volcanic field that underlie the Otowi Member and by the location of the Rio Grande, which provided base level for this landscape.

Pre-Tshirege landscape

Outlines of the pre-Tshirege landscape are preserved today by the contacts of the Tsankawi Pumice bed and the Tshirege Member with underlying rock units. Unconsolidated volcaniclastic deposits from the Cerro Toledo interval were eroded prefer-

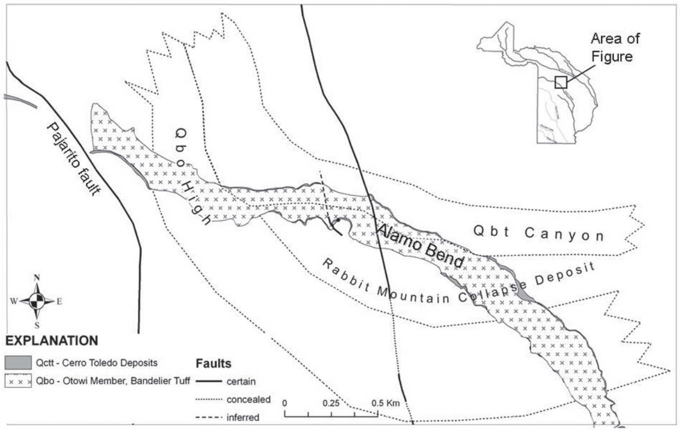

FIGURE 9. Map of upper Alamo Canyon through Alamo bend showing the orientation of a broad paleocanyon and an Otowi hill during post-Otowi time.

entially. Even the poorly welded Otowi Member appears to have been more resistant to erosion than volcaniclastic sediments. In the area where a broad paleocanyon existed in post-Otowi time, a new drainage system was formed. This new paleocanyon is marked by steeply dipping contacts (50°N) between the Otowi and Tshirege Members (Cerro Toledo deposits absent) on the south side of the canyon in upper Alamo Canyon that cross to the north side of the canyon at Alamo bend. Here contacts between the upper fluvial unit and the Tsankawi Pumice Bed show up to 40 m of relief. A planar contact between deposits of the lower fluvial unit and the Tsankawi Pumice Bed on the north side of upper Alamo Canyon defines the axis of this paleocanyon as sub-parallel and offset to the north of modern Alamo Canyon (Fig. 9). Southeast of Alamo bend, processes at work in post-Otowi time continued. Planar to shallowly dipping contacts of the Tsankawi Pumice Bed with underlying lower fluvial unit deposits define the gentle gradient of the more distal section of Alamo Canyon. The occurrence of lower fluvial unit deposits on both sides of the main drainage as well as in the southern fork of Alamo Canyon, indicate that this lower landscape appeared as a broad wash fed by braided streams that emptied into the Rio Grande.

FUTURE WORK

Cerro Toledo deposits in Bandelier National Monument record an interval of rapid landscape evolution. Definition of the stratigraphic units and mapping of these units provide information on how this landscape may have appeared during this time. Many unanswered questions remain. Study of thin sections and correlation of tephras through geochemical and geochronological analysis, as well as whole rock geochemistry of clasts will help to distinguish the origins of these deposits. Further work creating isopach and structure-contour maps, stream profiles, and cross sections, as well as interpolation of data using a Geographic Information System will provide an increasingly detailed view of the paleotopography of this southeastern portion of the Pajarito Plateau at the dawn of the Pleistocene.

ACKNOWLEDGMENTS

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REFERENCES

Broxton, D.E., and Reneau, S.L., 1995, Stratigraphic nomenclature of the Bandelier Tuff for the environmental restoration project at Los Alamos National Laboratory: Los Alamos National Laboratory, Report LA-13010-MS, 21 p.

Broxton, D.E., and Reneau, S.L., 1996, Buried early Pleistocene landscapes beneath the Pajarito Plateau, northern New Mexico: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 325-334.

Broxton, D.E., and Vaniman, D.T., 2005, Geologic framework of a groundwater system on the margin of a rift basin, Pajarito Plateau, north-central New Mexico: Vadose Zone Journal, v. 4, p. 522-550.

Cole, G., Carey, J.W., Burnette, L., and Miller, T., 2006, The 2005 three-dimensional, geologic model of the Pajarito Plateau: Los Alamos National Laboratory, Report LA-UR-06-3060. 123 p.

Dethier, D.P., 1997. Geologic map of the White Rock quadrangle, Los Alamos and Santa Fe Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 73, scale 1:24,000.

Dethier, D.P. and Kampf, 2007, Reconstructing pyroclastic flow dynamics and landscape evolution using the upper Bandelier Tuff, Puye Quadrangle, New Mexico: New Mexico Geological Society, 58th Field Conference, Guidebook, p. 336-345.

Goff, F., Gardner, J.N., and Reneau, S.L., 2002, Geology of the Frijoles 7.5-minute quadrangle, Los Alamos and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 42, scale 1:24,000.

Goff, F., Reneau, S.L., Lynch, S., Goff, C.J., Gardner, J.N., Drakos, P., and Katzman, D., 2005, Preliminary geology of the Bland 7.5-minute quadrangle: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 112, scale 1:24000.

Griggs, R.L., 1964, Geology and ground-water resources of the Los Alamos area, New Mexico: U.S. Geological Survey, Water Supply Paper 1753, 107 p.

Heiken, G., Goff, F., Stix, J., Tamanyu, S., Shafiqullah, M., Garcia, S., and Hagan, R., 1986, Intracaldera volcanic activity, Toledo caldera and embayment, Jemez Mountains, New Mexico: Journal of Geophysical Research, v. 91, (B2), p.1799-1815.

Izett, G., and Obradovich, J., 1994, $^{40}Ar/^{39}Ar$ age constraints for the Jaramillo normal subchron and the Matuyama-Bruhnes geomagnetic boundary: Journal of Geophysical Research, v. 99; p. 2925-2934.

Izett, G., Obradovich, J., Naeser, C., and Cebula, C., 1981, Potassium-argon and fission-track zircon ages of Cerro Toledo rhyolite tephra in the Jemez Mountains, New Mexico: U.S. Geological Survey, Professional Paper 1199-D, p. 37-43.

Justet, L. 1996, The geochronology and geochemistry of the Bearhead Rhyolite, Jemez volcanic field, New Mexico [M.S. Thesis]: Las Vegas, University of Nevada, 152 p.

Kelley, S.A., and Kelley, R.E., 2004, Paleotopography on the Otowi Member of the Bandelier Tuff: implications for landscape evolution of the Jemez Mountains, New Mexico: Geological Society of America, Abstracts with Programs: v. 36, p. 442.

Kelley, S.A., Osburn, G.R., and Kempter, K.A., 2007, Geology of Cañon de San Diego, southwestern Jemez Mountains, north-central New Mexico: New Mexico Geological Society, 58th Field Conference, Guidebook, p. 157-173.

Kempter, K.A., Kelley, S., Goff, F., and Rampey, M., 2004, Preliminary geologic map of the Polvadera Peak 7.5-minute quadrangle, Rio Arriba County, New

Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 96, scale 1:24,000.

Kempter, K.A., Kelley, S., Koning, D., Ferguson, C., Osburn, B., and Fluk, L., 2005, Preliminary geologic map of the Vallecitos 7.5-minute quadrangle, Rio Arriba and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 108, scale 1:24,000.

Leopold, L.B., 1951, Pleistocene climate in New Mexico: American Journal of Science, v. 249, p. 152-168.

Self, S., Heiken, G., Sykes, M.L., Wohletz, K., Fisher, R.V., and Dethier, D.P., 1996, Field excursions to the Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 134, 172 p.

Smith, G.I., 1984, Paleohydrologic regimes in the southwestern Great Basin 0-3.2 my ago, compared with other long records of "global" climate: Quaternary Research, v. 22, p. 1-17.

Smith, H.T.U. 1938, Tertiary geology of the Abiquiu quadrangle, New Mexico: Journal of Geology, v. 46, p. 933-965.

Smith, R.L., Bailey, R.A., and Ross, C.S., 1970, Geologic map of the Jemez Mountains, New Mexico: United States Geological Survey, Miscellaneous Geologic Investigations Map I-571, scale 1:125,000

Spell, T., McDougall, I., and Doulgeris, A., 1996, Cerro Toledo Rhyolite, Jemez volcanic field, New Mexico: Ar geochronology of eruptions between two caldera-forming events: Geological Society of America Bulletin; v. 108, p. 1549-1566.

Stix, J., 1989, Physical and chemical fractionation processes in subaerial and subaqueous pyroclastic rocks [Ph.D. dissertation]: University of Toronto, 420 p.

Stix, J., Goff, F., Gorton, M., Heiken, G., and Garcia, S.R., 1988, Restoration of compositional zonation in the Bandelier silicic magma chamber between two caldera-forming eruptions: geochemistry and origin of the Cerro Toledo Rhyolite, Jemez, Mountains, New Mexico: Journal of Geophysical Research, v. 93, (B6), p. 6129-6147.

Thompson, R.S., 1991, Pliocene environments and climates in the western United States: Quaternary Science Reviews, v. 10, p.115-132.

Photo of the type section of Cerro Toledo deposits in Alamo Canyon from the north side of the canyon at Alamo bend. Units are as follows: a, Otowi Member, Bandelier Tuff; b, lower fluvial unit; c, tephra sequence; d, volcanic breccia; e, upper fluvial unit; f, Tsankawi Pumice Bed; g, Tshirege Member, Bandelier Tuff. Height of exposure is ~ 120 m. See article by Jacobs and Kelley on page 308 for more details about this exposure.