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2007, pp. 239-247. https://doi.org/10.56577/FFC-58.239

in:

Geology of the Jemez Region II, Kues, Barry S., Kelley, Shari A., Lueth, Virgil W.; [eds.], New Mexico Geological Society 58 th Annual Fall Field Conference Guidebook, 499 p. https://doi.org/10.56577/FFC-58

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New Mexico Geological Society Guidebook, 58th Field Conference, Geology of the Jemez Mountains Region II, 2007, p. 239-247.

A CHRONOSTRATIGRAPHIC REFERENCE SET OF TEPHRA LAYERS FROM THE JEMEZ MOUNTAINS VOLCANIC SOURCE, NEW MEXICO

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ABSTRACT — Electron-microprobe analyses on volcanic glass separated from 65 pumice-fall and ash-flow tephra units of the Jemez Mountains, New Mexico, show that they are mainly rhyolites and dacites. From youngest to oldest, the units are: El Cajete Member of Valles Rhyolite (~50-60 ka); Tshirege Member including basal Tsankawi Pumice Bed of the Bandelier Tuff (both ~1.21-1.25 Ma); Cerro Toledo Rhyolite (~1.22-1.59 Ma); Otowi Member including basal Guaje Pumice Bed of the Bandelier Tuff (both ~1.61-1.68 Ma); the informal San Diego Canyon ignimbrites (~1.84-1.87 Ma); Puye Formation tephra layers (~1.75 - >5.3 Ma); upper Keres Group, Peralta Tuff Member of the Bearhead Rhyolite (~6.76-6.96 Ma); and lower Keres Group, Paliza Canyon Formation – Canovas Canyon Rhyolite (~7.4-<12.4 Ma). The Tshirege and Otowi Members of the Bandelier Tuff are difficult to distinguish from each other on the basis of electron-microprobe analysis of the volcanic glass; the Tshirege Member contains on average more Fe than the Otowi Member. The Cerro Toledo tephra layers are readily distinguishable from the overlying and underlying units of the Bandelier Tuff primarily by lower Fe and Ca contents. The San Diego Canyon ignimbrites can be distinguished from all members of the overlying Bandelier Tuff on the basis of Fe and Ca. Tuffs in the Puye Formation are dacitic rather than rhyolitic in composition, and their glasses contain significantly higher Fe, Ca, Mg, and Ti, and lower contents of Si, Na, and K. The Bearhead Rhyolite is highly evolved and can be readily distinguished from the younger units. We conclude that the Puye is entirely younger than the Bearhead Rhyolite and that its minimum age is ~1.75 Ma. The Paliza Canyon volcaniclastic rocks are chemically variable; they range in composition from dacite to dacitic andesite and differ in chemical composition from the younger units.

INTRODUCTION

We analyzed a large set of tephra layers from the Jemez Mountains volcanic source area of north-central New Mexico (Fig. 1), to serve as a reference set for chronostratigraphic correlations to areas outside the Jemez Mountains. Tephra erupted from the Jemez Mountains sources has been transported by air or by streams, and deposited in adjacent basins (for example, the Española and Albuquerque basins), forming stratigraphic marker beds.

Eruptive products of the Jemez Mountains volcanic field range from mid-Miocene (~15 Ma) to late Pleistocene and are related to extension along the Rio Grande rift and coincident intersection with the Jemez lineament (Gardner and Goff, 1984; Aldrich et al., 1986). These are formally assigned to the Keres Group in the south (~13 to 6 Ma), the Polvadera Group mainly in the north (~13 to ~2 Ma), and the Tewa Group in the central and flanking parts of the mountains (<2 Ma) (Bailey et al., 1969). Pre-Quaternary volcanism of basalt-andesite-dacite-rhyolite association formed the constructional phase of the Jemez Mountains. Explosive rhyolitic volcanism during the Quaternary formed the Toledo and Valles calderas. Although studies of Jemez Mountains volcanism are numerous (e.g., Smith and Bailey, 1966; Bailey et al., 1969; Smith et al., 1970; Gardner and Goff, 1984; Self et al., 1988, 1991, 1996; Stix et al., 1988; Turbeville and Self, 1988; Turbeville et al., 1989; Spell et al., 1990, 1996a, b; Lavine et al., 1996; WoldeGabriel et al., 1996, 2001, 2006), little work has been done to characterize the glass chemistry of the major tephra layers (e.g., Izett et al., 1972; Dunbar et al., 1996).

We analyzed volcanic glass separated from 65 pumice-fall and ash-flow tephra units of the major Jemez Mountains tephra layers, which span a time range from <12.4 Ma to ~0.05 Ma. Many of these units have been dated directly by others, mostly using K-Ar and $^{40}Ar/^{39}Ar$ techniques; those undated are, in many cases, bracketed between dated tephra layers. Sample preparation and analytical methods by electron microprobe are as described

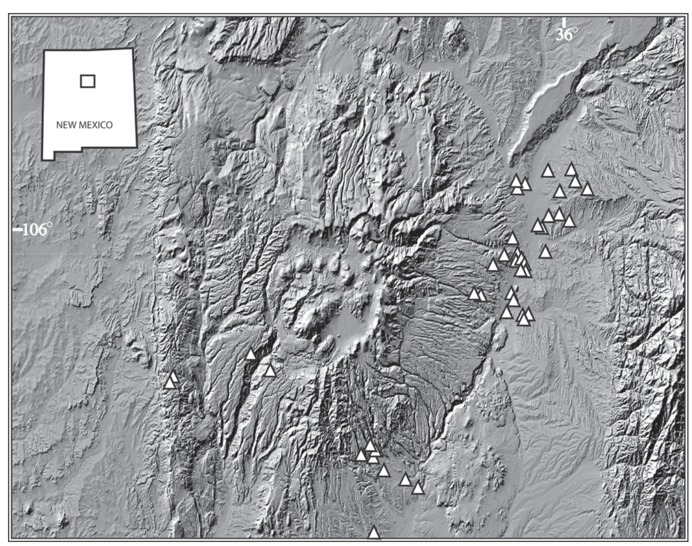

FIGURE 1. Shaded-relief image map showing location of tephra samples (white triangles) in the Jemez Mountains area, north-central New Mexico.

in Sarna-Wojcicki et al. (2005). In Table 1, we list the major groups of Jemez Mountains tephra layers analyzed in this study in stratigraphic order and essentially concordant age (youngest to oldest).

MAJOR JEMEZ MOUNTAINS TEPHRA LAYERS

El Cajete Member of Valles Rhyolite

The youngest eruptive products of the Jemez Mountains volcanic field consist of six intra-caldera members of the Valles Rhyolite (Bailey et al., 1969). The El Cajete Member of the Valles Rhyolite (El Cajete series of Self et al., 1988) is a widespread stratigraphic marker east, southeast, and south of the Valles caldera. Comprising three units of which the Plinian eruption produced a dispersed pumice-fall deposit (about 1.3 km^3), the El Cajete has a homogeneous high-silica rhyolitic composition (Appendix 1). Ages for the El Cajete range from about 45 to 73 ka based on electron spin resonance analyses of quartz phenocrysts (Toyoda et al., 1995), to about 48 to 63 ka based on thermoluminescence of soils buried by El Cajete pumice (Reneau et al., 1996), to about 60 ka based on ^{14}C of associated carbonized logs (Wolff and Gardner, 1995), to as much as 130 to 170 ka based on fission-track and U-Th disequilibrium (Self et al., 1988, 1991) and even older K-Ar and $^{40}Ar/^{39}Ar$ ages. We report the age as a range from ~50 to 60 ka (Table 1) accepting that the older ages were contaminated by xenocrysts or excess Ar (Reneau et al., 1996). El Cajete eruptions came after a ~460-ky period of quiescence (Wolff and Gardner, 1995).

TABLE 1. The major groups of Jemez Mountains volcanic field tephra layers analyzed in this study listed in stratigraphic order and essentially concordant age (youngest to oldest).

Unit	Deposit Type(s)	Age
El Cajete Member of Valles Rhyolite	Pumice fall	~50 – 60 ka[1]
Tshirege Member of the Bandelier Tuff	Ash flows	~1.21 – 1.25 Ma[2]
Basal Tsankawi Pumice Bed of the Tshirege Member	Pumice fall	
Cerro Toledo Rhyolite	Pumice fall	~1.22 – 1.59 Ma[3]
Otowi Member of the Bandelier Tuff	Ash flows	~1.61 – 1.68 Ma[2]
Basal Guaje Pumice Bed of the Otowi Member	Pumice fall	
San Diego Canyon ignimbrites	Ash flows and pumice falls	~1.84 – 1.87 Ma[4]
Puye Formation tephra layers	Pumice falls	~1.75 – >5.3 Ma[5]
Upper Keres Group: Peralta Tuff Member of the Bearhead Rhyolite	Pyroclastic breccias, ash flows, and pumice falls	~6.76 – 6.96 Ma[6]
Lower Keres Group: Paliza Canyon Formation – Canovas Canyon Rhyolite	Ash flows and pumice falls	~7.4 – <12.4 Ma[7]

[1] Toyoda *et al.* (1995), Wolff and Gardner (1995), Reneau *et al.* (1996)
[2] Spell *et al.* (1990), Phillips *et al.* (2006)
[3] Spell *et al.* (1996a, b)
[4] Smith *et al.* (2001)
[5] Dethier (2003), WoldeGabriel *et al.* (2001, 2006)
[6] McIntosh and Quade (1995), Smith *et al.* (2001)
[7] Goff *et al.* (1990), Lavine *et al.* (1996), WoldeGabriel *et al.* (2006)

Bandelier Tuff

The pre-Valles Rhyolite part of the Tewa Group comprises the bulk of the tephra analyzed for this study and is subdivided into the upper and lower members of the Bandelier Tuff (Tshirege and Otowi Members, respectively) and the intervening Cerro Toledo Rhyolite. The upper and lower members of the Bandelier Tuff are further subdivided into basal pumice-fall units (Tsankawi Pumice Bed of Tshirege and Guaje Pumice Bed of Otowi) and overlying ash-flow units (Table 1).

Major Pleistocene caldera-forming eruptions of the Bandelier Tuff totaling 650 km^3 (Self et al., 1996) spread tephra across a wide area. Identified as far as 700 km away in northwestern Texas (Izett et al., 1972), up to 10 cm of primary airfall in Socorro about 300 km south (Dunbar et al., 1996), and up to 3 m-thick layers 20 km from the vent (Self et al., 1996), the resultant 22 km-wide Valles caldera rivals the silicic volcanic centers of Yellowstone, WY, and Long Valley, CA.

Our studies indicate that the Tshirege and Otowi Members of the Bandelier Tuff are difficult to distinguish from each other on the basis of electron-microprobe analysis of the volcanic glass (Fig. 2). The Tshirege Member contains on average more Fe than the Otowi Member. The Cerro Toledo tephra layers are readily distinguishable from the overlying and underlying units of the Bandelier Tuff on the basis of glass composition, primarily by lower Fe and slightly higher Ca contents (Fig. 2).

Upper Bandelier Tuff—Tshirege Member and Basal Tsankawi Pumice Bed

The Tshirege Member comprises the upper of the two members of the Bandelier Tuff and is associated with the collapse of the Valles caldera (Self et al., 1996). The Tsankawi is the basal pumice-fall deposit (about 15 km^3) of the Tshirege Member, a succession of cliff-forming welded ash flows. $^{40}Ar/^{39}Ar$ dating establishes the age of this coupled unit at ~1.21 to 1.25 Ma (Spell et al., 1990; Phillips et al., 2006). Although the dominant wind direction at the time of eruption determined the distribution of the airfall tephra, the ignimbrite was widely distributed around the vent; the maximum measured thickness of the Tshirege Member is 250 m (Self et al., 1996).

Cerro Toledo Rhyolite

Between the upper and lower members of the Bandelier Tuff, the Cerro Toledo Rhyolite comprises a series of rhyolite domes, lava flows, and associated ash-fall deposits (Stix et al., 1988).

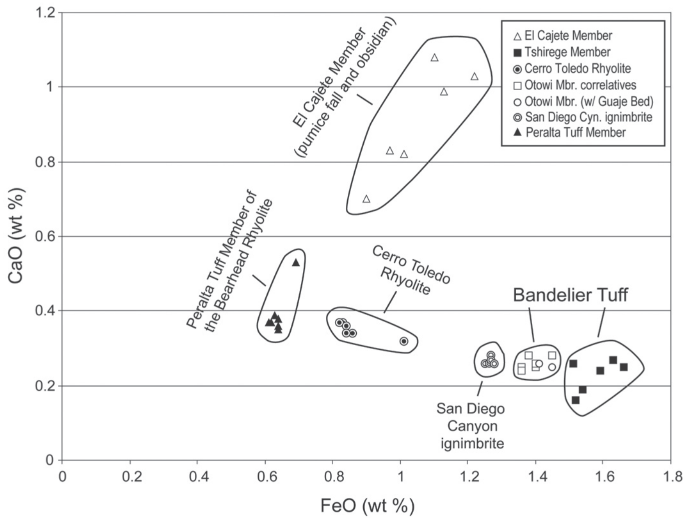

FIGURE 2. Weight percent of CaO versus FeO in glass shards of silicic Jemez Mountains tephra. Each point represents an average of 15-20 analyses.

Erupted within about 100 ky of the lower member of the Bandelier Tuff from along the caldera margin, these eruptions are small in volume compared to those of the upper and lower members of the Bandelier Tuff. Cerro Toledo Rhyolite eruptions continued for about 400 ky; the final event is about the same age as the upper member of the Bandelier Tuff (Spell et al., 1990, 1996a, b). Dated pumice-fall units indicate eruptive activity at >1.59, 1.54, 1.48, 1.37, and 1.22 Ma (Spell et al., 1996b). Well exposed in Los Alamos Canyon, the Cerro Toledo Rhyolite fills the Toledo embayment as mapped by Gardner and Goff (1996). Stix et al. (1988) described the high-silica rhyolite geochemistry and compositional zonation of the Cerro Toledo Rhyolite; Spell et al. (1996a, b) argued against progressive evolution of a single, closed-system magma chamber.

Lower Bandelier Tuff—Otowi Member and basal Guaje Pumice Bed

The Otowi Member comprises the lower of the two members of the Bandelier Tuff, the eruption of which resulted in the Toledo caldera. The Guaje is the basal pumice-fall deposit (about 20 km^3) of the Otowi Member, a massive pumiceous tuff breccia of ash-flow origin. This coupled unit is dated at 1.61 Ma by $^{40}Ar/^{39}Ar$ (Spell et al., 1990); more recent $^{40}Ar/^{39}Ar$ dating of welded ignimbrite produced a pooled age of 1.68 Ma (Phillips et al., 2006). Widely buried by the upper member, the maximum thickness of the Otowi Member is 180 m (Self et al., 1996).

San Diego Canyon ignimbrites

The earliest phases of rhyolitic explosive volcanism from the Jemez Mountains volcanic field, the San Diego Canyon ignimbrites (lower "A" and upper "B"; Turbeville and Self, 1988; Turbeville et al., 1989) are well exposed (up to 80 m thick) beneath the lower member of the Bandelier Tuff in the southwestern part of the Jemez Mountains. These ignimbrite units have identical $^{40}Ar/^{39}Ar$ dates of 1.84 to 1.87 Ma (Smith et al., 2001); earlier reported K-Ar ages may have been contaminated by xenocrysts (Spell et al., 1990). Virtually indistinguishable by major-element chemistry, the San Diego Canyon ignimbrites are high-silica rhyolites in composition (SiO_2 >75 wt. %) and have low abundances of CaO, MgO, and MnO (Spell et al., 1990; Appendix 1). Although chemically similar to the members of the Bandelier Tuff, the ash flows and fall pumice of the San Diego Canyon ignimbrites can be distinguished from all members of the overlying Bandelier Tuff on the basis of lower Fe (Fig. 2).

Puye Formation tephra layers

Flanking the east side of the northern Jemez Mountains, the Puye Formation is a volcaniclastic alluvial-fan sequence that developed in response to the growth and erosion of dacite domes (Waresback, 1986; Waresback and Turbeville, 1990). The Puye Formation comprises >15 km^3 of coarse-grained volcaniclastic sediments derived from the northeastern Jemez highlands from ~5 to 1.8 Ma (Waresback and Turbeville, 1990; WoldeGabriel et al., 2001). Well exposed in Rendija and Guaje Canyons, preservation of the Puye and intervening tephra layers was enhanced by nearly continuous aggradation of the clastic deposits in the space created by rifting along the Rio Grande and subsequent coverage by the lower Bandelier Tuff (Dethier, 2003).

Tuffs in the Puye Formation, other than the fall pumice of the San Diego Canyon ignimbrite ("B") near the top, are chemically quite different from the Tewa Group and San Diego Canyon units (Fig. 3). The Puye tuffs are dacitic rather than rhyolitic in composition, and their glasses contain significantly higher Fe_2O_3, CaO, MgO, and TiO_2, with lower contents of SiO_2, Na_2O, and K_2O (Appendix 1). Although we are able to correlate tuffs in the Puye Formation among sites and to sedimentary sections within the Española basin, numerical age control on tephra layers is sparse. WoldeGabriel et al. (2001, 2006) reported an $^{40}Ar/^{39}Ar$ age of 5.3 Ma for a vitric ash near the base.

Keres Group

The Keres Group (Bailey el al., 1969) consists of a lower (older) subgroup and an upper (younger) subgroup. The Paliza Canyon Formation basalts, andesites and dacites, and the Canovas Canyon Rhyolite form the lower Keres Group; the upper Keres Group comprises the Bearhead Rhyolite, which includes the Peralta Tuff Member (Lavine et al., 1996). $^{40}Ar/^{39}Ar$ ages reported for the Canovas Canyon Rhyolite and Paliza Canyon Formation range from ~9 to <12.4 Ma (Lavine et al., 1996; WoldeGabriel et al., 2006). Accepted $^{40}Ar/^{39}Ar$ ages for the Peralta Tuff Member of the Bearhead Rhyolite range from 6.76 to 6.96 Ma (McIntosh and Quade, 1995; Smith et al., 2001).

Tephra of the upper Keres Group, the Bearhead Rhyolite, is highly evolved, and can be readily distinguished from the younger units mentioned above on the basis of electron-microprobe glass chemistry (Fig. 3). Because no Bearhead Rhyolite tephra has been found in the Puye Formation, we conclude that the Puye is entirely younger than the Bearhead Rhyolite, ~7 Ma, and that its minimum age is equal to or younger than ~1.85 Ma (the age of the San Diego Canyon ignimbrite) at the top.

Tephra of the lower Keres Group, the Paliza Canyon Formation volcaniclastic rocks, are chemically quite variable (Fig. 3; Appendix 1), ranging in composition from dacite to dacitic andesite. These tephra layers also differ in chemical composition from the younger units.

CORRELATION OF JEMEZ MOUNTAINS TEPHRA TO SITES BEYOND THE SOURCE AREA

Tephra layers correlative with the Bandelier Tuff, Cerro Toledo Rhyolite, San Diego Canyon ignimbrites, and the Bearhead Rhyolite have been identified in sedimentary sections beyond the Jemez Mountains. Specifically, reworked ash and pumice of the Tshirege and Otowi Members of the Bandelier Tuff and the Cerro Toledo Rhyolite have been found at various locations in the Albuquerque basin (Connell, 2006), and in Quaternary alluvium overlying the Puye Formation. Ash of the Tsankawi Pumice Bed (basal airfall of the Tshirege Member) is found as far to the northwest as central Utah (Sarna-Wojcicki, unpubl. data), and ash of the Guaje Pumice Bed, basal airfall of the Otowi Member, is found east as far as central Texas (Izett et al., 1972). We correlate the San Diego Canyon ignimbrite ("B") to the top of the Puye Formation. The tephra layer in the upper Puye is a fall pumice, possibly representing an early Plinian eruptive phase of the San Diego Canyon ignimbrite or perhaps related to older, buried domes that date to ~2.3 Ma (Dethier, 2003). We have not yet identified tephra correlative with the lower Keres Group Paliza Canyon Formation tephra outside the Jemez Mountains.

CONCLUSION, USES OF THESE DATA, AND FURTHER WORK

Data obtained on these tephra layers are integrated with isotopic, magnetostratigraphic, and other data to provide a spatial and temporal framework for studies of surface and subsurface chronostratigraphy, structure, and hydrogeology in the Española and Albuquerque basins. The correlations and age control presented here, in combination with geologic mapping, provide a basic spatial and temporal framework for the Jemez Mountains–Española basin–Albuquerque basin study region. This region is ideal for developing a high-resolution Neogene chronostratigraphy because the Jemez Mountains have been a source of silicic volcanism for the past 13 Ma (Self et al., 1996). Tephra from these eruptions has been transported by wind and water throughout this region, and is well preserved within the depositional basins. These tephra layers provide time and space horizons for stratigraphic studies in the region, and are augmented by widespread tephra layers derived from outside sources. The data presented here are applicable to a wide variety of earth science studies, including geologic mapping, hydrology, geologic hazards, neotectonics, paleoenvironmental, and interdisciplinary studies.

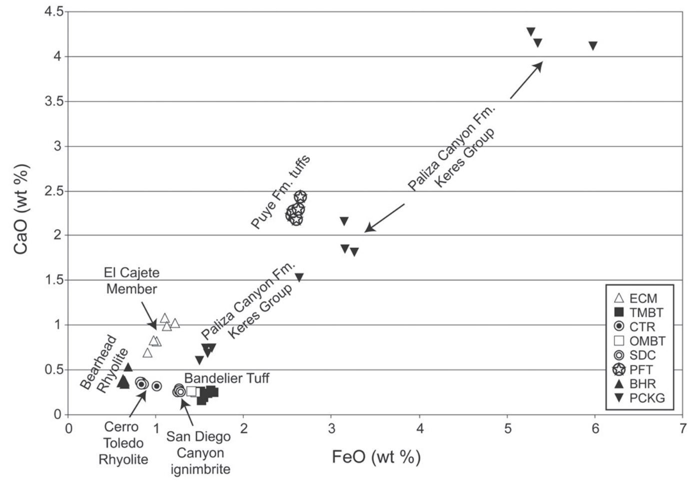

FIGURE 3. Weight percent of CaO versus FeO in glass shards of Jemez Mountains tephra. Each point represents an average of 15-20 analyses. ECM = El Cajete Member; TMBT = Tshirege Member of the Bandelier Tuff; CTR = Cerro Toledo Rhyolite; OMBT = Otowi Member of the Bandelier Tuff; SDC = San Diego Canyon ignimbrite; PFT = Puye Formation tuffs; BHR = Bearhead Rhyolite; PCKG = Paliza Canyon Formation of the lower Keres Group.

ACKNOWLEDGMENTS

We thank David Sawyer and Florian Maldonado, both of the U.S. Geological Survey, for their reviews of the manuscript. James P. Walker, formerly USGS, and Charles E. Meyer, retired USGS, analyzed some of the tephra samples by microprobe.

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APPENDIX 1. Electron-microprobe analysis of volcanic glass of pyroclastic rocks, obsidian, and proximal tephra erupted from the Jemez Mountains, northwestern New Mexico. Analyses are presented in stratigraphic order, from youngest to oldest in each section and among sections, except where uncertainty in stratigraphic position is indicated. Values given are weight-percent oxide, recalculated to 100 percent fluid-free basis (Total, R). About 20 individual glass shards or points were analyzed for each sample. Charles E. Meyer and James P. Walker, U.S. Geological Survey, Menlo Park, analysts.

Sample ID	T-# probe mount	Latitude in °N	Longitude in °W	Date	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Total, R
El Cajete Member Pumice, Valles Caldera, N.M. State Hwy. 4; ~50 – 60 ka														
Porphyritic obsidian overlying El Cajete pumice, near bridge over N.M. State Hwy. 4														
JM-EC-3	T395-9	35.8283	106.5916	8-3-98	76.44	13.08	0.80	0.09	0.02	0.70	0.18	3.85	4.82	99.98
Upper pumice-fall bed, >4 m thick, with pumice clasts to ~12 cm in long diameter, in road-cut near quarry														
JM-EC-2	T388-10	35.8156	106.5445	7-1-98	75.62	13.49	1.10	0.19	0.02	1.08	0.23	3.85	4.43	100.01
JM-EC-2	T395-8	35.81561	106.5445	8-3-98	76.88	12.87	0.90	0.13	0.04	0.70	0.13	3.63	4.71	99.99
JM-EC-2 _5um_beam	T399-10	35.81561	106.5445	10-21-98	76.88	12.94	1.01	0.16	0.04	0.82	0.18	3.41	4.55	99.99
Lower pumice-fall bed, 1.5-2 m thick with pumice clasts to ~8 cm in long diameter, in road-cut near quarry														
JM-EC-1	T399-7	35.8156	106.5445	10-21-98	75.68	13.37	1.22	0.24	0.05	1.03	0.24	3.69	4.48	100.00
JM-EC-1_POP1	T389-6	35.8156	106.5445	7-2-98	76.31	13.15	0.97	0.15	0.07	0.83	0.18	3.73	4.60	99.99
JM-EC-1_POP2	T389-6	35.8156	106.5445	7-2-98	76.30	13.46	1.13	0.20	0.03	0.99	0.27	3.15	4.49	100.02
Tephra in sediments above Puye Formation with chemical affinity to El Cajete Member pumice														
DN-98-16	T420-2	35.9587	106.1507	11-5-99	76.95	12.93	0.94	0.17	0.04	0.93	0.20	2.99	4.84	99.99
Bandelier Tuff, Tshirege Member, N.M. State Hwy. 4; ~1.21 – 1.25 Ma														
Unwelded flow-tuff, upper Bandelier, 7 m thick, third ash flow from base, matrix supported with pumice lapilli to 7 cm in long diameter, ridge between Pueblo and Los Alamos Canyons														
JM-TS-7	T398-9	35.8699	106.2196	10-21-98	77.19	12.09	1.54	0.01	0.08	0.19	0.06	4.36	4.48	100.00
JM-TS-7 (pumice frac.)	T388-2	35.8699	106.2196	7-1-98	77.03	12.29	1.52	0.01	0.11	0.16	0.05	4.34	4.49	100.00
Floury, fine- to medium-sand- and silt-sized tephra, ~1.5 m thick, overlying basal Tsankawi Pumice Bed, N.M. State Hwy. 4 west of water tanks														
JM-TS-6	T388-1	35.8700	106.1972	7-1-98	76.96	12.22	1.63	0.01	0.08	0.27	0.06	4.34	4.43	100.00
Basal Tsankawi Pumice Bed, 30 cm thick, sand- to gravel-sized pumice fall(?) overlying weathered top of middle and lower Bandelier Tuff														
JM-TS-5	T389-8	35.8696	106.1974	7-1-98	77.17	12.15	1.53	0.01	0.09	0.24	0.03	4.34	4.44	100.00
Bandelier Tuff, Tshirege Member, basal Tsankawi Pumice Bed, Pueblo Canyon; ~1.21 – 1.25 Ma														
Pumice-fall layer, 85 cm thick, overlying basal air fall of Tsankawi Pumice Bed														
JM-PC-21	T481-1	35.8832	106.2640	6-22-02	76.89	12.35	1.51	0.01	0.08	0.26	0.05	4.45	4.39	99.99
Upper part (60 cm) of 155-cm-thick compound, pumice-fall unit, with pumice lapilli to 2 cm in long diameter, sampled from lower 15 cm														
JM-PC-22A	T481-2	35.8832	106.2640	6-22-02	76.64	12.22	1.66	0.01	0.09	0.25	0.04	4.42	4.66	99.99
Lower part (70 cm) of upward-fining, 155-cm-thick compound, pumice-fall unit, with lapilli to ~4 cm in long diameter, sampled from basal ~20 cm (included as part of Tshirege Member, by Stix, 1989, but as part of upper Cerro Toledo Rhyolite by Spell et al., 1996)														
JM-PC-22B	T481-3	35.8832	106.2640	6-22-02	76.79	12.22	1.59	0.00	0.10	0.24	0.05	4.36	4.65	100.00
Cerro Toledo Rhyolite pumice-fall tephra, Pueblo Canyon, section 6 of Stix, 1989; ~1.22 – 1.59 Ma														
Massive pumice-fall unit, 1.8 m thick, with pumice clasts to 4 cm in long diameter, fining-upward; sampled from basal 20-30 cm of unit														
JM-PC-23	T481-4	35.8832	106.2640	6-22-02	77.12	12.71	0.83	0.05	0.07	0.37	0.11	4.02	4.72	100.00
JM-PC-23 _FranzBias	T481-5	35.8832	106.2640	6-22-02	77.16	12.71	0.84	0.05	0.06	0.36	0.11	3.97	4.75	100.01
Pumice-lithic-fall unit, > 20-30 cm thick, upward coarsening, with pumice lapilli to 2 cm in long diameter, base covered by talus														
JM-PC-24	T481-6	35.8832	106.2640	6-22-02	77.43	12.59	0.86	0.04	0.07	0.34	0.06	3.90	4.72	100.01

APPENDIX 1. Continued.

Sample ID	T-# probe mount	Latitude in °N	Longitude in °W	Date	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Total, R
Cerro Toledo Rhyolite pumice-fall tephra, Pueblo Canyon, section 15 of Spell et al., 1990; ~1.22 – 1.59 Ma														
Coarse pumice-fall with lithic fragments, 1.8 m thick, with pumice clasts to 9 cm in long diameter at base, (equivalent[?] to JM-PC-23 in section 6 of Stix, 1989; see above)														
JM-PC-25	T481-7	35.8835	106.2700	6-22-02	77.14	12.73	0.82	0.05	0.06	0.37	0.12	3.76	4.96	100.01
Oxidized, reworked pumice; basal 40 cm, pumice fall(?); sample from basal 30 cm of unit (equivalent[?] to JM-PC-24 in section 6 of Stix, 1989; see above)														
JM-PC-26	T481-8	35.8835	106.2700	6-26-02	77.51	12.50	0.84	0.04	0.06	0.34	0.09	3.54	5.09	100.01
Coarse pumice fall(?) or reworked pumice, with clasts up to 5 cm in long diameter, sampled from basal 20 cm														
JM-PC-27	T480-5	35.8835	106.2700	6-22-02	77.26	12.45	1.01	0.03	0.07	0.32	0.09	3.60	5.16	99.99
Cerro Toledo Rhyolite tephra in sediments overlying the Puye Fm., Puye quad.														
DN-98-10	T420-1	35.9533	106.1319	11-5-99	77.80	12.41	0.82	0.04	0.05	0.34	0.10	3.69	4.76	100.01
DN-98-17	T420-3	35.9580	106.1657	11-5-99	77.47	12.57	0.83	0.06	0.05	0.36	0.11	3.64	4.92	100.01
DN-97-57-1	T419-9	35.9395	106.2146	11-5-99	77.73	12.16	1.00	0.02	0.09	0.27	0.07	3.59	5.07	100.00
Cerro Toledo Rhyolite tephra in sediments overlying the Puye Fm., Puye quad., or reworked(?) Tsankawi Pumice Bed(?)														
DN-97-57-2	T419-10	35.9395	106.2146	11-5-99	77.24	12.10	1.58	0.01	0.10	0.25	0.06	4.03	4.63	100.00
Bandelier Tuff, basal Otowi Member, Los Alamos Canyon, N.M. Hwy. 502; ~1.61 – 1.68 Ma														
Guaje Pumice Bed, pumice fall at base of Otowi Member, ~2 m thick, with pumice clasts to 5 cm in long diameter, unconformably overlies basalt of Los Cerritos del Rio, sampled ~1.5 m above basal contact														
JM-GP-4	T389-7	35.8682	106.1984	7-1-98	77.32	12.28	1.45	0.01	0.09	0.25	0.06	3.83	4.71	100.00
Guaje Pumice Bed in sediments overlying the Puye Formation, Puye quad.														
DN-97-55	T380-8	35.9197	106.2327	3/13/98	76.81	12.57	1.40	0.01	0.08	0.25	0.05	4.22	4.61	100.00
DN-97-94	T380-10	35.9768	106.1102	3/13/98	76.89	12.48	1.40	0.01	0.08	0.26	0.05	4.27	4.57	100.01
DN-97-105b	T381-2	35.9827	106.1953	3/13/98	76.96	12.50	1.36	0.01	0.08	0.25	0.05	4.49	4.31	100.01
DN-97-117	T381-4	35.9513	106.1842	3/13/98	77.00	12.44	1.36	0.01	0.08	0.24	0.04	4.24	4.61	100.02
Bandelier Tuff, basal Otowi Member, overlying Puye Formation, Copar Mine area; ~1.61 – 1.68 Ma														
Guaje Pumice Bed, pumice fall, ~50-cm thick, with pumice lapilli to 1.5 cm in long diameter														
JM-CM-10	T390-10	35.9215	106.2119	7-1-98	77.07	12.21	1.41	0.01	0.07	0.26	0.05	3.86	5.05	99.99
San Diego Canyon ignimbrite, west of Agua Durme Springs and Ponderosa Rd., San Diego Canyon, 1.84 – 1.87 Ma (Smith et al., 2001)														
Very coarse pumice-flow tuff, several tens of meters thick, from ~15-20 m below contact with Otowi member of the Bandelier Tuff, with pumice clasts to 15 cm in long diameter; upper unit "B"														
JM-SD-30	T480-7	35.8067	106.6990	6-22-02	76.95	12.43	1.26	0.02	0.06	0.26	0.08	4.26	4.69	100.01
Coarse pumice-flow tuff, several tens of meters thick, with pumices to 8 cm in long diameter, collected ~5 m above base where it overlies andesite breccias and flows of the Paliza Canyon Formation; lower unit "A"														
JM-SD-31	T480-8	35.8066	106.6997	6-22-02	76.83	12.42	1.27	0.02	0.07	0.27	0.08	4.18	4.87	100.01
Coarse pumice-flow tuff, several tens of meters thick, base of San Diego Canyon ignimbrites; sampled 3-5 m above base of unit, San Diego Canyon, here overlying andesite and vitrophyre of Paliza Canyon Formation, ~1/3 mi west of Ponderosa Rd.														
JM-SD-28	T480-6	35.8109	106.6910	6-22-02	76.97	12.50	1.28	0.02	0.07	0.26	0.08	4.37	4.44	99.99
Pumice fall of San Diego Canyon ignimbrite, Copar Mine area; ~1.84 – 1.87 Ma														
Pumice fall of San Diego Canyon ignimbrite, basal unit, 30 cm thick; lower subunit (JM-CM-8), 15 cm thick, pumice lapilli to 2 cm in long diameter; upper subunit (JM-CM-9), pumice lapilli to 1.5 cm in long diameter														
JM-CM-8	T388-3	35.9216	106.2119	7-1-98	77.57	12.31	1.28	0.02	0.06	0.26	0.10	3.39	5.01	100.00
JM-CM-8 (pumice frac.)	T388-4	35.9216	106.2119	7-1-98	77.16	12.36	1.25	0.03	0.06	0.26	0.08	3.63	5.19	100.02
JM-CM-9	T390-9	35.9216	106.2119	7-1-98	77.70	12.29	1.27	0.02	0.07	0.28	0.10	3.47	4.81	100.01
Pumice fall tephra correlative to JM-CM-8 and JM-CM-9, San Diego Canyon ignimbrite, Puye quad														
DN-97-29a	T380-6	35.9112	106.2058	3/13/98	77.12	12.54	1.23	0.02	0.05	0.27	0.07	3.97	4.73	100.00

APPENDIX 1. Continued.

Sample ID	T-# probe mount	Latitude in °N	Longitude in °W	Date	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Total, R
Pumice-fall tuffs in upper Puye Formation														
DN-97-42	T380-7	35.9142	106.2095	3/13/98	72.15	15.52	1.39	0.21	0.09	0.64	0.27	4.86	4.85	99.98
DN-98-137	T421-7	35.9132	106.2098	11-5-99	72.56	15.05	1.43	0.19	0.09	0.61	0.29	4.75	5.03	100.00
Pumice-fall tuffs in middle Puye Formation, Guaje and Rendija Canyons														
Upper pumice-fall tuff, varies in thickness from 40 to 70 cm, with lapilli to 1.5 cm in long diameter, Guaje Canyon														
JM-GC-12	T436-5	35.9066	106.2017	3-2-00	70.55	15.42	2.65	0.79	0.04	2.44	0.53	4.20	3.39	100.01
Lower pumice-fall tuff, 1 m thick, with lapilli to 2 cm in long diameter, Guaje Canyon														
JM-GC-13	T389-5	35.9066	106.2017	7-1-98	71.04	15.17	2.60	0.70	0.05	2.19	0.56	3.76	3.92	99.99
JM-GC-13	T399-2	35.9066	106.2017	10-21-98	71.00	15.12	2.56	0.68	0.05	2.28	0.49	4.06	3.76	100.00
Pumice-fall tuff, 1-m thick, with lapilli to ~2 cm in long diameter, Rendija Canyon														
JM-RC-11	T391-5	35.9111	106.2409	7-1-98	70.86	15.17	2.62	0.69	0.04	2.30	0.57	4.05	3.70	100.00
Three compositionally similar pumice-fall tuffs, similar or correlative to, JM-RC-11, JM-GC-12 and JM-GC-13, middle Puye Fm., Puye quad.														
DN-97-14	T380-3	35.9972	106.1303	3/13/98	70.98	15.74	2.57	0.71	0.06	2.53	0.47	3.21	3.73	100.00
DN-98-72	T420-10	35.8803	106.2136	11-5-99	70.26	15.62	2.77	0.76	0.07	2.55	0.53	3.93	3.52	100.01
DN-98-134	T421-6	35.8856	106.2206	11-5-99	70.87	15.29	2.55	0.66	0.05	2.42	0.54	3.78	3.83	99.99
Pumice-fall tuffs in lower/middle(?) Puye Formation, ~3.8 Ma														
Bimodal tephra layer, stratigraphic relationship to three samples below is uncertain														
DN-98-26A _POP2	T420-4	35.9974	106.1648	11-5-99	72.82	14.98	1.95	0.50	0.05	1.94	0.35	3.80	3.62	100.01
DN-98-26A _POP1	T420-4	35.9974	106.1648	11-5-99	74.60	14.35	1.18	0.23	0.04	1.37	0.26	3.57	4.41	100.01
Compositionally similar dacitic tephra layers, stratigraphic relationship to two samples above is uncertain														
DN-98-31A	T420-5	35.9868	106.1267	11-5-99	73.06	14.69	1.87	0.45	0.04	1.85	0.37	3.74	3.93	100.00
DN-98-37	T420-7	35.9805	106.2067	11-5-99	73.42	14.90	1.67	0.40	0.04	1.64	0.31	3.82	3.81	100.01
DN-98-65	T420-9	35.9763	106.1512	11-5-99	72.87	15.05	1.80	0.45	0.07	1.87	0.33	3.94	3.63	100.01
Pumice-fall tuffs in lower Puye Formation														
Two compositionally similar pumiceous tephra layers, stratigraphic relationship to three samples below is uncertain														
DN-98-35	T420-6	35.9857	106.2116	11-5-99	74.14	14.41	1.54	0.35	0.04	1.46	0.34	3.60	4.11	99.99
DN-98-43A	T420-8	35.9492	106.1763	11-5-99	74.15	14.44	1.61	0.35	0.03	1.41	0.34	3.78	3.88	99.99
Two compositionally similar pumiceous tephra layers, stratigraphic relationship to above and below samples uncertain														
DN-98-100	T421-2	35.9269	106.1725	11-5-99	72.99	15.03	1.73	0.44	0.08	1.77	0.36	3.83	3.77	100.00
DN-98-132	T421-5	35.9067	106.2072	11-5-99	73.34	14.45	1.78	0.40	0.06	1.73	0.39	3.66	4.19	100.00
Tephra layer, stratigraphic relationship to four samples above is uncertain														
DN-98-81-A	T421-1	35.8803	106.2136	11-5-99	74.97	14.09	1.27	0.27	0.05	1.30	0.27	3.40	4.37	99.99
Pumice-flows, pumice-falls, and breccias of the Peralta Tuff Member of the Bearhead Rhyolite, Peralta Canyon														
Pumice-ash flow-tuff, 3 m thick, with a coarse gravel layer bed within it; sampled from near the base of the lower pumice flow														
JM-TR-18	T391-3	35.6654	106.4119	7-1-98	77.52	12.39	0.63	0.05	0.05	0.39	0.13	2.63	6.22	100.01
Obsidian from coarse, dome collapse(?) breccia, up to 9 m thick, consisting of angular rhyolite-flow rocks to 50 cm in long diameter and obsidian clasts in a cemented, fine-grained matrix.														
JM-TR-17	T391-4	35.6654	106.4119	7-1-98	77.76	12.32	0.64	0.05	0.06	0.38	0.12	3.51	5.16	100.00
Pumice-flow tuff, up to 3 m thick, with pumice blocks at base to 8 cm, fines upward; contains lithic clasts and perlite; fines-depleted ignimbrite(?); this unit channels down into underlying section in places; forms "hoodoos"														
JM-TR-16B	T391-1	35.6654	106.4119	7-1-98	77.45	12.35	0.62	0.05	0.07	0.37	0.11	2.87	6.11	100.00
Pumice-flow tuff lens, 3.5-4 m thick														
JM-TR-16A	T391-2	35.6654	106.4119	7-1-98	77.68	12.44	0.64	0.06	0.06	0.38	0.12	2.43	6.19	100.00

APPENDIX 1. Continued.

Sample ID	T-# probe mount	Latitude in °N	Longitude in °W	Date	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Total, R
Pumice-flow tuff with lithic clasts, 1-3.5 m thick														
JM-TR-15	T391-6	35.6654	106.4119	7-1-98	77.49	12.43	0.64	0.05	0.07	0.36	0.11	2.77	6.07	99.99
Basal pumice-fall tuff, 50-60 cm thick, with pumice lapilli to 4 cm long diameter, with abundant lithic fragments to 3 cm, unconformably overlies alluvial, debris-flow, and lacustrine(?) deposits, containing basaltic sand														
JM-TR-14	T389-4	35.6654	106.4119	7-1-98	77.56	12.37	0.61	0.05	0.06	0.37	0.14	2.54	6.30	100.00
Pumice-fall and pumice-flow tephra layers of the Paliza Canyon Formation, southeastern Jemez Mts.														
Andesitic tephra from near top (183 m) of stratigraphic section A, Boundary Peak														
AL-E5	T416-2	35.7577	106.4174	8-28-99	71.11	15.54	2.63	0.60	0.06	1.54	0.66	2.80	5.06	100.00
Dacitic tephra from near top (182 m) of stratigraphic section A, Boundary Peak														
AL-E23	T416-4	35.7577	106.4174	8-28-99	68.70	15.97	3.15	0.88	0.05	2.17	0.77	3.91	4.40	100.00
Canovas Canyon Rhyolite (Goff et al., 1990) from upper Sanchez Canyon, and dacitic tephra from near top (158 m) of stratigraphic section B in Sanchez Canyon														
AL-S61	T417-2	35.7303	106.3827	11-5-99	70.55	15.56	1.64	0.24	0.05	0.75	0.38	4.50	6.33	100.00
AL-G13	T417-3	35.7281	106.3792	11-5-99	70.68	15.51	1.57	0.26	0.06	0.75	0.39	4.41	6.37	100.00
Dacitic tephra near top (155 m) of section B in Sanchez Canyon, and Canovas Canyon Rhyolite (Goff et al., 1990) from upper Sanchez Canyon														
AL-G12	T416-5	35.7281	106.3792	8-28-99	71.88	15.18	1.59	0.21	0.05	0.69	0.36	4.05	5.98	99.99
AL-S5	T417-1	35.7460	106.3884	11-5-99	71.65	15.27	1.50	0.20	0.07	0.61	0.35	4.00	6.35	100.00
Dacitic tephra near middle (62 m) of section A, Boundary Peak														
AL-E2	T415-10	35.7577	106.4174	8-28-99	72.89	13.58	3.26	0.53	0.05	1.82	0.68	3.79	3.41	100.01
Bottom (49 m) dacitic tephra from section A, boundary Peak and dacitic tephra on west side of Cochiti Canyon across the canyon from stratigraphic sections D and E														
AL-E1	T415-9	35.7577	106.4174	8-28-99	64.18	16.71	5.35	1.66	0.09	4.16	1.02	4.66	2.18	100.01
AL-C14	T415-8	35.7522	106.4236	8-28-99	64.27	16.59	5.27	1.73	0.09	4.28	0.97	4.62	2.19	100.01
Dacitic tephra from between sections D and E in Cochiti Canyon (stratigraphic position uncertain)														
AL-C6	T415-7	35.7566	106.4159	8-28-99	64.61	15.46	5.98	1.66	0.10	4.12	1.26	4.45	2.37	100.01
Tephra near base (15 m) of stratigraphic section C														
AL-D2	T416-3	35.7545	106.4152	8-28-99	69.09	16.96	3.16	0.89	0.07	1.86	0.82	1.59	5.56	100.00