Distribution, geochemistry, and correlation of Pliocene tephra in the Pajarito Plateau

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DISTRIBUTION, GEOCHEMISTRY, AND CORRELATION OF PLIOCENE TEPHRA IN THE PAJARITO PLATEAU

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Abstract — The Pajarito Plateau, a deeply dissected east-tilted tableland capped by Quaternary Bandelier Tuff, occupies the western part of the Española Basin. Lava flows of variable compositions dominated the earliest volcanic eruptions in the area currently occupied by the plateau; however, small-volume pyroclastic deposits erupted in the southern and northeastern parts of the Jemez volcanic field during the late Miocene and Pliocene. A dozen proximal primary and reworked tephra units are interbedded within the Puye Formation in Ancho, Bayo, Rendija, Guaje, Sawyer, and Santa Clara Canyons. In Ancho Canyon at the southern part of the plateau, two primary tephra units are interbedded within pumice-bearing volcaniclastic sandstone below conglomerate of the Totavi Lentil at the base of the Pliocene Puye Formation that is capped by Pliocene basalt (3.04±0.5 Ma). In Bayo Canyon, primary pumice and vitric ash units occur at the base of the Puye Formation about 2 m above upper Miocene basalt (8.86±0.05 Ma). The vitric ash yielded an age of 5.3 Ma. None of the tephra units in Rendija, Guaje, and Santa Clara Canyons were dated but they mostly occur in the upper half of the Puye Formation above the conglomerate of the Totavi Lentil. Major element compositions of glass shards determined by electron microprobe analysis indicate that most tephra are low- and high-silica rhyolites except for a pumice unit that is rhyodacite to trachydacite in composition. The upper tephra units in Ancho and Bayo Canyons are chemically identical. Four of the tephra samples from Rendija and Guaje Canyons are chemically correlative and represent low-silica rhyolite, whereas three other samples have distinctive compositions of low- to high-silica rhyolite. The lower tephra in Ancho Canyon is chemically correlative to a bedded tuff in Guaje Canyon. Chemical correlation was also noted between Rendija and Santa Clara Canyon tephra units. Based on chemical similarities, most of the Pliocene tephra erupted from Tschicoma Formation centers in the northeastern part of the Jemez volcanic field. Stratigraphic relations and correlation suggest that the ages of tephra and sedimentary deposits of the Puye Formation generally increase southward. Preexisting structures and contemporaneous felsic and basaltic volcanism on the west and east sides of the plateau, respectively, dictated Pliocene sedimentation in the area currently defined by the plateau. Fluvial pumiceous sandstone and fanglomerate of dacite and basaltic rocks hosting the tephra represent at least three source areas that are dominated by these lithologic types.

INTRODUCTION

Small-volume tephra units of varying age, composition, and thicknesses commonly occur within the sedimentary sequence of the Pliocene Puye Formation that are mostly exposed along fault scarps and canyon walls of the Pajarito Plateau. The plateau, located between the Rio Grande and the Pajarito fault zone, is characterized by east-west-trending mesas that form the western part of the Española Basin of the Rio Grande rift in north central New Mexico (Fig. 1). The Quaternary Bandelier Tuff blankets the east-tilted mesas that are separated by east-trending deep canyons. Upper Oligocene to middle Miocene (25.5 -11.0 Ma) volcanic activity in the southern and eastern Jemez volcanic field consisted mostly of lava flows. The earliest tephra units related to Canovas Canyon Rhyolite in the southern Jemez volcanic field erupted in the late Miocene (9.63 Ma) (Smith et al., 1970; Gardner et al., 1986; Goff et al., 1990; WoldeGabriel et al., 2006). Additional tephra units of the Peralta Tuff Member (7.06-6.15 Ma) related to Bearhead Rhyolite erupted in the same area during the waning stages of Keres Group volcanism (Gardner et al., 1986; Goff et al., 1990; Justet and Spell, 2001; Smith, 2001). Pumice-rich, reworked tephra deposits also occur between mafic lavas (10.1 Ma) at the top of the Lobato Basalt in Santa Clara Canyon Plateau, suggesting the presence of another upper Miocene explosive volcanic center in the northeast part of the Jemez volcanic field (WoldeGabriel et al., 2006). Although most of the tephra units beneath the Pajarito Plateau are of early to late Pliocene age, older tephra deposits that are temporally correlative to the Peralta Tuff Member (7.06-6.15 Ma) were intersected in exploratory boreholes in the central part of the Pajarito Plateau (Broxton and WoldeGabriel, 2007, unpubl. $^{40}Ar/^{39}Ar$ data).

During the Plio-Pleistocene, silicic volcanism migrated northward to the central and eastern parts of the Jemez volcanic field and small- to large-volume pyroclastic eruptions and lava flows related to the Tschicoma Formation and the Bandelier Tuff inundated the area (Bailey et al., 1969; Smith et al., 1970; Gardner et al., 1986; Loeffler et al., 1988; Turbeville et al., 1989; Izett and Obradovich, 1994; Gardner and Goff, 1996; Broxton et al., 2007). According to Turbeville et al. (1989), at least 25 pyroclastic units erupted from dacitic to rhyolitic lava domes of the Tschicoma Formation occur within the Puye Formation in the northern part of the Pajarito Plateau. Minor basaltic tephra units erupted from the Pliocene Cerros del Rio volcanic field located mostly to the east of the plateau occur in the uppermost part of the Puye Formation (Turbeville et al., 1989; Dethier, 1997).

This report describes the location and distribution of the major tephra layers interbedded within the Puye Formation in the central and northern parts of the Pajarito Plateau. Brief petrographic descriptions and geochemical characteristics of discrete glass shards of the various tephra units are also presented. Based on field and laboratory characteristics of the units, correlations are established among the tephra units exposed from Ancho to Santa Clara Canyons (Fig. 1). The tephra stratigraphic markers provided temporal and spatial constraints on the development of the Puye Formation. Moreover, the provenance, depositional environments, and tectonic activities during the deposition of the Puye Formation along the western part of the Española Basin, currently occupied by the plateau are briefly highlighted.
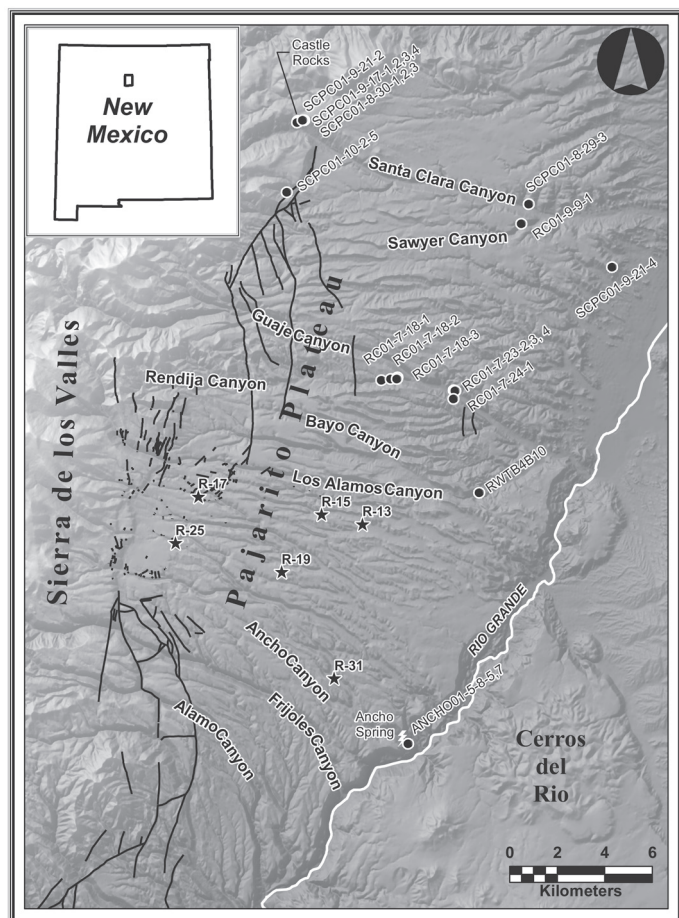
FIGURE 1. Map shows the location of tephra samples in the Pajarito Plateau of north central New Mexico (Inset map). Dark lines represent the Pajarito fault zone, which defines the western margin of the Española Basin. Solid stars indicate drill hole locations.

SAMPLES AND ANALYTICAL METHODS

More than 20 samples were collected from primary and reworked tephra interbedded within the stratigraphic sequence of the Puye Formation in Ancho, Bayo, Rendija, Guaje, Sawyer, and Santa Clara Canyons (Fig. 1). In outcrop, the pumice-rich units are matrix- to clast-supported, moderately sorted, and partially consolidated. The reworked pumice-rich tephra units are generally cemented with crystal-rich silty clays. Polished thin sections were prepared on all of the samples for petrographic examination and for electron microprobe analysis.

The major element compositions of discrete glass shards were determined using a Cameca SX50 electron microprobe at the Geology and Geomaterial Research Laboratory of the Earth Environmental Science Division of the Los Alamos National Laboratory. More than 25 glass shards were analyzed from each sample using 15 kV accelerating voltage, 15 μA beam current, and a 10 μm beam diameter. The average results of the analysis are given in Table 1. Obsidian and mineral standards were used to calibrate the major element analyses. Electron microprobe results with totals less than 90% were discarded.

DISTRIBUTION OF TEPHRA AND ANALYTICAL RESULTS

Although the tephra samples exhibited minor alteration, variation diagrams of least mobile major element oxides (Al_2O_3, CaO, FeO, TiO_2) were plotted to determine the range of composition and to check for correlation among the various tephra (Figs. 2, 3). Results from field studies and laboratory analyses of the various tephra are described by geographic locations from south to north along the length of the plateau.

Tephra of Ancho Canyon

Two pumice fallout units crop out within the Puye Formation directly below conglomerate of the Totavi Lentil in lower Ancho Canyon downstream from the Ancho Springs (Fig. 1). The local section consists, in descending stratigraphic order, of columnar-jointed Cerros del Rio basalt (~20 m), conglomerate of Totavi Lentil (20 m), orange pumiceous sandstone with interbedded primary tuff layer (~15 m), and a matrix-supported conglomerate lens within dark gray bedded, cross-bedded, and laminated volcaniclastic sandstone with abundant mafic volcanic pebbles and cobbles. The upper primary pumice (Ancho01-5-8-5) occurs within the lower half of the orange volcaniclastic sandstone. The pumice is light gray, strongly cemented and contains clay matrix. Pumice clasts are porphyritic with abundant sieved and zoned plagioclase and minor orthopyroxene, and a few magnetite grains. The lower tephra (Ancho01-5-8-7), which consists of an upper pumice and lower vitric ash, crops out at the base of the orange volcaniclastic sandstone about 4 m above cross-bedded and laminated dark gray volcaniclastic sandstone at the base of the section.

Both tephra units contain different major and trace element contents determined on bulk pumice (WoldeGabriel et al., 2006); these results are consistent with major element results from electron microprobe analysis. The upper pumice flow is rhyodacite to trachydacite, characterized by low SiO_2 and higher TiO_2, FeO, MgO, and CaO compared with the high-silica rhyolite pumice bed at the base of the section (Table 1).

Tephra of Bayo Canyon

At Bayo Canyon, in the northern part of the central Pajarito Plateau, the Puye Formation is directly capped by Bandelier Tuff, unlike the Ancho Canyon section where a thick sequence of upper Pliocene Cerros del Rio lavas is present above the Puye Formation. However, localized basaltic lava and tephra layers of Cerros del Rio age crop out above the Puye Formation close to the intersection of Bayo and Los Alamos Canyons (Fig. 1). A pumice (RWTB4-B4) and underlying vitric ash (RWTB4-8) crop out along a fault scarp at the base of the Puye Formation. The pumice unit is about 1.5 m thick, light gray, well sorted, and strongly indurated. The >1 m- thick vitric ash is bluish gray, well sorted, indurated, and crops out about 2 m above upper Miocene (8.86±0.1 Ma) basalt flows (WoldeGabriel et al., 2001).

No electron microprobe data were obtained on the pumice and vitric ash layers of lower Bayo Canyon. Instead, major and trace
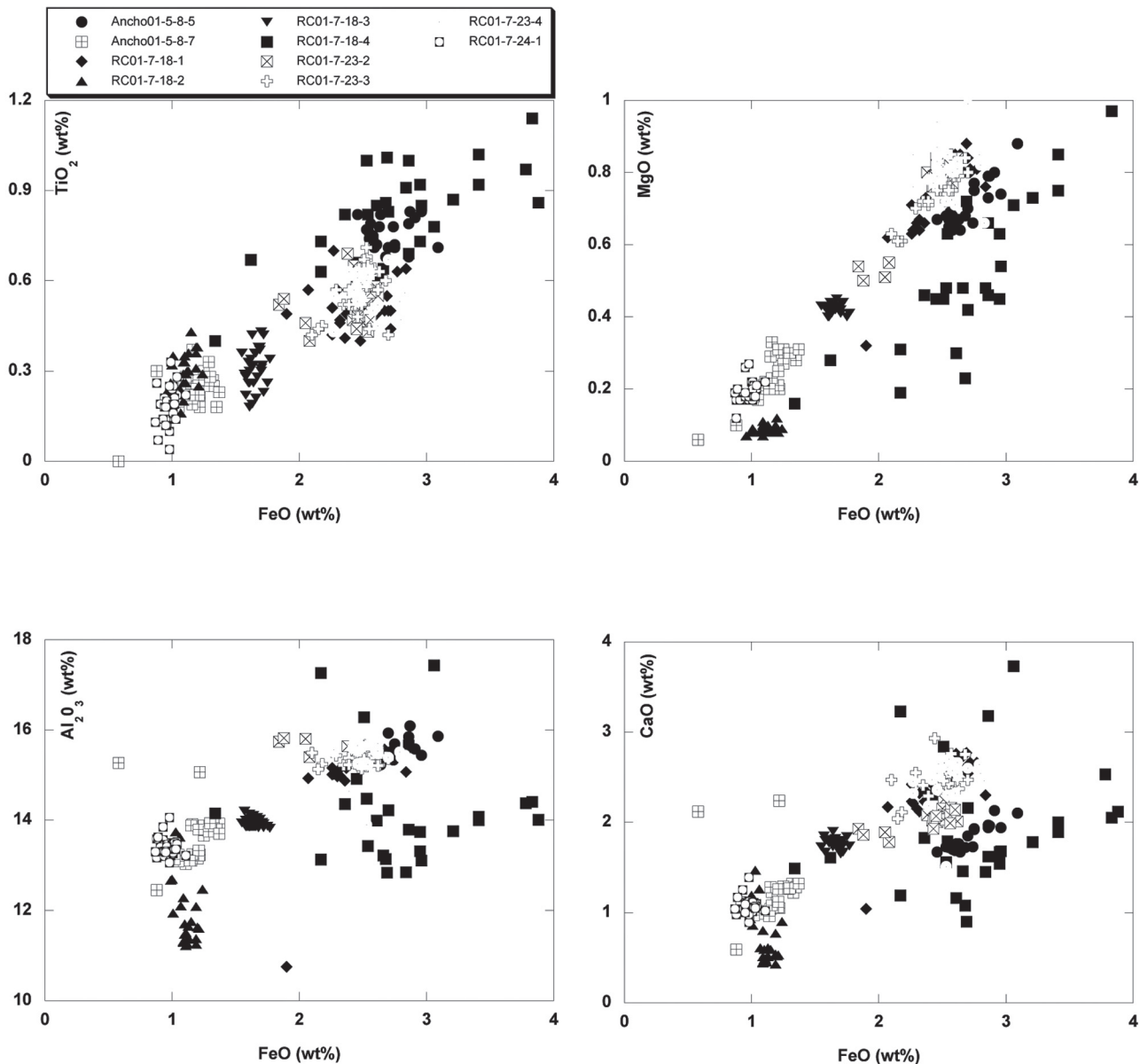
FIGURE 2. Variation diagrams of major element plots of tephra from Ancho, Rendija, and Guaje Canyons. Symbols represent different tephra samples.

element compositions were determined on bulk samples using X-ray fluorescence (WoldeGabriel et al., 2001). Like the Ancho Canyon tephra units, the pumice and vitric ash beds in Bayo Canyon have distinctive chemical composition. The pumice and vitric ash plot in the rhyodacite-trachydacite and rhyolite fields of the alkali vs. silica classification diagram of volcanic rocks (Le Bas et al., al., 1986). Consistent with their lithologic similarities, the upper pumice units in Ancho and Bayo Canyons are correlative, with similar low SiO_2 and higher TiO_2, FeO, MgO, and CaO concentrations.

Tephra of Rendija Canyon

A total of eight tephra samples were collected near the intersection of Rendija and Guaje Canyons north of Bayo Canyon

(Fig. 1). Three of the samples (RC01-7-18-1 to RC01-7-18-3) were collected along the north wall of Rendija Canyon about 1 km upstream from the intersection. The first sample (RC01-7-18-1) is light gray, clast-supported, and sorted primary pumice that crops out about 3 m above road level. It is indurated and coated with white crust. The pumice clasts are sparsely porphyritic with coarse sieve-textured and zoned plagioclase. A few grains of hornblende, orthopyroxene, and magnetite were also noted. The next sample (RC01-7-18-2) was collected more than 300 m downstream from the primary pumice and crops out in the middle section of the north wall of the canyon. It is poorly sorted and consists of coarse light gray pumice clasts. The pumices are porphyritic and contain abundant partially altered coarse, zoned, and sieved euhedral plagioclase. Minor amounts of orthopyroxene, hornblende, and quartz were also noted. A pumiceous sandstone
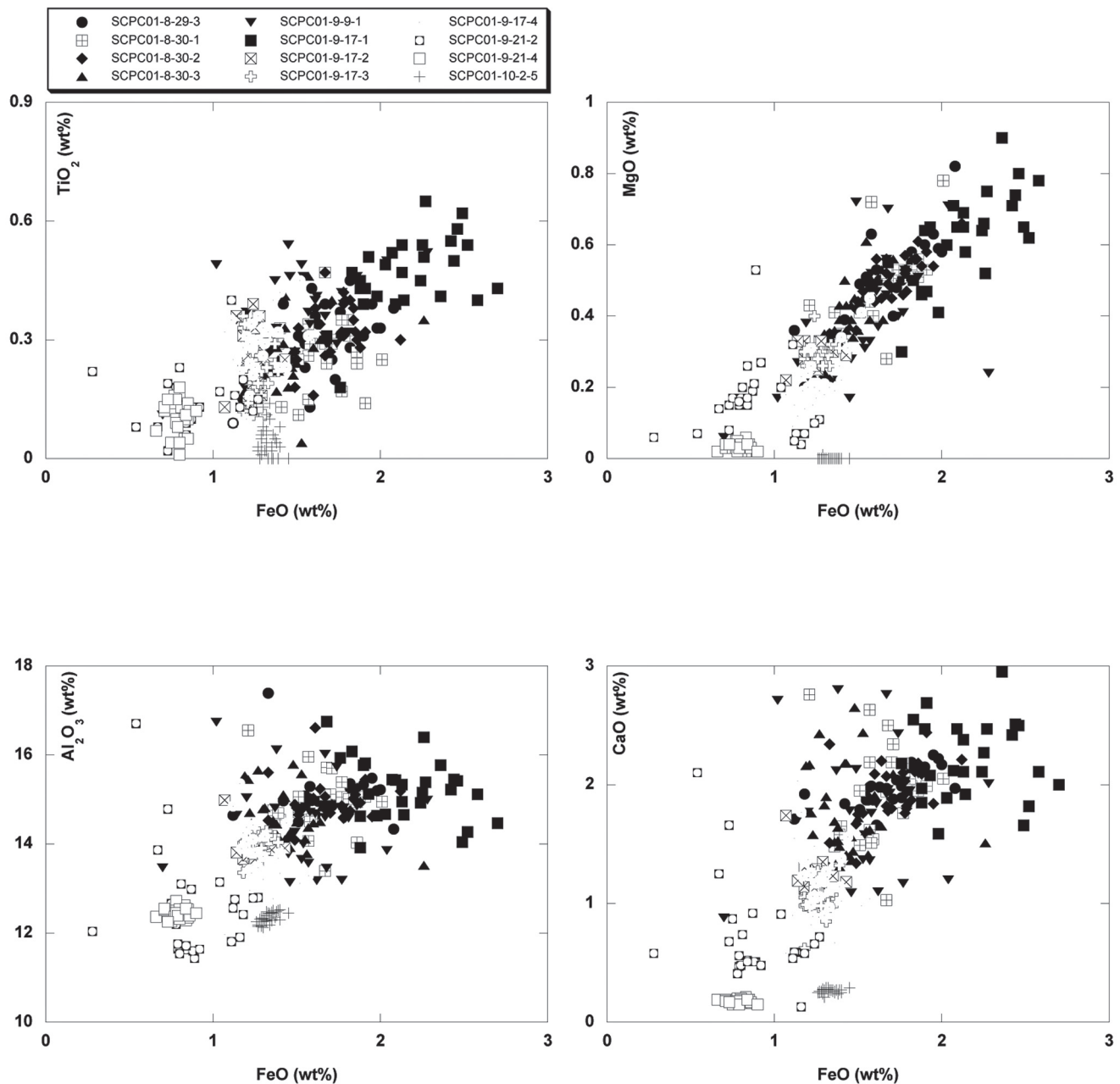
FIGURE 3. Variation diagrams of major element plots of tephra from Santa Clara Canyon and adjacent areas. Symbols represent different tephra samples.

(RC01-7-18-3) crops out in the uppermost part of the canyon wall, more than 600 m downstream from the previous outcrop (RC01-7-18-2). It is light gray, contains partially rounded clasts, and overlies the pumiceous deposit. The pumices are porphyritic with abundant plagioclase and minor orthopyroxene and hornblende. Volcaniclastic sandstone (RC01-7-23-1) with abundant altered pumice crops out at the base of the north wall close to the Rendija and Guaje Canyon intersection (Fig. 1). The pumice fragments are totally altered and no electron microprobe data was obtained.

Tephra of Guaje Canyon

An approximately 1 m-thick, medium gray, partially cemented and matrix-supported primary pumice fallout (RC01-7-23-2) deposit that is lithologically similar to a sample (RC01-7-18-1) in Rendija Canyon crops out on the north wall of Guaje Canyon, more than 10 m above a Totavi Lentil conglomerate and about 30 m above road level (Fig. 1). It is sparsely porphyritic and contains partially altered zoned and sieved plagioclase with trace amounts

TABLE 1. Major element compositions of Pliocene tephra samples from the Pajarito Plateau. The results were determined by electron microprobe analysis.

Sample Number	N	SiO$_2$	TiO$_2$	Al$_2$O$_3$	FeO	MgO	MnO	CaO	K$_2$O	Na$_2$O	P$_2$O$_5$	Oxide Total
ANCHO01-5/8-5	25	64.66	0.71	14.54	2.60	0.71	0.05	1.79	4.52	3.57	0.15	93.51
SD		1.30	0.10	0.20	0.43	0.24	0.03	0.50	0.93	0.96	0.06	1.45
ANCHO01-5/8-7	26	70.56	0.22	12.77	1.10	0.23	0.03	1.15	4.64	3.05	0.04	93.97
SD		1.52	0.06	0.57	0.16	0.06	0.02	0.31	0.43	0.47	0.03	1.48
RC01-7-18-1	27	66.68	0.49	14.33	2.35	0.70	0.04	2.28	3.39	4.04	0.13	94.64
SD		1.80	0.07	0.85	0.21	0.11	0.03	0.32	0.10	0.24	0.04	0.70
RC01-7-18-2	26	74.23	0.29	11.52	1.07	0.09	0.03	0.67	6.05	2.47	0.04	96.60
SD		1.73	0.06	0.79	0.07	0.01	0.02	0.28	0.33	0.38	0.04	2.01
RC01-7-18-3	30	70.38	0.29	13.32	1.58	0.41	0.03	1.69	3.86	3.62	0.04	95.44
SD		0.92	0.06	0.20	0.05	0.01	0.02	0.05	0.07	0.13	0.03	1.23
RC01-7-23-2	30	65.88	0.50	14.47	2.26	0.71	0.04	1.90	3.23	3.87	0.07	93.11
SD		1.11	0.07	0.25	0.18	0.09	0.03	0.09	0.12	0.20	0.03	1.42
RC01-7-23-3	29	66.42	0.53	14.48	2.34	0.71	0.04	2.32	3.39	4.01	0.08	94.52
SD		0.66	0.08	0.12	0.14	0.05	0.02	0.17	0.12	0.16	0.04	0.62
RC01-7-23-4	26	65.25	0.51	14.39	2.36	0.76	0.11	2.30	3.23	3.88	0.10	93.08
SD		1.23	0.06	0.49	0.14	0.06	0.32	0.23	0.24	0.36	0.04	1.73
RC01-7-24-1	31	72.37	0.18	12.81	0.93	0.18	0.07	1.03	4.57	3.15	0.03	95.56
SD		0.41	0.06	0.22	0.05	0.03	0.23	0.08	0.33	0.31	0.02	0.63
SCPC01-8-29-3	27	67.36	0.28	13.94	1.53	0.47	0.04	1.85	3.33	3.86	0.07	92.95
SD		1.24	0.09	0.66	0.25	0.11	0.03	0.34	0.37	0.37	0.08	1.52
SCPC01-8-30-1	22	68.93	0.25	14.11	1.54	0.49	0.04	1.81	3.29	3.72	0.06	94.47
SD		1.57	0.08	0.64	0.18	0.21	0.02	0.39	0.29	0.20	0.03	1.86
SCPC01-8-30-2	31	69.09	0.31	14.15	1.61	0.46	0.05	1.86	3.34	3.79	0.08	94.97
SD		1.29	0.06	0.44	0.19	0.09	0.03	0.33	0.19	0.20	0.03	1.28
SCPC01-8-30-3	34	69.84	0.25	13.84	1.37	0.39	0.04	1.66	3.50	4.00	0.06	95.18
SD		1.39	0.09	0.57	0.19	0.16	0.03	0.35	0.24	0.24	0.04	1.51
SCPC01-9-9-1	26	66.68	0.35	13.30	1.43	0.36	0.03	1.67	3.79	3.60	0.07	91.47
SD		1.47	0.09	0.92	0.30	0.15	0.02	0.48	0.75	0.50	0.04	1.73
SCPC01-9-17-1	24	66.18	0.45	13.98	2.12	0.58	0.04	2.07	3.27	3.57	0.08	92.55
SD		1.19	0.11	0.76	0.46	0.16	0.02	0.37	0.32	0.45	0.03	2.11
SCPC01-9-17-2	28	70.19	0.25	12.94	1.16	0.27	0.03	1.14	4.12	3.25	0.03	93.56
SD		0.89	0.06	0.32	0.06	0.02	0.02	0.12	0.17	0.18	0.03	1.13
SCPC01-9-17-3	22	70.16	0.22	13.10	1.18	0.28	0.03	0.91	3.90	3.40	0.01	93.36
SD		0.93	0.07	0.35	0.06	0.03	0.02	0.10	0.18	0.23	0.01	1.49
SCPC01-9-17-4	30	72.08	0.28	13.22	1.23	0.21	0.02	1.15	4.48	3.30	0.02	96.16
SD		0.97	0.07	0.75	0.11	0.08	0.02	0.30	0.37	0.44	0.02	1.01
SCPC01-9-21-2	24	73.78	0.14	12.00	0.85	0.15	0.03	0.70	4.46	2.96	0.02	95.23
SD		1.36	0.07	1.25	0.23	0.10	0.03	0.41	0.74	0.75	0.02	1.38
SCPC01-9-21-4	29	73.58	0.10	11.78	0.75	0.03	0.04	0.17	4.63	3.49	0.01	94.62
SD		1.04	0.04	0.19	0.05	0.01	0.03	0.01	0.27	0.24	0.01	1.38
SCPC01-10-2-5	30	73.54	0.05	11.76	1.27	0.00	0.07	0.25	4.43	3.93	0.01	95.35
SD		0.64	0.04	0.11	0.04	0.00	0.02	0.02	0.36	0.22	0.01	0.71

N=Number of glass shard analyzed.

SD=Standard deviation of averaged analysis.

of biotite and orthopyroxene. Similar pumice (RC01-7-23-3) was also sampled about 100 m to the east of the previous outcrop, and exposed about 3 m above another pumice layer (RC01-7-23-4). Pumice clasts in the two samples (RC01-7-23-3 and 4) are moderately porphyritic with coarse-zoned and sieved plagioclase grains and glomeroporphyritic clots of plagioclase, hornblende, and biotite in a glassy matrix. Both pumice beds are of similar thickness but they are separated by massive and bedded sandstone with abundant dacite clasts.

More pumice beds are exposed in the lower half of the south wall of Guaje Canyon, along the fence line between Los Alamos County and San Ildefonso Pueblo. The upper pumice bed is simi-

lar to pumice outcrops exposed along the north wall of the canyon across from this section. The underlying pumice unit (RC01-7-24-1) crops out in the lower half of the canyon wall. It is dark gray and consists of bedded pumice and ash layers and reworked tuff in ascending order. The pumices are porphyritic with abundant plagioclase, sanidine, hornblende, and biotite with minor quartz. Conglomerate of the Totavi Lentil is exposed about 4 m below the lower tuff.

The tephra samples from Rendija and Guaje Canyons represent chemically distinct glass shards, except for one sample (RC01-7-18-4) that contains multiple populations of glass shards (Table 1,;Fig. 2). Most of the tephra samples (RC01-7-18-1, RC01-7-23-2, RC01-7-23-3, and RC01-7-23-4) are chemically identical and represent a low-silica rhyolite unit. The other tephra units (RC01-7-18-2, RC01-7-18-3, and RC01-7-24-1) have higher silica contents but they plot as separate clusters in the major element variation diagram (Fig. 2). For example, two of the pumice units (RC01-7-18-2 and RC01-7-18-3) from Rendija Canyon represent high-silica end members, whereas the pumice layer (RC01-7-24-1) from the south wall of Guaje Canyon represents an intermediate composition and half of the shards are chemically similar to the lower pumice unit in Ancho Canyon (Table 1; Fig. 2).

Tephra from mesa top south of Santa Clara Canyon

An isolated reworked tephra deposit with interbedded primary pumice (SCPC01-9-21-4) crops out to the south of Sawyer Canyon along the eastern edge of a mesa (Fig. 1). The pumice bed occurs in the middle part of a volcaniclastic unit (>2 m thick) that is sandwiched between bedded sandstone and a thick sequence (> 50 m) of fanglomerate of the Puye Formation. The bedded pumice layer is about 40 cm thick, clast-supported, sorted, and poorly consolidated. It is glassy and sparsely porphyritic with minor sanidine and quartz. Another pumice deposit (SCPC01-10-2-5) is exposed along the Pajarito fault zone and in a nearby road cut located to the west of Santa Clara Canyon (Fig. 1). Although the top and bottom parts of the outcrop are obscured by talus and vegetation, the massive pumice deposit is sorted, clast supported, poorly consolidated, and about 2 m thick. Sparse phenocrysts of coarse quartz, plagioclase, and sanidine are embedded in a fresh glassy matrix. Light brown to orange vapor phase minerals are common in between individual pumice clasts.

Both samples are high-silica rhyolite with minor variations in major element contents (Fig. 3). Although both pumice deposits contain generally similar Al_2O_3, TiO_2, MgO, and CaO contents, obvious differences are noted in their SiO_2, K_2O, Na_2O, and FeO compositions (Table 1). For example, the pumice deposit to the south of Sawyer Canyon contains slightly higher SiO_2 and K_2O and lower FeO than the thick pumice exposed along the Pajarito Fault zone.

Tephra of Santa Clara Canyon east of Pajarito fault zone

Upper Miocene and Pliocene primary and reworked tephra units crop out in Santa Clara Canyon in the northern part of the Pajarito Plateau. Most of the tephra units occur within the Puye Formation along the north wall of Santa Clara Canyon upstream and downstream from the Pajarito fault zone intersection (Fig. 1). Two reworked and totally altered upper Miocene pumice deposits crop out at the top of Santa Fe Group sedimentary section about 50 m below conglomerate of the Totavi Lentil in the eastern part of Santa Clara Canyon. However, only the Pliocene pumice and vitric ash deposits interbedded within the Puye Formation are described here. A massive, white, clast-supported, reworked pumice-rich unit (SCPC01-8-29-3) that is poorly sorted, reverse graded, and mixed with dacite fragments crops out about 20 m above road level on the north wall of the canyon (Fig. 1). It is porphyritic with coarse, zoned, and partially altered plagioclase, coarse biotite, and minor hornblende in a glassy matrix.

Another reworked coarse volcaniclastic sandstone with abundant pumice clasts occurs about 2 m above a conglomerate of the Totavi Lentil in Sawyer Canyon about 0.5 km upstream from its intersection with Santa Clara Canyon (Fig. 1). The pumice-rich deposit (SCPC01-9-9-1) is brownish gray, fairly sorted, matrix supported, and mixed with dacite and quartzite fragments (Table 1). The pumice-rich deposit is exposed in the middle part of the section below a fanglomerate that contains abundant dacite boulders and cobbles. Pumice clasts are embedded in a crystal-rich volcaniclastic sandstone with abundant lithic fragments. The pumice clasts contain coarse plagioclase and minor hornblende.

Tephra of Santa Clara Canyon west of Pajarito fault zone

A thick (5-7 m), partially baked pumice-rich volcaniclastic unit (SCPC01-9-21-2) occurs beneath upper Miocene (10.16±0.06 Ma) lava at the top of the Polvadera Group in Santa Clara Canyon (WoldeGabriel et al., 2006). About 300 m downstream from the upper Miocene outcrop, a thick sequence of primary and reworked tephra deposit of the Puye Formation crops out on a fault block that is displaced down to the east. Three pumice units were sampled from this section (known as 'Castle Rocks'), which is characterized by several boulder-capped spires made up of primary and reworked tephra layers (Fig. 1). A sample (SCPC01-8-30-1) from the base of a 0.6 m-thick pumice layer above a fanglomerate sequence of dacite boulders and cobbles is massive, medium gray, moderately sorted and indurated. The pumice deposit contains abundant dacite lithic fragments that are smaller than the pumice clasts. It is fairly porphyritic with partially altered plagioclase, coarse biotite, and hornblende. The pumice bed is underlain by a mixture of clast-supported basaltic and dacitic cobbles and boulders.

A 0.4 m-thick coarse pumiceous sandstone separates the lower pumice unit (SCPC01-8-30-1) from the next sample (SCPC01-8-30-2). This upper pumice bed is massive, medium gray, moderately sorted and moderately indurated. It contains similar phenocrysts but fewer dacite fragments compared with the underlying pumice unit. Bedded coarse pumiceous sandstone and fanglomerate crop out above the second pumice unit. The upper pumice deposit (SCPC01-8-30-3), interbedded within a volcaniclastic sandstone, is thicker (1.5 m) and occurs about 2.4 m above the

middle pumice. Like the underlying two pumice layers, it is massive, sorted, and partially consolidated. Less abundant but similar minerals phase were noted in the upper pumice unit. The sample is more reworked and contains a silty clay matrix. The section at 'Castle Rocks' is capped by fanglomerate.

Additional pumice samples were collected from primary and reworked tephra deposits on the west side of the 'Castle Rocks' section, close to fault contact with middle and upper Miocene Polvadera Group lava flows and volcaniclastic deposits (Fig. 1). A pumice (SCPC01-9-17-1) deposit in the middle of the Puye Formation consists of a basal coarse layer with an upper reworked vitric ash. It is about 0.5 thick, massive, and is sandwiched between fanglomerate deposits with abundant dacite boulders and cobbles. It is sparsely porphyritic with minor amounts of plagioclase and fine-grained hornblende. Another pumice layer (SCPC01-9-17-2) crops out at the top of the tephra sequence about 6 m above the previous sample. It is massive, matrix supported, strongly consolidated, and crystal-rich with glomeroporphyritic clusters of coarse plagioclase, biotite, and hornblende grains in a glassy matrix.

Two additional pumice samples were collected from the lower half of the section. The outcrops are generally similar to the overlying pumice units. A pumice layer (SCPC01-9-17-3) that is about 10 m below the first sample (SCPC01-9-17-1) is massive, clast-supported, and contains abundant fine-grained dacite lithic fragments. It is porphyritic and contains similar mineral assemblages as the overlying pumice deposits. This pumice layer occurs between orange silty clay with lenses of coarse sandstone and an underlying thick (15 m) fanglomerate. Partially reworked and altered pumice (SCPC01-9-17-4) defines the base of the section. It is about 0.6 m thick, poorly bedded, and sandwiched between fanglomerate units containing abundant basaltic lithic fragments of variable sizes. The pumice fragments are porphyritic and contain similar phenocrysts like the overlying pumice beds, suggesting eruption from the same source.

The tephra samples from Santa Clara Canyon and adjacent areas are low- to high-silica rhyolite (Fig. 3). Except for the two samples collected from the mesas between Guaje and Santa Clara Canyons (SCPC01-9-21-4 and SCPC01-10-2-5), most of the Santa Clara Canyon samples exhibit minor scattering that is consistent with mixing of glass shards having slightly different compositions (Table 1; Fig. 3). Despite the scattering, three tephra samples (SCPC01-8-30-1 to SCPC01-8-30-3) from the 'Castle Rocks' section are chemically similar to two pumice units that crop out near the intersection of Sawyer and Santa Clara Canyons east of the Pajarito fault zone (Table 1; Figs. 1, 3). Three additional samples (SCPC01-9-17-2 to SCPC01-9-17-4) collected at the western part of the 'Castle Rocks' section exhibit tighter cluster in the variation diagram, consistent with less contamination (Fig. 3). Minor chemical variation exists between the pumice outcrops collected on the east and west sides of the 'Castle Rocks' section. One of the samples (SCPC01-9-17-1) from the middle part of the west side of 'Castle Rocks' is more mafic with slightly higher FeO and TiO_2 contents than the rest of the pumice deposits exposed at the section (Figs. 1, 3).

DISCUSSION

The variation diagrams show chemical correlations and differences among the various tephra units interbedded within the Pliocene Puye Formation of the Pajarito Plateau (Figs. 2. 3). Most of the tephra samples belong to low- and high-silica rhyolite (70-79 wt % SiO_2), except for a rhyodacite to trachydacite (68-69 wt% SiO_2) sample (Ancho01-5-8-5) from Ancho Canyon. Despite having distinct compositions, the tephra are characterized by narrow ranges of chemical variation in Al_2O_3 (11-16 Wt%), CaO (0.2-3 wt%), FeO (0.6-1 wt%), MgO (0-1wt%), and TiO_2 (0-1wt%) concentrations (Table 1).

Source of Pliocene tephra in the Pajarito Plateau

We compared our major element results with published chemical data of Tschicoma Formation flows to determine the source of the tephra units described here. According to Turbeville et al. (1989), the tephra deposits in Guaje and Santa Clara Canyons were derived from the Tschicoma eruptive centers at the northeastern part of the Jemez volcanic field. However, their published bulk pumice chemical data are dacitic, containing higher CaO (3.35-3.42 wt%), Fe_2O_3 (3.49-3.61 wt%), and MgO (1.48-1.61 wt%) oxides (data included in Loeffler et al., 1988) compared with the rhyodacite to trachydacite tephra (Ancho01-5-8-5) from Ancho Canyon.

Chemical data from the Rhyodacite of Rendija Canyon and from the Dacite of Caballo Mountain in the Sierra de los Valles (Broxton et al., 2007) are chemically similar to most of the tephra described for Rendija and Guaje Canyons (Table 1). For example, the major (SiO_2=66.2-66.3 wt%, TiO_2=0.49-0.55 wt%; Fe_2O_3=3.40-4.23 wt%, MgO=1.76-1.87 wt%, and CaO=3.48-3.54 wt%) and trace (Ba=1080-1330 ppm, Sr=553-612 ppm, and Zr=149-172 ppm) element contents of bulk chemistry of the Dacite of Caballo Mountain (Broxton et al., 2007) are mostly identical to the bulk chemistry (SiO_2=62.64-66.07 wt%, TiO_2=0.49-0.55 wt%; Fe_2O_3=3.40-3.52 wt%, MgO=1.85-2.08 wt%, CaO=2.5-3.62 wt%, Ba=877-1052 ppm, Sr=349-582 ppm, and Zr=154-179 ppm) of pumice in Ancho (Ancho01-5-8-7) and Bayo (RWTB4B10) Canyons (WoldeGabriel et al., 2001, 2006). Moreover, chemical data (SiO_2=69.7-71.3 wt%, TiO_2=0.33-0.38 wt%; Fe_2O_3=2.54-2.95 wt%, MgO=0.88-1.47 wt%, CaO=2.18-2.23 wt%) from the Rhyodacite of Rendija Canyon (Broxton et al., 2007) are chemically similar to a widespread low-silica rhyolite unit from Ancho, Rendija, and Guaje Canyons (Table 1).

Despite older ages (7.5-5.8 Ma), the chemical data for the early El Rechuelos Rhyolite flows (SiO_2=72.33-73.68 wt%, Al_2O_3=13.91-14.29 wt%, TiO_2=0.25-0.28 wt%; Fe_2O_3=1.60-1.78 wt%, MgO=0.26-0.31 wt%, CaO=1.22-1.43 wt%) from Loeffler et al. (1988) are generally similar to the Santa Clara Canyon pumice units (SiO_2=65.82-73.87 wt%, Al_2O_3= 12.26-14.39 wt%, TiO_2=0.18-0.37 wt%; Fe_2O_3=1.42-1.88 wt%, MgO=0.22-0.63 wt%, CaO=1.58-2.11 wt%). The compositional similarity suggests that most of the tephra deposits in Santa Clara Canyon

probably erupted from the early El Rechuelos Rhyolite center. A group of high-silica pumice deposits from Santa Clara Canyon contain low Al_2O_3, TiO_2, Fe_2O_3, MgO, and CaO contents and no correlative source areas were identified.

Correlation of Pliocene tephra in the Pajarito Plateau

Field characteristics, petrographic results, and major element chemical data of the various tephra samples from the Pliocene Puye Formation were compared to each other to identify correlative units that can be used as stratigraphic markers. Although major element data from electron microprobe show minor variations (Table 1), the bulk major and trace element contents of two pumice deposits at the base of the Puye Formation in Ancho and Bayo Canyons are identical (WoldeGabriel et al., 2001, 2006). The high CaO content in the Bayo pumice is due to secondary calcite cement.

High-silica pumice samples from the uppermost part of the Puye Formation in Rendija, (RC01-7-18-3) and Santa Clara (SCPC01-8-29-3, SCPC01-8-30-1 to SCPC01-8-30-3, and SCPC01-9-9-1, SCPC01-9-17-1) Canyons are also correlative. They contain similar amounts of Fe_2O_3=1.55-1.65 wt% and CaO=1.56-1.80 wt% and lower MgO=0.39-0.44 wt% contents (Table 1).

The upper Miocene pumice-rich volcaniclatic unit (SCPC01-9-21-2) at the top of the Polvadera Group is chemically distinct from the Pliocene tephra of the Puye Formation and contains the highest silica (78-79 wt%) content. The pumice outcrop that caps the Puye Formation to the south of Sawyer Canyon (SCPC01-9-21-4) is correlative to pumice beds of the Cerro Toledo Formation, whereas the thick pumice along the Pajarito fault zone is correlative to the Tsankawi Pumice of the Bandelier Tuff.

Volcanic, tectonic, and sedimentation records in the Pajarito Plateau

The Pliocene stratigraphic sequence of the Pajarito Plateau records complex interactions of contemporaneous tectonic activities, felsic and basaltic volcanism, and extensive erosion and voluminous alluvial fan and fluvial sedimentation along the western part of the Española Basin. In the Pliocene, basaltic volcanism and faulting dictated the sedimentation process in the south-central part of the area currently defined by the plateau. For example, in Frijoles Canyon, the stratigraphic sequence contains <2 m of Totavi Lentil conglomerate related to ancestral river gravel deposits, interbedded within a thick (>100 m) Pliocene (3.03-2.68 Ma) basaltic lava and hydromagmatic basaltic tephra sequence (WoldeGabriel et al, 2006). No alluvial fan deposits occur in the section. However, a few kilometers to the north of Frijoles Canyon, exploratory boreholes (Fig. 1) drilled for groundwater characterization intersected thick interbedded basaltic lava flows of Cerros del Rio and alluvial fans and fluvial deposits of the Puye Formation in R-31 (~130 m of Cerros del Rio Lava, 21 m of alluvial fan, and 68 m of Totavi Lentil conglomerate in descending stratigraphic order), R-19 (29 m of alluvial fan, 47 m of Cerros del Rio lava, 137 m of lower fanglomerate, and 110 m of pumiceous sedimentary deposits), and R-25 (330 m of alluvial fan facies) (Broxton et

al., 2001, 2002; Vaniman et al., 2002). The distribution of the various lithologic units suggests that the accumulation of thick Puye Formation alluvial fans and fluvial deposits were mostly confined to the north of Frijoles Canyon (Fig. 1).

In Ancho Canyon, pumice-rich alluvial fan deposits below Totavi Lentil conglomerate (15-20 m thick) are thinner compared with alluvial fans intersected in R-19, R-25, and R-31 drill holes. Pumice cuttings from pumiceous beds interbedded within alluvial fans intersected in exploratory boreholes (R-7, R-13, R-15, R-19, R-25) in the central Pajarito Plateau, to the north of Frijoles and Ancho Canyons, yielded late Miocene to early Pliocene ages (7.5-5.03 Ma, Broxton and WoldeGabriel, unpubl.). These results suggest older and thicker alluvial fan deposits accumulated close to the source of the sediments from the Sierra de los Valles eruptive centers and at close proximity to the location of the current western margin of the Española Basin. The Upper Miocene pumice cuttings from the central Pajarito Plateau are temporally correlative to the Peralta Tuff Member of the Bearhead Rhyolite (7.06-6.15 Ma) center in the southern Jemez volcanic field (Justet and Spell, 2001; Smith, 2001). In Ancho and Bayo Canyons, the Puye Formation sequence is younger than 5.31±0.02 Ma (WoldeGabriel et al., 2001). Based on field relations and tephra correlation, the Puye Formation deposits in Rendija, Guaje, and Santa Clara Canyons are younger than the Ancho and Bayo Canyon alluvial fans because the Pliocene tephra to the north of Bayo Canyon occur at a higher elevation and above conglomerate of the Totavi Lentil.

The occurrence of older alluvial fans below the central and north-central part of the Pajarito Plateau is also consistent with the distribution of upper Miocene lavas in the area (WoldeGabriel et al., 2001, 2006). For example, upper and middle Miocene volcanic rocks are exposed at Ancho, Bayo, and Santa Clara Canyons. In the same locations, Puye Formation alluvial fans and fluvial deposits are substantially reduced in thickness. However, in the intervening areas of central and north-central Pajarito Plateau (i.e., between Ancho and Bayo and between Bayo and Santa Clara Canyons), extensive alluvial fan and fluvial sediments of the Puye Formation occur above thick upper Miocene and middle Miocene mafic lava flows (Broxton et al., 2001, 2002; Vaniman et al., 2002; WoldeGabriel et al., 2006). The distribution and thickness of the Puye Formation suggests contemporaneous sedimentation and subsidence close to the foothills of the Sierra de los Valles eruptive centers. The occurrence of the Tschicoma Formation eruption centers along the eastern part of the Jemez volcanic field, the continuous supply of sediments, and the increased thickness of the alluvial fans of the Puye Formation suggest a contemporaneous active fault zone more or less along the current location of the western boundary fault of the Española Basin, suggesting that the Pajarito fault zone was active during the Pliocene (WoldeGabriel et al., 2006).

The tephra units in Ancho, Bayo, Rendija, Guaje, and Santa Clara Canyons are mostly interbedded within different lithologic units of pumiceous sandstone and dacite and basaltic fanglomerate deposits. This association suggests different source areas contributed to the western part of the Española Basin during the Pliocene.

SUMMARY AND CONCLUSIONS

Although upper Miocene pumiceous deposits were encountered in boreholes in the central part of the Pajarito Plateau, most of the tephra deposits of Pliocene age are widely distributed within the Puye Formation in the area currently defined by the Pajarito Plateau. Chemical correlation was established among the tephra beds exposed between Ancho and Santa Clara Canyons. These tephra are chemically related to high- and low-silica rhyolite lavas and tephra of the Dacite of Rendija Canyon and Dacite of Caballo Mountain located along the northeastern part of the Jemez volcanic field. The deposition of the Puye Formation appears to have been dictated by preexisting structures and by contemporaneous felsic and mafic volcanism related to Tschicoma Formation centers in the Sierra de los Valles and the Cerro del Rio volcanic field, respectively.

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