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DISTRIBUTION OF DACITE LAVAS BENEATH THE PAJARITO PLATEAU, JEMEZ MOUNTAINS, NEW MEXICO

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Abstract—Boreholes drilled for groundwater characterization at Los Alamos National Laboratory (LANL) encountered four petrographically and chemically distinct dacite lavas beneath the Pajarito Plateau. Coarsely porphyritic lavas with 17-38% phenocrysts (42-74% plagioclase, up to 28% pyroxene, 15-43% amphibole) and 64.9-66.3% SiO_2 occur in boreholes in the southwest part of LANL. Modal mineralogy and chemistry links these lavas to Cerro Grande, a Sierra de los Valles dacite dome west of the study area. Boreholes in the west-central part of LANL encountered a thin dacite lava with 22% phenocrysts (81-83% plagioclase, 12-15% pyroxene, and 1% relict amphibole) and relatively high SiO_2 (67.4%) overlying equally thin basaltic lavas of the Cerros del Rio volcanic field. Boreholes in the northern part of LANL encountered thicker fine-grained dacitic lava with 2-5% phenocrysts (up to 35% plagioclase, 61-88% pyroxene, absent or minor amphibole) and relatively low SiO_2 (~63.5%). One borehole in the east-central part of LANL encountered a sequence of three crystal-poor (4-6% phenocrysts) dacite lavas, with ~66% SiO_2, 4-6% resorbed quartz and trace amounts of resorbed olivine, intercalated with basalt. Pajarito Plateau dacite lavas erupted over a relatively short time interval (2.3-3.6 Ma) during which both the Jemez Mountains and Cerros del Rio volcanic fields were active. The southwestern group of dacites probably represents a thick lobe of Cerro Grande lava that flowed ~3.5 km eastward into the subsiding Española Basin. Other plateau dacites, which do not correlate with dacites exposed in the Sierra de los Valles, probably represent local eruptions within the western part of the basin. Thickness variations and spatial distribution indicate the northern group of dacites probably erupted from a buried vent near the Pajarito fault zone. The dacites encountered in the west-central and eastern parts of LANL represent minor pulses of dacite volcanism in areas dominated by basaltic volcanism of the Cerros del Rio volcanic field. The Pajarito Plateau dacites overlap spatially and temporally with intermediate volcanic rocks in the eastern part of the Jemez volcanic field and with mafic volcanic rocks in the western part of the Cerros del Rio volcanic field. The distinctive compositional and petrographic characteristics of the Plateau dacites probably reflect a transitional style of magmatism that developed in the narrow region between these adjacent, concurrently active volcanic fields.

INTRODUCTION

Eight boreholes drilled for environmental restoration and seismic hazards programs at Los Alamos National Laboratory (LANL) encountered previously unknown dacite lavas beneath the Pajarito Plateau (Figs. 1, 2). These dacite lavas are of interest because they are less permeable than the enclosing Puye Formation, one of the major Pajarito Plateau aquifer units (Purtymun, 1984, 1995). Additionally, perched-intermediate groundwater beneath the Pajarito Plateau is commonly associated with buried lava flows (Robinson et al., 2005). Variations in modal mineralogy, mineral texture, and chemistry suggest that these lavas represent four separate pulses of dacite volcanism. Understanding the spatial distribution of these low-permeability dacite lavas in the subsurface is important for groundwater monitoring and for modeling groundwater and contaminant flow between LANL and surrounding communities. This paper describes the distribution of these four dacite lavas in the subsurface and summarizes their diagnostic chemical and petrographic characteristics.

GEOLOGIC SETTING

The Pajarito Plateau is an east-dipping ignimbrite plateau that overlies the western part of the Española Basin of the Rio Grande rift (Fig. 1). The Pajarito fault zone, a major active rift-bounding fault in the western part of the Española Basin, separates the Pajarito Plateau from the Jemez Mountains to the west. The surface geology of the Pajarito Plateau is dominated by the Quaternary Bandelier Tuff, which erupted from the Valles caldera between 1.61 and 1.22 Ma (Griggs, 1964; Smith et al., 1970; Izett and Obradovich, 1994; Spell et al., 1996). The principal groundwater resource beneath the plateau occurs within Miocene and Pliocene fluvial sedimentary rocks that fill the western portion of the Española Basin (Griggs, 1964; Purtymun, 1995). Miocene and Pliocene basalts and Pliocene dacite lavas are intercalated with the basin-fill sedimentary deposits, and they are significant components of the local aquifer (WoldeGabriel et al., 1996, 2001, 2006; Broxton and Vaniman, 2005). These lavas represent eruptions near the margins of the Jemez Mountains volcanic field (JMVF) and the Cerros del Rio volcanic field (CdRVF), located west and southeast of the Pajarito Plateau, respectively (Fig. 1).

Lavas of the JMVF most relevant to this investigation belong to the Tschicoma Formation of the Polvadera Group (Griggs, 1964; Smith et al., 1970; Broxton et al., 2007). The Tschicoma Formation is best exposed in the Sierra de los Valles, the mountainous highlands west of Los Alamos. Tschicoma lavas in the Sierra de los Valles erupted from overlapping dacite dome complexes that include the proximal source areas at Cerro Grande, Pajarito Mountain, and the headwaters of Rendija Canyon (Gardner et al., 2006; Broxton et al., 2007). Samples of flows collected on Cerro Grande and Pajarito Mountain yield $^{40}Ar/^{39}Ar$ ages of 3.07 ± 0.11 to 3.35 ± 0.17 Ma and 2.93 ± 0.06 to 3.09 ± 0.08 Ma,

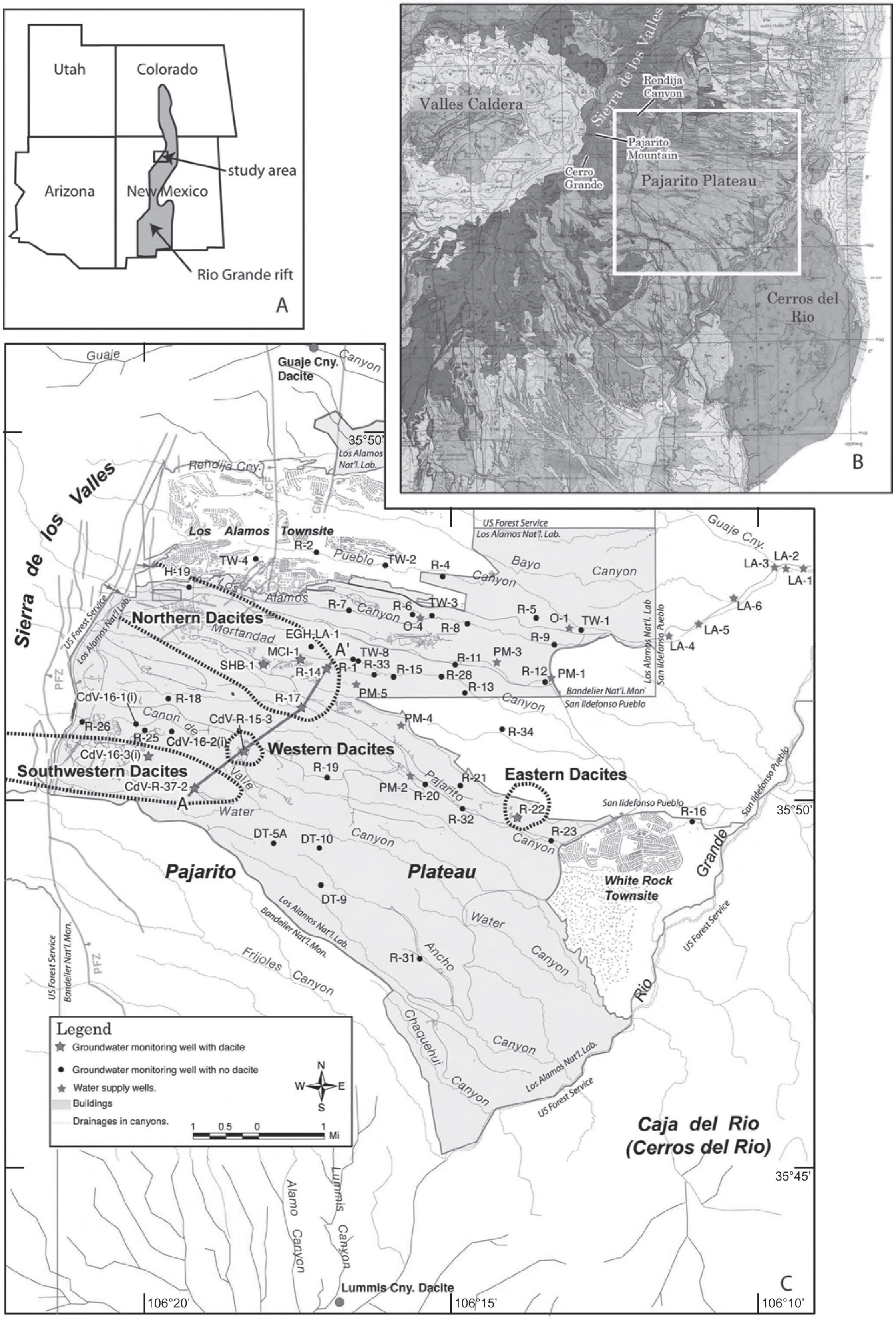

FIGURE 1. Location map. A. Index map (modified from Gardner and Goff, 1984) shows the location of the Pajarito Plateau in relation to the Rio Grande rift. B. Location map (modified from Smith et al., 1970) shows the Pajarito Plateau, the Cerros del Rio volcanic field, and the Valles caldera and Sierra de los Valles of the Jemez Mountains volcanic field. The Sierra de los Valles are made of Tschicoma Formation dacite lavas. The Cerros del Rio volcanic field is mostly mafic in composition with minor andesite to dacite lavas. C. Map of the study area. Los Alamos National Laboratory is shown as the gray area. See legend for borehole and well symbols. Cross section A-A' is included as Figure 6.

respectively (Broxton et al., 2007). Rendija Canyon rhyodacite has $^{40}Ar/^{39}Ar$ ages ranging from 4.98 $\pm$ 0.05 Ma to 5.36 ± 0.02 Ma (Broxton et al., 2007).

The CdRVF is mainly exposed as the Caja del Rio basalt plateau on the east side of the Rio Grande (Fig. 1). The exposed part of the volcanic field trends north-south for ~40 km and is up to 20 km wide. The volcanic field extends an additional 11 km beneath the Pajarito Plateau, but the Bandelier Tuff covers it (Dransfield and Gardner, 1985; Broxton and Reneau, 1996). The exposed portion of the volcanic field is made up of about a dozen volcanoes and >70 cinder cone, plug, and tuff ring vents (Kelley, 1978; Aubele, 1979). Basalts and related intermediate-composition lavas erupted primarily between 2.3 and 2.8 Ma are the predominant rock types in the CdRVF (Dethier, 1997; WoldeGabriel et al., 1996, 2001; Sawyer et al., 2002; Baldridge, 2005). Minor dacites occur in the CdRVF, particularly at Tetilla Peak where a small dacite dome caps a mainly latite to trachyandesite volcanic edifice (Sawyer et al., 2002). Although basaltic andesite to andesite composition lavas have been documented in outcrop in White Rock Canyon and east of the Rio Grande (Dethier, 1997; Sawyer et al., 2002), CdRVF dacites have not been documented previously west of the Rio Grande.

METHODS

Point counts of major mineral phases, including plagioclase, pyroxene, and amphibole, were done on 18 thin sections of cuttings from boreholes CdV-16-3(i), CdV-R-37-2, CdV-R-15-3, R-14, SHB-1, and R-22 and of core from MCI-1 (Figs.1, 2) with an average of 970 counts per thin section (Table 1). Phases <0.1 mm in diameter, including groundmass plagioclase, were counted as matrix rather than phenocrysts. No thin sections are currently available for R-17, so this sample was not characterized petrographically. Point counts for borehole samples were compared with point counts of samples from Tschicoma lavas exposed in the Sierra de los Valles (Table 1; Broxton et al., 2007).

Major and trace elements were analyzed using an automated Rigaku wavelength-dispersive X-ray fluorescence (XRF) spectrometer. Samples were first crushed and homogenized in 5-10 g portions in a tungsten-carbide ball mill. Sample splits were heated at 110°C for 4 hrs, and then allowed to equilibrate at ambient laboratory conditions for 12 hrs. To obtain the fusion disks, one-gram splits were mixed with 9 g of lithium tetraborate flux and initially heated in a muffle furnace for 45 min at 1100°C, followed by a second heating for 1 hr at 1150°C. Additional one-gram splits were heated at 1000°C to obtain the Loss on Ignition (LOI) measurements to be used in the data reduction program. Elemental concentrations were calculated by comparing X-ray intensities for the samples to those for 21 standards of known composition using “consensus values” from Govindaraju (1994). Raw intensities were adjusted using a fundamental parameters program for matrix corrections (Criss, 1979). Abundances of REE and several other trace elements in some borehole samples were determined at Washington State University using the methods of Knaack et al. (1994).

Plagioclase and pyroxene mineral chemistry was determined by electron probe microanalysis (EPMA), using a Cameca SX50 electron microprobe, equipped with four wavelength dispersive spectrometers (WDS) at LANL. Quantitative WDS analyses were obtained at 15 kV accelerating voltage and 15 nA beam current. Although these data did not prove diagnostic for correlations, systematic variations in plagioclase composition in well R-22 dacites provide insights into petrogenesis and the analyses are presented. Calibrations of all analyzed elements and analytical conditions were carried out on natural standards. Data reduction followed the ZAF method.

TABLE 1. Point counts of thin sections from outcrop and borehole dacite samples.

	Cerro Grande outcrop	Pajarito Mtn outcrop	Rendija Canyon outcrop	CdV-R-37-2 cuttings	CdV-16-3(i) cuttings	MCI-1** core	R-14** cuttings	CdV-R-15-3 cuttings	R-22 cuttings
% total (range)									
Phenocrysts	21	24	16	17-38	19-25	2	3	18-26	4-6
Matrix	79	76	84	63-83	75-81	98	97	74-82	94-96
% phenocrysts (range)									
Plagioclase	71	69	29	42-70	56-74	6-35	0-23	81-83	52-73
Opx + cpx	9	10	0	0-28	3-19	61-88	69-82	12-15	18-21
Amph + alt mafic after amph	16	17	0	15-43	19-24	0	0	1	0
Opaque	5	4	2	2-12	2-4	0	0	3	2-3
Quartz	0	0	20	0	0	4	0	0	4-7
Sanidine	0	0	14	0	0	0	0	0	0
Altered mafic (unidentifiable)	0	0	4	0	0	6	8-18	0	2-17
Total Samples Counted	1	1	1	6	4	2	2	2	2
Total points	1865	1966	1061	7016	4197	2133	824	1507	1418

**Only phenocrysts identifiable by optical petrography were counted as phenocrysts. Smaller phases were counted as matrix. Groundmass plagioclase is the most common phase in these samples, but larger plagioclase grains are absent to rare.

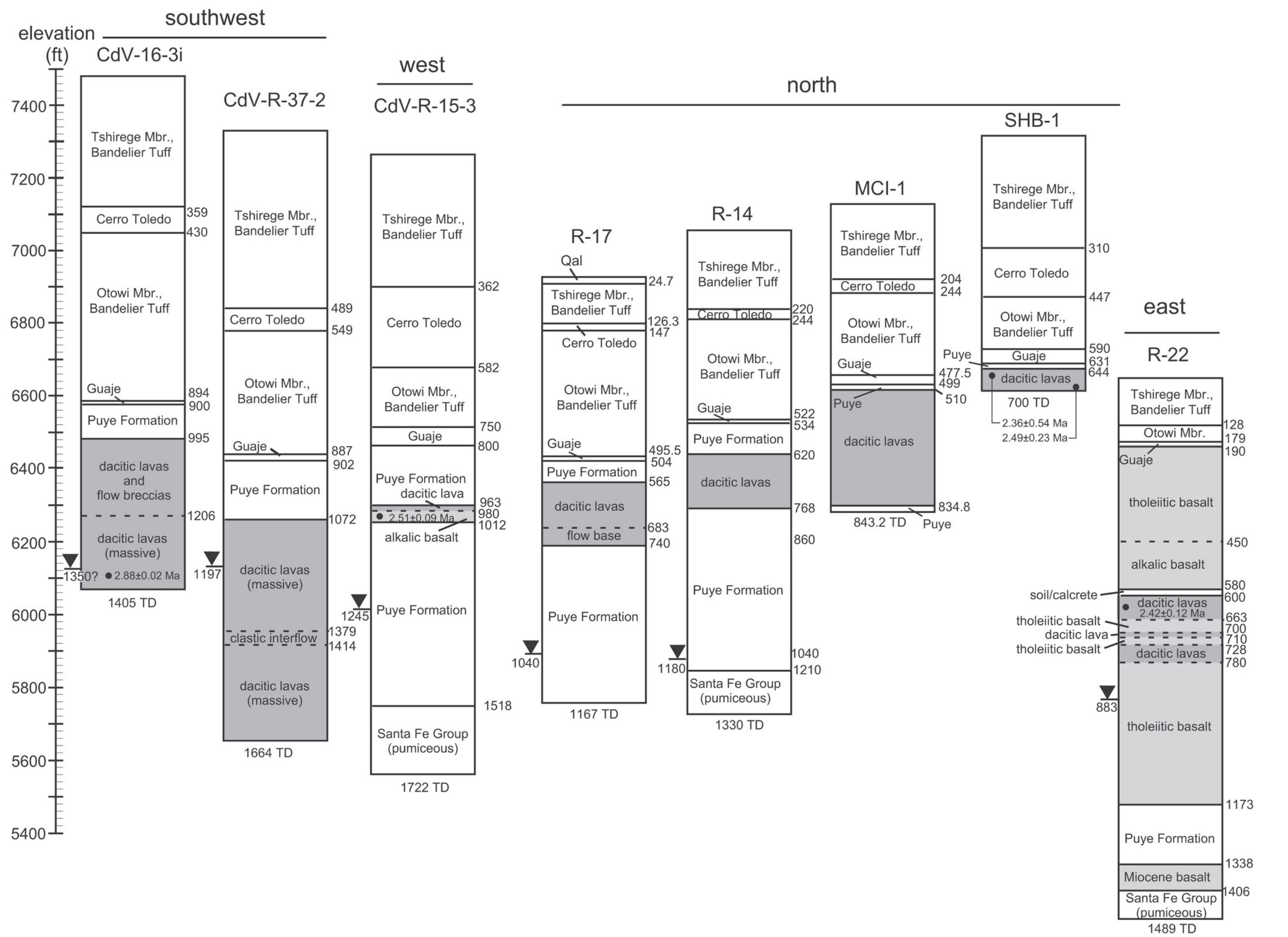

FIGURE 2. As-drilled well logs of dacite-bearing boreholes, showing thickness and elevation above sea level of southwestern, western, northern, and eastern dacites. Boreholes CdV-16-3(i), CdV-R-37-2, and SHB-1 did not fully penetrate the dacite.

RESULTS

Pajarito Plateau dacites cluster into four petrographically and chemically distinct groups of lava flows inferred to be separate extrusive bodies. The locations of these four groups are shown in Figure 1, and they are described by their geographic areas in the following discussion. Table 1 presents petrographic data and Table 2 presents representative major and trace element data for borehole dacites and for potential Tschicoma source rocks.

Southwestern dacite

The southwestern lavas (boreholes CdV-16-3(i) and CdV-R-37-2) consist of a thick stack (> 592 ft) of coarsely porphyritic hornblende dacite lava flows with 17-38 vol. % total phenocryst content (Fig. 2; Table 1). Plagioclase is the most abundant phenocryst, representing 42-74% of total phenocrysts in the drill cuttings. Two populations of plagioclase phenocrysts are present: euhedral crystals up to several millimeters in diameter with sieved cores and relatively clear rims (Fig. 3A) and smaller unsieved twinned laths (Fig. 3B). Abundant microlites give these rocks a trachytic texture. Hornblende (Fig. 3C) is the dominant mafic phase, accounting for 15-43% of the total phenocryst content, whereas clinopyroxene and orthopyroxene together represent up to 28% of the total phenocryst content.

Dacite lavas in boreholes CdV-16-3(i) and CdV-R-37-2 overlap chemically with each other and with hornblende-bearing dacite lavas of Cerro Grande (Figs. 4, 5), although with small vertical variations within the lava sequences in the two boreholes. In CdV-R-37-2, silica content decreases with depth from 66.4 wt % to 64.9 wt %. In CdV-16-3(i), silica content increases with depth from 65.75 to 66.71 wt %. Borehole images from a formation microimager log show flow breaks within the thick sequence of dacite in CdV-R-37-2. The flow breaks include thin sedimentary or brecciated regions of lower resistivity than the surrounding massive lavas. The petrographic similarities between lavas in CdV-R-37-2 and CdV-16-3(i) indicate a cogenetic origin with little time between eruptions. A sample from CdV-16-3(i) yielded an $^{40}Ar/^{39}Ar$ age of 2.88 ± 0.02 Ma (Broxton et al., 2007).

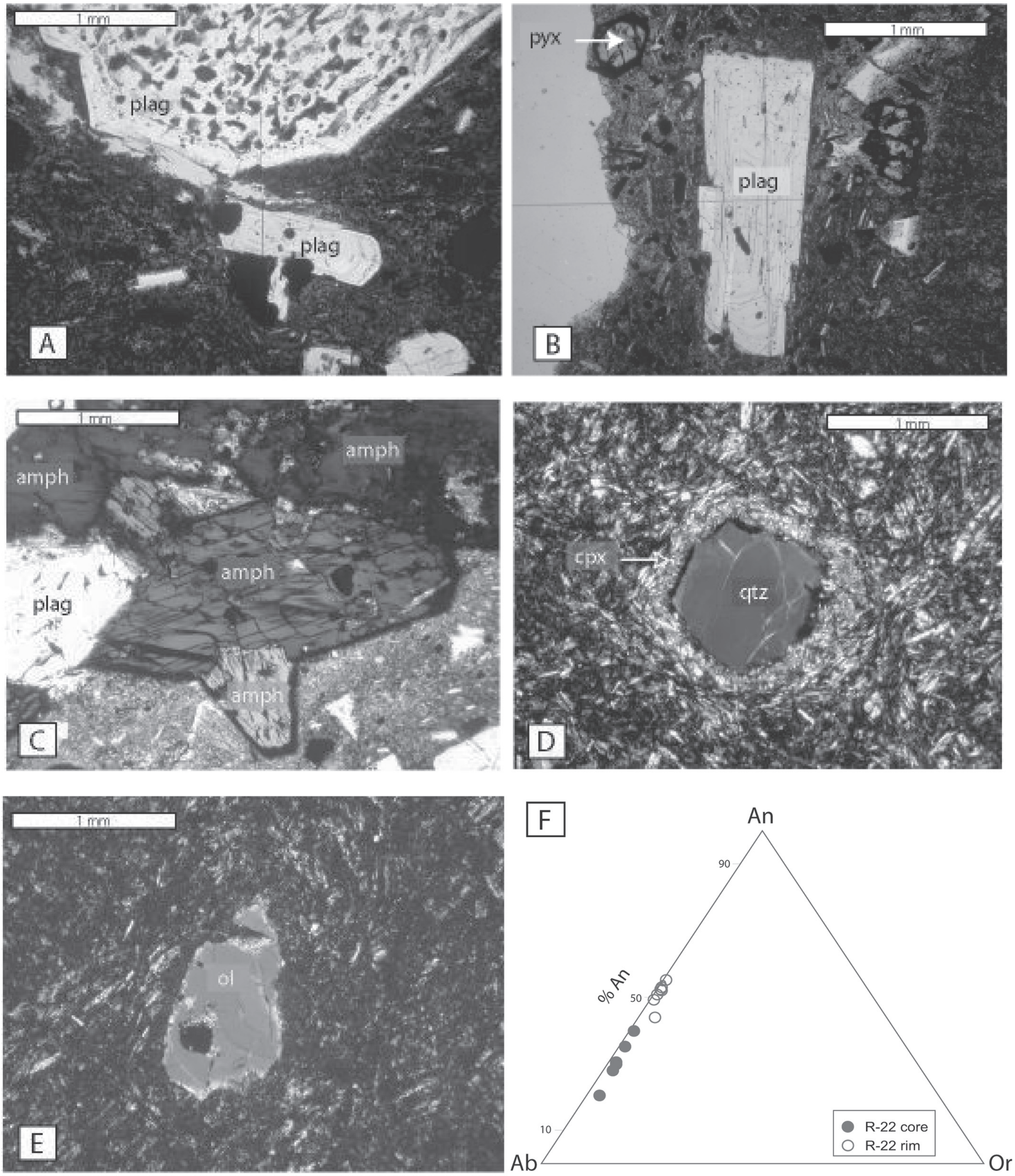

FIGURE 3. Photomicrographs of phenocrysts in Pajarito Plateau dacites. A. Large, sieved plagioclase grains are common in dacite lavas from wells CdV-R-37-2 and CdV-16-3(i) in the southwest part of LANL (sample CdV-16-3(i) 1040-1045). B. Smaller zoned plagioclase phenocrysts are also common in the southwest lavas (sample CdV-16-3(i) 1040-1045). C. Hornblende phenocrysts are diagnostic of Cerro Grande dacite, Tschicoma Formation (sample CdV-R-37-2 1654-1659). D. Trace quartz grains have reaction rims of clinopyroxene revealed in cross polars (sample MCI-1 531.0-531.3). E. Trace, resorbed olivine grains are included in dacite lavas from well R-22 in the eastern part of LANL (sample R-22 768-773). F. Plagioclase analyses from R-22 dacites show increasing anorthite components from core to rim.

Western dacite

A 3 m-thick dacite lava in CdV-R-15-3 overlies a basaltic trachyandesite flow that has chemical and temporal affinities with the CdRVF. This thin dacite has relatively high SiO_2 (66.9-67.4 wt %; Fig. 4) and phenocryst content (18-26 vol. %) with 81-83% plagioclase, and 12-15% pyroxene. Amphibole is rare, accounting for only 1% of the phenocrysts (Table 1). Euhedral plagioclase grains in the CdV-R-15-3 dacite are significantly smaller (< 1 mm) than those in the southwestern lavas and are generally unsieved. Microlites in the groundmass give these cuttings a trachytic texture similar to that of the southwestern dacites.

The dacite at CdV-R-15-3 appears not to be related to dacite at CdV-R-37-2 and CdV-16-3(i) or to dacites in the northern part of LANL despite their proximity to each other. A north-south cross section shows that the dacite at CdV-R-15-3 is higher in elevation than the dacite at CdV-R-37-2 and probably represent a younger flow unit (Fig. 6). This is consistent with the $^{40}Ar/^{39}Ar$ age of 2.88 $\pm$ 0.02 Ma for the dacite at CdV-R-37-2 (Broxton et al., 2007) and 2.51 $\pm$ 0.09 Ma for the basaltic trachyandesite that underlies the dacite at CdV-R-15-3 (unpubl. data). The dacite flows in CdV-R-37-2 and in CdV-16-3(i) are significantly thicker than the flow in CdV-R-15-3.

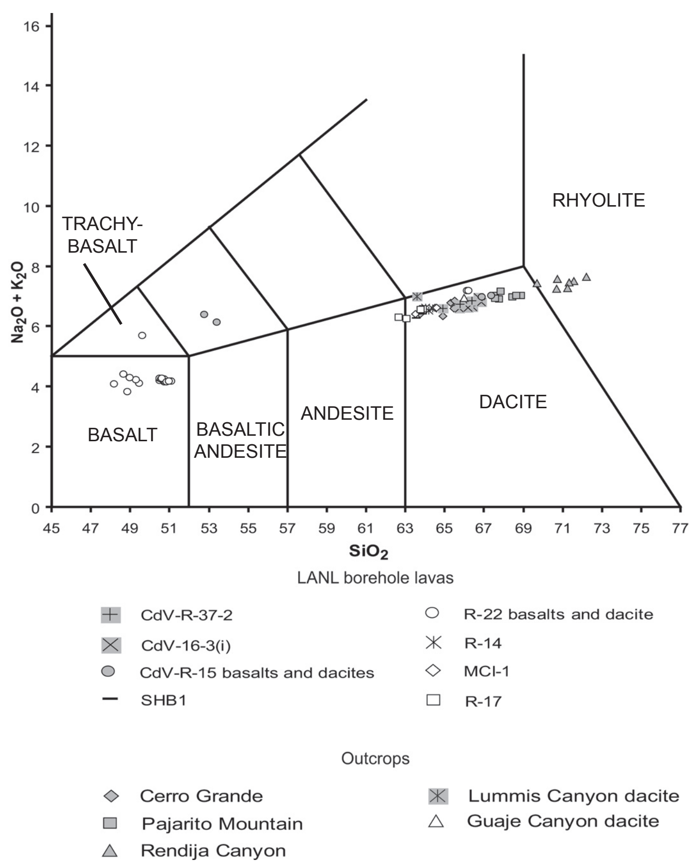

FIGURE 4. Total alkali-silica diagram IUGS classification of volcanic rocks (after Le Bas et al., 1986) shows the range of precaldera compositions in outcrop and borehole samples from both the JMVF and CdRVF. **Cerros del Rio mafic lava compositions from Duncker et al. (1991) and Wolff et al. (2005).

Northern dacite

Lavas in boreholes SHB-1, MCI-1, R-14, and R-17 form a distinct petrographic and chemical group in the northern part of the study area (Fig.1). Where penetrated, these lavas are 148 to 325 ft thick (Fig. 2). Lithologic logs from older boreholes H-19 (Test Hole 19.6.17.234 of table 1 in Griggs, 1964) and EGH-LA-1 (13B of table XVII-B in Purtymun, 1995) suggest that these dacites were encountered by those boreholes as well (Fig.1). These dacites are distinctive in their relatively low SiO_2 (62.38-64.4 wt %), and correspondingly high TiO_2 (0.64-0.67 wt %), CaO (4.62-4.83 wt %), and P_2O_5 (0.25-0.27 wt %) (Figs. 4, 5). These lavas are crystal-poor with only 2-5% phenocrysts. Groundmass plagioclase is the most common phase, but crystals are <0.1 mm, so they were classified as matrix rather than phenocrysts during the point counts. Unlike microlites in the southwestern lavas, groundmass plagioclase grains in the northern lavas are readily apparent in back-scattered electron imaging but not under a petrographic microscope. Clinopyroxene and orthopyroxene phenocrysts dominate grains >0.1 mm, comprising up to 100% of the phenocrysts encountered in point counts (Table 1). SHB-1 samples yielded $^{40}Ar/^{39}Ar$ ages of 2.36 $\pm$ 0.54 to 2.49 $\pm$ 0.23 Ma (Broxton et al., 2007).

Resorbed quartz grains (Fig. 3D) comprise up to 4% of phenocrysts at the top of the dacite at borehole MCI-1 (531 and 666 ft depth). Quartz grains were not observed in R-14 or SHB-1 thin sections. Additionally, crystal content in MCI-1 increases from 2% to 5% with depth, with the highest crystal content encountered near the base of the lavas at a depth of 800 ft. Lithologic and borehole gamma logs indicate that these lavas consist of several flow units separated by interflow breccias, so variations in crystal content suggest that these lavas record multiple flows from a common source.

Eastern dacite

At borehole R-22, three dacite flows 10 to 63 ft thick are intercalated within a 983 ft-thick sequence of Cerros del Rio lavas dominated by basalt (Fig. 2). The dacites occur in the central part of the lava sequence and are separated by tholeiitic basalts. The dacites contain 65.3-66% SiO_2, ~0.52% TiO_2, 3.68-3.78% CaO, and 0.26-0.27% P_2O_5 (Table 2; Fig. 5). Phenocrysts make up 4-6 % of the rock and consist of plagioclase, clinopyroxene, orthopyroxene, and quartz (Table 1). The three lavas are chemically and petrographically similar and therefore are probably derived from the same source. Dacite cuttings from R-22 contain trace amounts of both resorbed olivine and resorbed quartz (Figs. 3D, E). Plagioclase grains show a systematic reverse-zoning trend towards more anorthitic compositions from core to rim (Fig. 3F). A sample of dacite collected from a depth interval of 622 to 628 ft yielded an $^{40}Ar/^{39}Ar$ age of 2.42 $\pm$ 0.12 Ma (Broxton et al., 2007).

Dacites in outcrops

Two outcrops of Pajarito Plateau dacite were sampled as part of this investigation to determine if they could be correlated with

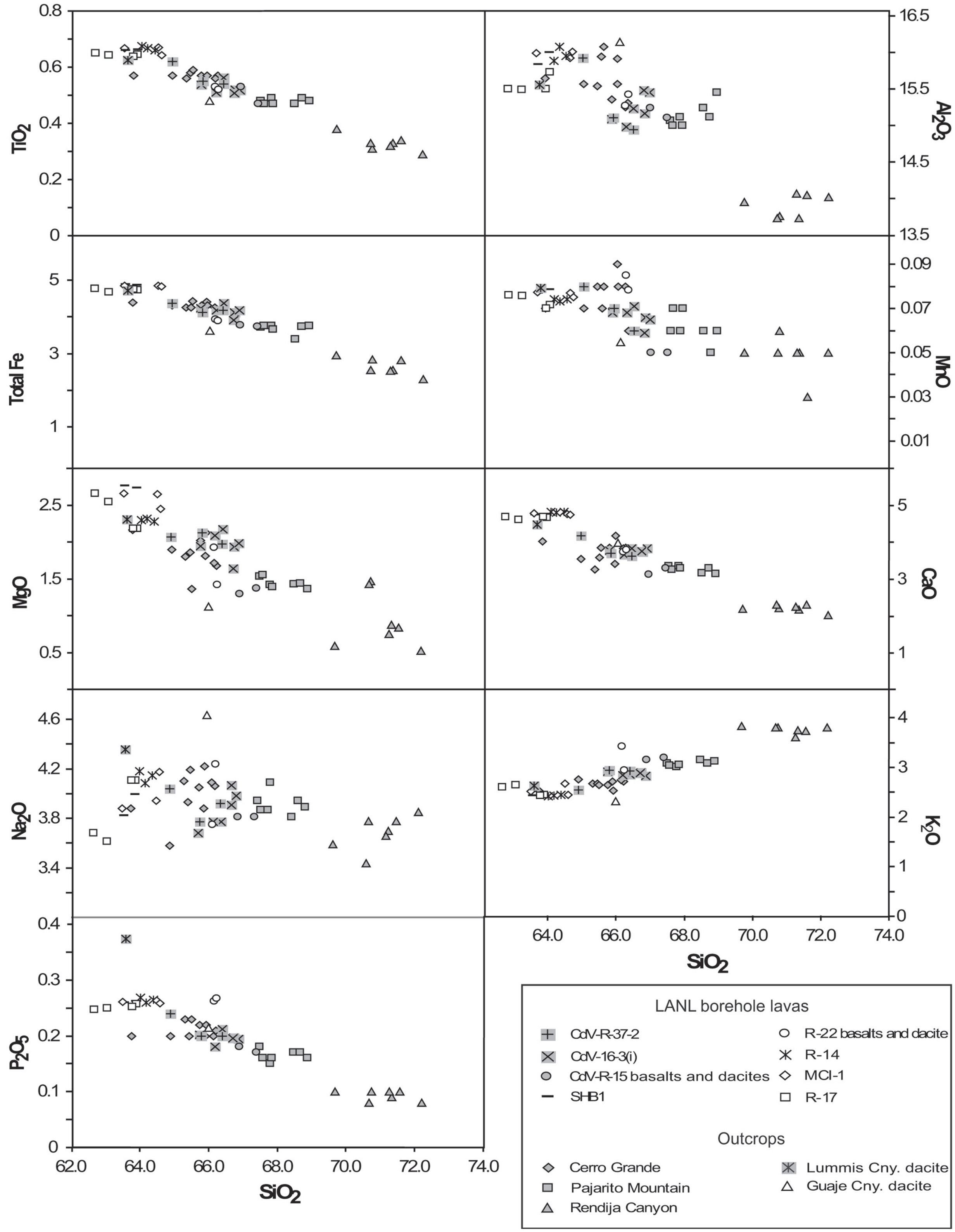

FIGURE 5. Harker variation diagrams of borehole and outcrop dacites on the Pajarito Plateau. Lavas from southwestern boreholes overlap with Cerro Grande dacite. Dacite from CdV-R-15-3 does not overlap with southwestern lavas. Northern lavas from SHB-1, R-17, R-14, and MCI-1 plot together in bivariant plots of major elements vs. SiO_2. Their low SiO_2, and high TiO_2, CaO, and P_2O_5 distinguish these lavas from other dacites on the Pajarito Plateau, including those in nearby outcrops

TABLE 2. Representative XRF whole rock data of dacites found in outcrop and boreholes on the Pajarito Plateau. XRF reports all iron as Fe_2O_3. Some samples were titrated to determine FeO content as well. Blank entries indicates that a constituent was not analyzed or not reported. Major and trace elements were determined by XRF at LANL. REE and additional trace elements for borehole samples were analyzed by ICP-MS at Washington State University; major and trace elements for samples from Cerro Grande and Rendija Canyon outcrops are from Broxton et al. (2007).

Outcrop or Borehole #	outcrop	outcrop	outcrop	outcrop	outcrop	CdV-R-37-2	CdV-16-3(i)	MCI-1	R-17	R-14	SHB-1	CDV-R-15-3	R22
Sample interval (depth bgs)	**6-22-83-4**	**6-22-83-7**	**11-19-84-3**	**DEB3/05-1**	**DEB9/05-1**	**1389-1394**	**1195-1200**	**666.2-666.6**	**575-580**	**703-708**	**656**	**972-977**	**768-773**
	Cerro Grande	**Pajarito Mtn**	**Rendija Canyon**	**Lummis Canyon**	**Guaje Canyon**	**Cerro Grande[+]**	**Cerro Grande**	**Northern Lava**	**Northern Lava**	**Northern Lava**	**Northern Lava[°]**	**CdR (west)[ø]**	**CdR (east)[»]**
SiO_2 wt %	65.9	68.5	70.7	63.6	66.0	65.8	66.6	64.4	63.1	64.0	63.6	67.4	66.0
TiO_2 wt %	0.57	0.47	0.33	0.62	0.48	0.55	0.52	0.64	0.64	0.67	0.66	0.47	0.52
Al_2O_3 wt %	15.6	15.2	13.7	15.6	16.2	15.1	15.3	16.0	15.5	16.0	15.8	15.1	15.4
FeO wt %						1.91				1.76			0.95
Fe_2O_3 wt %	4.40	3.39	2.54	4.72	3.63	2.21	4.08	4.81	4.69	2.86	4.88	3.73	2.93
MnO wt %	0.09	0.06	0.05	0.08	0.05	0.07	0.06	0.08	0.08	0.07	0.08	0.05	0.08
MgO wt %	1.81	1.43	1.43	2.30	1.12	2.12	1.85	2.44	2.54	2.31	2.77	1.37	1.41
CaO wt %	3.42	3.18	2.31	4.48	3.98	3.71	3.78	4.73	4.62	4.78	4.75	3.30	3.78
Na_2O wt %	3.88	3.81	3.44	4.36	4.63	3.77	3.96	4.16	3.61	4.07	3.82	3.81	4.22
K_2O wt %	2.71	3.15	3.81	2.63	2.31	2.95	2.89	2.44	2.64	2.43	2.43	3.20	2.93
P_2O_5 wt %	0.20	0.17	0.08	0.37	0.21	0.20	0.20	0.26	0.25	0.26	0.26	0.17	0.27
LOI				0.06	0.32	0.70	0.46	0.33	1.29	0.36		0.40	0.37
Total %	98.6	99.4	98.4	98.7	98.6	99.1	99.3	99.9	97.6	99.2	99.0	99.0	98.5
V ppm				73	70	63	68	74	82	92	68	56	57
Cr ppm				42	12	39	47	57	44	58	59	31	23
Ni ppm				16	9	22	29	40	33	40	35	19	17
Zn ppm				92	73	57	90	88	69	67	51	43	49
Rb ppm				45	31	49	49	37	39	37	33	65	47
Sr ppm				854	957	505	505	667	631	654	670	439	653
Y ppm				24	<8	16	22	12	17	21	14	24	17
Zr ppm				206	168	177	170	186	183	186	193	176	185
Nb ppm				17	<8	17	11	18	19	19	18	10	29
Ba ppm				1421	1233	1307	1226	1175	1165	1164	1197	1331	1398

[+] Kopp et al., 2003 [ø] Kopp et al., 2002 [»] Ball et al., 2002

the dacites found in the boreholes. The first dacite is exposed in the floor of Guaje Canyon, about 0.4 km west of the Guaje Mountain fault (Fig.1). The exposed thickness of this lava is 30 ft, but the base is covered. The dacite is overlain by about 100 ft of Puye Formation. This strongly flow-banded lava is characterized by a pervasive reddish tan color that may be related to alteration. The lava contains 66% SiO_2, 0.48% TiO_2, 3.98% CaO, and 0.21% P_2O_5 (Table 2; Fig. 5). Phenocrysts make up about 7.5% of the rock and consist of 2% subhedral, zoned plagioclase, 5% sub- to euhedral, highly oxidized amphiboles, and 0.5% euhedral orthopyroxene. A preliminary $^{40}Ar/^{39}Ar$ age for this dacite is 9.5 Ma, indicating that this lava is part of the Lobato Formation (S. Kelley, personal commun., 2007).

The second dacite outcrop is exposed in a small hill north of the mouth of Lummis Canyon in Bandelier National Monument (Fig. 1). The flow is characterized by an 8.2 ft-thick basal vitrophyre that grades abruptly upwards to platy crystalline lava. The platy foliation is rotated to high-angle orientations, possibly indicating the proximity to a nearby vent. The dacite overlies tan-green, crudely bedded, basaltic phreatomagmatic (maar) deposits of Cerros del Rio age. The dacite contains 63.6% SiO_2, 0.48% TiO_2, 3.98% CaO, and 0.21% P_2O_5 (Table 2; Fig. 5). Phenocrysts are sparse (~0.5%) and consist of 0.2 to 1 mm clinopyroxene and subordinate orthopyroxene. This lava is most similar to the crystal-poor rocks of the northern and eastern dacites. However differences in chemistry and mineralogy indicate that it does not correlate to any of the dacites encountered in boreholes on the Pajarito Plateau.

DISCUSSION

Pajarito Plateau dacites erupted in an area transitional between the JMVF and CdRVF volcanic fields. Except for the southwestern group, these dacites differ significantly from the dominant lavas of the adjacent volcanic fields. For example, Tschicoma lavas in adjacent portions of the JMVF consist of coarsely porphyritic

TABLE 2. continued

Outcrop or Borehole #	outcrop	outcrop	outcrop	outcrop	outcrop	CdV-R-37-2	CdV-16-3(i)	MCI-1	R-17	R-14	SHB-1	CDV-R-15-3	R22
Sample interval (depth bgs)	6-22-83-4	6-22-83-7	11-19-84-3	DEB3/05-1	DEB9/05-1	1389-1394	1195-1200	666.2-666.6	575-580	703-708	656	972-977	768-773
	Cerro Grande	Pajarito Mtn	Rendija Canyon	Lummis Canyon	Guaje Canyon	Cerro Grande	Cerro Grande	Northern Lava	Northern Lava	Northern Lava	Northern Lava	CdR (west)	CdR (east)
La	38.1	35.42	35.6			36.0	35.5	36.6		37.1	36.8	39.4	44.9
Ce	69.6	57.02	61.8			60.4	59.7	60.8		61.4	61.2	63.5	70.6
Pr		6.27				6.36	6.28	6.30		6.44	6.41	6.92	6.96
Nd	28.5	23.14	20.6			23.5	23.3	23.6		24.0	23.7	25.5	24.7
Sm	5.10	4.55	4.02			4.70	4.57	4.75		4.74	4.77	4.99	4.65
Eu	1.30	1.23	0.706			1.31	1.29	1.42		1.44	1.45	1.30	1.34
Gd	3.95	3.70	3.35			3.85	3.73	3.87		3.92	3.95	3.95	3.73
Tb	0.557	0.54	0.442			0.56	0.55	0.57		0.58	0.59	0.57	0.57
Dy		3.03				3.16	3.13	3.19		3.29	3.31	3.23	3.23
Ho	0.662	0.58	0.647			0.61	0.60	0.63		0.63	0.65	0.61	0.64
Er		1.49				1.57	1.59	1.65		1.69	1.68	1.60	1.68
Tm	0.274	0.21	0.297			0.23	0.23	0.24		0.24	0.24	0.23	0.25
Yb	1.65	1.28	1.90			1.37	1.39	1.46		1.48	1.49	1.41	1.56
Lu	0.242	0.20	0.278			0.22	0.22	0.23		0.23	0.24	0.23	0.25
Ba	1410	1330	890			1292	1259	1176		1183	1184	1312	1400
Th	4.81	4.85	14.9			4.62	4.80	5.11		5.12	5.04	6.33	9.91
Nb		11.92				12.7	13.2	16.1		16.3	16.1	15.2	23.5
Y		15.89				16.5	16.9	17.4		17.7	17.8	16.7	17.1
Hf	4.66	4.73	4.02			4.57	4.60	4.38		4.47	4.44	4.78	4.22
Ta	1.19	0.84	3.35			0.89	0.90	1.01		1.02	1.01	1.13	1.70
U	1.39	1.14	5.24			1.08	1.21	1.25		1.26	1.22	1.60	2.69
Pb		17.21				15.9	14.6	15.5		14.0	14.1	16.5	18.5
Rb	43	60.5	107			47	51	34		35	34	59	45
Cs	0.351	0.92	15.5			0.87	0.79	0.31		0.30	0.55	0.77	0.61
Sr	499	417	313			515	502	650		660	650	463	623
Sc	8.4	7.2	4.96			8.7	9.7	10.8		11.1	11.0	8.0	7.6

dacites and rhyodacites with large, heavily resorbed plagioclase grains in a trachytic groundmass. CdRVF lavas are dominated by basalts and basaltic andesites. CdRVF dacitic lavas are rare.

Potential Tschicoma sources for the Pajarito Plateau dacites include the eruptive centers of Cerro Grande, Pajarito Mountain, and Rendija Canyon. The dacites and rhyodacites from these sources are chemically and petrographically distinct (Broxton et al., 2007). Cerro Grande lavas have the lowest SiO_2 content (63.8-66.2 wt %) of the three proximal, known source areas (Figs. 4, 5). Rendija Canyon rhyodacite represents the high SiO_2 end of the spectrum (69.7-72.2 wt %) (Table 2). Pajarito Mountain dacites are intermediate between Cerro Grande and Rendija Canyon rhyolite with 67.5-68.9 wt % SiO_2. Euhedral amphibole phenocrysts with varying degrees of oxide replacement are diagnostic of Cerro Grande dacite (Goff et al., 2002; Broxton et al., 2007). Quartz comprises ~20% of the total phenocrysts in Rendija Canyon rhyodacite. Pajarito Mountain dacite contains neither quartz nor hornblende, but it does include both clinopyroxene and orthopyroxene phenocrysts.

The hornblende-bearing southwestern borehole dacites closely match the chemical and petrographic characteristics of the Cerro Grande dacite, and may represent eastern flow lobes of this dome complex. Cerro Grande dacites are more than 500 ft thick at CdV-R-37-2 (Kopp et al., 2003), but they are absent in deep boreholes R-25 and R-26 a short distance to the north (Fig. 1). The southern extent of these lavas in the subsurface is not known. The spatial distribution of these dacites suggests that they flowed down the east flank of Cerro Grande and for more than 3.5 km across the western part of the Española Basin. Continued subsidence, sedimentation, and volcanism in the area resulted in burial of these lavas by up to 170 ft of Puye Formation and 900 ft of Bandelier Tuff.

The northern dacites form a distinct group that differs from any of the known Tschicoma source areas in the Sierra de los Valles. Rendija Canyon Rhyodacite in Pueblo Canyon is the Tschicoma outcrop closest to the northern lavas (Kempter and Kelley, 2002). However, Rendija Canyon Rhyodacite is more phenocryst-rich than the northern lavas (Table 1), and it has a much higher (69.7-72.2 wt %) SiO_2 content (Fig. 5). Other Tschicoma lavas in the

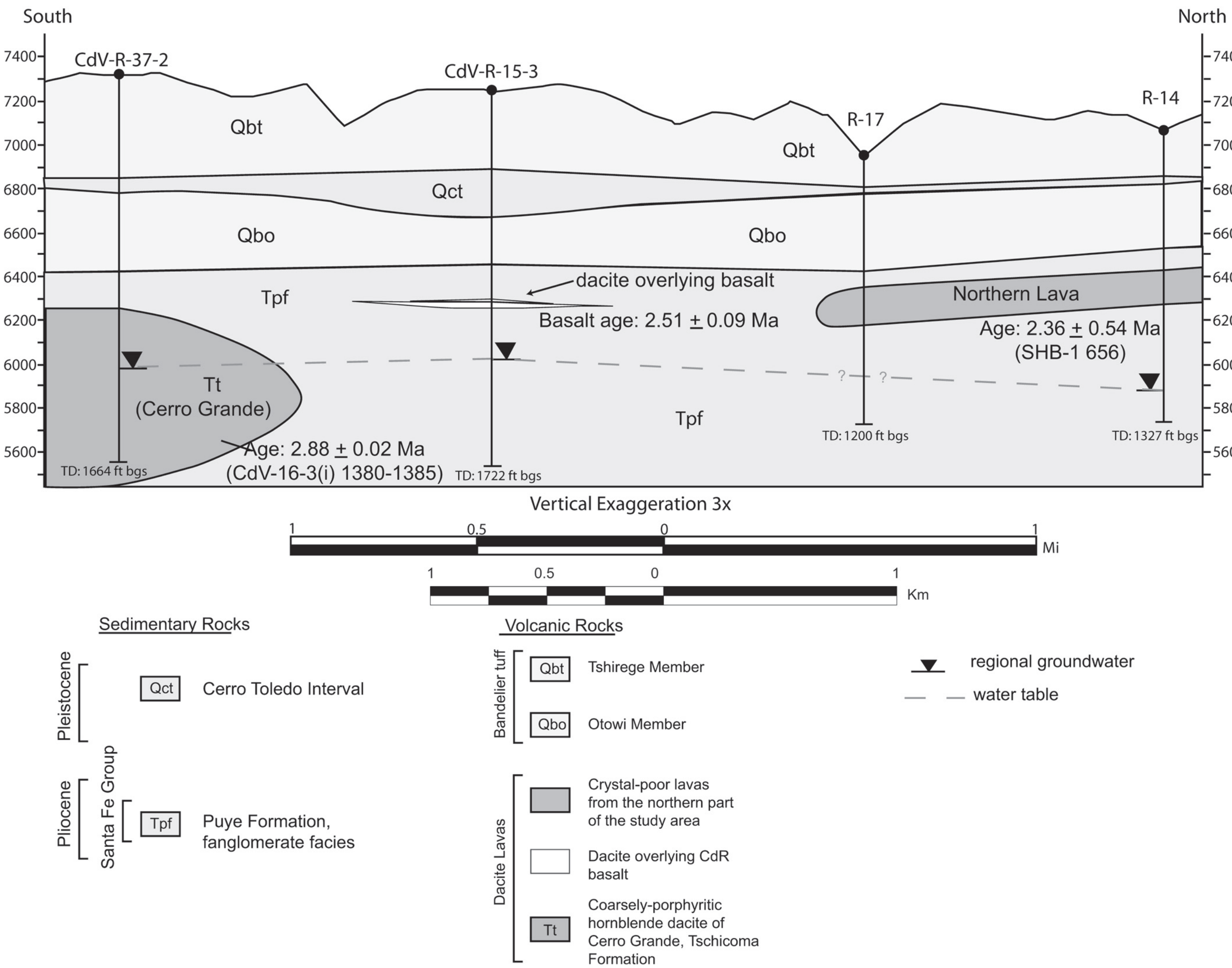

FIGURE 6. Cross section A-A' (see Fig. 1 for line of section) shows that dacite lavas in the western part of LANL form three distinct groups.

Sierra de los Valles are coarsely porphyritic as well, distinguishing them from the crystal-poor northern lavas. The northern lavas are younger (2.36 to 2.49 Ma) than nearby Tschicoma Formation lavas (2.88 ± 0.02 Ma to 5.36 ± 0.02 Ma), more closely associating them temporally with the Cerros del Rio volcanic field (primarily 2.3 to 2.8 Ma). Lithologic logs for H-19 (Griggs, 1964) and EGH-LA-1 (Purtymun, 1995, 13A in table XVII-B) suggest that the northern dacites were also penetrated by these boreholes. We believe the source area for the northern lavas probably lies near the western margin of the Pajarito Plateau, buried beneath the Bandelier Tuff. Faults and fractures of the PFZ probably provided conduits for their ascent to the surface.

Dacites are rare in the main exposures of the CdRVF (Sawyer et al., 2002), and there is no evidence for a temporal trend toward more silicic compositions. On the Pajarito Plateau, dacites of the western and eastern groups overlap spatially with the western part of the CdRVF. Dacites at R-22 occur in the center of a thick stack of basalts and dacite at CdV-R-15-3 overlies basalt; these relations suggest a temporal association between the central and eastern dacite and CdRVF basalt. This confirms the assertion of Rowe et al. (2007), based on similarity between mafic enclaves in Tschicoma dacites and CdRVF mafic lavas, that Tschicoma dacitic and CdRVF mafic magmas coexisted between 2 and 3 Ma. The lack of volcanic rocks with compositions intermediate between the dacites and basalts indicates that the Pajarito Plateau was the site of bimodal volcanism with the eruption of small volumes of dacites overlapping and extending west of the volumetrically more significant CdRVF basalts. The presence of resorbed quartz surrounded by clinopyroxene reaction rims (Fig. 3D), resorbed olivine (Fig. 3E), and reverse zoning of plagioclase phenocrysts (Fig. 3F) suggest that the dacites mixed with basaltic magmas prior to eruption. However, further trace element chemistry and isotope analysis is needed to understand the genetic relationship between the basalt and dacite in R-22.

Chemical discrimination among Pajarito Plateau dacite lavas

The discussion above distinguishes the four groupings of southwestern, western, northern, and eastern dacites by relating petrographic character to SiO_2 content. Other major elements align with these subdivisions to some extent, but the trace-element compositions of these four groups provide clearer distinctions, as well as some constraints on differences in origin or evolution of the dacitic magmas.

Silica vs. Rb/Sr

The northern and eastern dacites, with <65% SiO_2, have a slightly lower range of Rb content and distinctly higher Sr compared with the other dacites (Fig. 7a). The higher Sr/Rb ratios of these lavas are expected as a feature of less evolved dacitic compositions, as documented for dacitic sources that contribute clasts to the Puye Formation (Broxton et al., 2002).

Lanthanide and Actinide elements

Chondrite-normalized lanthanide element patterns indicate no significant difference among the heavy lanthanides (Gd to Lu) but modest variation in the slopes of the light lanthanides (La to Sm). For most of the dacites, La/Sm variation falls along a consistent trend (Fig. 7b) that could allow, but does not prove, variation within a single magma source. The eastern dacite of R-22, however, has an exceptionally high La content that falls away from this trend and would be difficult to reconcile with derivation from a common source.

All of the dacites have similar U/Th ratios (Fig. 7). However, the eastern dacite of R-22 is distinctly enriched in U and Th. This enrichment coupled with the high La content might indicate a more evolved magma, yet the SiO_2 content of the R-22 dacite is not elevated significantly. More probably, this dacite is derived from a distinct source; Rowe et al. (2007) found two distinct dacite types, with similar trace element abundances to those described here, in the Tschicoma Formation and ascribe their origins to two distinct crustal components, on the basis of isotopic data.

SUMMARY

Lavas in Pajarito Plateau boreholes and outcrops record the eruption of multiple Pliocene dacites that were subsequently buried by the Puye Formation and Bandelier Tuff. The dacites are similar in composition to Tschicoma lavas exposed in the JMVF, but they more closely overlap the distribution and ages of mafic lavas of CdRVF. Except in the case of Cerro Grande lavas, the dacites differ in significant ways from dominant rock types found in both JMVF and CdRVF. The distinct compositional and petrographic characteristics of the Pajarito dacites probably reflect a transitional style of magmatism that developed in the narrow region between these adjacent, concurrently active volcanic fields.

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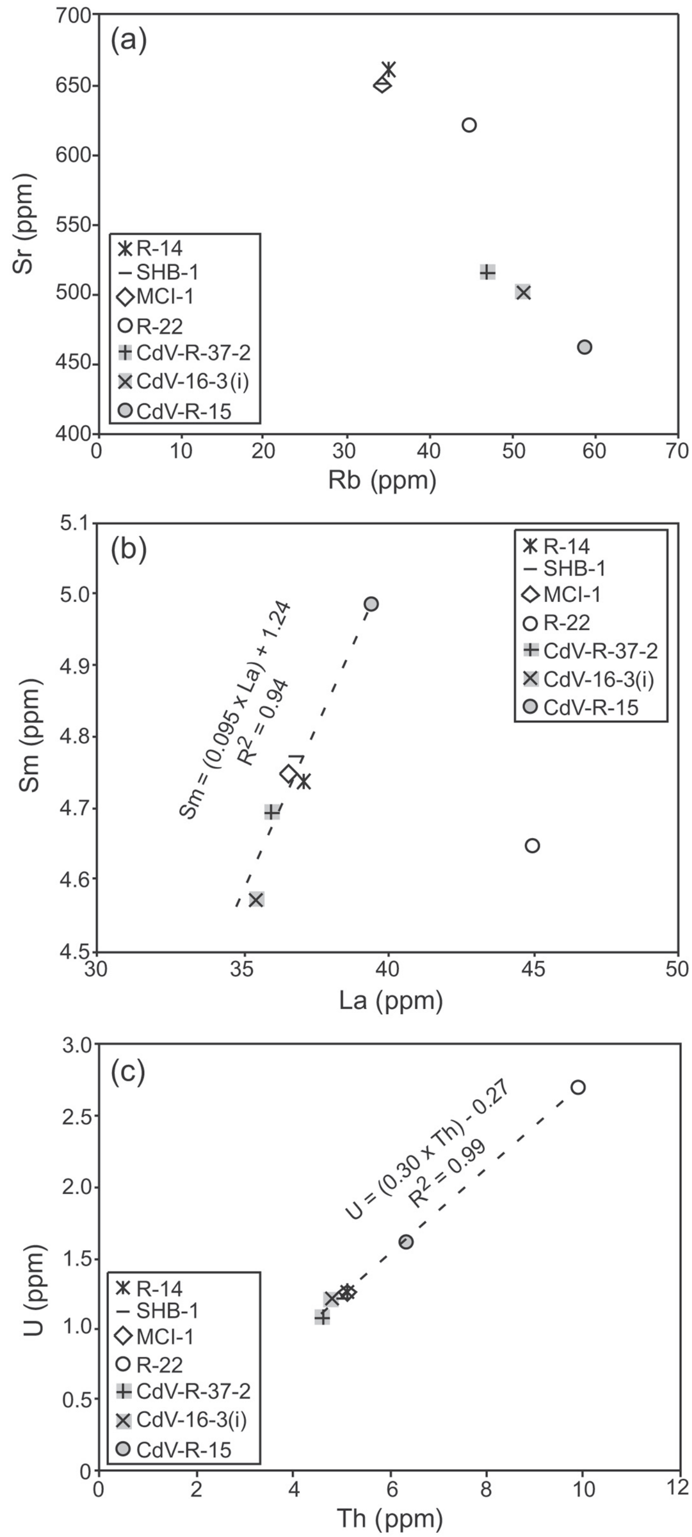

FIGURE 7. Trace element data for Pajarito Plateau dacites. (a) Rb vs. Sr; (b) Sm vs. La; and (c) U vs. Th. Linear regression in (b) is for all samples exclusive of R-22; linear regression in (c) is for all samples.

REFERENCES

Aubele, J.C., 1979, The Cerros del Rio volcanic field, New Mexico: New Mexico Geological Society, 30th Field Conference, Guidebook, p. 243-252.

Baldridge, W.S., 2005, Pliocene-Quaternary volcanism in New Mexico and a model for genesis of magmas in continental extension, *in* Mack, G.H., and Giles, K.A., eds., The geology of New Mexico, a geologic history: New Mexico Geological Society, Special Publication 11, p. 313-330.

Ball, T., Everett, M., Longmire, P., Vaniman, D.T., Stone, W., Larssen, D., Greene, K., Clayton, N., and McLin, S., 2002, Characterization well R-22 completion report: Los Alamos National Laboratory, Report LA-13893-MS, 42 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. 1-29.

Broxton, D., Warren, R., Longmire, P., Gilkeson, R., Johnson, S., Rogers, D., Stone, W., Newman, B., Everett, M., Vaniman, D., McLin, S., Skalski, J., and Larssen, D., 2002, Characterization well R-25 completion report: Los Alamos National Laboratory, Report LA-13909-MS, 77 p.

Broxton, D.E., WoldeGabriel, G., Peters, L., Budahn, J., and Luedemann, G., 2007, Pliocene volcanic rocks of the Tschicoma Formation, eastern-central Jemez volcanic field: chemistry, petrography, and age constraints: New Mexico Geological Society, 58th Field Conference, Guidebook, p. 284-295.

Criss, J., 1979, Criss Software Inc., 12204 Blaketon St., Largo, MD 20870.

Dethier, D.P., 1997, Geology of 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.

Dransfield, B.J., and Gardner, J.N., 1985, Subsurface geology of the Pajarito Plateau, Espanola Basin, New Mexico: Los Alamos National Laboratory, Report LA-10455-MS, 15 p.

Duncker, K.E., Wolff, J.A., Harmon, R.S., Leat, P.T., Dickin, A.P., and Thompson, R.N., 1991, Diverse mantle and crustal components in lavas of the NW Cerros del Rio volcanic field, Rio Grande Rift, New Mexico: Contributions to Mineralogy and Petrology v. 108, p. 331-345.

Gardner, J.N., and Goff, F., 1984. Potassium-argon dates from the Jemez volcanic field: implications for tectonic activity in the north-central Rio Grande rift: New Mexico Geological Society, 35th Field Conference, Guidebook, p. 75-81.

Gardner, J.N., Goff, F., Reneau, S.L., Sandoval, M.M., Drakos, P.G., Katzman, D., and Goff, C.J., 2006, Preliminary geologic map of the Valle Toledo quadrangle, Los Alamos and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 133, scale 1:24,000.

Goff, F., Gardner, J.N., and Reneau, S.L., 2002, Geology of Frijoles quadrangle, Los Alamos and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, scale 1:24,000.

Govindaraju, K., 1994, 1994 compilation of working values and sample description for 383 geostandards: Geostandards Newsletter, v. 18, p. 15-35.

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.,

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

Kelley, V.C., 1978. Geology of Española Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 48, scale 1:125,000.

Kempter, K.A. and Kelley, S., 2002, Preliminary geologic map of the Guaje Mountain 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 55, scale 1:24,000.

Knaack, C., Cornelius, S., and Hooper, P.R., 1994, Trace element analysis of rocks and minerals by ICP-MS: Department of Geology, Washington State University, Open file report.

Kopp, B., Crowder, A., Everett, M., Vaniman, D.T., Hickmott, D.D., Stone, W., Clayton, N., Pearson, S., and Larssen, D., 2002, Well CdV-R-15-3 completion report: Los Alamos National Laboratory Report LA-13906-MS, 47 p.

Kopp, B., Everett, M., Lawrence, J.R., WoldeGabriel, G., Vaniman, D., Heikoop, J., Stone, W., McLin, S., Clayton, N., and Larssen, D., 2003, Well CdV-R-37-2 completion report: Los Alamos National Laboratory, Report LA-14023-MS, 39 p.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology v. 27, p. 745-750.

Purtymun, W.D. 1984, Hydrologic characteristics of the main aquifer in the Los Alamos area: development of ground water supplies: Los Alamos National Laboratory, Report LA-9967-MS, 44 p.

Purtymun, W.D., 1995, Geologic and hydrologic records of observation wells, test holes, test wells, supply wells, springs, and surface water stations in the Los Alamos area: Los Alamos National Laboratory, Report LA-12883-MS, 339 p.

Robinson, B.A., Broxton, D.E., and Vaniman, D.T., 2005, Observations and modeling of deep perched water beneath the Pajarito Plateau: Vadose Zone Journal, v. 4, p. 637-652.

Rowe, M.C., Wolff, J.A., Gardner, J.N., Ramos, F.C., Teasdale, R., and Heikoop, C.E., 2007, Development of a continental volcanic field: petrogenesis of pre-caldera intermediate and silicic rocks and origin of the Bandelier magmas, Jemez Mountains (New Mexico, U.S.A.). Journal of Petrology, in revision.

Sawyer, D.A., Shroba, R.R., Minor, S.A., and Thompson, R.A., 2002, Geologic map of the Tetilla Peak quadrangle, Santa Fe and Sandoval Counties, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2352, scale 1:24,000.

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

Spell, T.L., McDougall, I., and Doulgeris, A.P., 1996, Cerro Toledo Rhyolite, Jemez volcanic field, New Mexico: $^{40}Ar/^{39}Ar$ geochronology of eruptions between two caldera-forming events: Geological Society of America Bulletin, v. 108, p.1549–1566.

WoldeGabriel, G., Laughlin, A.W., Dethier, D.P., and Heizler, M., 1996, Temporal and geochemical trends of lavas in White Rock Canyon and the Pajarito Plateau, Jemez volcanic field, New Mexico: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 251-261.

WoldeGabriel, G., Warren, R.G., Broxton, D.E., Vaniman, D.T., Heizler, M.T., Kluk, E.C., and Peters. L., 2001, Episodic volcanism, petrology, and lithostratigraphy of the Pajarito Plateau and adjacent areas of the Española Basin and the Jemez Mountains: New Mexico Museum of Natural History and Science, Bulletin 18, p. 97-129.

WoldeGabriel, G., Warren, R., Cole, G., Goff, F., Broxton, D., Vaniman, D., Peters, L., Naranjo, A., and Kluk, E., 2006. Volcanism, tectonism, chronostratigraphic records, in the Pajarito Plateau of the Espanola Basin, New Mexico, USA: Los Alamos National Laboratory, Report LA-UR-06-6089, 122 p.

Wolff, J.A., Rowe, M.C., Teasdale, R., Gardner, J.N., Ramos, F.C., and Heikoop, C.E., 2005, Petrogenesis of pre-caldera mafic lavas, Jemez Mountains volcanic field (New Mexico, USA): Journal of Petrology v. 46, 407-439.