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Neogene Rhyolites of the Northern Jemez Volcanic Field, New Mexico

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Volcanic centers previously mapped as the 2.0 Ma El Rechuelos Rhyolite in the northern Jemez volcanic field, New Mexico, include three distinct episodes of rhyolitic volcanism. An early (7.5 Ma) extrusive dome of flow-banded biotite rhyolite and an intermediate (5.8 Ma) rhyolite, possibly a volcanic neck, correspond in age to rhyolites of the Keres Group in the southern Jemez volcanic field. Three other extrusive domes of aphyric, pumiceous rhyolite and obsidian comprise a late volcanic episode, dated at 2.0 Ma. We retain the name El Rechuelos Rhyolite only for these late centers. Another center, farther north than the others but previously mapped with the El Rechuelos Rhyolite, is a ducite pumice ring whose age (5.2 Ma), petrography, major- and trace-element chemistry, and Sr initial ratio all suggest it should be included with rocks of the Tschicoma Formation. Nd and Sr isotopic ratios of the Neogene rhyolites of the northern Jemez volcanic field suggest that these rhyolites were not produced by partial melting of either upper or lower crust. Rather, they may have been generated from a mantle-derived mafic magma, such as the nearby Lobato Basalt, by fractional crystallization with concomitant assimilation of small amounts (< 6%) of lower crust. If the El Rechuelos is derived from a lower crustal magma chamber, as seems likely, then it is not related to the Bandelier magma system, even though it is part of a continuum of rhyolite volcanism ranging from 3.6 Ma to 130,000 years ago that includes the Bandelier and precursor rhyolitic units.

INTRODUCTION

Rocks of the Jemez volcanic field in north-central New Mexico are subdivided into the Keres (> 10–6.5 Ma), Polvadera (7.4–2.0 Ma), and Tewa (< 1.4 Ma) groups [*Bailey et al.*, 1969; *Smith et al.*, 1970; *Bailey and Smith*, 1978]. Recent work by *Gardner and Goff* [1984] and *Gardner et al.* [1986] indicates that the Keres and Polvadera groups overlap significantly in age and that both groups include rocks older than 13 m.y. Studies by *Kite et al.* [1982] show that the Polvadera and Tewa groups also overlap in age. Unexpected age relations are still being found in the Jemez volcanic field; hence continued radiometric dating, field, and petrologic studies are crucial for a full understanding of its evolution.

The Polvadera Group includes the Lobato Basalt, the Tschicoma Formation, and the El Rechuelos Rhyolite. This latter formation, as originally defined [*Bailey et al.*, 1969; *Smith et al.*, 1970], was comprised of five discrete domes and one pumice cone or ring, all located in the northern Jemez volcanic field, north of the Valles caldera (Figures 1 and 2). One dome yielded a K-Ar date of 2.0 Ma [*Dalrymple et al.*, 1967], which was generally considered as the approximate age of this formation.

This paper reports recent K-Ar dates, whole-rock major- and trace-element analyses (including the rare earth elements), petrographic data (including microprobe analyses), and Sr and Nd isotopic ratios of these rhyolitic domes. Our new K-Ar dates clearly distinguish three episodes of Neogene rhyolitic volcanism in the northern Jemez volcanic field, at 7.5, 5.8, and 2.0 Ma (Table 1 and Figure 2), confirming the inference of *Bailey et al.* [1969] that the two southernmost domes were older, based on their degree of denudation and alteration. We have informally named the 7.5 and 5.8 Ma rhyolites the "early" and "intermediate" rhyolites, respectively, and retained the name "El Rechuelos" only for the 2.0 Ma episode.

METHODS

Whole-rock major-element compositions (Table 2) were obtained on a Rigaku automated X ray fluorescence (XRF) system using an end-window rhodium target, operating at 40 kV and 50 mA. Samples for XRF were prepared as fused discs with a 1:9 mixture of powdered sample to lithium tetraborate flux, without an added heavy element for absorbance. Data were reduced using a fundamental parameters method [*Criss*, 1980; *Valentine*, 1983]. Details of run times and accuracy are given by *Bower* [1985] and *Bower and Valentine* [1986].

Whole-rock trace-element compositions were determined by instrumental neutron activation analysis (INAA) and by isotope-source XRF. Hf, U, Th, Ta, Cs, Sc, La, Ce, Sm, Eu, Dy, Yb, and Lu were determined by INAA. Rock powders were irradiated in plastic vials in the graphite thermal column of the Los Alamos National Laboratory's Omega West Reactor, with a neutron flux of 6×10^{12} neutrons/cm^{2}s. An initial 20-s irradiation was followed by a 20-min decay period and then by gamma ray spectroscopy for detection of the short-lived isotopes. The vials were then re-irradiated for 96 s, followed by a 14-day decay period and then by counting of the long-lived nuclides. The details of this procedure, as well as of the data reduction, are described by *Garcia et al.* [1982] and

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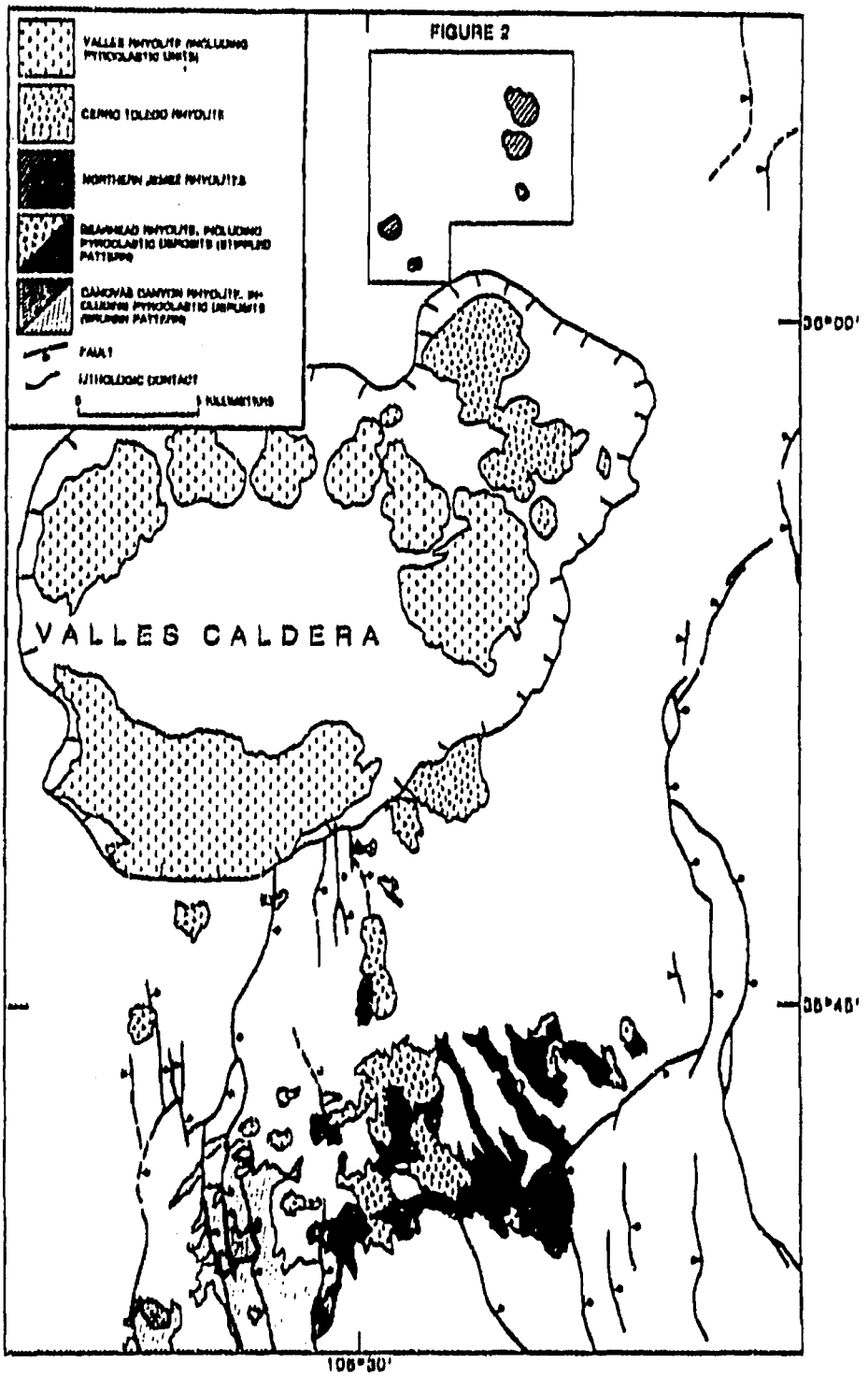

Fig. 1. Location map showing Neogene rhyolitic domes of the northern Jemez volcanic field (this work), rhyolitic domes and pyroclastic deposits of similar age in the southern Jemez volcanic field, and Plio-Pleistocene rhyolitic units (mainly domes and flows) within the Valles caldera [after *Smith et al.*, 1970; *Gardner*, 1985; *Heiken et al.*, 1986].

Minor et al. [1982], Rb, Sr, Ba, Nb, and Zr were determined by isotope-source XRF, using a Kevex system at the U.S. Geological Survey (USGS) in Denver. These analyses were done on pressed powders, and 1-min counts of fluoresced X rays were made using both ^{109}Cd and ^{241}Am sources for each sample.

The ^{87}Sr/^{86}Sr ratios were measured using a rhenium triple-filament mode of ionization, on a 6-inch, 60°-sector, Nier-type mass spectrometer, also at the USGS in Denver. ^{87}Sr/^{86} values were normalized for ^{86}Sr/^{88}Sr = 0.1194 to correct f the differential efficiency of ionization for the various isotop and the system was standardized using a value of 0.70801 f the Eimer and Amend Standard $SrCO_3$. From numerous re licate analyses made on the same mass spectrometer, the an lytical precision at the 95% confidence level is estimated better than ±0.00005 (C. E. Hedge, personal communicati

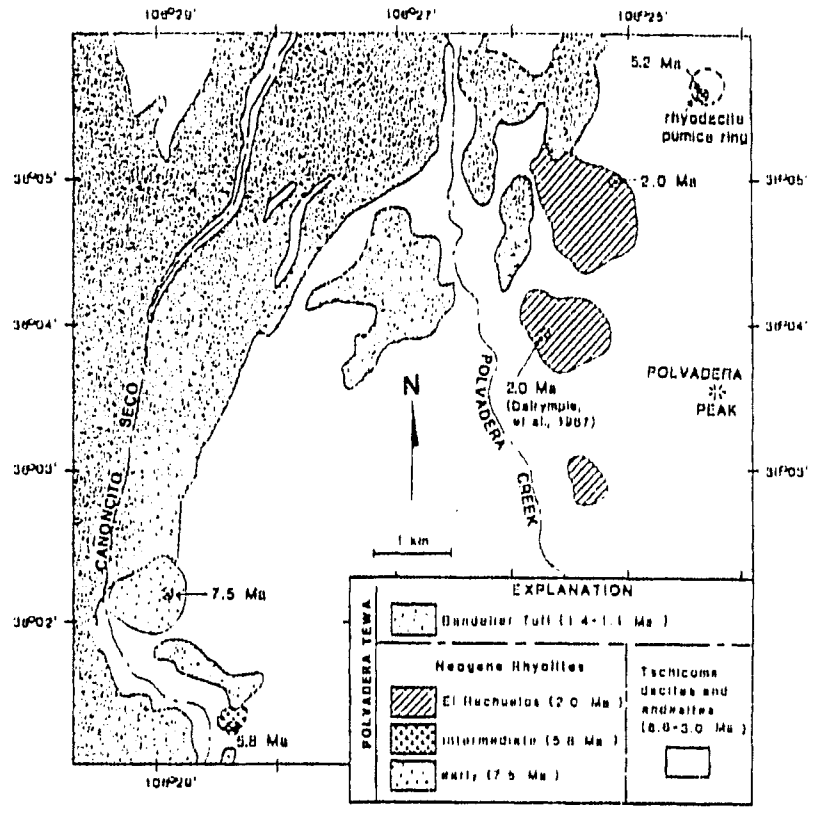

Fig. 2. Simplified geologic map showing the locations and age relations of Neogene rhyolitic centers in the northern Jemez volcanic field and the locations of dated samples (after *Bailey et al.*, 1969; *Smith et al.*, 1970; and this work).

1984). Rb and Sr concentrations were determined by isotope-source XRF, except for low Sr concentrations, which were determined by isotope-dilution mass spectrometry.

The K-Ar ages and Rb/Sr of the samples were used to calculate initial $^{87}Sr/^{86}Sr$ from the measured ratios. The high Rb/Sr of the El Rechuelos Rhyolite produced a significant change between the measured and the initial $^{87}Sr/^{86}Sr$ (Table 3). In the earlier rhyolites, the smaller Rb/Sr produced much smaller changes between the measured and initial $^{87}Sr/^{86}Sr$ (even though their ages are greater). Devitrification is a serious problem in obtaining reliable whole-rock $^{87}Sr/^{86}Sr$ on rhyolites, since it invariably changes the Rb/Sr ratio. Therefore only fresh (nondevitrified) samples can give reliable initial $^{87}Sr/^{86}Sr$. The intermediate rhyolite is extensively devitrified, and no fresh whole-rock sample could be found; therefore an initial $^{87}Sr/^{86}Sr$ for this center was determined using a feldspar separate.

$^{143}Nd/^{144}Nd$ were determined at the USGS in Denver, using a 12-inch, 60°-sector, Nier-type mass spectrometer. These values were normalized using $^{146}Nd/^{144}Nd = 0.7219$, and have an analytical uncertainty of ±0.000020. Analyses of minerals were obtained on a Cameca Camebax electron microprobe, as described by *Vaniman et al.* [1982]. A barite standard was used for barium calibration and was checked against the BaO content of 0.52% in orthoclase standard OR-1. Strontium contents in feldspars and glasses were below the detection limits of the electron microprobe.

Potassium-argon dates were obtained from separated groundmass feldspars in the Laboratory of Isotope Geochemistry at the University of Arizona, using methods described by *Damon et al.* [1983].

PETROGRAPHY AND MINERAL CHEMISTRY

The rhyolites of the three episodes are petrographically distinctive. In particular, the anorthite (An) content of plagioclase and the Ba content of both plagioclase and sanidine decrease from the oldest to youngest rhyolites (Figure 3). Edenitic amphibole occurs in the 7.5 Ma rhyolite but is not found in the younger rhyolites. In addition, the 7.5 Ma rhyolite has abundant phenocrysts of biotite, whereas the younger rhyolites contain biotite only as a microphenocryst or groundmass phase.

Early Rhyolites (7.5 Ma)

The larger and older of the two rhyolite centers along Cañoncito Seco (Figure 2) consists of flow-banded biotite rhyolite, with biotite concentrated in layers parallel to the flow

TABLE 1. Ages of Neogene Rhyolites, Northern Jemez Volcanic Field

Sample	Location		K Analyses		Radiogenic Ar, $\times 10^{-12}$ mol/g		Percent Atmospheric ^{40}Ar		Age, m.y. ± 1σ
	Latitude	Longitude	Individual %K	Mean	Individual Analyses	Mean	Individual Analyses	Mean	
P-70, feldspar: El Rechuelos Rhyolite	36°5.03'N	106°25.35'W	3.926 3.889 3.917	3.911	13.75 13.58 13.58 13.79 13.59	13.66	68.3 67.5 67.6 67.1 67.6	67.6	2.01 ± 0.06
P-80, feldspar plus glass: Intermediate Rhyolite	36°1.07'N	106°28.53'W	1.506 1.492 1.498 1.498	1.499	15.2 15.0 15.0 15.0 15.1 15.2	15.1	41.6 42.0 41.9 41.9 41.7 41.8	41.8	5.80 ± 0.2
P-8, biotite: Early Rhyolite	36°2.17'N	106°28.97'W	6.918 6.913 6.933 6.928 6.882 6.928	6.921	90.4 90.8 90.9	90.7	61.2 61.0 61.1	61.1	7.54 ± 0.28
ER1-2, biotite: Tschicoma pumice ring	36°5.08'N	106°24.35'W	6.539 6.514 6.577	6.543	58.1 59.1 59.4 60.3	59.2	81.4 81.6 81.6 81.4	81.5	5.21 ± 0.25

banding. This rhyolite has abundant phenocrysts of plagioclase and biotite, as well as microphenocrysts of plagioclase. The plagioclase phenocrysts are up to 5 mm long, commonly with inner zones "sieved" by glass inclusions and with rims free of such inclusions. These phenocrysts are normally zoned from An_{50} to An_{25-35}. Plagioclase microphenocrysts range from An_{40} to An_{25}. Groundmass plagioclase is An_{25} to An_{15}, with up to 0.9% BaO. The phenocryst rims contain the same amount of barium, whereas the phenocryst cores, as well as the microphenocrysts, have Ba contents below microprobe detection limits (0.25% BaO). Groundmass sanidine (Or_{62}) contains 1.8–2.6% BaO.

Biotite phenocrysts have Mg/(Mg + total Fe) (denoted by Mg') of 0.55–0.60, Al/Si of 0.43–0.48, TiO_2 of 4.2–4.9 wt %, and BaO of 0.3–1.2 wt %. Microphenocrysts of endenitic amphibole have Mg' of 0.64–0.68, Al/Si of 0.15–0.20, $^{VI}Al/^{IV}Al \sim 0.5$, and TiO_2 of 1.2–1.7 wt %. Quartz is absent, and zircon is a common accessory phase.

Although this center is rhyolitic in composition, the phenocryst mineralogy is typical of dacitic rocks of the Tschicoma Formation (Polvadera Group). The compositions and habits of plagioclase, biotite, and amphibole in the early (7.5 Ma) rhyolite and in the Tschicoma dacites are very similar [*Loeffler*, 1984; *Vanman and Baldridge*, 1985].

Intermediate Rhyolite (5.8 Ma)

The southernmost rhyolite dome, exposed along Cañoncito Seco, is partially covered by Bandelier Tuff (Figure 2). This rhyolite is also strongly flow banded and contains abundant microphenocrysts of sanidine (Or_{62-66}), oligoclase-anorthoclase (An_{20-17}), and quartz. Biotite is sparsely distributed as a microphenocryst but is common in the groundmass.

Unique to this dome is the occurrence of anorthoclase-sanidine-quartz microphenocryst intergrowths with a myrmekitic texture (Figure 4). These intergrowths contain homogeneous sanidine and anorthoclase, unlike the strongly zoned feldspars recorded by *Lofgren and Gooley* [1977] for intergrowths formed under extrusive cooling conditions. *Hibbard* [1979] suggested that such myrmekitic intergrowths form after a volatile fluid phase has been removed. Thus the myrmekitic intergrowths may represent a hypabyssal environment in which the magma was partially degassed while cooling. Plagioclase in the myrmekitic intergrowths is more sodic (An_{15-10}) than the plagioclase microphenocrysts (An_{20-17}).

Small groundmass feldspars consist of sanidine and anorthoclase similar in composition to the myrmekitic intergrowths. Like the 7.5 Ma rhyolite and in contrast to the El Rechuelos Rhyolite (Figure 3), the sanidines contain significant amounts of barium (0.8–2.2% BaO). Biotites of this 5.8 Ma rhyolite also contain significant amounts of barium (0.5–1.0% BaO) and are otherwise similar to the biotites of the 7.5 m.y. old rhyolite (Mg' = 0.52–0.62, Al/Si = 0.43–0.45, TiO_2 = 3.8–4.1 wt %). This rhyolite was vitrophyric, but the glass is extensively devitrified. In addition, the rock is very hard and dense and contains silica minerals deposited within vugs. The silicification, together with the myrmekitic textures indicating a hypabyssal environment, suggests that this center may have been a volcanic neck.

El Rechuelos Rhyolite (2.0 Ma)

The three late El Rechuelos Rhyolite domes which occur along Polvadera Creek (Figure 2) consist of aphyric, pumiceous rhyolite with obsidian. Crystals larger than 50 μm are rare in all of these domes, but microphenocrysts up to 2 mm in size occur in flow-banded portions of the larger dome. These microphenocrysts consist of sanidine (Or_{66-69}), oligoclase (An_{12-15}), and quartz; biotite occurs only as small crystals a few micrometers in size (Mg' = 0.53–0.56, Al/Si = 0.41–0.43, TiO_2 = 2.5–3.8 wt %). The groundmass contains albite, anorthoclase, and sanidine. The groundmass glass contains pervasive but minor clay alteration along perlitic fractures, as well as stellate devitrification centers composed of feldspar and silica minerals. The abundance of barium in feldspars and

TABLE 2. Major- and Trace-Element Analyses of Neogene Rhyolites of the Northern Jemez Volcanic Field

	Tschicoma Rhyodacite Average	Northern Pumice Ring		Beathead Rhyolite (6.2 Ma)	Early (7.5 Ma) Rhyolite			Intermediate (5.8 Ma) Rhyolite			El Rechuelos Rhyolite (2.0 Ma)								
											South Dome				Central Dome		North Dome		
		ER 1-2	ER 1-4	JG80-49*	ER 5-7	P8	P9	ER 6-9	P13B	P60	ER 2-6	ER 2-2	P19	P70	ER 3-3	P22	ER4-1B	ER4-2B	P23
SiO_2	69.00	69.75	71.07	76.16	72.33	73.68	73.63	75.13	77.16	75.62	74.75	74.57	75.04	75.58	74.77	75.76	74.42	74.18	75.84
TiO_2	0.43	0.26	0.26	0.11	0.26	0.25	0.28	0.12	0.23	0.12	0.08	0.08	0.26	0.08	0.08	0.24	0.09	0.08	0.17
Al_2O_3	14.54	15.59	15.17	12.11	14.29	13.91	14.18	12.61	13.08	12.84	12.47	12.56	12.29	12.53	12.45	12.80	12.27	12.39	12.81
$Fe_2O_3^T$	3.04	2.32	1.60	0.68	1.60	1.79	1.60	0.95	0.76	0.85	0.61	0.61	0.65	0.73	0.54	0.59	0.61	0.58	0.58
MnO	0.06	0.06	0.04	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.06	0.06
MgO	1.18	0.77	0.72	0.04	0.31	0.26	0.31	0.07	0.05	0.08	0.04	0.05	0.07	0.00	0.05	0.04	0.10	0.06	0.06
CaO	2.76	2.64	2.54	0.40	1.43	1.29	1.22	0.44	0.42	0.45	0.48	0.47	0.48	0.49	0.45	0.47	0.59	0.48	0.51
Na_2O	3.81	3.65	3.71	3.92	4.52	3.98	4.11	4.29	4.13	3.23	3.90	3.61	3.56	3.52	3.74	3.93	3.60	3.74	3.66
K_2O	3.60	3.27	3.20	4.61	3.89	3.88	3.98	4.41	4.42	4.24	4.70	4.53	4.76	4.71	4.74	4.52	4.85	4.71	4.71
P_2O_5	0.13	0.06	0.02	0.05	0.06	0.05	0.06	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01
LOI	1.23	1.48	1.39	0.37	0.34		0.45	0.27	0.19		2.17	3.20	2.81		3.17	2.17	3.03	3.20	2.07
Total	99.79	99.85	99.72	98.52	99.09	99.16	99.89	98.37	100.55	97.51	99.26	100.04	99.98	97.71	100.03	100.57	99.61	99.48	100.48
Rb	81	46	58	154	77			96			138	135			139		136	147	
Cs	2.0	1.8		3.1	1.9			3.0			4.6				5.3		4.5		
U	3.36	0.91		4.12	2.92			4.1			8.0				8.0		8.0		
Th	11.1	4.1		12.0	10.1			11.8			16.7				20.4		18.1		
Nb	18	4	5		20			32			39	38			40		37	39	
Ta	2.5	1.0			3.3			3.3			4.9				6.2		5.3		
Sr	403	397	393	62	253			37			<5	<5			<5		<5	<5	
Ba	1030	1360	1280	800	1430			820			20	35			17		23	20	
Zr	136	111	109	127	151			83			55	57			58		50	57	
Hf	4.4	3.9		3.2	5.2			3.4			3.1				3.7		3.1		
Sc	6.6	4.95		3.1	3.39			3.52			2.70				3.11		2.51		
La	41	28.2		30.4	49			22.9			19.6				17.2		22.2		
Ce	73	50		52	88			46			39				44		41		
Sm	4.1	3.3			5.2			4.7			3.6				3.6		4.1		
Eu	0.91	0.80		0.51	1.02			0.48			0.24				0.17		0.20		
Dy	3.3	2.3		5.0	4.3			5.8			3.8				3.6		3.4		
Yb	1.8	1.5		2.6	3.0			3.0			2.1				2.6		2.6		
Lu	0.26	0.17			0.36			0.40			0.25				0.32		0.36		

Average Tschicoma rhyodacite [*Loeffler*, 1984] given for comparison. $Fe_2O_3^T$ is total Fe as Fe_2O_3. LOI is loss on ignition.
*Data for JG80-49 are from *Gardner et al.* [1986].

TABLE 3. Whole-Rock Sr and Nd Isotopic Data for Neogene Rhyolites, Northern Jemez Volcanic Field

	Tschicoma Pumice Ring ER 1-2	Early (7.5 Ma) Rhyolite ER 5-7	Intermediate (5.8 Ma) Rhyolite P80	El Rechuelos Rhyolite (2.0 Ma) South ER 2-4	El Rechuelos Rhyolite (2.0 Ma) Central ER 3-3
Weight percent SiO_2	69.75	72.33	76.14	75.58	74.77
Age, m.y.	5.2	7.5	5.8	2.0	2.0
Sr, ppm	397	253	562	4.18	4.60
Rb, ppm	46	77	14.2	144	139
$^{87}Rb/^{86}Sr$*	0.335	0.880	0.0730	99.6	87.3
$(^{87}Sr/^{86}Sr)$ meas.	0.70507	0.70537	0.705191	0.70800	0.70814
$(^{87}Sr/^{86}Sr)_0$‡	0.70505	0.70528	0.70513	0.70517	0.70506
Sm, ppm		4.71			3.04
Nd, ppm		28.0			12.8
$(^{143}Nd/^{144}Nd)_0$§		0.512453			0.512574
ϵ_{Nd}*		−3.6			−1.2

*$^{87}Rb/^{86}Sr = 2.80 \times$ (ppm Rb/ppm Sr).
†Determined on feldspar separate.
‡Calculated using the following equation: $(^{87}Sr/^{86}Sr)_0 = (^{87}Sr/^{86}Sr)_{meas} - (^{87}Rb/^{86}Sr)\lambda t$ with $\lambda = 1.42 \times 10^{-11}\ yr^{-1}$.
§Measured, uncorrected for age.
*Using current-day bulk earth $(^{143}Nd/^{144}Nd) = 0.512636$.

biotite is below electron microprobe detection limits (0.25% BaO).

Northern Pumice Ring

This pumice ring, which is located 4.0 km north of Polvadera Peak (Figure 2), contains phenocrysts of zoned and unzoned plagioclase, rounded and embayed quartz, biotite ($Mg' = 0.58$–0.64, $TiO_2 = 4.4$–4.6%, $BaO = 0.3$–0.8%), and hornblende ($Mg' = 0.66$–0.67, $Al/Si = 0.20$–0.29, $TiO_2 = 1.7\%$) in a matrix of microlites and glass. Unzoned plagioclase phenocrysts are An_{60}; other phenocrysts are normally zoned from An_{60} to An_{40}. The high calcium content of the plagioclase cores indicates disequilibrium and may have resulted from assimilation, magma mixing, or nonequilibrium fractional crystallization. In any case, this phenocryst assemblage is similar to that of the Tschicoma dacites [*Loeffler*, 1984; *Pantman and Baldridge*, 1985].

MAJOR- AND TRACE-ELEMENT COMPOSITIONS

Among the northern Jemez rhyolites, substantial differences in major- and trace-element compositions correlate with age (Table 2). For example, FeO, Na_2O, Sr, Ba, Zr, and the light rare earth elements (LREEs) decrease with decreasing age, whereas K_2O, Rb, Cs, U, Th, Nb, and Ta increase with decreasing age. In addition, a negative Eu anomaly becomes greater with decreasing age (Figure 5). Fractionation modeling using observed phenocryst phases shows that the three rhyolite episodes are not related to each other by simple crystal fractionation. Together with petrographic differences, these results indicate that each phase of activity (7.5, 5.8, and 2.0 Ma) was an independent magmatic event.

The systematic differences from the early to the El Rechuelos rhyolites are consistent with a greater degree of fractionation, probably of plagioclase, sanidine, biotite, and accessory zircon, of successively younger rhyolites from more mafic magmas. The fact that the degree of fractionation correlates with time may be entirely fortuitous or may reflect some process associated with the development of a major silicic magma system. Until intermediate rocks are identified that are possibly cogenetic with the rhyolites, detailed fractionation modeling remains hypothetical.

SR AND ND ISOTOPIC RATIOS

The initial $^{87}Sr/^{86}Sr$ for all rhyolites from the northern Jemez range from 0.70513 to 0.70566 (Figure 6, Table 3). The initial $^{87}Sr/^{86}Sr$ of all of the northern Jemez rhyolites are lower than rhyolites of the Keres Group ($^{87}Sr/^{86}Sr = 0.70701$–$0.70858$ [*Loeffler*, 1984]), although only two measurements exist for the Keres Group rhyolites, and thus their possible range is unknown. The rhyolites from the northern Jemez overlap with the known range of $^{87}Sr/^{86}Sr$ values of the Keres and Tschicoma Group andesites and dacites ($^{87}Sr/^{86}Sr = 0.70444$–$0.70531$); only one El Rechuelos sample (ER3-3) is higher, but the combined 1-σ errors in Rb, Sr, and age determinations for this sample could permit a calculated initial $^{87}Sr/^{86}Sr$ below 0.70500.

$^{143}Nd/^{144}Nd$ ratios were determined for the early and El Rechuelos rhyolites (Table 3). Both are slightly enriched relative to bulk earth, with ϵ_{Nd}, defined as $10^4[(^{143}Nd/^{144}Nd)_{meas}/(^{143}Nd/^{144}Nd)_{chondrite} - 1]$, equal to −3.6 and −1.2, respectively.

DISCUSSION

Petrogenesis

It is not presently possible to construct a detailed major- and trace-element petrogenetic model for these rhyolites, for three reasons. (1) No cogenetic intermediate rocks, which would constrain the evolution of the rhyolites, are known. Nearby dacites of the Tschicoma Formation have ages between 6.6 and 3.0 Ma [*Olsen et al.*, 1987] and thus may have formed concurrently with the intermediate rhyolite but not with the early and El Rechuelos rhyolites. Dacites of the region are very complex, and more age, chemical, and mineralogic data are needed before possible relations to the rhyolites can be tested. Moreover, the common occurrence of mafic clots within the dacites suggests that a basaltic component was critical to the evolution of most if not all of the silicic

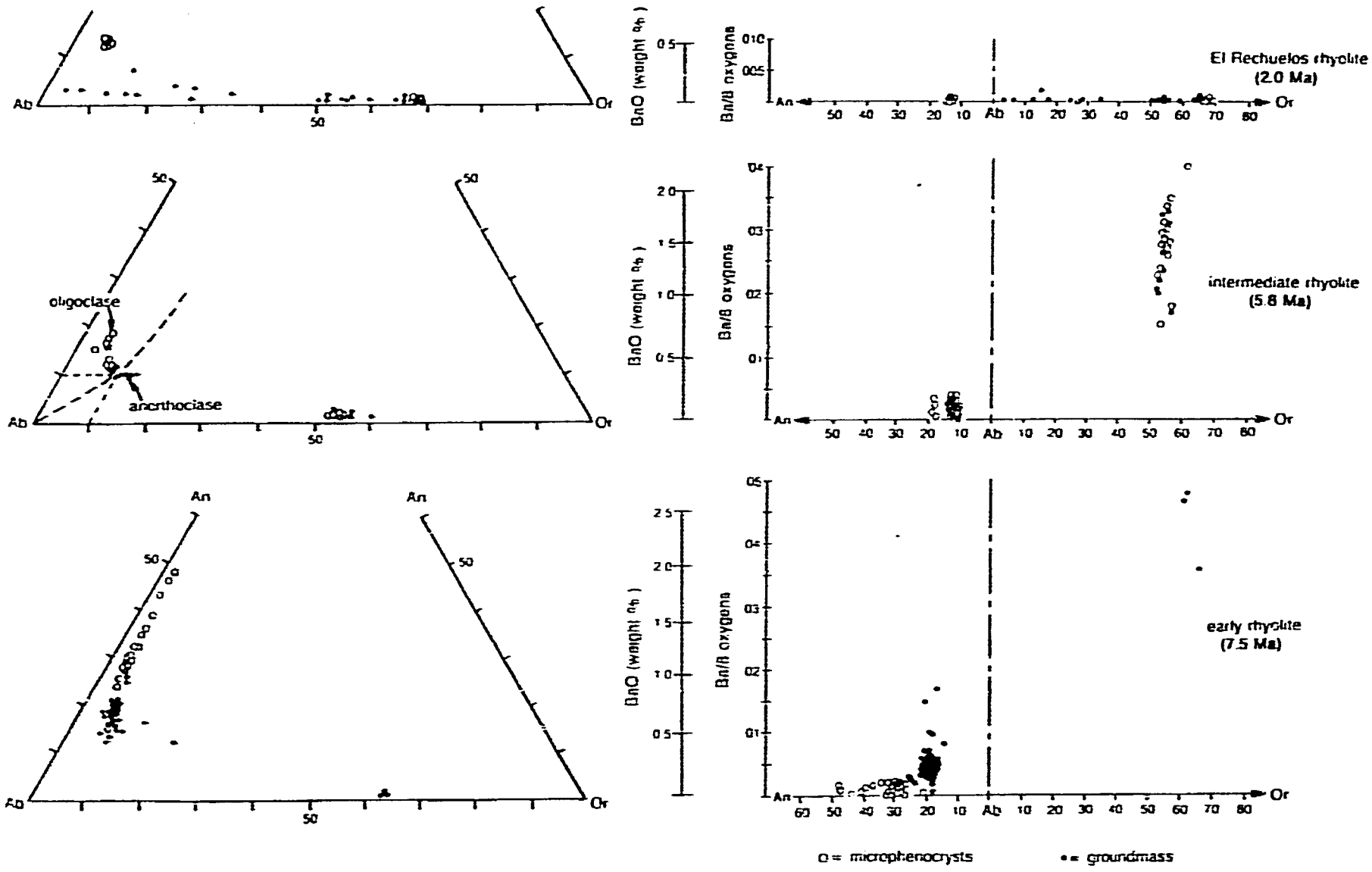

Fig. 3. Ca-Na-K compositions and barium contents (as wt % BaO and as Ba cations per 8-oxygen stoichiometric formula) of feldspars from the three Neogene rhyolitic episodes of the northern Jemez volcanic field.

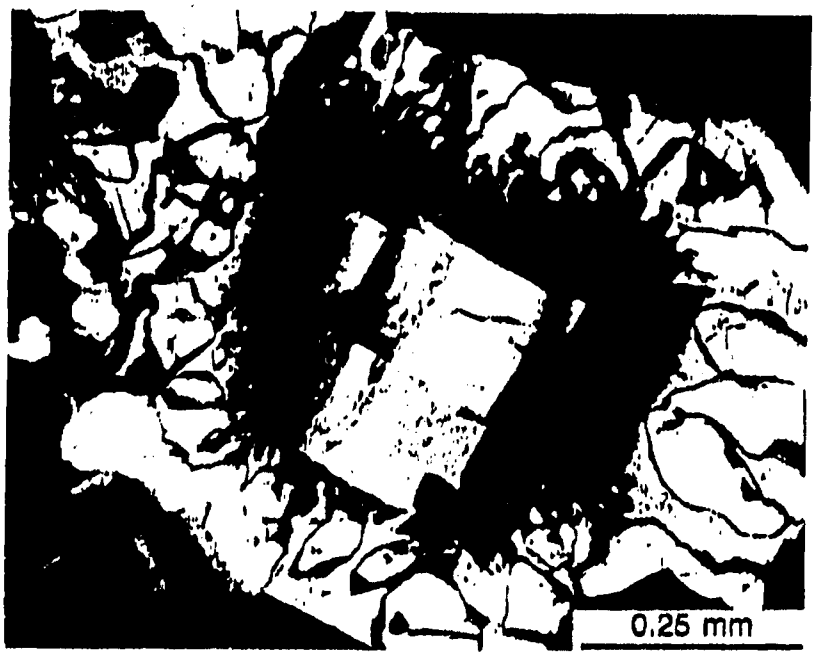

Fig. 4. Sanidine microphenocryst from the 5.8 Ma rhyolite with a fine-grained (inner) and coarse-grained (outer) myrmekitic rim of sanidine-anorthoclase-quartz intergrowth.

magmas in this region, and we therefore concentrate in this paper on tests of basaltic parentage. (2) We do not know the full range of chemical and isotopic compositions of the nearby Lobato and El Alto basalts [e.g., *Smith et al.*, 1970], to which the early and El Rechuelos rhyolites, respectively, are probably related. (3) For the intermediate rhyolite there are no closely associated basaltic rocks to which the rhyolite might be related. Nevertheless, the chemical and isotopic data allow us to place constraints on the origin of the rhyolites. We explore several possibilities below.

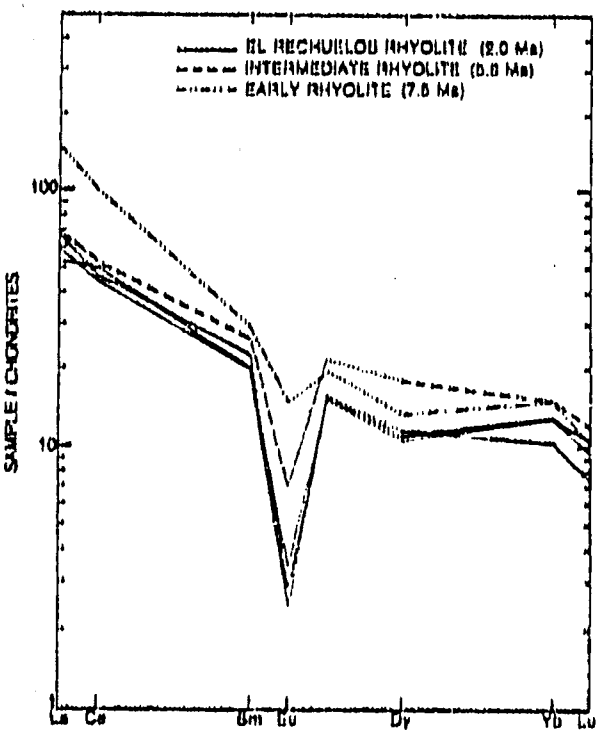

Fig. 5. Chondrite-normalized REE profiles for the three episodes of Neogene rhyolitic volcanism. The profiles are dashed between Eu and Dy to show the probable configuration of the Eu anomalies (Gd was not analyzed). For normalization, chondritic values (in ppm) were taken from *Hanson* [1980]: La, 0.33; Ce, 0.88; Sm, 0.18; Eu, 0.069; Dy, 0.325; Yb, 0.200; and Lu, 0.034 ppm.

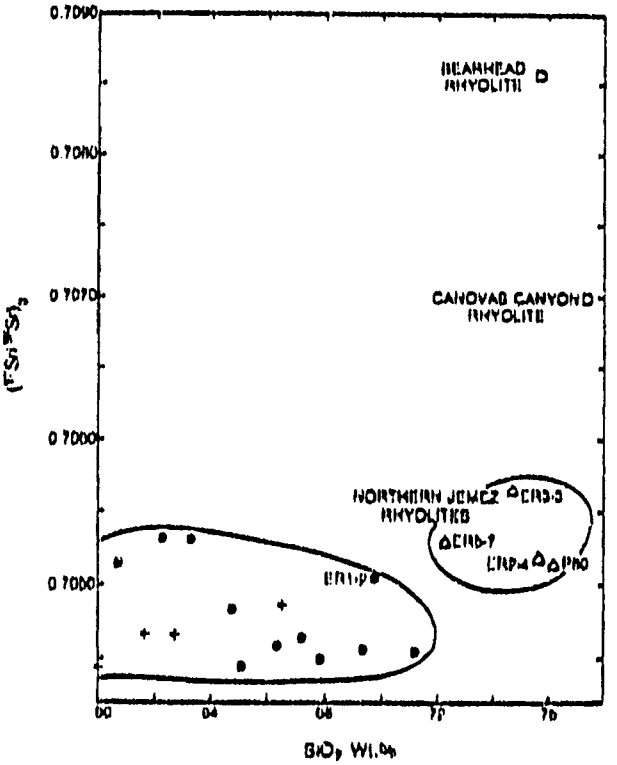

Fig. 6. Initial $^{87}Sr/^{86}Sr$ plotted against SiO_2 for the Neogene rhyolites of the northern Jemez volcanic field, for rhyolites of the Keres Group, and for andesites and dacites of the Polvadera and Keres groups (solid circles and crosses, respectively). Data from this work and from *Loughlin* [1984].

Single silicic magma? The different Nd isotopic ratios of the early ($\varepsilon_{Nd} = -3.6$) and El Rechuelos rhyolites ($\varepsilon_{Nd} = -1.2$) rule out their relationship to each other by any simple, single-stage model of fractional crystallization combined with assimilation of upper crust in a long-lived magma chamber, as we proposed previously [*Loeffler et al.*, 1985].

Crustal anatexis? The low $^{87}Sr/^{86}Sr$ (<0.70814) of the northern Jemez rhyolites rules out their origin by direct anatexis of the upper crust. Nearly all Precambrian granitic (and thus presumably upper crustal) rocks of New Mexico have $^{87}Sr/^{86}Sr$ greater than 0.72 [*Perry et al.*, 1987]. Direct anatexis of any crust, lower or upper, can also be ruled out on the basis of the ε_{Nd} values of these Neogene rhyolites, which are much higher than values measured for the Proterozoic crust of this region (−11 to −15 [*DePaolo*, 1981*a*; *Nelson and DePaolo*, 1985; *Perry et al.*, 1987]).

Assimilation/fractional crystallization of basalt? The Sr and Nd isotopic ratios are compatible with generation of the rhyolites from a mantle-derived magma, such as the Lobato Basalt, by fractional crystallization in combination with assimilation of crust. We therefore modeled the isotopic data for the rhyolites using the assimilation-fractional crystallization (AFC) model of *DePaolo* [1981*b*]. We used the Lobato Basalt (Sr = 1150 ppm, $^{87}Sr/^{86}Sr = 0.70430$, Nd = 45 ppm, $^{143}Nd/^{144}Nd = 0.512665$, $\varepsilon_{Nd} = +0.6$ (B. M. Loeffler and K. Futa, unpublished data, 1987) as the parental magma for these models, since it is a major basaltic unit that was erupted close in proximity and in age (14–7.6 Ma [*Gardner et al.*, 1986]) to the rhyolites. The young (approximately 3 Ma) El Alto Basalt would represent a better choice for the parent of the El Rechuelos Rhyolite, but the Nd concentration of this unit has not been measured. We note, however, that the initial $^{87}Sr/^{86}Sr$ and ε_{Nd} for at least one El Alto sample (0.70436 and +0.2 [*DePaolo and Wasserburg*, 1976]) are very similar to the Lobato.

It was impossible to obtain satisfactory results with AFC modeling by assimilation of any reasonable upper crustal compositions, even for the relatively radiogenic El Rechuelos Rhyolite. In contrast, assimilation of lower crustal compositions gave good results. For example, the early rhyolite can be modeled from the Lobato Basalt by assuming assimilation of lower crust with the composition $^{87}Sr/^{87}Sr = 0.7057$, $^{143}Nd/^{144}Nd = 0.511867$ ($\varepsilon_{Nd} = -15$), 350 ppm Sr, and 50 ppm Nd. The model requires a ratio of the assimilation rate to fractionation rate (r) of 0.15 and a ratio of remaining to initial melt (F value) of 0.29. This model results in assimilation of 5.1% lower crust relative to the mass of the parental magma (using the assimilation equation of *Farmer and DePaolo* [1983]). The model also requires a bulk $D_{Sr} = 4.2$, which is reasonable, since plagioclase is an observed phenocryst phase and since the K_D for Sr becomes greater as the melt becomes more felsic [*Bornhorst*, 1980]. The model also requires a $D_{Nd} = 1.4$, which is reasonable for felsic melts, especially since zircon is an observed phenocryst.

Similarly, the El Rechuelos Rhyolite can be produced with an r value of 0.055 for assimilation of lower crust with the composition $^{87}Sr/^{86}Sr = 0.7060$, $^{143}Nd/^{144}Nd = 0.511867$ ($\varepsilon_{Nd} = -15$), 350 ppm Sr, and 40 ppm Nd. In this case the percentage of lower crust assimilated relative to the initial volume of parental magma is less than 2%. A $D_{Sr} = 6$ is required to bring the Sr concentration down. This value is high but not unreasonable [*Bornhorst*, 1980]. The required $D_{Nd} = 2$ is also reasonable, since in high-silica rhyolites the LREEs may become compatible in some of the abundant minerals [*Mahood and Hildreth*, 1983]. Also, small quantities of allanite or monazite may have been fractionated, which would reduce Nd [*Miller and Mittlefehldt*, 1982], although neither phase has yet been observed in thin section.

From the results of this AFC modeling, we conclude that derivation of these rhyolites by fractionation from basaltic parents similar to the Lobato Basalt, contaminated by small amounts of lower crust, is likely. The simplest interpretation of these results, and the one that we presently favor, is that these rhyolites were fractionated in lower-crustal magma chambers. This inferred depth contrasts with current interpretations regarding the shallow depth of the Bandelier system (4–7 km [*Smith*, 1979]). A problem with the model of a lower-crustal magma chamber may be the difficulty of getting high-viscosity rhyolitic magmas to the surface from the lower crust. Viscosities of H_2O-saturated rhyolitic magmas may possibly be as low as 10^5 P in the lower crust, but will increase rapidly to greater than 10^4 P as water is lost and pressure decreases during ascent [*Fisher and Schmincke*, 1984; *Kushiro*, 1980].

Alternatively, the Lobato Basalt we used as a parental composition may not have been a realistic choice. Possibly the basalts (or intermediate compositions) that were parental to these rhyolites were themselves contaminated by lower crust and were then fractionated in shallow (upper crustal) magma chambers without further contamination. To evaluate this second hypothesis will require additional isotopic data on the associated Lobato and El Alto basalts and on possible intermediate compositions. However, we consider this hypothesis less likely because (1) it is more complex and (2) it requires upper crustal fractionation without significant assimilation.

Relationship to the Miocene Keres Group: Nomenclature

The early (7.5 Ma) and intermediate (5.8 Ma) rhyolites have ages similar to the high-silica Canovas Canyon and Bearhead rhyolites of the Keres Group (12.4–6.2 Ma [*Gardner et al.*, 1986]). Furthermore, these centers lie on a NNE trend with the Canovas Canyon and Bearhead Rhyolite centers (Figure 1), which were themselves partly controlled by NNE trending faults [*Gardner*, 1985]. It is therefore plausible that the early and intermediate rhyolites may be petrogenetically related to rhyolites of the Keres Group in the southern Jemez volcanic field, as suggested by *Gardner et al.* [1986]. The early rhyolite is lower in silica (73% versus 76%), lower in Rb (77 ppm versus 139–185 ppm), higher in Sr (253 ppm versus 56–60 ppm), and is in other respects different from the Keres Group rhyolites [*Gardner et al.*, 1986]. These differences might be accounted for by either contamination of the early rhyolite with, or less complete fractionation from, a more mafic magma.

The intermediate rhyolite is very similar in composition to the Keres Group rhyolites (compare ER 6-9 with JG80-49 in Table 2). The Sr isotopic compositions of these two rhyolites are different (Figure 6), but distinctions based on only two data points are necessarily limited. More data are needed on the compositional and isotopic ranges of Keres Group rhyolite compositions before the early and intermediate rhyolites can be correlated with or distinguished from them with certainty. Thus until the rhyolites of the Keres Group are better characterized, we prefer to distinguish the Neogene rhyolites in the northern Jemez from the Keres Group rhyolites by the informal terms "early" and "intermediate" rhyolites.

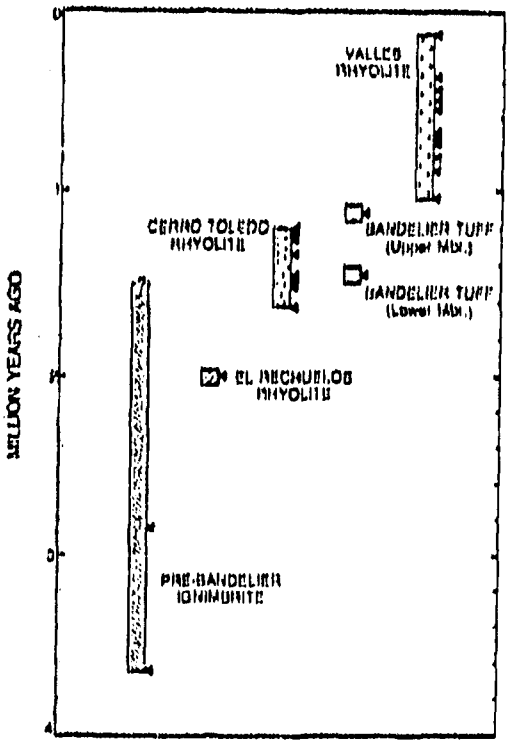

Fig. 7. Timing of Pliocene and Pleistocene rhyolitic volcanism of the Jemez volcanic field. Solid triangles indicate K-Ar dates and show age control for each unit. Data points are generalized where several dates occur within short time intervals. For the Cerro Toledo Rhyolite, three age determinations slightly exceed the accepted age of 1.45 Ma for the lower Bandelier Tuff. Yet from stratigraphic relations of pyroclastic units and their inferred correlations to domes, all units of the Cerro Toledo are assumed to have been erupted between the lower and upper Bandelier Tuffs [*Heiken et al.*, 1986]. Data are from *Gardner et al.* [1986], *Self et al.* [1986], *Heiken et al.* [1986], and this work. Upper limit on pre-Bandelier ignimbrite(?) is from *Smith* [1979].

Relationship to Pliocene and Quaternary Rhyolites

Rhyolitic lavas, including the caldera-forming lower and upper Bandelier rhyolite tuffs, were erupted as domes and as tephra from 3.6 Ma to about 130,000 years ago (Figure 7) [*Gardner et al.*, 1986; *Self et al.*, 1986; *Heiken et al.*, 1986]. The nomenclature of these various Pliocene and Quaternary rhyolitic units reflects differences in age and location, but should not obscure the fact that all are related to the development of a single magma system. Chemical differences among these rhyolites reflect the processes by which such a system evolves.

A detailed comparison of the El Rechuelos Rhyolite to all of the other Pliocene and Quaternary rhyolites is beyond the scope of this paper. A large amount of compositional data on these units is presented by *Gardner et al.* [1986], *Self et al.* [1986], and *Heiken et al.* [1986]. Basically, all of the Pliocene and Quaternary rhyolites, with the possible exception of the El Rechuelos Rhyolite, are probably related to the Bandelier system. The distribution and major-element compositions of the "pre-Bandelier ignimbrites" [*Self et al.*, 1986], which range from 3.6 to about 1.5 Ma [*Gardner et al.*, 1986], suggest that they may represent leaks from a proto-Bandelier magma chamber or from magma chambers that later coalesced and evolved into the Bandelier magma body [*Self et al.*, 1986]. Similarly, the Cerro Toledo Rhyolite tuffs and domes, which were erupted between the lower and upper Bandelier Tuff [*Heiken et al.*, 1986], were also probably an intermediate stage between the two major eruptions from the Bandelier magma chamber. The Valles Rhyolite, which consists of domes, flows, and tuffs, was erupted inside Valles caldera after caldera collapse and thus represents late, generally quiescent eruptive products derived from the Bandelier magma chamber.

The fact that the El Rechuelos Rhyolite closely predates (by 0.6 m.y., Figure 7) the Cerro Toledo Rhyolite and was erupted less than 5 km away might suggest that both units were derived from a single magma chamber. Compositional data are not definitive regarding the possible relationship of the El Rechuelos to the Cerro Toledo Rhyolite. Although similar in their major-element compositions, these two rhyolite units are substantially different in their trace-element compositions. Specifically, the El Rechuelos Rhyolite has lower incompatible-element contents (La = 17–22 ppm, Yb = 2.1–2.6 ppm, Rb = 135–147 ppm, Zr = 50–58 ppm) than the Cerro Toledo Rhyolite (La = 31–50 ppm, Yb = 4.2–7.9 ppm, Rb = 120–220 ppm, Zr = 90–180 ppm [*Heiken et al.*, 1986]). These differences are compatible with either (1) derivation of the two rhyolites from separate chambers or (2) derivation from a single magma chamber in which differentiation, crustal interactions, and the concentration of incompatible elements increase with time.

No Sr or Nd isotopic data are available for the Cerro Toledo Rhyolite with which to evaluate this second possibility. However, the lower limit of initial $^{87}Sr/^{86}Sr$ for the Bandelier Tuff ($(^{87}Sr/^{86}Sr)_0 \geq 0.70588$; D. M. Loeffler and K. Futa, manuscript in preparation, 1987) is slightly higher than the El Rechuelos ($(^{87}Sr/^{86}Sr)_0 = 0.70517$–$0.70566$; Table 3). This difference is small enough that the Bandelier Tuff (and presumably also the Cerro Toledo Rhyolite) could be derived from the same magma chamber from which the El Rechuelos Rhyolite was derived.

Nevertheless, we prefer the first alternative, i.e., that the El Rechuelos was derived from a separate chamber, because the Nd isotopic data indicate that the El Rechuelos Rhyolite was formed in the lower crust, whereas the Cerro Toledo Rhyolite is related to the Bandelier chamber, which formed in the upper crust [*Smith*, 1979; *Heiken et al.*, 1986]. Additional chemical and isotopic data are required for the Cerro Toledo Rhyolite and for the Bandelier Tuff before the possible relationship of the El Rechuelos to other Neogene rhyolitic units can be better constrained.

Summary

In summary, the three episodes of Neogene rhyolitic volcanism in the northern Jemez volcanic field (the early, intermediate, and El Rechuelos rhyolites) represent three separate magma batches. The early (7.5 Ma) and El Rechuelos rhyolites (and, by analogy, the intermediate (5.8 Ma) rhyolite) were probably derived from a basalt (such as the Lobato) by fractionation with concomitant assimilation of lower crust. Thus most likely, the El Rechuelos was erupted from a separate magma chamber derived from the lower crust and was not an early product of the Bandelier magma chamber, even though it was erupted soon before the Bandelier and during the prolonged activity of Bandelier-precursor rhyolites (pre-Bandelier ignimbrites [*Self et al.*, 1986]).

The 7.5–2.0 Ma age span of these rhyolites indicates that rhyolitic volcanism occurred throughout a long part of the history of the Jemez volcanic field north of the Valles and Toledo calderas, and not just closely preceding the Bandelier

eruptions. This work continues the process, begun by *Gardner et al.* [1986], *Self et al.* [1986], and *Heiken et al.* [1986], of clarifying the stratigraphic relations of lithologic units in the Jemez volcanic field.

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REFERENCES

Bailey, R. A., and R. L. Smith, *Volcanic geology of the Jemez Mountains, New Mexico*, Guidebook to Rio Grande Rift in New Mexico and Colorado, *Circ. N. M. Bur. Mines Miner. Res., 163*, 184–196, 1978.

Bailey, R. A., R. L. Smith, and C. S. Ross, *Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico*, *U.S. Geol. Surv. Bull., 1274-P*, 19 pp., 1969.

Bornhorst, T. J., Major- and trace-element geochemistry and mineralogy of upper Eocene and Quaternary volcanic rocks of the Mogollon-Datil volcanic field, southwestern New Mexico, Ph.D. thesis, 1108 pp., *Univ. of N. M., Albuquerque*, 1980.

Bower, N. W., Optimization of precision and accuracy in X-ray fluorescence analysis of silicate rocks, *Appl. Spectrosc., 39*, 697–703, 1985.

Bower, N. W., and G. Valentine, A critical comparison of sample preparation methods for major and trace element determinations using X-ray fluorescence, *X Ray Spectrom., 15*, 73–78, 1986.

Criss, J. W., Fundamental parameter calculations on a laboratory microcomputer, *Adv. X Ray Anal., 23*, 93–97, 1980.

Dalrymple, G. B., A. Cox, R. R. Doell, and C. S. Gromme, Pliocene geomagnetic polarity epochs, *Earth Planet. Sci. Lett., 2*, 163–173, 1967.

Damon, P. E., M. Shafiqullah, and K. F. Clark, Geochronology of the porphyry copper deposits and related mineralization of Mexico, *Can. J. Earth Sci., 20*, 1052–1071, 1983.

DePaolo, D. J., Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic, *Nature, 291*, 193–196, 1981a.

DePaolo, D. J., Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization, *Earth Planet. Sci. Lett., 53*, 189–202, 1981b.

DePaolo, D. J., and G. J. Wasserburg, Inferences about magma sources and mantle structure from variations of $^{143}Nd/^{144}Nd$, *Geophys. Res. Lett., 3*, 743–746, 1976.

Farmer, G. L., and D. J. DePaolo, Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure, 1, Nd and Sr isotopic studies in the geocline of the northern Great Basin, *J. Geophys. Res., 88*, 3379–3401, 1983.

Fisher, R. V., and H.-U. Schmincke, *Pyroclastic Rocks*, 472 pp., Springer-Verlag, New York, 1984.

Garcia, S. R., W. K. Hensley, M. M. Minor, M. M. Denton, and M. A. Fuka, An automated multidetector system for instrumental neutron activation analysis of geological and environmental materials, in *Atomic and Nuclear Methods in Fossil Energy Research*, edited by F. Filby, B. Carpenter, and R. Ragaini, pp. 133–140, Plenum, New York, 1982.

Gardner, J. N., Tectonic and petrologic evolution of the Keres Group: Implications for the development of the Jemez volcanic field, Ph.D. thesis, 293 pp., Univ. of Calif., Davis, 1985.

Gardner, J. N., and F. Goff, Potassium-argon dates from the Jemez volcanic field: Implications for tectonic activity in the north-central Rio Grande rift, *Field Conf. Guidebk. N. M., Geol. Soc., 35*, 75–81, 1984.

Gardner, J. N., F. E. Goff, S. Garcia, and R. C. Hagan, Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico, *J. Geophys. Res., 91*, 1763–1778, 1986.

Hanson, G. N., Rare earth elements in petrogenetic studies of igneous systems, *Annu. Rev. Earth Planet. Sci., 8*, 371–406, 1980.

Heiken, G., F. Goff, J. Stix, S. Tamanyu, M. Shafiqullah, S. Garcia, and R. Hagan, Intercaldera volcanic activity, Toledo caldera and embayment, Jemez Mountains, New Mexico, *J. Geophys. Res., 91*, 1799–1815, 1986.

Hibbard, M. J., Myrmekites as a marker between preaqueous and postaqueous phase saturation in granitic systems, *Geol. Soc. Am. Bull., 90*, 1047–1062, 1979.

Kite, W. M., S. Self, F. E. Goff, and J. V. Wright, Pliocene explosive silicic volcanism in the Jemez Mountains, New Mexico (abstract), *Eos Trans. AGU, 63*, 1131, 1982.

Kushiro, I., Viscosity, density, and structure of silicate melts at high pressures, and their petrological applications, in *Physics of Magmatic Processes*, edited by B. Hargraves, pp. 93–120, Princeton University, Princeton, N. J., 1980.

Loeffler, B. M., Major- and trace-element and strontium- and oxygen-isotope geochemistry of the Polvadera Group, Jemez volcanic field, New Mexico: Implications for the petrogenesis of the Polvadera Group, Ph.D. thesis, 259 pp., *Univ. of Colo., Boulder*, 1984.

Loeffler, B. M., D. T. Vaniman, W. S. Baldridge, and M. Shafiqullah, Variations within the El Rechuelos Rhyolite, northern Jemez Mountains, New Mexico (abstract), *Eos Trans. AGU, 66*, 397, 1985.

Lofgren, G. E., and R. Gooley, Simultaneous crystallization of feldspar intergrowths from the melt, *Am. Mineral., 62*, 217–228, 1977.

Mahood, G., and W. Hildreth, Large partition coefficients for trace elements in high-silica rhyolites, *Geochim. Cosmochim. Acta, 47*, 11–30, 1983.

Miller, C. F., and D. W. Mittlefehldt, Depletion of light rare-earth elements in felsic magmas, *Geology, 10*, 129–133, 1982.

Minor, M. M., W. K. Hensley, M. M. Denton, and S. R. Garcia, An automated activation analysis system, *J. Radioanal. Chem., 70*, 459–471, 1982.

Nelson, B. K., and D. J. DePaolo, Rapid production of continental crust 1.7 to 1.9 b.y. ago: Nd isotopic evidence from the basement of the North American mid-continent, *Geol. Soc. Am. Bull., 96*, 746–754, 1985.

Olsen, K. H., W. S. Baldridge, and D. T. Vaniman, Development of magma chambers and crustal evolution beneath continental silicic volcanic centers: Geophysical and petrological evidence from the northeastern Jemez Mountains, New Mexico, paper presented at Hawaii Symposium on How Volcanoes Work, AGU, Hilo, Jan. 19–23, 1987.

Perry, F. V., W. S. Baldridge, and D. J. DePaolo, The role of asthenosphere and lithosphere in the genesis of late Cenozoic basaltic rocks from the Rio Grande rift and adjacent regions of the southwestern United States, *J. Geophys. Res., 92*, 9193–9213, 1987.

Self, S., F. Goff, J. N. Gardner, J. V. Wright, and W. M. Kite, Explosive rhyolitic volcanism in the Jemez Mountains: Vent locations, caldera development and relation to regional structure, *J. Geophys. Res., 91*, 1779–1798, 1986.

Smith, R. L., Ash-flow magmatism, *Spec. Pap. Geol. Soc. Am., 180*, 5–27, 1979.

Smith, R. L., R. A. Bailey, and C. S. Ross, Geologic map of the Jemez Mountains, New Mexico, *U.S. Geol. Surv. Map I-571*, 1970.

Valentine, G., Procedures for analysis of silicate rocks and minerals at Los Alamos National Laboratory by X-ray fluorescence, *Los Alamos Natl. Lab. Rep., LA-9663-MS*, 33 pp., 1983.

Vaniman, D. T., and W. S. Baldridge, Studies of Tschicoma andesites and dacites, and of rocks previously categorized as "El Rechuelos" rhyolites, *Los Alamos Natl. Lab. Rep., LA-10439-C*, 60–62, 1985.

Vaniman, D. T., B. M. Crowe, and E. S. Gladney, Petrology and geochemistry of hawaiite lavas from Crater Flat, Nevada, *Contrib. Mineral. Petrol., 80*, 341–357, 1982.

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