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POTASSIUM-ARGON DATES FROM THE JEMEZ VOLCANIC FIELD: IMPLICATIONS FOR TECTONIC ACTIVITY IN THE NORTH-CENTRAL RIO GRANDE RIFT

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INTRODUCTION

The Jemez Mountains volcanic edifice straddles the western margin of the Rio Grande rift which is locally expressed as three basins (Fig. 1). Volcanism in the Jemez Mountains has been intimately related to mid-Miocene through Quaternary tectonic activity of the Rio Grande rift (i.e., tectonic activity following the mid-Miocene volcanic hiatus of Chapin and Seager, 1975). Our work in the volcanic field has shown that tectonic activity has had a major influence on the dominant magmatic processes that were operative during various episodes of the volcanic field's development (e.g., Gardner, 1983, 1984). Hence, information regarding tectonic activity in the north-central rift can be inferred from studies of structures and timing of volcanism, with additional credibility provided by the petrology and petrogenesis of the volcanic products themselves. A discussion of the geochemical evidence for the petrogenetic models we use is beyond the scope of this paper; however, data supporting the petrogenetic models include major- and trace-element, microprobe, and Sr and 0 isotopic analyses (Gardner, 1982, 1983, 1984; Loeffler, 1984). In this paper we outline the geology and petrogenesis of the volcanic field, present new and existing radiometric dates, note variations of volcanism with respect to time, present some important relations of certain fault zones in the area, and summarize these data with emphasis on implications for tectonic activity in the north-central Rio Grande rift.

OUTLINE OF GEOLOGY AND PETROGENESIS

The Keres Group (Fig. 2), which comprises nearly half of the volume of the entire volcanic field, consists of rocks derived from magmas of two distinct sources: the upper mantle and the lower crust. Mafic magmas derived from the upper mantle differentiated through a broad spectrum of compositions, but gave rise to about 1,000 km' of two-pyroxene andesite. Magmas derived from partial melts of lower crust produced relatively minor volumes of chemically distinctive high-silica rhyolite. The Keres Group volcanism was accompanied by intense rifting, as suggested by field relations of mafic—intermediate rocks interbedded with widespread deposits of lahars and immature basin-fill gravels of

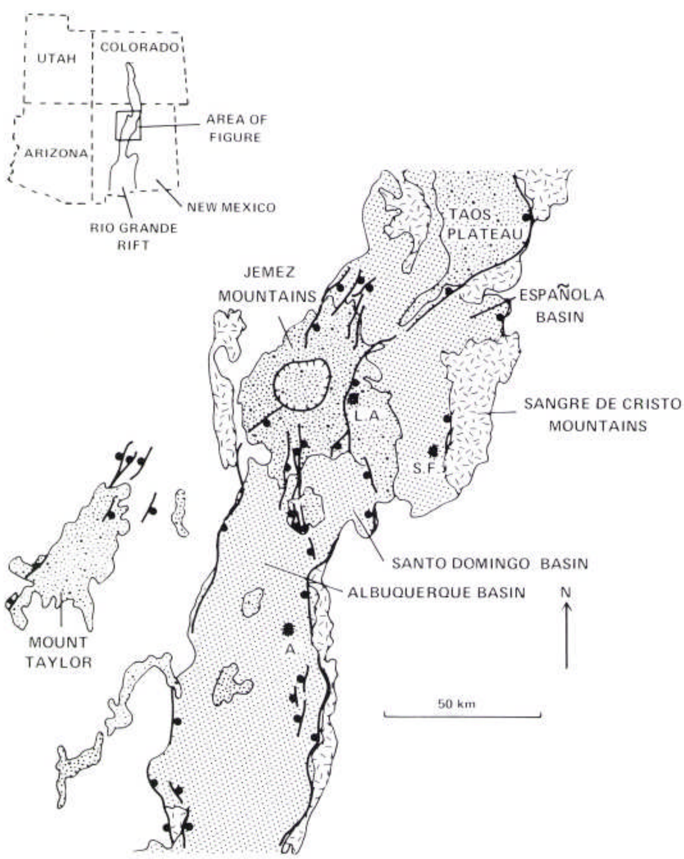

FIGURE 1. Locality map showing generalized relations of the Jemez volcanic field (Jemez Mountains) to basins of the north-central Rio Grande rift. Major fault zones are shown schematically. Random dash = Precambrian rocks; coarse, regular stipple = Tertiary–Quaternary rift-fill sediments; irregular stipple = Tertiary–Quaternary volcanic rocks. LA, SF, and A are Los Alamos, Santa Fe, and Albuquerque, respectively (modified from Baldridge and others, 1983).

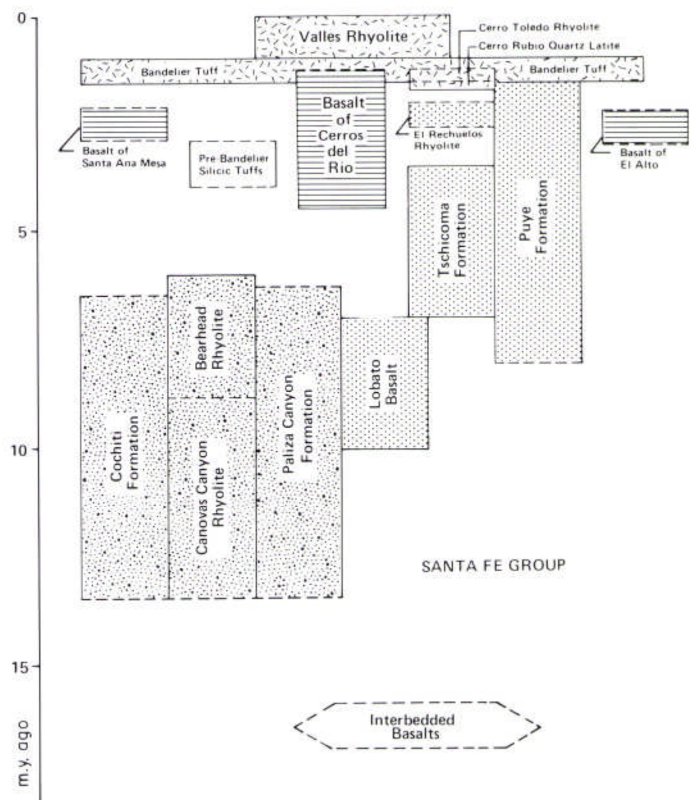

FIGURE 2. Generalized stratigraphic relations of major units in the vicinity of the Jemez volcanic field. Irregular stipple = Keres Group formations; coarse, regular stipple = Polvadera Group formations; random dash = Tewa Group formations; horizontally ruled pattern = young basalt fields, as indicated. Dashed lines indicate uncertainty. This figure is also a schematic south-to-north (left-to-right) section through the volcanic field (from Gardner, 1984; modified from Bailey and others, 1969).

the Cochiti Formation (Fig. 2), and fault control of the locations of high-silica rhyolite vents.

The best model for the genesis of the Tschicoma Formation (Fig. 2), whose latites and quartz latites dominate the 500 km' Polvadera Group (1. D. MacGregor, pers. comm. 1981), involves mixing of mafic and silicic magmas (Loeffler, 1984). End-member compositions for this mixing are approximated by basalt or basaltic andesite and high-silica rhyolite of the Keres Group. Smith and others (1970) indicate a paucity of faults in exposures of the Tschicoma Formation, and no apparent relations of vent locations to faults. While volcaniclastic debris derived from the Polvadera Group formed fan deposits of substantial volume (Puye Formation, Fig. 2) farther east in the Espanola Basin, field reconnaissance indicates virtually no significant basin-fill deposits intercalated with the Polvadera volcanic pile.

Mantle-derived magmas erupted at the basinward periphery of the main body of the volcanic field on the south, east, and north as the basalt fields of Santa Ana Mesa, Cerros del Rio, and El Alto, respectively (Figs. 2, 3) (Smith and others, 1970; Baldridge, 1979). The Tewa Group volcanism, dominated by the rhyolitic Bandelier Tuff, provided the culminating phase of the development of the Jemez volcanic field (Fig. 2). More than 500 km' of tuff erupted from a large, zoned magma chamber whose bulk composition was probably identical to the Tschicoma latitic compositions (Smith, 1979; Self and others, in prep.). Spatial and temporal overlap of the Bandelier magma and Tschicoma-like latite eruption supports this suggestion for the probable bulk composition of the Bandelier magma chamber, and strongly suggests parental relations of the Tschicoma Formation to the Tewa Group (Doell and others, 1968; Smith and others, 1970; Smith, 1979; Gardner, 1983, 1984; Self and others, in prep.).

POTASSIUM—ARGON DATES AND TIMING OF VOLCANISM

Twenty new potassium—argon dates (Table 1) have been obtained to constrain the timing of Keres Group volcanism. Sample F81-50, a basanite from a sequence of alkali basalts interbedded with lower Santa Fe Group arkosic sediments east of St. Peter's dome (Fig. 3), has yielded the oldest date in the area, of 16.5 ± 1.4 m.y. (see Table 1). While these alkali basalts are probably not petrogenetically related to volcanism in the Jemez volcanic field, they may be indicative of the onset of the thermal and tectonic events that have driven, or influenced, magmatism throughout development of the volcanic field (Gardner, 1984). Field relations together with the data of Table 1 (samples JG80-53 and F82-108) indicate the Keres Group volcanic activity began >13 m.y. ago. The Keres Group volcanism apparently waned by about 6 m.y. ago (samples JG80-49, JG8162, F82-77, and F82-117; Table 1), and overlapped with early Tschicoma Formation volcanism (Fig. 2).

The new dates (Table 1), a compilation of 95 available dates from the Jemez volcanic field and nearby areas (Table 2), and detailed geologic mapping, make possible the refinement of stratigraphic relations shown in Figure 2. Perhaps the most significant result of the refinement of stratigraphic relations is that the cyclic nature of volcanism implied by the formal stratigraphy is erroneous (see fig. 2 of Bailey and others, 1969; and Smith and others, 1970). Volcanic activity has been essentially continuous in the Jemez Mountains for the last 13 m.y. The Lobato Basalt volcanism occurred entirely within the time span of the Paliza Canyon activity, and, based on the dates and field relations, the boundary between the Canovas Canyon and Bearhead Rhyolites in Figure 2 is somewhat arbitrary.

Figure 4 is a graphic depiction of the compilation of dates plotted with respect to the predominant petrogenetic magma type outlined above. A number of features of Figure 4 are particularly noteworthy:

(1) While eruptions of the mantle-derived basaltic magmas spanned the volcanic field's entire >13 m.y. history, there was a gap in basaltic volcanism in the period 7-4 m.y. ago. Stratigraphic constraints on the dated basalts indicate that this gap is not the result of sampling bias. Those mantle-derived basalts that were erupted after the 7-4 m.y. lull in basaltic volcanism are the basalts of Santa Ana, Mesa, Cerros del Rio, and El Alto, which are distinctly peripheral to, and partially encircle, the main body of

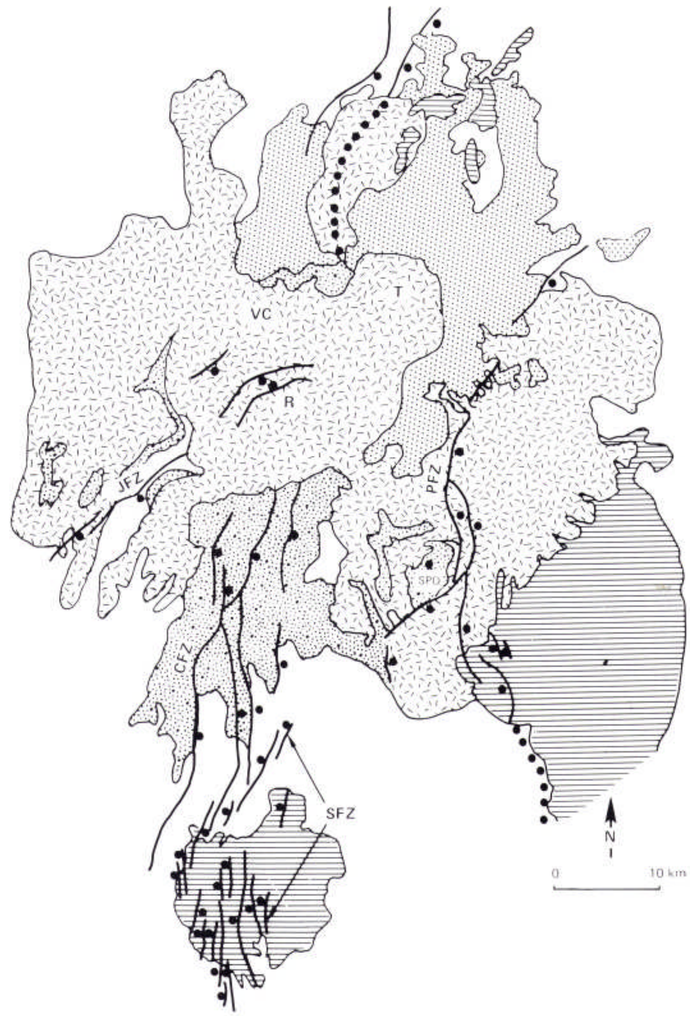

FIGURE 3. Generalized map showing distribution of major stratigraphic groups (patterns are the same as Figure 2) and the major fault zones in the Jemez Mountains. JFZ = Jemez fault zone; SFZ = Santa Ana Mesa fault zone; CFZ = Cañada de Cochiti fault zone; PFZ = Pajarito fault zone; VC = Valles caldera; R = resurgent dome of VC; T = Toledo embayment; and SPD = St. Peter's dome (from Gardner, 1984; modified from Smith and others, 1970).

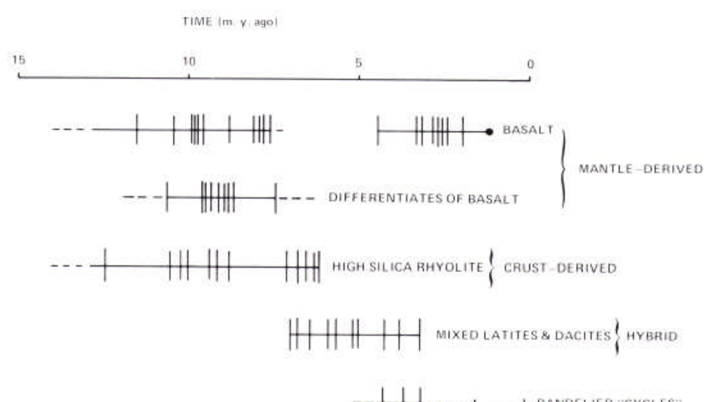

FIGURE 4. Dates of Jemez volcanic rocks (Table 2) plotted with respect to dominant magma type of Gardner (1982, 1983, 1984) and Loeffler (1984). Each vertical line represents a K–Ar date. Solid lines indicate continuous eruption of a given magma type, inferred from field relations, and dashed lines indicate uncertainty. Numerous dates from Tewa Goup—solid line for "Bandelier cycles"—not plotted for clarity.

TABLE 1. New K–Ar dates of rocks from the Jemez volcanic field and immediate vicinity.

Sample No.	Location	Rock Type	Material[2]	%K	Weight Sample, g	Moles Radiogenic ^{40}Ar	% Radiogenic ^{40}Ar	Age, Myr[1]	Comments	Lab[3]
JG80-44	35°49,8'N.Lat., 106°37.7' W. Long. from Cinder Cone @ 7735' elev., Ponderosa Quad.	Andesite	W/R	2.90	0.66078	3.539×10^{-11}	14	10.6 ± 1.4	Borrego Mesa	K
JG80-47c	SW 1/4, NE 1/4, Sec 24, T18N, R3E, 8880' elev., Redondo Peak Quad.	Rhyolite	W/R	4.07	0.46564	2.896×10^{-11}	24	8.79 ± 0.66	Dome near Cerro Pelado	K
JG80-48	SW 1/4, SW 1/4, Sec 27T18N, R3E; 1 km west of Cerro del Pino, Redondo Peak Quad.	Latite	Hbd	1.07	0.41310	7.763×10^{-12}	7	10.1 ± 2.5	Cerro del Pino	K
JG80-49	NW 1/4, SE 1/4, Sec 34, T18N, R3E; 1-3/4 km south of Cerro del Pino, Bear Springs Peak Quad.	Rhyolite	W/R	4.51	0.78161	3.785×10^{-11}	58	6.18 ± 0.09	Dome south of Cerro del Pino	K
JG80-53	Center Sec 2 T17N, R3E, 7720' elev., north wall of Paliza Cyn. Bear Springs Peak Quad.	Basalt	W/R W/R	1.27 1.14	0.48151 0.64379	1.223×10^{-11} 1.907×10^{-11}	24 10	11.5 ± 0.8 14.9 ± 2.7 (13.2 ± 1.24)	Lava flow overlies Conovas Canyon tuff	
JG80-55	NW 1/4, SE 1/4, NW 1/4, Sec 10; NW wall of Paliza Cyn. Bear Springs Peak Quad.	Andesite	W/R	3.07	0.69869	3.313×10^{-11}	6	8.88 ± 2.7	Plug in bottom of Paliza Canyon	K
JG81-50	35°42.9'N. Lat., 106°33' W. Long.; 1/4 km east of BM8009, Bear Springs Peak Quad.	Latite	Plag.	0.93	1.04681	1.252×10^{-11}	8	7.40 ± 1.6	Ruiz Peak area	K
JG81-62	35°46.1'N. Lat., 106°32.8' W. Long.; 1/2 km NW of Paliza Cyn., 1-3/4 km south of Cerro Pelado; Redondo Peak Quad.	Andesite	W/R	2.19	0.94874	2.297×10^{-11}	12	6.36 ± 0.95	Plug in Paliza Canyon	K
F80-79	Center Sec 7, T19N, R3E; Jemez Springs 15' Quad.	Latite	W/R*	2.44	0.71482	1.276×10^{-11}	7	4.21 ± 1.3	Tschicoma flow overlies Keres Group in west wall, Valles Caldera	K
F81-50	35°43.7' N. Lat., 106°22' W. Long. in Medio Canyon, Cochiti Dam Quad.	Basalt	W/R W/R W/R	0.964 1.020 1.220	0.4419 0.4608 0.4446	1.523×10^{-11} 1.381×10^{-11} 1.235×10^{-11}	11 16 10	16.5 ± 1.4	Basalt in lower Santa Fe Group beneath east side St. Peter's Dome	G G G
F82-33	35°46'N. Lat., 106°21' W. Long. 3/4 km southwest of Boundary Peak, Frijoles Quad.	Latite	W/R W/R	2.62 2.383	1.89414 0.57225	7.927×10^{-11} 23.175×10^{-12}	20 18.4	9.19 ± 0.74 9.77 ± 0.5 (9.48 ± 0.44)	Dome overlies Santa Fe Group, east side St. Peter's Dome	K G
F82-77	35°47.2' N. Lat. 106°22.3' W. Long., west side of conical dome.	Rhyolite	W/R	4.35	0.76275	3.587×10^{-11}	9	6.22 ± 1.2	Rabbit Hill Dome	K
F82-79	NW 1/4, SE 1/4, Sec 20, T18N, R5E, Bland Quad., east side Cochiti Canyon	Latite	W/R	2.70	0.5624	23.2×10^{-12}	23	8.8 ± 0.5	Dome in Upper Cochiti Canyon	G
F82-84	35° 44.5' N. Lat., 106° 24.8' W. Long., Cañada Quad., east side Cochiti Canyon	Rhyolite	W/R*	4.04	0.73427	4.808×10^{-11}	10	9.32 ± 1.6	Rhyolite intrudes andesite and capped by Peralta Tuff, Cochiti Canyon	K
F82-102	East edge, SE 1/4, Sec 5, T17N, R5E, Cañada Quad., east side Medio dia Canyon	Rhyolite	W/R	4.47	0.67200	4.828×10^{-11}	12	9.24 ± 1.5	Dome overlain by Peralta Tuff, Medio dia Canyon	K
F82-103	35°43.5' N. Lat., 106°22.7' W. Long., of Sanchez Canyon	Rhyolite	W/R	3.95	0.69057	4.964×10^{-11}	19	10.5 ± 0.9	Dome intrudes laharic deposits, west wall Sanchez Canyon	K
F82-108	35°43.5' N. Lat., 106°22.7' W. Long., bottom of Sanchez Canyon	Rhyolite	W/R W/R W/R	3.154 3.098 3.329	0.4614 0.4914 0.70743	3.359×10^{-11} 3.475×10^{-11} 4.734×10^{-11}	6 6 8	13.2 ± 3.3 11.6 ± 2.3 (12.4 ± 1.98)	Flow overlies tuff, Sanchez Canyon	G G K
GF82-117	35°44' N. Lat., 106°, 26.5' W. Long., bottom of Bland Canyon	Rhyolite	W/R	4.39	0.78136	3.888×10^{-11}	19	6.52 ± 0.59	Rhyolite intrudes Peralta Tuff, Bland Canyon	K
GF82-1	35°44' N. Lat., 106° 24.5' W. Long., west side Cerro Boletas	Rhyolite	W/R	4.08	0.77410	3.701×10^{-11}	23	6.74 ± 0.47	Rhyolite intrudes Peralta Tuff, west side Cerro Boltetas	K
F83-19	35°44.6' N. Lat., 106°22.8' W. Long., north side Cerro Picacho	Rhyolite	W/R	3.873	0.5322	25.51×10^{-12}	48.8	7.12 ± 0.4	Cerro Picacho Dome	G

EXPLANATION: 1. All dates calculated with decay and abundance constants of Steiger and Jager (1977).
2. Material analyzed: W/R = whole rock; W/R* = whole rock with magnetic fraction removed; Hbd = hornblende; plag = plagioclase.
3. Laboratory: K = D. Krummenacher, Dept. of Geology, San Diego State Univ., CA.
G = H. Krueger, Geochron Laboratories, MA.

the volcanic field (Fig. 3). Earlier basaltic volcanism, >13-7 m.y. old, comprises the basalts of the Paliza Canyon Formation and the Lobato Basalt of the Keres and Polvadera Groups, respectively (Fig. 2, Table 2).

(2) Magmas derived by differentiation of mantle-derived material were erupted early in the volcanic field's history, in the period >10-7 m.y.B.P. These magmas are represented predominantly by the andesites and less voluminous latites of the Paliza Canyon Formation of the Keres Group (Table 2).

(3) High-silica rhyolite magmas, derived from partial melts of lower crust, were continuously erupted in the period >13-6 m.y.B.P., early in the field's history. These crustal partial melts are the tuffs and domes of the Canovas Canyon and Bearhead Rhyolites of the Keres Group.

(4) Latites, quartz latites, and dacites formed by mixing of basalt or basaltic andesite and high-silica rhyolite magmas began to be erupted about 7 m.y. ago, at the same time as the beginning of the 7-4 m.y. lull in basaltic volcanism mentioned in (1) above. Furthermore, the onset of the eruption of these mixed latites and dacites was essentially contemporaneous with the cessation of eruption of differentiates of basalt (Paliza Canyon intermediate rocks) and the high-silica rhyolites discussed in (2) and (3) above, respectively.

(5) The onset of the Tewa Group volcanism ("Bandelier cycles") was essentially contemporaneous with the revival of basaltic volcanism at about 4 m.y.B.P., discussed in (1) above, and overlapped with the waning eruptions of mixed magmas discussed in (4).

FAULT ZONES

Figure 3 shows the four major fault zones in the immediate vicinity of the Jemez volcanic field as the Jemez, Santa Ana Mesa, Pajarito, and Canada de Cochiti fault zones. The reader familiar with the general geology of the Jemez Mountains will note apparent discrepancies between the names we employ for fault zones and names used by some previous workers (e.g., Kelley and others, 1976; Kelley, 1978; Woodward and Ruetschilling, 1976; Woodward and others, 1977). It is important to realize that the names we use are applied to fault zones, not

TABLE 2. Compilation of dates of Jemez volcanic rocks only.

TEWA GROUP: Valles Rhyolite Date	Ref.	TEWA GROUP: Tschirege Member (Bandelier Tuff) Date	Ref.	TEWA GROUP: Toledo Rhyolite Date	Ref.	TEWA GROUP: Otowi Member (Bandelier Tuff) Date	Ref.	Pre-Bandelier Silicic Tuffs Date	Ref.	El Alto, Santa Ana Mesa, and Cerros del Rio "Basalt Fields" Date	Ref.
0.13 ± 0.10	(10)										
0.434 ± 0.015	(4)	1.02 ± 0.04	(4)	1.22 ± 0.04	(4)	1.37 ± 0.04	(4)	3.15 ± 0.89	(9)	1.96 ± 0.06	(6)
0.494 ± 0.015	(4)	1.06 ± 0.03	(4)	1.25 ± 0103	(9)	1.44 ± 0.04	(4)	3.64 ±1.64	(9)	2.4 ± 0.3	(6)
0.502 ± 0.015	(4)	1.09 ± 0.03	(4)	1.28 ± 0.02	(9)	1.48 ± 0.09	(4)	4.2 ± 0.3(?)	(6)	2.5 ± 0.3	(1)
0.535 ± 0.015	(4)	1.1 ± 0.1	(2)	1.28 ± 0.07	(4)					2.6 ± 0.4	(1)
0.692 ± 0.015	(4)	1.19 ± 0.04	(4)							2.6 ± 0.4	(1)
0.707 ± 0.019	(4)	1.24 ± 0.05	(4)							2.6 ± 0.2	(6)
0.726 ± 0.015	(4)									2.78 ± 0.44	(6)
0.823 ± 0.074	(4)									2.76 ± 0.44	(7)
0.884 ± 0.028	(4)									2.8 ± 0.7	(8)
0.886 ± 0.019	(4)									2.8 ± 0.5	(8)
1.04 ± 0.05	(4)									2.8 ± 0.1	(6)
1.15 ± 0.03	(4)									2.8 ± 0.1	(6)
1.25 ± 0.11	(4)									3.1 ± 1.0	(8)
										3.2 ± 0.1	(2)
										4.4 ± 0.1	(2)

El Rechuelos Rhyolite Date	Ref.	POLVADERA GROUP: Tschicoma Formation Date	Ref.	POLVADERA GROUP: Lobato Basalt Date	Ref.
2.07 ± 0.06*	(3)	3.15 ± 0.28	(6)	7.6 ± 0.4	(8)
		3.77 ± 0.12*	(3)	7.63 ± 0.16*	(3)
		4.2 ± 0.3	(6)	7.8 ± 0.5	(8)
		4.21 ± 1.3	(5)	7.8 ± 0.7	(8)
		5.0 ± 0.7	(6)	7.9 ± 0.5	(8)
		5.16 ± 0.13*	(3)	8.1 ± 0.2	(6)
		5.65 ± 0.82*	(3)		
		5.78 ± 0.18*	(3)	9.6 ± 0.3	(6)
		6.36 ± 0.95	(5)	9.6 ± 0.2	(2)
		6.82 ± 0.17*	(3)	9.7 ± 0.3	(2)
		6.87 ± 0.33*	(3)	9.8 ± 0.4	(1)
				9.9 ± 1.0	(8)

KERES GROUP: Bearhead Rhyolite Date	Ref.	Paliza Canyon Formation (Latitic Rocks) Date	Ref.	Paliza Canyon Formation (Andesitic Rocks) Date	Ref.	Paliza Canyon Formation (Basaltic Rocks) Date	Ref.	Canovas Canyon Rhyolite Date	Ref.
6.18 ± 0.09	(5)	7.4 ± 1.6	(5)			8.8 ± 0.3	(6)	9.24 ± 1.5	(5)
6.22 ± 1.2	(5)	8.8 ± 0.5	(5)	8.69 ± 0.38*	(3)	10.4 ± 0.5**	(6)	9.32 ± 1.6	(5)
6.52 ± 0.59	(5)	9.11 ± 0.19*	(3)	8.88 ± 2.7	(5)	13.2 ± 1.24	(5)	10.0 ± 0.3	(6)
6.74 ± 0.47	(5)	9.33 ± 0.19*	(3)	9.0 ± 0.3	(6)			10.2 ± 0.3	(6)
7.1 ± 0.2	(6)	9.48 ± 0.44	(5)	9.5 ± 2.5	(6)			10.5 ± 0.9	(5)
7.12 ± 0.4	(5)	10.1 ± 2.5	(5)	10.6 ± 1.4	(5)			12.4 ± 1.98	(5)
8.79 ± 0.66	(5)								

* = Date recalculated with decay and abundance constants of Steiger and Jager (1977) or by methods of Dalrymple (1979).

** = Date on basalt of Chamisa Mesa (Bailey et al., 1969).

References:
(1) Bachman and Mehnert (1978)
(2) Baldridge and others (1980)
(3) Dalrymple and others (1967)
(4) Doell and others (1968)
(5) This work
(6) Leudke and Smith (1978)
(7) Manley (1976b)
(8) Manley and Mehnert (1981)
(9) Self and others (in prep.)
(10) Marvin and Dobson (1979)

to individual faults. The Canada de Cochiti and Santa Ana Mesa fault zones are commonly referred to as a single zone, also known as the San Felipe fault zone. However, we distinguish two fault zones based on age and sense of displacement: the Santa Ana Mesa fault zone is the active eastern boundary of the Albuquerque Basin south of the Jemez Mountains, and the Canada de Cochiti zone is the inactive (see below) western boundary of the Espanola Basin east of, and containing, the Jemez Mountains. While the fault zones shown in Figure 3, except the Canada de Cochiti zone, are currently seismically active (Cash and others, 1982), most important to this discussion are the Pajarito and Canada de Cochiti zones.

The Canada de Cochiti fault zone is a broad swath of north-trending normal faults that cuts the Keres Group rocks in the southern Jemez Mountains. The fault zone is obliterated by the Valles caldera, but is exposed in Mesozoic—Tertiary rocks north of a paleovalley eroded along the faults and filled with unfaulted Bandelier Tuff (dotted fault in Fig. 3) (Smith and others, 1970; Lawrence, 1979). Most faults in the Canada de Cochiti fault have a down-to-the-east sense of displacement, and we estimate more than 500 m of cumulative offset across the fault zone. Because the volcanic and volcaniclastic deposits of the Keres Group are both cut by faults of this zone and thicken to the east across the fault zone, these faults were active during the Keres Group volcanism. Rhyolites of the Canovas Canyon and Bearhead Formations are intruded along these faults, but commonly the Bearhead domes (see Table 2) are not themselves faulted. Hence, faults of this zone originally represented the western boundary of the Espanola Basin of the Rio Grande rift and became inactive sometime prior to about 6 m.y. ago.

The Pajarito fault zone is a narrow band of north- and northeast-trending normal faults (Griggs, 1964; Smith and others, 1970; Golombek, 1981) which, we suggest, defines the present western boundary of the Espanola Basin of the Rio Grande rift. A very deep part of the Espanola Basin is adjacent to this fault zone, as suggested by more than 1,500 m of basin-fill sediments immediately east of the fault zone (Budding, 1978; Cordell, 1978; Goff and Grigsby, 1982). Faults of this zone show predominantly down-to-the-east sense of displacement and evidence of episodic or multiple faulting events indicated by progressively larger amounts of offset in older rock units (Griggs, 1964). The Pajarito fault zone offsets the I.1-m.y.-old Bandelier Tuff by more than 100 m, and, as mentioned above, is currently seismically active (Griggs, 1964; Smith and others, 1970; Cash and others, 1982). Based in part on the work of Manley (1976a, 1979) in the northern Espanola Basin, Golombek (1981, 1983) and Golombek and others (1983) have suggested that the Pajarito fault zone became active since about 5 m.y. ago. Thus, fault activity bounding the western margin of the Espanola Basin apparently shifted from the Canada de Cochiti fault zone, discussed above, to the Pajarito fault zone since roughly 6-5 m.y. ago.

The northeast-trending segment of the Pajarito fault zone southeast of St. Peter's dome appears to be older than portions of the fault zone further north, and is probably not directly related to the Espanola Basin (Figs. 1, 3). Movements on this segment of the fault have caused tilting of large blocks northwest of the fault trace with increasing amounts of tilt in progressively older rock units (Smith and others, 1970). Contrary to the conclusions of Golombek (1981; 1983), our detailed mapping corroborates these relations shown on the regional map of Smith and others (1970). Eocene Galisteo Formation rocks dip 25-45° NW, Santa Fe Group deposits dip 5-15° NW, and lower Keres Group rocks dip __10° NW (Gardner, 1984; Goff, in prep.), indicating this segment of the Pajarito fault zone is at least older than lower Santa Fe Group deposits at this locality (>16.5 m.y.B.P., see sample F81-50 in Table 1).

The northeast trend and substantially older age than portions of the fault zone further north suggest that this segment of the Pajarito fault zone may be associated with the northeast-trending Santo Domingo Basin. Alternatively, this older, northeast-trending segment of the fault zone may reflect the structural grain imparted to the area by the Jemez lineament, which is locally manifested as the Jemez fault zone, resurgent and subsurface structures in Valles caldera, and the Toledo embayment (Fig. 3) (Smith and others, 1970; Goff and Kron, 1980; Goff and Gardner, 1980; Goff, 1983; Gardner, 1983, 1984; Self and others, in prep.).

SUMMARY AND DISCUSSION

Following the mid-Miocene volcanic hiatus of Chapin and Seager (1975), revived rifting in the vicinity of the Jemez Mountains began about 16.5 m.y. ago as indicated by the age of the basanitc within the lower Santa Fe Group (sample F81-50, Table 1) and the age of the northeast-trending segment of the Pajarito fault zone near St. Peter's dome. From 13 to 10 m.y.B.P. tectonic activity was probably intense. Basalts and high-silica rhyolites were vented during this period along faults of the Canada de Cochiti zone; they are interbedded with immature basin-fill gravels and lahars of the Cochiti Formation. The Cochiti Formation deposits thicken dramatically from west to east into the rift across the Canada de Cochiti fault zone. In the period 10-7 m.y.B.P., basalt, high-silica rhyolite, and differentiates of basalt were rapidly vented (Fig. 5) because open conduits were provided by on-going extension across the Canada de Cochiti fault zone. Golombek and others (1983) suggest that intense tectonic activity in the area occurred around 10 m.y. ago, which for the most part agrees with our inferences from field relations and the fact that more than half the volume of the entire volcanic field was erupted during the 3 m.y. interval 10-7 m.y. ago (Fig. 5). Golombek (1981, 1983), however, suggests that tectonic activity around 10 m.y.B.P. was concentrated within a now-buried graben in the central Espanola Basin, east of the Pajarito fault zone, in order to account for the apparent discrepancy between estimates of maximum offset on the Pajarito fault zone and the tremendous thickness of basin-fill material immediately adjacent to the fault, as indicated by various geophysical studies. Golombek (1981, 1983) cites the gravity interpretation of Budding (1978), and Golombek and others (1983) cite the gravity model of Cordell (1979) as evidence of this hidden graben.

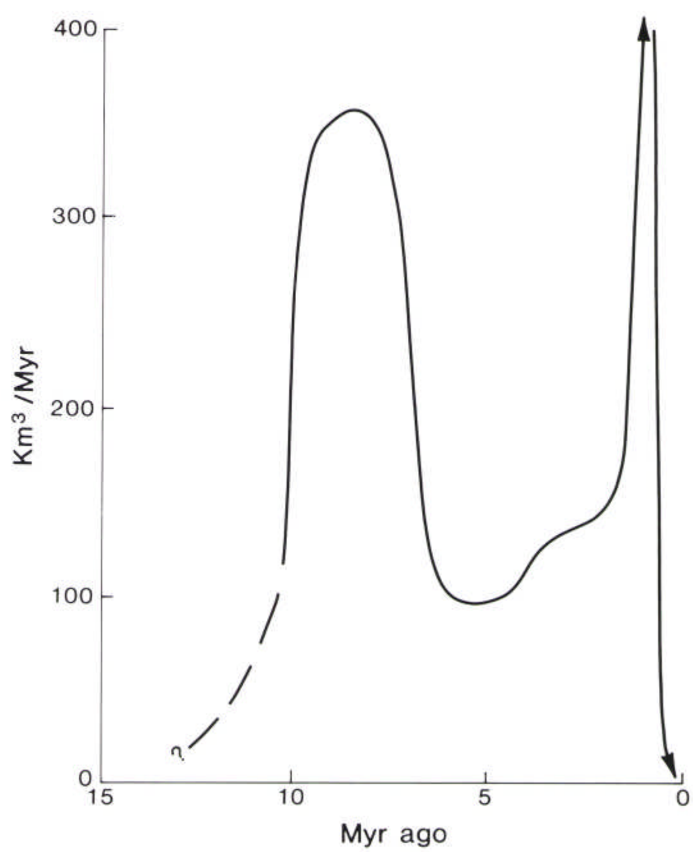

FIGURE 5. "Rate" of volcanism (volume per unit time) vs. time (m.y.B.P.) for Jemez volcanic activity. Plot goes off-scale with major Bandelier ash-flow eruptions (from Gardner, 1984).

Other geophysical studies in the same area (detailed gravity by Williams, 1979; seismic reflection by E. F. Homuth, pers. comm. 1979; see also summary in Goff and Grigsby, 1982, and Cordell, 1979, profile C—C') do reveal intrabasin faults, but do not corroborate the existence of a large, buried graben. Furthermore, scrutiny of Budding's (1978) interpretive cross sections reveals that the position of the Pajarito fault zone is plotted incorrectly: the gravity low ("buried graben") is not some distance east of the Pajarito fault zone, it is *bounded* by the fault zone on the west. Our work indicates that displacement across the Canada de Cochiti fault zone together with a post-4 m.y.B.P. displacement on the Pajarito fault zone can accommodate most of the 1,500 m of basin-fill sediment immediately east of the Pajarito fault zone. Hence, tectonic activity prior to 10 m.y.B.P. was probably not restricted to central parts of the Espanola Basin, but rather was concentrated within the Canada de Cochiti fault zone, defining the western boundary of the basin.

At about 7-6 m.y.B.P., differentiates of basalt and high-silica rhyolite stopped being erupted, mixed magmas began to be eruped, and there was a sharp reduction in the "rate" of volcanic activity (Fig. 5). At about the same time, the beginning of the 7-4 m.y.B.P. lull in basaltic volcanism occurred, and the Canada de Cochiti fault zone became inactive. Furthermore, the 7-4 m.y. lull (or a sharp reduction in the apparent volume of basaltic volcanism during this period) has been noted elsewhere in or near the rift (Baldridge and Perry, 1983; A. W. Laughlin, pers. comm. 1983; Seager and others, 1984) and may be indicative of events of regional significance. Because of the intimate association of basaltic volcanism and intense tectonism earlier in the volcanic field's history, we suggest that the gap in basaltic volcanism is indicative of a lull in tectonic activity. The reduction in the rate of volcanic activity and the petrogenetic transition from differentiates of basalt to hybrid latites at about 7 m.y. ago reflect a change in the dominant magmatic processes in response to the tectonic lull. Instead of being rapidly vented, as in earlier, more tectonically active stages of the field's development, pockets of basalt or basaltic andesite began to coalesce with pockets of high-silica rhyolite and continued to grow into large magma chambers from which small portions were erupted as hybrid latitic lavas. It is probable that these large, hybrid-magma chambers developed chemical and mineralogical zonation, and ultimately gave rise to the Bandelier Tuff (Smith, 1979; Self and others, in prep.). Spatial and temporal overlap of Bandelier-like and Tschicoma-like hybrid eruptions further suggests parental relations of Tschicoma magma chambers to the Tewa Group (Doell and others, 1968; Smith and others, 1970; Smith, 1979; Gardner, 1983, 1984; Self and others, in prep.).

Manley (1976a, 1979) suggests intense faulting during the period 5-3 m.y.B.P. in the Velarde graben in the northern Espanola Basin, and Golombek (1981, 1983) and Golombek and others (1983) estimate that the Pajarito fault zone became active around 5 m.y. ago. As a refinement of this estimate, we suggest that basin-bounding activity shifted from the Canada de Cochiti zone to the north-trending part of the Pajarito fault zone at about 4 m.y.B.P. Golombek (1981. 1983) suggests that the position of the Pajarito fault zone is controlled by the location of an abrupt facies change from volcanic to volcaniclastic rocks. It is improbable that these deposits, which constitute a thin veneer relative to the sequence of units cut by the fault zone and the minimum depth of penetration of the fault (e.g., see Goff and Grigsby, 1982), could control the position of the fault. Instead, we suggest that during the 7-4 m.y. tectonic lull the development of large, hybrid-magma chambers within the crust beneath the center of the volcanic field caused a shift in basin-bounding faulting from the Canada de Cochiti zone to the Pajarito zone, with revived tectonism at about 4 m.y.B.P. renewed basaltic volcanism at about 4 m.y. ago, caused by revived tectonic activity, gave rise to the basalt fields that are peripheral to, and partially encircle, the main body of the volcanic field. The peripheral positions of these young basalt fields may also indicate the existence of large magma chambers beneath the center of the volcanic field. Tectonic activity has continued from about 4 m.y. ago to the present, accompanied by the voluminous eruptions of Bandelier Tuff from the large, hybrid-magma chambers.

Golombek and others (1983) present rates of extension for the Espanola Basin which, in light of the new K—Ar dates presented herein and our evidence for episodic rifting for >16.5 m.y., are probably unrealistic. Golombek and others (1983) also provide an estimate of about 10% total extension across the basin. It is not clear from their discussion what data were used to generate this estimate, but if they did not include the movements on the Canada de Cochiti fault zone, as may be inferred from the above discussion of the "buried graben," their estimate is much less than minimal.

The interval that we suggest as a tectonic lull (7-4 m.y. ago) is precisely the interval that is widely cited as one of rapid uplift throughout the Rio Grande rift (e.g.. Chapin, 1979). The works of Axelrod and Bailey (1976), Taylor (1975), and Scott (1975) are cited in support of rapid uplift occurring 7-4 m.y. ago; however, these authors only state that uplift in the Rio Grande region must have occurred sometime *since* 7 m.y. ago. Manley (1979) presents evidence that relatively intense faulting occurred in the Velarde graben in the northern Espanola Basin sometime during 5-3 m.y.B.P. Therefore, our suggestion of the 7-4 m.y. tectonic lull is consistent with, and/or supported by, the works of Axelrod and Bailey (1976), Scott (1975), Taylor (1975), and Manley (1979).

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The entire main line route of the Southern San Luis Valley Railroad is visible in this picture, running from the Colorado Aggregate Company yard behind the camera to Blanca in the distance.