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Stratigraphic Relations and Lithologic Variations in the Jemez Volcanic Field, New Mexico

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Over 100 radiometric dates and recent detailed geologic mapping allow some refinements of the stratigraphic relations of major units and generalization of temporal lithologic variations in the Jemez volcanic field. Volcanism had begun in the area by about 16.5 Ma with episodic eruptions of alkaline basalts. By 13 Ma, alkaline volcanism had been replaced with eruptions of more voluminous olivine tholeiite. High-silica rhyolite, derived from melts of lower crust, also was erupting by about 13 Ma. Basalt and high-silica rhyolite continued to be erupted until about 7 and 6 Ma, respectively, but effusions of dominantly andesitic differentiates of basalt that began as early as about 12 Ma volumetrically overshadowed all other eruptive products between 10 and 7 Ma. From 7 to 3 Ma the dominant erupted lithology was dacite, which appears to have been generated by mixing of magmas whose compositions are approximated by earlier andesites and high-silica rhyolites. Less than 4–3 Ma volcanism was dominated by eruption of rhyolitic tuffs. Field relations, geochemistry, and dates specifically indicate the following with regards to stratigraphic relations: (1) distinctions among basalt of Chamisa Mesa, Paliza Canyon Formation basalts, and Lobato Basalt for other than geographic reasons are artificial; basaltic volcanism was continuous in volcanic field from >13 to 7 Ma, (2) Canovas Canyon and Bearhead rhyolites form a continuum of high-silica rhyolite volcanism from >13 to 6 Ma, (3) hypabyssal and volcanic rocks of the Cochiti mining district probably represent the exhumed interior of a Keres Group volcano(s), (4) temporal overlaps exist among the major stratigraphic groups which may imply some genetic relations, and (5) the Tewa Group formation Cerro Rubio Quartz Latite may more appropriately be considered part of the Tschicoma Formation of the Polvadera Group. Preliminary analysis of hydrothermal alteration in the context of the volcanic stratigraphy suggests at least three distinct hydrothermal events have occurred in the volcanic field's history.

INTRODUCTION

With increasing scientific interest focused on the Jemez volcanic field because of the Continental Scientific Drilling Program, numerous detailed geological, geochemical, and petrologic studies (for example, this special section) of various aspects of the Jemez Mountains have been done since the pioneering work of the U.S. Geological Survey [e.g., *Iddings*, 1890; *Ross*, 1931, 1938; *Doell and Dalrymple*, 1966; *Smith and Bailey*, 1966, 1968; *Smith et al.*, 1970]. As commonly occurs when more detailed information becomes available, revisions of or substitutes for earlier geologic models are necessary. The purpose of this paper is to present stratigraphic relations, based on new field and radiometric data, together with generalized temporal lithologic variations which have important implications for the development of the Jemez volcanic field and probably the Bandelier Tuff magmatic system(s).

Bailey et al. [1969] and *Smith et al.* [1970] developed a formalized stratigraphy for the volcanic and volcaniclastic rocks of the Jemez volcanic field. They divided the volcanic field into the three stratigraphic groups from oldest to youngest, Keres, Polvadera, and Tewa. A compilation of available dates (Table 1) and field relations indicate temporal overlap among all groups (Figure 1), but the three stratigraphic groups retain much of their petrological significance, as implied by *Bailey et al.* [1969].

Stratigraphic relations within a complex volcanic field such as the Jemez Mountains are not as straightforward as in most sedimentary sequences. Too commonly, genetic relations for the volcanic rocks overshadow purely stratigraphic considerations. Hence instead of attempting to redefine the stratigraphy of the Jemez volcanic field, in this paper we point out stratigraphic and lithologic relations of major units so as to provide a skeletal framework from which further refinements may be made. Although the formal stratigraphy was based on excellent field geology and some radiometric dates for the pre-Tewa Group rocks, the cyclic, bimodal nature of volcanism it implies is misleading (see below). However, it is our intention that this paper complement *Bailey et al.* [1969], not replace it.

Figure 1 is a summary of the refined stratigraphic relations that are discussed in this paper. The reader will find comparison of Figure 1 to Figure 2 of *Bailey et al.* [1969] instructive. Figure 2 shows the distribution of the major stratigraphic groups in the Jemez Mountains, and Figure 3 together with Table 2 provide an index of geographic localities mentioned in the text.

Lithologic nomenclature for rocks of the Jemez volcanic field is problematic and has been discussed in detail elsewhere [*Gardner*, 1985]. Both chemical and modal classification

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TABLE 1. Compilation of Dates of Jemez Volcanic Rocks

Tewa Group

Valles Rhyolite		Tshirege Member (Bandelier Tuff)		Cerro Toledo Rhyolite		Otowi Member (Bandelier Tuff)		Cerro Rubio Quartz Latite		Pre-Bandelier Silicic Tuffs		El Alto, Santa Ana Mesa, and Cerros del Rio "Basalt Fields"	
Date, Ma	Reference	Date, Ma	Reference	Date, Ma	Reference	Date, Ma	Reference	Date, Ma	Reference	Date, Ma	Reference	Date, Ma	Reference
0.13 ± 0.10	10	1.02 ± 0.04	4	1.20 ± 0.03	13	1.37 ± 0.04	4	2.18 ± 0.09	13	2.85 ± 0.07	17	1.96 ± 0.06	6
0.365 ± 0.061	15	1.06 ± 0.03	4	1.22 ± 0.04	4	1.44 ± 0.04	4	3.59 ± 0.36	13	3.64 ± 1.64	9	2.4 ± 0.3	6
0.434 ± 0.015	4	1.09 ± 0.03	4	1.23 ± 0.02	14	1.48 ± 0.09	4					2.5 ± 0.3	1
0.494 ± 0.015	4	1.1 ± 0.1	2	1.24 ± 0.03	13							2.6 ± 0.4	1
0.502 ± 0.015	4	1.19 ± 0.04	4	1.27 ± 0.02	13							2.6 ± 0.4	1
0.535 ± 0.015	4	1.24 ± 0.05	4	1.33 ± 0.02	13							2.6 ± 0.2	6
0.692 ± 0.015	4			1.38 ± 0.05	13							2.78 ± 0.44	6
0.707 ± 0.019	4			1.47 ± 0.04	14							2.76 ± 0.44	7
0.726 ± 0.015	4			1.47 ± 0.05	13							2.8 ± 0.7	8
0.823 ± 0.074	4			1.50 ± 0.05	13							2.8 ± 0.5	8
0.884 ± 0.028	4											2.8 ± 0.1	6
0.886 ± 0.019	4											2.8 ± 0.1	6
1.04 ± 0.05	4											3.1 ± 1.0	8
												3.2 ± 0.1	2
												4.4 ± 0.1	2
												4.62 ± 0.12	11

Polvadera Group

El Rechuelos Rhyolite		Tschicoma Formation		Lobato Basalt	
Date, Ma	Reference	Date, Ma	Reference	Date, Ma	Reference
2.01 ± 0.06	11	3.15 ± 0.28	6	7.6 ± 0.4	8
2.07 ± 0.06†	3	3.77 ± 0.12†	3	7.63 ± 0.16†	3
		3.98 ± 0.18	12	7.8 ± 0.5	8
		4.2 ± 0.3	6	7.8 ± 0.7	8
		4.21 ± 1.3	5	7.9 ± 0.5	8
		5.0 ± 0.7	6	8.1 ± 0.2	6
		5.16 ± 0.13†	3	9.07 ± 0.22	12
		5.65 ± 0.82†	3	9.20 ± 0.25	11
		5.78 ± 0.18†	3	9.56 ± 0.24	16
		6.36 ± 0.95	5	9.6 ± 0.3	6
		6.82 ± 0.17†	3	9.6 ± 0.2	2
		6.87 ± 0.33†	3	9.7 ± 0.3	2
				9.8 ± 0.4	1
				9.9 ± 1.0	8
				10.12 ± 0.27	11
				10.17 ± 0.24	12
				10.30 ± 0.30	12
				10.30 ± 0.30	16
				10.40 ± 0.03	12
				10.67 ± 0.30	16
				10.76 ± 0.28	11
				14.05 ± 0.33	12

Keres Group

Bearhead Rhyolite		Paliza Canyon Formation: Dacitic Rocks		Paliza Canyon Formation: Andesitic Rocks		Paliza Canyon Formation: Basaltic Rocks		Canovas Canyon Rhyolite	
Date, Ma	Reference	Date, Ma	Reference	Date, Ma	Reference	Date, Ma	Reference	Date, Ma	Reference
5.8 ± 0.2(?)*	11	7.4 ± 1.6	5	8.69 ± 0.38†	3	8.8 ± 0.3	6	8.79 ± 0.66	5
6.18 ± 0.09	5	8.8 ± 0.5	5	8.88 ± 2.7	5	10.4 ± 0.5‡	6	9.24 ± 1.5	5
6.22 ± 1.2	5	9.11 ± 0.19†	3	9.0 ± 0.3	6	13.2 ± 1.24	5	9.32 ± 1.6	5
6.52 ± 0.59	5	9.33 ± 0.19†	3	9.5 ± 2.5	6			10.0 ± 0.3	6
6.74 ± 0.47	5	9.48 ± 0.44	5	10.6 ± 1.4	5			10.2 ± 0.3	6
6.81 ± 0.15	18	10.1 ± 2.5	5					10.5 ± 0.9	5
7.1 ± 0.2	6	11.2±0.3 (Stein, 1983)						12.4 ± 1.98	5
7.12 ± 0.4	5								
7.54 ± 0.28(?)*	11								

Where possible, multiple dates on the same unit have been deleted. Question mark indicates uncertain or problematic stratigraphic assignment.

References: (1) *Bachman and Mehnert* [1978] (10) *Martin and Dobson* [1979]
(2) *Baldridge et al.* [1980] (11) D. T. Vaniman and W. S. Baldridge (unpublished data, 1985)
(3) *Dalrymple et al.* [1967] (12) M. J. Aldrich (unpublished data, 1985)
(4) *Doell et al.* [1968] (13) *Heiken et al.* [this issue]
(5) *Gardner and Goff* [1984] (14) *Izett et al.* [1980]
(6) *Leudke and Smith* [1978] (15) *Goff et al.* [this issue]
(7) *Manley* [1976] (16) M. J. Aldrich and D. Dethier (unpublished data, 1984)
(8) *Manley and Mehnert* [1981] (17) *Self et al.* [this issue]
(9) *Kite et al.* [1982] (18) J. N. Gardner and F. Goff (unpublished data, 1985)

*Mapped as El Rechuelos Rhyolite by *Smith et al.* [1970].
†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].

schemes tend to obscure the diversity of rock types in the volcanic field. With few exceptions the rocks of the volcanic field are subalkaline (Figure 4), and are of the calc-alkaline series [*Smith et al.*, 1978; *Lawrence*, 1979; *Gardner*, 1985]. In fact, most andesites of the Jemez Mountains satisfy the criteria suggested by *Gill* [1981] for high-potassium orogenic andesites [*Gardner*, 1985]. For all of these reasons, we include selected chemical analyses of each major unit (Table 3), and adopt an approach to rock nomenclature based primarily on SiO_2 content, as follows: less than 53% SiO_2, basalt; 53–64% SiO_2, andesite; 64–70% SiO_2, dacite; 70–75% SiO_2, rhyolite; and greater than 75% SiO_2, high-silica rhyolite. A noteworthy result of our approach to rock nomenclature is that what we refer to simply as dacites have been variously called dacites, latites, quartz latites, and rhyodacites by other workers.

In a final section of this paper we briefly discuss hydrothermal alteration events that have occurred throughout the history of the Jemez volcanic field. Although the timing of these hydrothermal events is presently poorly constrained, a discussion of hydrothermal activity in the context of the volcanic stratigraphy has never been previously attempted.

INCEPTION OF VOLCANISM

Based on field relations and 25 new radiometric dates, *Gardner and Goff* [1984] suggested that "Jemez volcanism" began greater than 13 Ma. They reported, however, the oldest date yet obtained from the volcanic field as 16.5 ± 1.4 Ma on a basanite (Table 3) from a sequence of alkali basalts interbedded with Santa Fe Group sediments near St. Peter's dome (Figures 2 and 3). *Gardner* [1985] concluded that the Santa Fe Group alkali basalt sequence is unrelated to Keres Group rocks, but all geochemical data are consistent with derivation of both groups' mafic magmas from similar upper mantle sources. *Gardner* [1985] suggested, however, that although they had a petrogenesis separate from "Jemez volcanic rocks," the alkali basalts interbedded with the Santa Fe Group near St. Peter's dome mark the onset of the thermal and tectonic events that have caused development of the volcanic field. As such, regardless of stratigraphic assignment, these alkali basalts could be construed as marking the inception of "Jemez volcanism." *Aldrich* [this issue] reports a date of 14.05 ± 0.33 Ma on a unit mapped as Lobato Basalt [*Smith et al.*, 1970] in the northeastern Jemez Mountains. No petrologic data are yet available for this dated basalt, but *Aldrich* [this issue] reports that it, too, is interbedded with Santa Fe Group sediments. Hence inception of "Jemez volcanism" is more a semantical problem than a geologic problem. Clearly, volcanism in the area had begun by about 16.5 Ma, and some rocks assigned to formal stratigraphic groups of the Jemez volcanic field have ages greater than 13–14 Ma.

KERES GROUP

Bailey et al. [1969] defined the Keres Group as being composed of the three formations, Canovas Canyon Rhyolite, Paliza Canyon, and Bearhead Rhyolite, and an informally designated unit, the basalt of Chamisa Mesa. Field relations and radiometric dates indicate that Keres Group volcanic activity spanned the period from greater than 13–6 Ma (Figure 1 and Table 1; see also *Gardner and Goff* [1984]). Keres Group rocks are best exposed in the southern Jemez Mountains and in the northern rim of Valles caldera (Figures 2 and 3). Although the group contains a full spectrum of rock compositions from olivine tholeiite basalt to high-silica rhyolite (Table 3), it is volumetrically dominated by andesites of the Paliza Canyon Formation. In fact, the reconstructed distribution of Keres

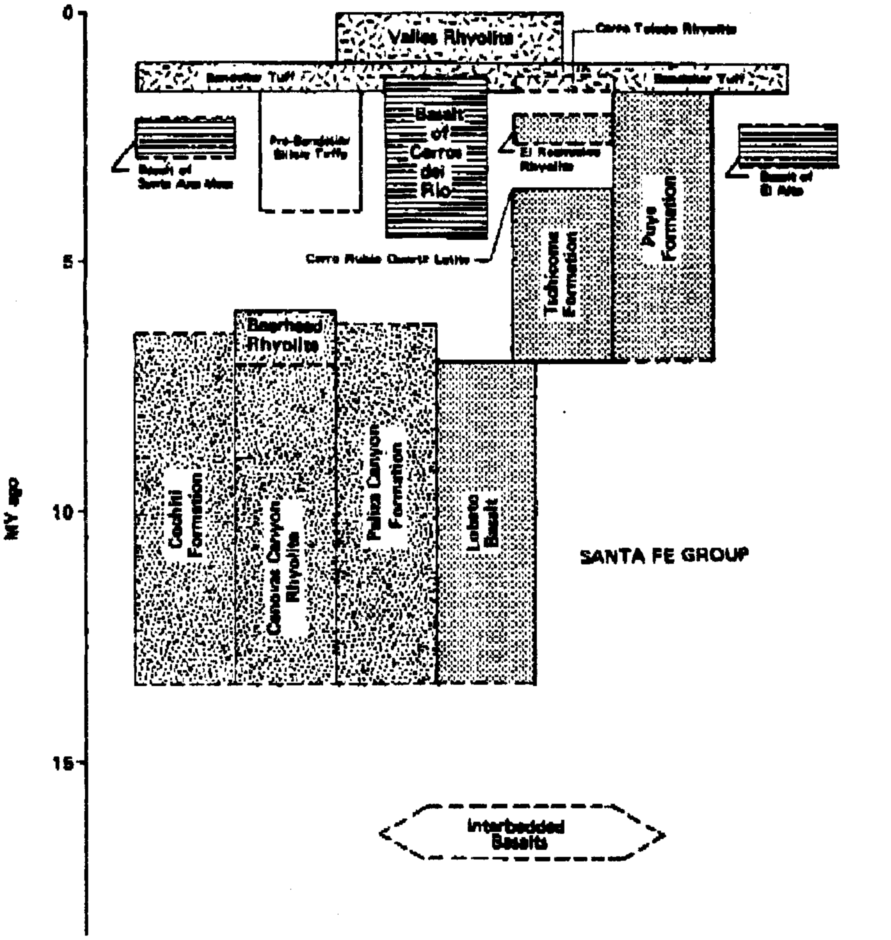

Fig. 1. Generalized stratigraphic relations of major units in the vicinity of the Jemez volcanic field. Irregular stipple, Keres Group formations; coarse, regular stipple, Polvadera Group formations; random dash, Tewa Group formations; horizontally ruled pattern, young basalt fields, as indicated. Dashed lines indicate uncertainty. Also a schematic south-to-north (left-to-right) section through the volcanic field (modified from *Gardner and Goff* [1984] and *Gardner* [1985]).

Group rocks after accounting for effects of faulting, erosion, and caldera formation [*Self et al.*, this issue] (also see discussion by *Gardner* [1985]) suggests that rocks of this group easily constituted about 1000 km^3, half of the volume of the entire volcanic field.

Nowhere has the true stratigraphic base of the group yet been identified. Near St. Peter's dome (Figures 2 and 3), the Keres Group volcanic rocks unconformably overlie arkosic basin-fill sediments of the Santa Fe Group. Interbedded with the Santa Fe Group are the only true alkaline basalts yet found in the Jemez Mountains, the stratigraphically highest of which has yielded a date of 16.5 ± 1.4 Ma (Table 3) [*Gardner and Goff*, 1984]. These basalts and sedimentary rocks may be indicative of the onset of rifting that initiated and enabled development of the volcanic field.

In the south central Jemez Mountains, Keres Group rocks overlie hydrothermally altered volcanic and hypabyssal rocks of the Cochiti mining district (Figure 3) [*Smith et al.*, 1970] (Bland group of *Stein* [1983]). Although *Smith et al.* [1970] showed the contact as unconformable, R. A. Bailey (personal communication, 1980) stated that the map contact was placed somewhat arbitrarily because of uncertain relations between the two groups. *Smith et al.* [1970] showed that the Bland group rocks were of probable Eocene or Oligocene age, apparently based on their resemblance to similar rocks in the Cerrillos Hills and Ortiz Mountains; however, *Ross et al.* [1961] presented an "inconclusive lead alpha age determination on zircons" of 19 Ma. *Stein* [1983] obtained a K-Ar date on feldspar from a monzonite porphyry, one of the younger units in the Bland group, of 11.2 ± 0.3 Ma. Reconnaissance in the Bland group indicates that andesitic dikes are numerous, "country rock" in the area is two-pyroxene andesite, and high-silica rhyolite is abundant. All of these rock types, including the monzonite porphyry, are petrographically very similar to Keres Group rocks. Furthermore, *Wronkiewicz et al.* [1984] indicated that gold mineralization in the Cochiti district postdates Bearhead Rhyolite (7–6 Ma). These relations, together with Stein's date, suggest the Cochiti district rocks may be the interior of a dissected Keres Group volcano.

In the western Jemez Mountains, Keres Group rocks unconformably overlie Paleozoic-Mesozoic limestones and red beds [*Smith et al.*, 1970]. Paliza Canyon basalt and Cerro del Pino dacite (see below) lie unconformably on an irregular erosional surface on a faulted(?) sequence of tuffaceous wacke, arkosic arenite, and conglomerate of problematic correlation. *Smith et al.* [1970] depicted the sedimentary sequence as "Abiquiu Tuff of *Smith* [1938]," but R. A. Bailey (personal communication, 1980; R. L. Smith and R. A. Bailey, unpublished mapping, 1980) and K. Manley (personal communication, 1983) suggested that the sequence may correlate with the Santa Fe Group.

The younger limit of Keres Group volcanism is about 6 Ma,

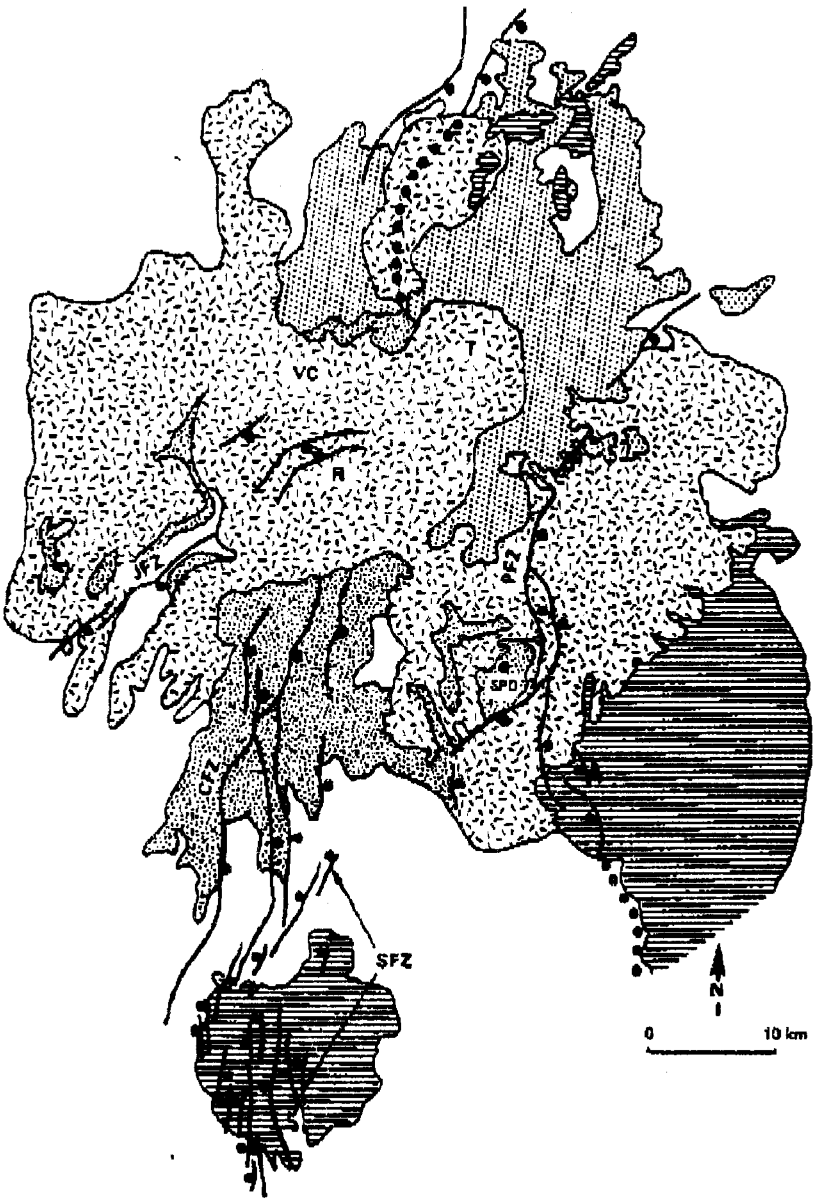

Fig. 2. Generalized map showing distribution of major stratigraphic groups (patterns are the same as Figure 1) and the major fault zones in the Jemez Mountains. JFZ, Jemez fault zone; SFZ, Santa Ana Mesa fault zone; CFZ, Cañada de Cochiti fault zone; PFZ, Pajarito fault zone; VC, Valles caldera; R, resurgent dome of VC; T, Toledo embayment; and SPD, St. Peter's dome (from *Gardner and Goff* [1984]; modified from *Smith et al.* [1970]).

based on K-Ar dates of the Bearhead Rhyolite (Table 1). As shown in Figure 1, waning Keres Group volcanic activity overlapped the early activity of Polvadera Group formations. Consistent with the relations suggested by the K-Ar dates, conformable and unconformable contacts exist between the two groups in the northern wall of the Valles caldera, and substantial volumes of undated two-pyroxene andesites north of Valles caldera, petrographically identical to those of the Keres Group, are included in the Polvadera Group by *Smith et al.* [1970]. Furthermore, two rhyolite domes mapped as Polvadera Group rocks by *Smith et al.* [1970] intrude and overlie Polvadera dacites; these two domes are probably Keres Group rhyolites in age and chemistry (see El Rechuelos Rhyolite, below). Over much of the area, domes, ash flows, and pumice deposits of the Tewa Group rest unconformably on (or locally intrude) a rugged erosional topography on the Keres Group.

Bailey et al. [1969] originally supposed that the basalt of Chamisa Mesa was one of the oldest units in the Jemez volcanic field primarily because of relations on Borrego Mesa (Figure 3) (R. A. Bailey, personal communication, 1983) where Chamisa Mesa basalt is separated from Paliza Canyon basalt by a sequence of Canovas Canyon tuff. This was apparently confirmed by a date of 10.4 ± 0.5 Ma on Chamisa Mesa basalt [*Leudke and Smith*, 1978], the oldest at that time in the Jemez volcanic field. New dates (Table 1) [*Gardner and Goff*, 1984] and petrographic and geochemical data [*Crowley*, 1984; *Gardner*, 1985] show that the basalt of Chamisa Mesa is indistinguishable from basalts of the Paliza Canyon Formation. We include therefore, as did *Ross et al.* [1961] in their "early basalt," the basalt of Chamisa Mesa within the Paliza Canyon Formation.

Bailey et al. [1969] defined the Cochiti Formation, a volcaniclastic sequence essentially contemporaneous with the

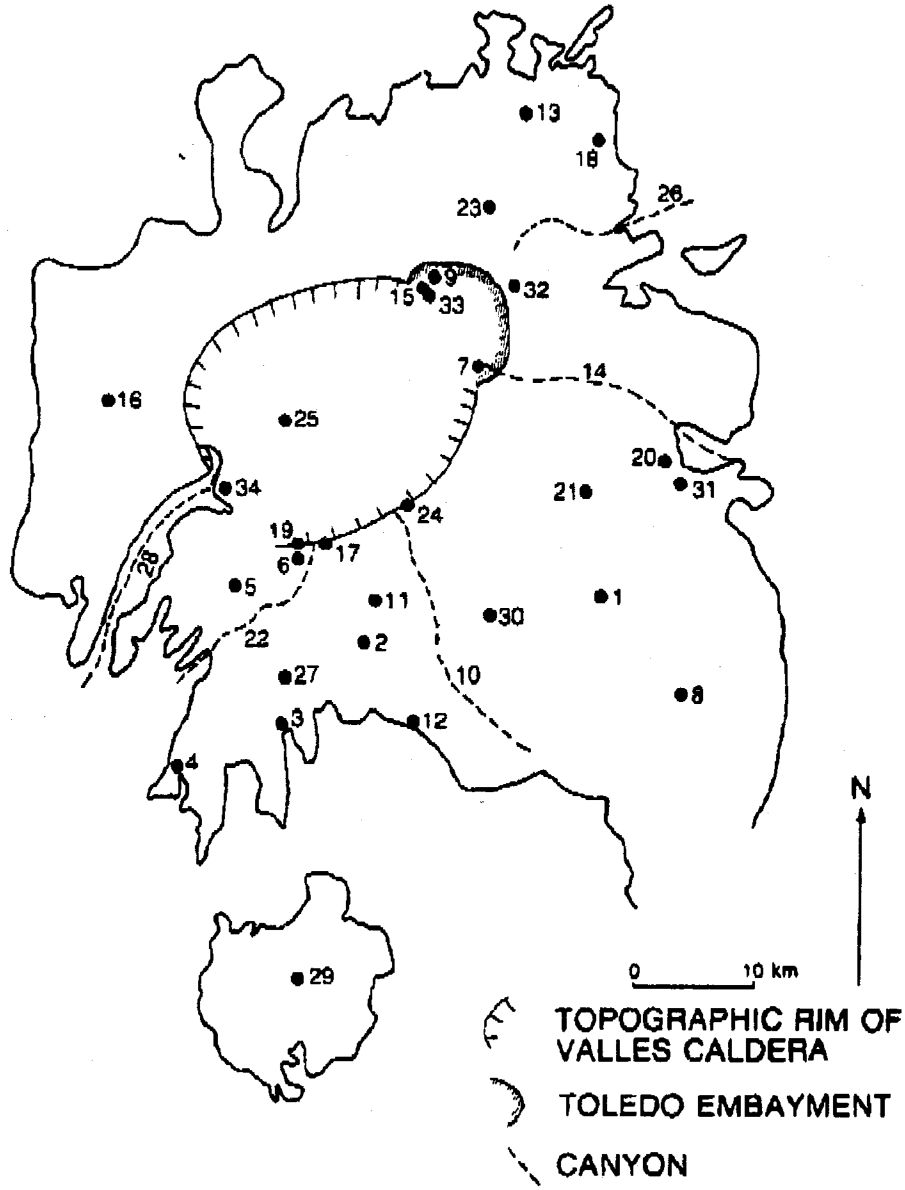

Fig. 3. Base map of Figure 2 showing geographic localities. See Table 2 for index to localities.

Keres Group but did not include it within any of the stratigraphic groups of the Jemez volcanic field. Other workers have included portions of the Cochiti Formation as part of the Santa Fe Group [e.g., *Hawley*, 1978; *Manley*, 1978]. Because of intimate spatial, temporal, genetic, and tectonic relations to formations of the Keres Group (see below), we include in this discussion the Cochiti Formation as part of the Keres Group.

Canovas Canyon Rhyolite

The Canovas Canyon Rhyolite consists of domes, plugs, and ash flows of high-silica rhyolite (Table 3). Rocks of this formation most commonly are aphyric with only a few discernible crystals of plagioclase, sanidine, quartz, and biotite. *Gardner* [1985] argues that the best model for the genesis of Canovas Canyon high-silica rhyolites involves their derivation from partial melts of lower crustal, granulitic rocks. Type exposures of the formation are in the Bear Springs area (Figure 3) [*Bailey et al.*, 1969], most of which is currently inaccessible because of private land ownership.

The rocks of this formation overlie the Santa Fe Group in many localities and are interbedded with, or intrude, rocks of the Paliza Canyon Formation and the laharic and basin fill deposits of the Cochiti Formation (see below). Where eruptive centers for these rhyolites can be identified, they invariably lie on faults of the Cañada de Cochiti fault zone (Figure 2).

While existing K-Ar dates of this formation cluster around 10 Ma, geologic relations with a dated Paliza Canyon basalt and two dates on a dome indicate that the formation is greater than 13 Ma (Table 1) [*Gardner and Goff*, 1984]. Rocks of the Canovas Canyon Rhyolite are petrographically and chemically indistinguishable from those of the Bearhead Rhyolite (Table 3), and high-silica rhyolites are interbedded or intrude throughout the Keres Group sequence. Field and radiometric data indicate the two formations form a continuum of high-silica rhyolite volcanism from greater than 13–6 Ma. We have placed a somewhat arbitrary boundary at about 7 Ma between the Canovas Canyon and Bearhead rhyolites (Figure 1). This boundary is the approximate age of a prominant stratigraphic marker, the Peralta Tuff Member of the Bearhead Rhyolite (Table 1) [see *Bailey et al.*, 1969; *Smith et al.*, 1970].

TABLE 2. Index to Localities of Figure 3

Map Number	Location
1	Bandelier National Monument
2	Bearhead Peak
3	Bear Springs
4	Borrego Mesa
5	Cerro del Pino
6	Cerro Pelado
7	Cerro Rubio
8	Cerros del Rio
9	Cerro Toledo
10	Cochiti Canyon
11	Cochiti Mining District (Bland)
12	Colle and Peralta Canyons intersect
13	El Alto
14	Guaje Canyon
15	Indian Point
16	Jemez Plateau
17	Las Conchas
18	Lobato Mesa
19	Los Griegos
20	Otowi Ruin
21	Pajarito Plateau
22	Paliza Canyon (Peralta and Colle Canyons intersect 12)
23	Polvadera Peak
24	Rabbit Mountain
25	Resurgent dome of Valles caldera
26	Rio del Oso
27	Ruiz Peak
28	San Diego Canyon
29	Santa Ana Mesa
30	St. Peter's dome
31	Tsankawi Ruin
32	Tschicoma Mountain
33	Turkey Ridge
34	VC-1 core hole

Paliza Canyon Formation

Smith et al. [1970] divided the Paliza Canyon Formation into three informal map units of "mainly basalt," "mainly andesite," and "dacite, rhyodacite, and quartz latite." *Gardner* [1985] subdivided the andesitic unit of *Smith et al.* [1970] into two sequences of intermediate composition rocks whose eruptions were accompanied by on-going effusions of rhyolite and basalt of the Keres Group and basaltic effusions of the Polvadera Group (Figure 1).

Paliza Canyon basalt. The unit consists of multiple flows of olivine tholeiite basalt derived from upper mantle periodite similar to that from which the Santa Fe Group alkali basalts were derived [*Gardner*, 1985]. Table 3 contains two analyses of Paliza Canyon basalt; typical compositions show evidence of fractionation of primarily olivine and clinopyroxene. Both sheetlike and intracanyon flows are interbedded with Canovas Canyon Rhyolite, laharic and basin fill deposits of the Cochiti Formation, and the lower Paliza Canyon andesitic unit. On Borrego Mesa (Figure 3) the unit conformably(?) overlies the Santa Fe Group. In that the unit yields similar K-Ar dates (Table 1) and has field relations similar to the Canovas Canyon Rhyolite, Paliza Canyon basaltic activity reasonably began at about the same time, greater than 13 Ma. For the most part, Paliza Canyon basalt underlies the andesites and dacites of the Paliza Canyon Formation, but basalts can be found interbedded with all Keres Group units except for Bearhead Rhyolite. *Luedke and Smith* [1978] report a date of 8.8 ± 0.3 Ma on Paliza Canyon basalt, and dates in the range 9.6 ± 0.3 to 7.4 ± 0.16 Ma [*Leudke and Smith*, 1978; *Dalrymple et al.*, 1967] on Lobato Basalt in the northern Jemez Mountains indicate a continuum of basaltic volcanism in the Jemez volcanic field, from greater than 13 to 7 Ma (Table 1 and Figure 1).

Paliza Canyon "andesites." The lower part of the Paliza Canyon "mainly andesite" map unit of *Smith et al.* [1970] consists of flows and domes of hypersthene-augite andesite and hornblende dacite which are poorly preserved and poorly exposed. The lower portion of the unit postdates earliest Canovas Canyon Rhyolite and Paliza Canyon basalt volcanism but is interbedded with the upper Canovas Canyon Rhyolite, Paliza Canyon basalt, and the lower Cochiti Formation. Stratigraphic relations with dated Canovas Canyon Rhyolite domes suggest that Paliza Canyon intermediate composition volcanism had begun by 12 Ma. Field relations further suggest

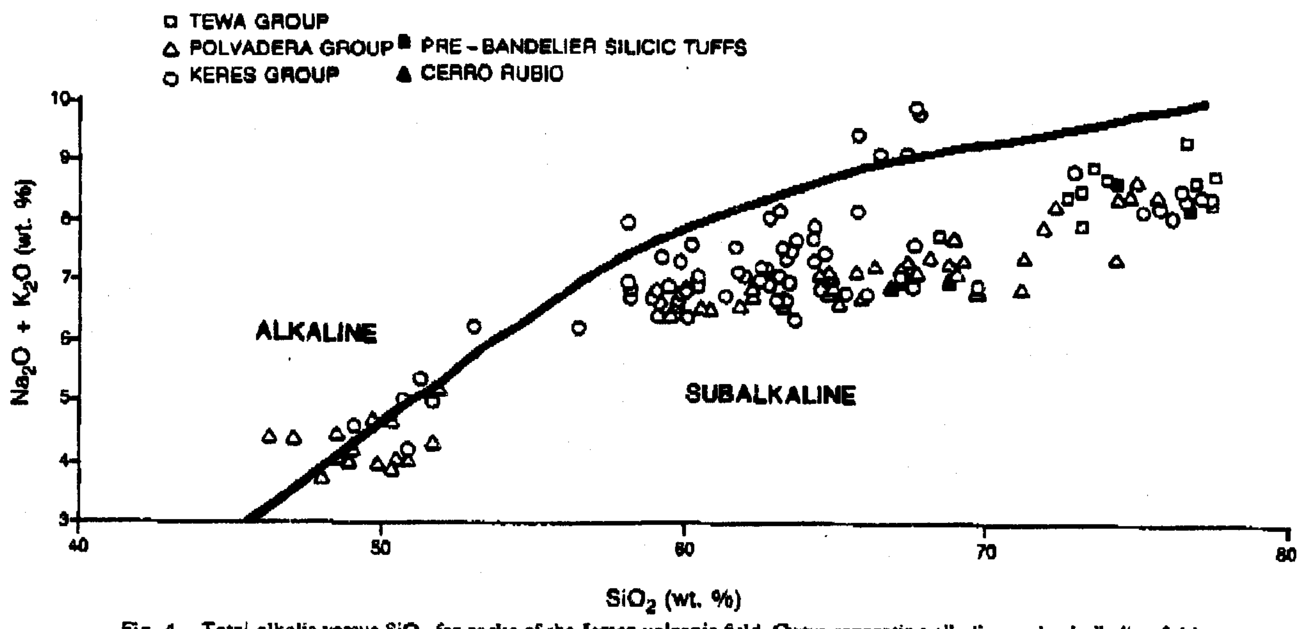

Fig. 4. Total alkalis versus SiO_2 for rocks of the Jemez volcanic field. Curve separating alkaline and subalkaline fields is from *Irvine and Baragar* [1971]. Data are from Table 3, *Loeffler* [1984], *Gardner* [1985], and J. N. Gardner and F. Goff (unpublished data, 1985).

TABLE 3. Chemical Analyses of Rocks From Each Major Stratigraphic Unit of the Jemez Volcanic Field

	Santa Fe Group Basanite	Paliza Canyon Basalts		Canovas Canyon Rhyolite		Paliza Canyon Andesite		Paliza Canyon Dacite		Bearhead Rhyolite	Lobato† Basalt	Tschicoma† Andesite	Tschicoma Dacite
	F81-50	JG80-53	F81-22	JG81-51	JG80-47C	Type 1 JG80-28	Type 2 JG81-4B	Type 1 JG81-31	Type 2 JG81-20A	JG80-49	SB224	JM153	JG80-12
Approximate age, Ma	16.5	13.2	11	11	8.7	8	8	9	8	6.18	8	6.5	5
						Major Elements							
SiO_2	43.82	50.62	50.95	76.08	76.63	59.98	63.47	66.48	67.45	76.16	50.51	60.76	67.21
TiO_2	2.36	1.76	1.37	0.12	0.12	1.09	0.83	0.68	0.48	0.11	1.47	0.93	0.51
Al_2O_3	13.74	17.77	15.65	11.77	12.36	16.37	16.75	15.75	15.43	12.11	16.00	16.54	15.28
Fe_2O_3*	12.35	10.27	9.34	0.68	0.77	6.40	4.45	3.27	3.89	0.68	11.05	6.02	3.68
MnO	0.17	0.15	0.13	0.05	0.04	0.08	0.09	0.07	0.05	0.07	0.16	0.09	0.06
MgO	10.65	3.91	7.96	0.07	0.09	2.66	1.65	0.58	1.12	0.04	6.71	2.54	1.69
CaO	10.00	9.08	8.33	0.54	0.47	5.27	3.87	1.91	3.10	0.40	9.56	4.62	3.40
Na_2O	3.26	3.99	3.25	3.71	3.80	4.25	4.23	5.49	3.79	3.92	3.11	3.74	3.90
K_2O	1.47	1.29	1.01	4.57	4.62	2.55	3.18	3.81	3.14	4.61	0.93	2.82	3.18
P_2O_5	0.87	0.66	0.34	···	0.03	0.40	0.25	0.19	0.12	0.05	0.40	0.22	0.14
L.O.I.	2.16	1.16	1.43	0.43	0.41	0.47	1.33	0.57	0.60	0.37	0.61	0.82	1.46
Total	100.85	100.66	99.76	98.02	99.34	99.52	100.10	98.80	99.17	98.52	100.51	99.10	100.51
						Trace Elements							
Cl	···	···	···	300	480	···	620	···	200	380	n.a.	n.a.	500
Sc	24.9	23	26.3	1.9	3.2	12.9	8.1	6.1	5.5	3.1	30.5	13	5.1
V	260	254	176	···	···	144	78	31	56	···	220	104	58
Cr	350	27	280	···	···	25	11	···	31	···	250	29	22
Zn	···	72	···	···	21	71	52	52	30	···	n.a.	n.a.	···
Rb	65	30	n.a.	185	139	55	68	95	64	154	14	50	79
Sr	1058	1053	n.a.	56	60	718	769	505	470	62	716	649	510
Zr	···	151	n.a.	116	112	241	360	454	232	127	133	201	189
Nb	n.a.	20	n.a.	27	20.6	19.6	25.3	39	14.7	27.3	13	20	17.3
Cs	94	···	4.7	5.5	3.9	···	2.2	2.1	0.7	3.1	···	0.6	1.4
Ba	1400	710	590	n.a.	810	1280	1440	2400	1390	800	483	1157	1180
La	48	52	21.6	41.1	27.3	50.2	57.9	114	42.9	30.4	30	49	44.1
Ce	96	73	43	54	54	73	83	129	56	52	54	97	54
Nd	50	n.a.	···	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sm	9.4	7.0	4.5	2.5	3.9	5.8	6.1	13	5.3	4.4	5.8	7	4.4
Eu	2.3	2.2	1.21	0.25	0.40	1.6	1.6	2.1	0.93	0.51	1.50	1.43	1.0
Dy	5.2	5.5	4.2	1.4	3.8	4.3	5.1	12.2	3.2	5.0	5.0	5.1	3.0
Yb	2.0	2.9	1.9	1.7	3.0	2.2	3.3	5.3	1.5	2.6	2.6	2.7	1.5
Hf	4.9	4.1	3.4	3.5	3.5	5.4	6.3	9.0	3.8	3.2	3.5	5.5	3.5
Th	4.4	6.1	2.0	22.5	12.9	7.7	9.4	14.3	3.4	12.0	3.0	8.4	7.5
U	1.47	2.18	0.72	6.19	3.94	2.62	2.92	5.22	1.38	4.12	0.85	2.56	3.29

	Cerro Rubio Quartz Latite F83-245	Pre-Bandelier Ignimbrite "B"† F82-92	El Rechuelos† Rhyolite ER 3-3	Lower Bandelier Pumice F82-11	Cerro Toledo Rhyolite: Cerro Toledo F81-145	Cerro Toledo Rhyolite: Cerro Trasquilar F81-139	Upper Bandelier Tsankawi Pumice F82-94	Redondo Creek Rhyolite F81-109	Valles Rhyolite: San Antonio Mountain F80-74	Valles Rhyolite: Banco Bonito F82-7
Approximate age, Ma	3.6	2.85	2.02	1.45	1.38	1.27	1.09	1.0	0.54	0.13
Major Elements										
SiO_2	66.9	74.4	74.8	73.6	77.0	75.2	72.7	73.2	74.0	73.2
TiO_2	0.47	0.10	0.08	0.04	0.08	0.08	0.08	0.36	0.14	0.29
Al_2O_3	15.2	11.8	12.4	11.9	12.2	11.9	12.2	12.8	13.2	13.5
Fe_2O_3*	3.43	1.54	0.55	1.40	1.19	1.01	1.47	1.04	1.09	1.84
MnO	0.05	0.06	0.06	0.07	0.05	0.07	0.08	0.03	0.05	0.05
MgO	1.42	0.08	0.05	0.10	0.02	0.03	0.05	0.09	0.15	0.63
CaO	3.32	0.33	0.45	0.24	0.14	0.26	0.33	0.69	0.67	1.58
Na_2O	3.60	4.00	3.74	4.36	4.21	4.22	3.08	3.66	3.76	3.84
K_2O	3.20	4.67	4.74	4.61	4.47	4.49	5.36	4.86	5.03	4.11
P_2O_5	0.15	0.005	...	0.005	0.005	0.005	0.005	0.01	0.01	0.06
L.O.I.	1.37	3.35	3.17	4.26	0.25	3.19	4.01	3.63	1.96	0.24
Total	99.11	100.34	100.04	100.59	99.62	100.46	99.37	100.37	100.06	99.34
Trace Elements										
Cl	390	1620	...	2800	790	1990	2200	680	680	500
Sc	6.5	2.7	3.11	0.58	1.09	1.16	1.01	2.9	2.2	4.0
V	64	...	...	16	12	14	...	...	...	19
Cr	51	5	...	5	...	4.2	...	3.6	4.0	12
Zn	73	40	...	20	60	80	33	30	40	30
Rb	52	155	139	330	205	230	330	110	160	165
Sr	500	...	...	9.9	...	10	...	...	...	...
Zr	160	180	58	190	130	150	350	210	125	160
Nb	n.a.	n.a.	40	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cs	0.8	4.1	5.3	10.5	4.6	8.1	18	3.8	5.4	5.2
Ba	1170	...	17	...	...	...	...	1000	320	900
La	34	59	17.2	52	31	36	91	57	47	46
Ce	68	113	44	109	72	80	117	106	89	77
Nd	19	30	...	47	18	29	60	21	21	25
Sm	4.4	8.0	3.6	13.9	7.0	7.4	16.6	5.5	5.6	4.5
Eu	1.08	0.16	0.17	2.4	0.10	0.09	0.05	0.68	0.27	0.51
Dy	2.6	8.0	3.6	18.5	10.2	11.6	28	5.3	6.8	3.8
Yb	1.56	5.6	2.6	12.2	5.7	8.1	15.4	3.0	4.9	3.5
Hf	5.0	8.2	3.7	12.0	8.6	8.8	14.0	8.2	4.9	5.2
Th	4.6	21.1	20.4	43	24	26	40	15.6	23	23
U	1.16	6.7	8.0	15.9	8.5	8.2	11.8	4.2	6.3	5.7

See *Gardner* [1985] for analytical methods and quality of data.
*Total iron as Fe_2O_3 from analysis.
†Chemical data from *Loeffler* [1984].

that intense faulting within the Cañada de Cochiti fault zone (Figure 2) accompanied lower Paliza Canyon andesitic volcanism, causing a paucity of outcrops of and the best preservation of samples of the lower Paliza Canyon andesitic unit as angular cobbles in the immature basin fill gravels of the Cochiti Formation.

Upper Paliza Canyon "andesite" is the most voluminuous and widespread unit of the Keres Group. The sequence is composed of multiple flows of two-pyroxene andesite, minor pyroclastic deposits, and minor domes and flows of dacitic rocks. On Cerro Pelado and in the northern topographic rim of Valles caldera (Figures 2 and 3) the thickness of the unit exceeds 300 m. Large blocks of andesite of this unit occur in the caldera fill tuff in Valles caldera [*Goff and Gardner*, 1980; R. L. Smith and R. A. Bailey, personal communication, 1980]. Union Geothermal Company has penetrated "substantial" thicknesses of andesite and andesitic cinder (> 300 m) of this unit in their exploration drilling in the resurgent dome of Valles caldera (Figure 3) [*Nielson and Hulen*, 1984; R. Denton, personal communication, 1980]. Hence the reconstructed distribution (see *Self et al.* [this issue] and *Gardner* [1985] for discussion), after accounting for effects of erosion, faulting, and caldera formation, suggests that the original volume of this unit was nearly half of the volume of the entire volcanic field.

In the southern and southeastern portions of the Jemez Mountains, the upper Paliza Canyon andesitic unit is separated from the lower portions of the unit by a thick interval of interbedded Canovas Canyon tuff, Paliza Canyon basalts, and laharic and basin fill deposits of the lower Cochiti Formation. In the south central portions of the Jemez Mountains, the unit overlies the rocks of the Cochiti mining district (see above) (Figure 3). On the western side of the area, andesites of this unit unconformably overlie Mesozoic-Paleozoic rocks, Miocene sedimentary rocks, or Paliza Canyon basalts.

Near Las Conchas, in the southern rim of Valles caldera (Figure 3), upper Paliza Canyon andesites unconformably overlie hydrothermally altered Paliza Canyon basalts, locally separated by a thin sandstone. In the southern Jemez Mountains the upper Paliza Canyon andesite is locally and conformably capped by the young Paliza Canyon dacites (see below) and is intruded by several dacite plugs of Tschicoma Formation age and chemistry. Exposures of upper Paliza Canyon andesite in the northern rim of Valles caldera are locally in both conformable and unconformable contact with overlying Tschicoma Formation andesites and dacites. Commonly, a silicified sandstone separates the Paliza Canyon andesites from Tschicoma dacites near the Toledo embayment (Figures 2 and 3). Thus field relations and K-Ar dates (Table 1) constrain the upper limit of Paliza Canyon andesite to about 7 Ma.

Young Paliza Canyon dacites. Plugs, domes, and breccias of dacitic rocks intrude and overlie all units of the Keres Group except for Bearhead Rhyolite. Most voluminous of these are the dome complexes comprising the mountain peaks Los Griegos, Las Conchas, Cerro del Pino, and Ruiz (Figure 3). Although they exhibit some petrographic variability, rocks of this unit tend to be coarsely porphyritic with plagioclase, two pyroxenes, and hornblende ± biotite. Commonly, outcrops of this unit contain 1–10% vesicular clots of Ca-plagioclase and acicular hornblende. Petrographically, some rocks of this unit are similar to dacites of the Tschicoma Formation.

The upper Paliza Canyon andesite is the youngest unit that these dacites overlie. One date of 10.1 ± 2.5 (Table 1) obtained on Cerro del Pino (Figure 3) is probably only reasonable at the younger limit of reported error. Although the dated dome is only in unconformable contact with Paliza Canyon basalt, essentially contemporaneous domes of the Cerro del Pino complex overlie upper Paliza Canyon andesites immediately to the east. In a few localities, dacitic rocks of this unit are intruded by domes of Bearhead Rhyolite (7–6 Ma; see below). K-Ar dates and field relations suggest, therefore, that the age of this unit is probably 9–7 Ma (Table 1).

Table 3 shows the chemical composition of a typical Paliza Canyon andesite (type 1) and a compositionally extreme Paliza Canyon dacite (type 1). *Gardner* [1985] demonstrated that most Paliza Canyon basalts, andesites, and dacites represent a differentiation sequence with little or no interaction of the magmas with crustal material; he noted, however, that small volumes of Keres Group andesites and dacites, very similar to Tschicoma Formation rocks, have been generated by mixing and homogenization of andesitic and high-silica rhyolitic magmas (Type 2 andesite and dacite, Table 3).

Bearhead Rhyolite

The high-silica rhyolite plugs, domes, and tuffs of this formation are chemically and petrographically indistinguishable from the Canovas Canyon Rhyolite (Table 3), and *Gardner* [1985] suggested derivation of Bearhead from partial melts of lower crustal granulitic rocks. Included in this formation is the Peralta Tuff Member which consists of massive lithic tuff, bedded ash fall, and water-worked ash as typified by exposures near the intersection of Colle and Peralta Canyons (Figure 3). Eruptive centers, where they have been identified, lie on faults of the Cañada de Cochiti fault zone (Figure 2).

Bailey et al. [1969] stated that the Bearhead Rhyolite is unconformably overlain by pediment gravels, correlative to formations of late Pliocene-early Pleistocene age. As mentioned above, field relations and K-Ar dates (Table 1 and Figure 1) indicate a continuum of rhyolitic volcanism through Canovas Canyon and Bearhead time, from greater than 13 to 6 Ma. We restrict the term Bearhead Rhyolite to those high-silica rhyolites that postdate Paliza Canyon Formation volcanism to be consistant with the usage of *Bailey et al.* [1969] and *Smith et al.* [1970]. Thus a boundary at about 7 Ma, which is the approximate age of the Peralta Tuff, separates Canovas Canyon and Bearhead rhyolites. The younger limit of Bearhead activity appears to be about 6 Ma (Figure 1).

Cochiti Formation

Bailey et al. [1969] define the Cochiti Formation as "a thick sequence of volcanic gravel and sand, consisting of basalt, andesite, dacite and rhyolite detritus derived from penecontemporaneous erosion of units of the Keres Group." As such, the formation is interbedded with units that span the time encompassed by Keres Group volcanism [see *Bailey et al.*, 1969].

Deposits of this formation consist primarily of lahars, vent breccias, and gravels. The gravels contain angular cobbles of dacite and andesite of the Paliza Canyon Formation, with subordinate amounts of Paliza Canyon basalt and Canovas Canyon Rhyolite, set in a volcanic sand matrix. Commonly interbedded with the lower Cochiti Formation are Paliza Canyon basalts and Canovas Canyon tuffs. The Cochiti Formation pinches out in the western Jemez Mountains but is about 30 m thick in Paliza Canyon and thickens to greater than 200 m in the vicinity of Cochiti Canyon and St. Peter's dome area where the detritus was being washed to the east into developing basins of the Rio Grande rift (Figures 2 and 3).

The geometry of the Cochiti Formation suggests that the Cañada de Cochiti fault zone was, in effect, a zone of growth faults bounding the west side of the Rio Grande rift. The coarse cobble size, poor sorting, and crudely developed bedding of the basin fill deposits are indicative of relatively intense rift faulting that accompanied the early stages of development of the volcanic field.

POLVADERA GROUP

The Polvadera Group consists of the three formations from oldest to youngest, Lobato Basalt, Tschicoma Formation, and El Rechuelos Rhyolite [*Bailey et al.*, 1969]. Relations of the group to the Puye Formation are analogous to the relations of the Keres Group to the Cochiti Formation, except that the Puye Formation is a large alluvial fan [*McPherson et al.*, 1984]. Hence, as with the Keres Group and the Cochiti Formation, we include the Puye Formation as part of the Polvadera Group in our discussion. The level of stratigraphic detail, discussed above for the Keres Group, is not yet available within the Polvadera Group. Our discussion is based largely on our reconnaissance work, relations published by *Griggs* [1964], *Bailey et al.* [1969], and *Smith et al.* [1970], and personal communications from individuals working on various aspects of the Polvadera Group. Polvadera Group rocks are best exposed in the northern Jemez Mountains (Figure 2), but a few deeply incised plugs of Tschicoma dacite, which intrude upper Paliza Canyon andesite, have been found in the southern Jemez Mountains [*Gardner*, 1985]. As defined by *Bailey et al.* [1969], the Polvadera Group contains a spectrum of whole rock compositions (Table 3), but it is volumetrically dominated by nearly 500 km^3 of Tschicoma Formation dacite (I. D. MacGregor, personal communication, 1981).

Lobato Basalt

The Lobato Basalt consists of multiple flows of olivine basalt which are similar in petrography, chemistry, and petrogenesis to Paliza Canyon basalts (Table 3) [*Loeffler*, 1984; *Gardner*, 1985; *Baldridge and Vaniman*, 1985, R. A. Bailey, personal communication, 1983]. In fact, distinction between Lobato and Paliza Canyon basalts for reasons other than geographic distribution may be somewhat artificial given their petrologic and temporal similarities (Table 1 and Figure 1). The Lobato Basalt forms prominent mesas, such as Lobato Mesa (Figure 3), in the northeastern Jemez Mountains, and overlies Abiquiu Tuff and Santa Fe Group sediments. One early dacite flow of the Tschicoma Formation is interbedded with the basalts in Rio del Oso (Figure 3) [*Bailey et al.*, 1969]. For the most part, however, the Lobato Basalt is conformably overlain by the Tschicoma Formation. Numerous dikes of Lobato Basalt intrude Santa Fe Group sediments in the northeastern Jemez Mountains [*Smith et al.*, 1970]. Radiometric dates on Lobato Basalt indicate that the largest volume of the formation was erupted between about 10 and 7 Ma (Table 1). *Aldrich* [this issue], however, cites a date of 14.05 ± 0.33 Ma on a basalt, interbedded with Santa Fe Group sediments, which was mapped as Lobato Basalt by *Smith et al.* [1970]. Basalts interbedded with the Santa Fe Group in the northeastern Jemez Mountains are particularly problematic with respect to assignment to stratigraphic groups. Because of their spatial and temporal relations, many of these basalts are tabulated as "Lobato Basalt" in Table 1 (see, for example, *Baldridge et al.* [1980] and *Manley and Mehnert* [1981]).

Tschicoma Formation

The Tschicoma Formation was defined by *Griggs* [1964] and consists of voluminous domes and flows of dacite typified by exposures on Tschicoma and Polvadera peaks (Figure 3), with subordinant amounts of andesite. Tschicoma Formation andesites are typically porphyritic with plagioclase, augite, and hypersthene, very similar to those of the Paliza Canyon Formation. Data of *Smith et al.* [1970] and *Loeffler* [1984] suggest most Tschicoma andesites (Table 3) are a younger (about 7 Ma?) generation of Paliza Canyon-like differentiates of basalt that have experienced contamination with upper(?) crustal material. Tschicoma dacites (Table 3) are commonly coarsely porphyritic with plagioclase, augite, hypersthene, and hornblende ± biotite and appear to have been generated by mixing and homogenization of magmas whose compositions are well approximated by Paliza Canyon andesites and Keres Group high-silica rhyolites [*Gardner*, 1982, 1983; *Loeffler*, 1984; *Gardner*, 1985]. The Tschicoma Formation unconformably overlies Abiquiu Tuff and the Santa Fe Group in the northern Jemez Mountains. Flows of the Tschicoma Formation interfinger with deposits of the Puye Formation. Both conformable and unconformable contacts exist between the Tschicoma Formation and the Paliza Canyon Formation in the rim of Valles caldera, and both conformable and unconformable contacts exist between the Tschicoma Formation and Lobato Basalt. Radiometric dates for the Tschicoma Formation span approximately 7–3 Ma (Table 1) and Tschicoma Formation volcanism overlapped both waning Keres Group volcanism and early Tewa Group volcanism (Figure 1).

El Rechuelos Rhyolite

Bailey et al. [1969] proposed the name El Rechuelos Rhyolite for the rhyolite that forms five small domes and a small pumice cone in the northern Jemez Mountains west and north of Polvadera Peak (Figure 3). *Loeffler* [1984] and *Vaniman and Baldridge* [1985] indicate significant petrographic and chemical variability in the formation. The "El Rechuelos petrographic type" of D. T. Vaniman and W. S. Baldridge (unpublished data, 1985) appears to be about 2 Ma (Tables 1 and 3), but the remainder of the formation may be petrogenetically unrelated. In fact, two domes, recognized by *Bailey et al.* [1969] as being older than the rest of the formation, have been dated at 7.5 ± 0.3 Ma and 5.8 ± 0.2 Ma (D. T. Vaniman and W. S. Baldridge, unpublished data, 1985). These dates together with preliminary chemical data suggest that the older El Rechuelos domes may be Keres Group rhyolites contaminated with more mafic magma.

Puye Formation

The Puye Formation, described by *Griggs* [1964] and defined by *Bailey et al.* [1969], consists of gravels, lahars, conglomerates, and tuffs derived from, for the most part, and interbedded with other formations of the Polvadera Group. In contrast to the somewhat analogous Cochiti Formation, the Puye Formation forms a broad alluvial fan [*McPherson et al.*, 1984] whose deposits extend in the pre-Bandelier Tuff subsurface 15 km south-southwest of the nearest surface exposures [*Dransfield and Gardner*, 1985]. These relations, in contrast to the geometry of Cochiti Formation deposits, may indicate deposition of most of the Puye Formation in a period of relative tectonic inactivity. Stratigraphic relations with Tschicoma Formation rocks, Cerros del Rio basalts, and the Bandelier Tuff suggest that the Puye Formation ranges in age from about 7 to 1.45 Ma [*Bailey et al.*, 1969].

TEWA GROUP

As defined by *Griggs* [1964], *Bailey et al.* [1969], and *Smith et al.* [1970], the Tewa Group includes from oldest to youngest the formations Bandelier Tuff, Cerro Toledo Rhyolite, Cerro Rubio Quartz Latite, and Valles Rhyolite, and these workers show the lower (Otowi) member of the Bandelier Tuff (1.45 Ma [*Doell et al.*, 1968]) as the oldest unit in the group. However, at least three pre-Bandelier silicic tuffs have now been recognized in the southwestern Jemez Mountains [*Kite et al.*, 1982; *Self et al.*, this issue], and new K-Ar dates and interpretations of field relations regarding Cerro Rubio Quartz Latite (Table 1) reveal that it is much older than previously thought [*Heiken et al.*, this issue]. Based on the dates of Table 1 the Tewa Group, as defined, spans 3.6–0.13 Ma and overlaps with the age of upper Polvadera Group rocks.

Chemically, the group consists almost entirely of rhyolite (Table 3) and by far the largest volume of rhyolite is represented by the Bandelier Tuff [*Smith and Bailey*, 1966]. Although presumed to be a comagmatic sequence [*Smith*, 1979], published geochemical data from the Tewa Group are sparse.

Tewa Group deposits unconformably blanket or intrude most older volcanic units of the Jemez volcanic field and are best exposed within the Valles and Toledo calderas, the Toledo embayment, and on the plateaus that flank the east, west, and north sides of the Jemez Mountains (Figures 2 and 3).

Cerro Rubio Quartz Latite

The Cerro Rubio Quartz Latite consists of two very similar domes that lie within the eastern Toledo embayment (Figures 2 and 3) [*Heiken et al.*, this issue]. Petrographically, the two domes are nearly identical, containing small phenocrysts of hornblende, plagioclase, hypersthene, sparse biotite, and rare quartz in a devitrified groundmass. *Smith et al.* [1970] indicate that the north dome of this pair is a shallow intrusion, but their textures are identical.

Based on apparent field relations in the canyons surrounding these domes, *Smith et al.* [1970] interpreted the Cerro Rubio Quartz Latite to be intrusive into the Cerro Toledo Rhyolite which also fills the Toledo embayment. In addition, *Smith* [1979] indicated that the northern dome was emplaced after the eruption of the upper (Tshirege) member of the Bandelier Tuff, while the tuff was still hot. It appears to us that the Cerro Toledo Rhyolite intrudes the Cerro Rubio domes and that only Bandelier Tuff, showing no evidence of alteration or effects of intrusion, overlies the domes. Our interpretation is substantiated by two K-Ar dates on plagioclase separates that yield ages of 2.18 ± 0.09 Ma for the northern dome and 3.59 ± 0.36 Ma for Cerro Rubio [*Heiken et al.*, this issue].

Cerro Rubio Quartz Latite is mineralogically and chemically similar to the dacitic rocks that compose the major volume of the Tschicoma Formation (Table 3). Because the age of Cerro Rubio Quartz Latite is within the time span of Tschicoma volcanism, we suggest that the two domes of Cerro Rubio Quartz Latite are shallow intrusions or the eroded cores of extrusive domes of the Tschicoma Formation that have been partially obliterated during formation of the Toledo embayment.

Pre-Bandelier Silicic Tuffs

Not included in the formal stratigraphy of *Bailey et al.* [1969] is a sequence of at least three tuffs older than, but chemically (Table 3) and petrographically similar to, the Bandelier Tuff [*Smith*, 1979; *Kite et al.*, 1982; *Self et al.*, this issue]. This unnamed sequence of pumice beds and ash fall and ash flow tuffs underlies the Otowi Member of the Bandelier Tuff along the southwestern wall of Valles caldera and farther south in San Diego Canyon (Figure 3). *Nielson and Hulen* [1984] recognized this group of tuffs in many deep geothermal wells at the bottom of the caldera-fill sequence inside Valles caldera, and the tuffs are also present in the cor[e] from core hole VC-1 near the southwestern ring fracture zon[e] of the caldera (Figure 3) [*Goff et al.*, this issue]. Pumice deposits inferred to be correlative to these tuffs are found in the upper Puye Formation northeast of Valles caldera (B. Turbeville, personal communication, 1984). Although correlations are still problematic and the uncertainty of one K-Ar date is large (Table 1), these tuffs were probably erupted 3.6–1.5 Ma; *Smith* [1979] inferred the age of one of these tuffs to be 1.9–1.5 Ma.

Chemically, a sample of pre-Bandelier "Ignimbrite B" pumice closely resembles both lower and upper Bandelier pumice except for variations in the ratio of alkalis. Petrographically, the pumices contain abundant quartz and sanidine phenocrysts and sparse mafic minerals.

Bandelier Tuff

The Bandelier Tuff consists of upper (Tshirege) and lower (Otowi) members formed during catastrophic eruption of the Valles (1.12 Ma) and Toledo (1.45 Ma) calderas, respectively [*Smith and Bailey*, 1966; *Doell et al.*, 1968; *Smith et al.*, 1970; *Izett et al.*, 1980]. Each member contains a prominant ash fall bed at the base; the Guaje Pumice is at the base of the Otowi and the Tsankawi Pumice is at the base of the Tshirege [*Bailey et al.*, 1969]. The Bandelier Tuff forms two superposed thick composite ash flow sheets that are best exposed in canyons of the Jemez and Pajarito plateaus, west and east of Valles caldera (Figure 3). Generally, the upper (Tshirege) member is the more densely welded of the two units, and welding increases as distance from their caldera sources decreases. Inside Valles caldera, Bandelier Tuff varies from fres[h] very densely welded tuff to silicified welded tuff to hydrothermally altered tuff and tuff breccia [*Goff and Gardner*, 1980]. Both members contain lithic fragments of precaldera volcanic rocks, Paleozoic sedimentary rocks, and rare Precambrian fragments, although the lower member is clearly more lithic rich [*Bailey and Smith*, 1978; *Eichelberger and Koch*, 1979; *Potter*, 1983; *Self et al.*, this issue].

Petrographically, the tuffs contain abundant quartz and sanidine phenocrysts and sparse mafic minerals in a eutaxitic groundmass. The uppermost part of the upper member contains anorthoclase and hypersthene, whereas the lower part of the member contains sanidine and fayalite [*Smith and Bailey*, 1966; *Doell et al.*, 1968]. Sanidine may display a pronounced irridescence that is most common in densely welded zones. Chemically, the Bandelier Tuff is composed of rhyolite having low CaO, K_2O, and Na_2O contents that are variable.

Cerro Toledo Rhyolite

The Cerro Toledo Rhyolite was originally defined by *Griggs* [1964] and consists of a group of many coalesced domes inside the Toledo embayment, an arc of four domes believed to represent a remnant of Toledo caldera moat volcanism, and a single dome (Rabbit Mountain) that was erupted on the eastern margin of Toledo caldera (Figure 3) [*Smith et al.*, 1970; *Goff et al.*, 1984; *Heiken et al.*, this issue]. Domes and tuffs of Cerro Toledo Rhyolite intrude the two domes of Cerro Rubio Quartz Latite, as mentioned above, but are overlain by welded upper Bandelier Tuff. Tuffs, flows, and flow breccias from Rabbit Mountain occur between the two members o[f] Bandelier Tuff in some canyons east of the Toledo caldera. A sequence of ash falls best correlated with Cerro Toledo Rhyolite inside the Toledo embayment occurs between the two members of the Bandelier Tuff on the northern Pajarito Plateau (Figure 3) [*Heiken et al.*, this issue]. Based on these field relations, the dates of the tuffs [*Izett et al.*, 1980] and recent dates on the domes [*Heiken et al.*, this issue] the age of Cerro Toledo Rhyolite spans 1.50 ± 0.05 to 1.20 ± 0.03 Ma (Table 1).

Petrographically, most domes and tuffs are aphyric to sparsely porphyritic containing small phenocrysts of quartz, sanidine, and plagioclase, and sparse phenocrysts of biotite, hornblende, or pyroxene in a glassy, flow-banded groundmass. A major exception is the group of porphyritic domes forming Turkey Ridge and Indian Point (Figure 3) which contain abundant quartz, sanidine, and sparse biotite. Chemically, the domes and tuffs are composed of high-silica rhyolite having slightly more SiO_2 but slightly less Fe_2O_3* (total iron) and Al_2O_3 than Bandelier Tuff (Table 3).

Valles Rhyolite

The Valles Rhyolite [*Griggs*, 1964; *Bailey et al.*, 1969] consists of domes, flows, and tuffs erupted inside Valles caldera after caldera collapse. The formation includes lavas emplaced contemporaneously with growth of the resurgent dome as well as moat rhyolites that postdate and surround the resurgent dome [*Smith and Bailey*, 1968; *Smith et al.*, 1970]. *Bailey et al.* [1969] divided the Valles Rhyolite into six members which are not discussed in detail here. Age determinations indicate the Valles Rhyolite ranges from 1.04 to 0.13 Ma (Table 1) [*Doell et al.*, 1968; *Marvin and Dobson*, 1979], although determinations on the two oldest members were not successful because of extensive hydrothermal alteration. We note, also, that four domes of the Valle Grande Member in the northern part of Valles caldera have ages that range from 1.22 ± 0.04 to 1.50 ± 0.05 Ma which predate the age of Valles caldera and thus should be considered part of the Cerro Toledo Rhyolite [*Goff et al.*, 1984; *Heiken et al.*, this issue].

The Valles Rhyolite includes the products of the youngest volcanic eruptions in the Jemez Mountains. Although most units lie entirely within Valles caldera, the relatively young Battleship Rock tuff, El Cajete pumice, and Banco Bonito obsidian have flowed through a breach in the southwestern caldera wall [*Smith et al.*, 1970]. Thus these units locally overlie rocks substantially predating formation of Valles caldera.

Petrographically, the Valles Rhyolite is a very heterogeneous group as noted by *Bailey et al.* [1969]. Units vary from aphyric to coarsely porphyritic, and the Redondo Creek member is characterized by the absence of quartz. Chemically, there are two types: a high-silica rhyolite type consisting of the early Deer Canyon, Redondo Creek, and Valle Grande members and a lower-silica type consisting of the younger Battleship Rock, El Cajete, and Banco Bonito members (Table 3). The latter type contains less SiO_2 but more Fe_2O_3*, MgO, CaO, TiO_2, and P_2O_5 than the high-silica rhyolite type. A recently discovered, unnamed rhyolite penetrated by the VC-1 core hole in the southwestern moat zone of Valles caldera (Figure 3) is also of the lower-silica chemical type (F. Goff, unpublished data, 1985) [see *Goff et al.*, this issue]. Thus the group of youngest units of the Valles Rhyolite all lie in the southwestern moat zone and are chemically distinct from other units in the formation.

EL ALTO, SANTA ANA MESA, AND CERROS DEL RIO BASALT FIELDS

The young basalt fields, Santa Ana Mesa, El Alto, and Cerros del Rio, flank the Jemez Mountains on the south, north, and east (Figures 2 and 3). Petrologic studies of *Baldridge* [1979] indicate a petrogenesis for these small fields unrelated to the Jemez, although *Crowley* [1984] suggested derivation of Cerros del Rio basalts from mantle similar, in many respects, to the mantle from which *Gardner* [1985] inferred derivation of most Keres Group mafic rocks. Because of their spatial and temporal relations, however, these young basalt fields do bear implications for tectonic and magmatic evolution within the Jemez volcanic field (see discussions of *Gardner and Goff* [1984] and *Gardner* [1985]).

Cinder cones, maars, and flows of predominantly basalt with subordinant andesite comprise the three basaltic fields [*Smith et al.*, 1970; *Aubele*, 1978]. *Baldridge* [1979] recognized both tholeiitic and alkaline compositions. These lavas began to be erupted at about 4.6 Ma, and though the youngest date on these basalts is 1.96 ± 0.06 (Table 1), at least one flow is interbedded between the Otowi and Tshirege members of the Bandelier Tuff [*Smith et al.*, 1970]. Thus the minimum span of time for this basaltic activity is 4.6 to 1.45 or 1.12 Ma.

HYDROTHERMAL ALTERATION EVENTS

Most exposed rocks of the Jemez volcanic field are fresh and unaltered. However, because of the well-known active hydrothermal systems, the presence of Valles caldera, and some preliminary evidence of multiple hydrothermal events throughout the volcanic field's history, a brief discussion of hydrothermal alteration in the Jemez Mountains is appropriate. More detailed discussions of individual hydrothermal alteration events in the Jemez Mountains may be found in the work by *Charles et al.* [this issue], *Goff et al.* [this issue], *Hulen and Nielson* [this issue], and *Wronkiewicz et al.* [1984]. Hydrothermal alteration assemblages, regardless of age, are restricted to the Cochiti mining district, parts of the topographic rim of Valles caldera, and within Valles caldera (Figure 3).

In the Cochiti mining district there appears to have been two hydrothermal events. An older event that caused widespread propyllitic alteration of hypabyssal rocks which are probably Keres Group equivalents occurred as a result of hydrothermal convection probably induced by Keres Group (Paliza Canyon Formation?) volcanism. The younger hydrothermal event in the Cochiti mining district postdates Bearhead Rhyolite (7–6 Ma) and caused localized argillic alteration associated with quartz veins and gold and silver mineralization [*Wronkiewicz et al.*, 1984]. We speculate that this argillic alteration and associated mineralization was a late-stage deuteric event from a pulse of high-silica rhyolite volcanism in Bearhead Rhyolite time.

In parts of the topographic rim of Valles caldera there is propyllitic alteration of Keres and Polvadera group rocks. Near Las Conchas (Figure 3), propyllitically altered Paliza Canyon basalt is overlain by unaltered upper Paliza Canyon andesites. Immediately east of Las Conchas, however, the propyllitic alteration affects upper Paliza Canyon andesites, and in the north-northwestern rim of Valles caldera the propyllitic alteration affects Tschicoma Formation rocks. Hence this propyllitic alteration may have occurred in more than one event, but the altered rocks are confined to within a few hundred meters of the topographic rim of the caldera. If these relations can be interpreted as indicative of an incipient ring fracture hydrothermal conduit system, then the alteration is pre-Valles caldera (1.12 Ma) and possibly pre-Toledo caldera (1.45 Ma) in age.

In research borehole VC-1 near the southwestern part of Valles caldera there is significant phyllic alteration of Paleozoic sedimentary rocks and mineralization including molybdenite, sphalerite, galena, chalcopyrite, and pyrite [see *Goff et al.*, this issue; *Hulen and Nielson*, this issue]. Postcaldera volcanic rocks in VC-1 are unaltered, and current bottom hole temperatures are too low for precipitation of the mineral assemblage observed [*Hulen and Nielson*, this issue]. We suggest, therefore, that the hydrothermal alteration in VC-1 is pre-Toledo caldera in age (1.45 Ma) and probably most closely related to the caldera topographic rim environment, discussed above.

Within Valles caldera there is extensive argillic to advanced argillic alteration exposed at the surface. The best examples of the intracaldera alteration environment can be found around the active acid-sulfate springs at Sulphur Springs, west of the resurgent dome of the caldera (Figure 3) [*Charles et al.*, this issue]. Alteration of post-Valles caldera rocks and old siliceous sinter deposits suggest that this postcaldera hydrothermal system has boiled down to deeper levels to form a vapor-rich cap [*Goff et al.*, 1985]. *Hulen and Nielson* [this issue] postulate that the active hydrothermal system beneath the resurgent dome of Valles caldera may have withdrawn to greater depth as one possibility to reconcile the positions of observed alteration assemblages with current downhole temperatures. The present Valles caldera geothermal system contains at least three zones of hydrothermal upflow recognized from thermal gradient data [*Swanberg*, 1983]. Steam activity was reported in 1882 (*Santa Fe Daily New Mexican*, October 15, 1882) in areas that are currently inactive. Thus one should consider the active system to be dynamic as the intracaldera rhyolitic activity, structural development, and hydrology have changed in the last 1.12 Ma.

We conclude, based on available data, that there are at least three distinct hydrothermal events associated with magmatic events that have occurred in the volcanic field's history: (1) associated with Keres Group (Paliza Canyon Formation?) volcanism, (2) associated with late Bearhead Rhyolite volcanism, and (3) associated with postcaldera residual heat from magma chambers parental to most of the Tewa Group. The hydrothermal activity noted in the caldera topographic rim environment may represent multiple events related to the late Bearhead event, Tschicoma volcanism, early Tewa Group volcanism, and/or combinations of all of these.

CONCLUSIONS

1. Volcanic activity in the vicinity of the Jemez Mountains has not been successive basalt through rhyolite cycles and probably was never a truely bimodal basalt-rhyolite association, as has been inferred [e.g., *Christiansen and Lipman*, 1972] from the formal stratigraphy [*Bailey et al.*, 1969; *Smith et al.*, 1970]. Volcanic activity has been essentially continuous since at least 13 Ma, and the only strictly bimodal period of volcanism may have been at about 13 Ma; however, we suggest that volcanism at about 13 Ma was dominantly mafic. Although volcanism less than 3 Ma could be construed as bimodal, we believe that the thermal, tectonic, and magmatic events relating to the Bandelier Tuff magmatic system and the young, flanking basalts are sufficiently distinct that application of the term bimodal is misleading.

2. Volcanism in the vicinity of the Jemez Mountains had begun by 16.5 Ma with alkali basalts. By 13–14 Ma, episodic alkaline volcanism was replaced by more voluminous, rapid effusions of olivine tholeiite and differentiates of olivine tholeiite. By about 13 Ma the rate of accumulation of volcanic rocks far exceeded the local rate of sedimentation of the Santa Fe Group.

3. Based on field relations, petrography, geochemistry, and K-Ar dates, stratigraphic distinctions among Paliza Canyon basalt, basalt of Chamisa Mesa, and Lobato Basalt are artificial except for geographic reasons. All of these basalt units are part of a continuum of basaltic volcanism from >13 to 7 Ma that was contemporaneous with, but volumetrically overwhelmed by, dominantly andesitic activity.

4. Intermediate composition volcanism probably began by about 12 Ma, but between less than 10 to about 7 Ma upper Paliza Canyon andesite, derived from olivine tholeiite by differentiation, was erupted, constituting nearly half of the volume of the entire volcanic field.

5. Canovas Canyon and Bearhead rhyolites form a continuum of high-silica rhyolite volcanism from >13 to about 6 Ma that was essentially contemporaneous with Paliza Canyon Formation volcanism.

6. The petrography and geometry of Cochiti Formation deposits suggest that active Rio Grande rift faulting and rapid basin development accompanied Keres Group volcanism. The petrography and geometry of the Puye Formation, on the other hand, suggest that Tschicoma and some El Rechuelos volcanism occurred in a period of relative tectonic inactivity.

7. Bland group rocks of the Cochiti mining district probably represent the exhumed interior of a Keres Group volcano(s).

8. Temporal overlaps between Keres Group and Tschicoma Formation volcanism and between Tschicoma Formation and Tewa Group volcanism may indicate genetic relations among these units. Geochemical data of *Loeffler* [1984] and *Gardner* [1985] confirm genetic relations between the Keres Group and Tschicoma Formation.

9. As a stratigraphic unit, Cerro Rubio Quartz Latite is insignificant and should probably be considered as simply part of the Tschicoma Formation.

10. At least three distinct hydrothermal alteration events can be tentatively related to magmatic events in the volcanic field's history.

11. Through time, dominant lithologies in the volcanic field have been (1) 13–10 Ma, mantle-derived olivine tholeiite, crust-derived high-silica rhyolite, and unknown volumes of intermediate composition differentiates of the basalt, (2) 10–7 Ma, andesite derived from olivine tholeiite by differentiation, (3) 7–3 Ma, dacite generated by hybridization of mantle-derived and crust-derived melts, and (4) less than 4–3 Ma, rhyolitic tuffs, erupted from large, zoned magma chambers.

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