The Geology of New Mexico, A Geologic History, New Mexico Geological Society, p. 295–312.

LATE CENOZOIC GEOCHRONOLOGY OF VOLCANISM AND MINERALIZATION IN THE JEMEZ MOUNTAINS AND VALLES CALDERA, NORTH CENTRAL NEW MEXICO

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INTRODUCTION

The Jemez Mountains volcanic field (JMVF) is located at the intersection of the north-trending Rio Grande rift (RGR) and the northeast-trending Jemez volcanic lineament (JVL) (Fig. 1). The Jemez volcanic pile is rather circular (Fig. 2), straddling the west edge of the Española basin segment of the RGR and the southeastern edge of the Colorado Plateau (Fig. 1). The JVL is noted for the alignment of several Miocene to Quaternary volcanic fields (Mayo, 1958) and was once thought to represent a hot spot trace (Suppe et al., 1975). However, there are no compositional or age progressions along the JVL. By far the largest volume of volcanic rocks along the JVL occurs in the JMVF (about 2000 km^3) due to the intersection of deep-seated structures. Conductive heat flow along the west margin of the RGR near the Jemez Mountains averages about 120 mW/m^2 whereas conductive heat flow along the west margin of Valles caldera is about 210 mW/m^2 (Goff and Grigsby, 1982). Convective heat flow within present-day Valles caldera may locally exceed 5000 mW/m^2 due to the active hydrothermal system within it (Morgan et al., 1996). Two gravity lows occur within the Jemez Mountains region: a north-trending low on the east associated with thick, low-density fill in the Española basin and an asymmetric, circular low associated with low-density fill in Valles caldera (Cordell, 1978; Segar, 1974, Goff et al., 1989).

$^3He/^4He$ isotope measurements of present geothermal gases have R/R_a values as high as 6, which can only originate from a deep mantle/magmatic source (Goff and Gardner, 1994). Wolff and Gardner (1995) argued that the youngest eruptive products from the caldera represent new magma generated by basalt injection and crustal melting and that this may mark the onset of a new cycle of volcanism. Recently, Steck et al. (1998) synthesized seismic data beneath the Valles caldera (5–16 km deep) identifying a mid-crustal low velocity zone. Their modeling suggests that this zone contains a minimum melt fraction of 13%. Steck et al. (1998) also found low velocities extending to the crust-mantle boundary (roughly 39 ± 10 km) and believe this may be caused by underplating or injection of new basalt magma into the bottom of the Valles magma chamber. Thus, the central JMVF and Valles caldera overlie fresh, crystallizing magma and the potential for future eruptions still exists.

Volcanism in the Jemez Mountains was first described by J. W. Powell during reconnaissance work in the 1880s (Powell, 1961). Iddings (1890) presented petrographic and chemical data on vari-

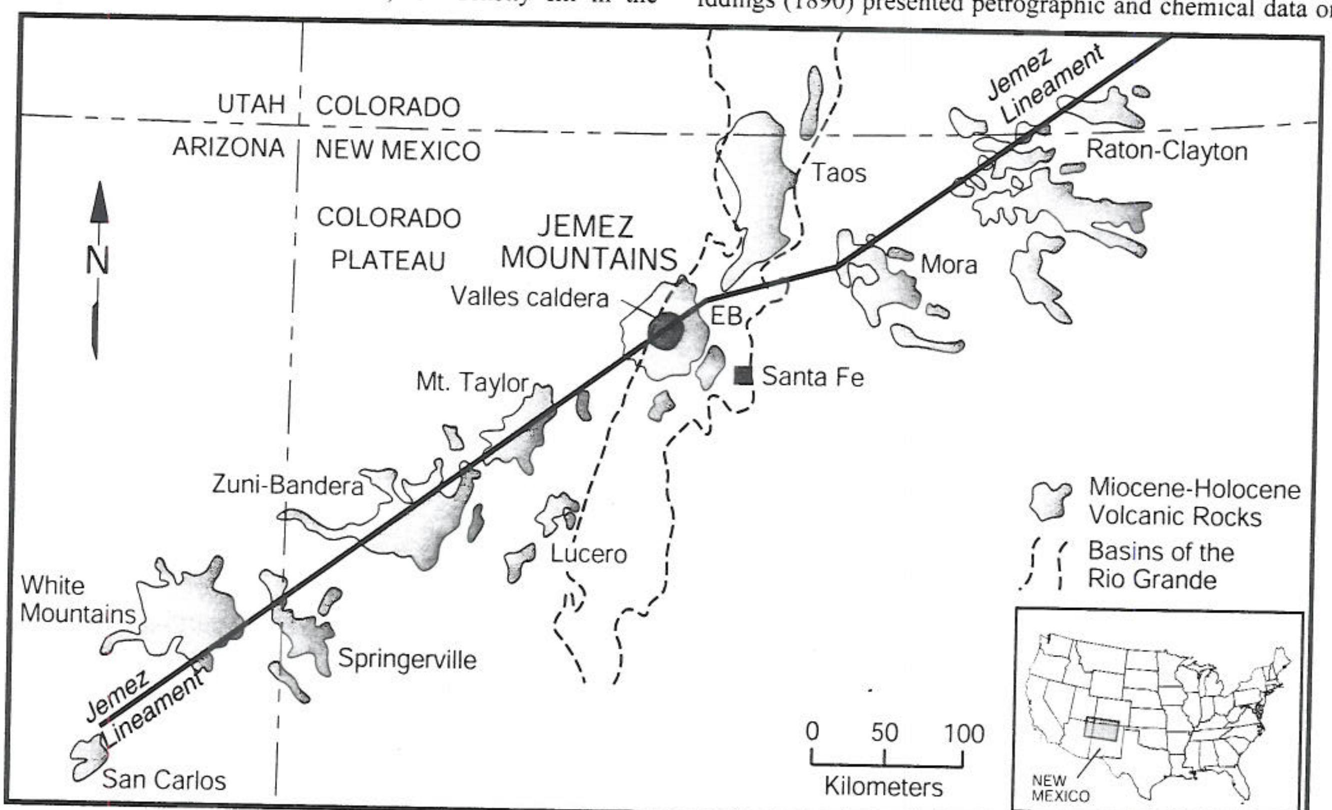

FIGURE 1. Location map of the Jemez Mountains and Valles caldera with respect to the Jemez volcanic lineament, the Colorado Plateau and the Rio Grande rift. **EB** = Española basin segment of the rift.

FIGURE 2. False-color LANDSAT image of the Jemez Mountains and Valles caldera, New Mexico. Peaks in the Jemez Mountains reach elevations of 3230 m, thus higher elevations are thickly forested and intermountain basins are lush grasslands. Note agricultural lands along major streams in surrounding arid areas; **C** = Rio Chama northwest of Española, **J** = Jemez River at Jemez Pueblo, **R** = Rio Grande at Cochiti Pueblo, **N** = southern Nacimiento fault zone and uplift, and **V** = Valle Grande in the southeastern caldera. The image clearly shows the circular arrangement of post-caldera domes around the central resurgent uplift inside the caldera.

ous units in the volcanic pile including Bandelier Tuff and quartz-bearing basalts. Comprehensive geologic work by the U.S. Geological Survey began in the 1920s (Ross, 1938). Although Jemez Mountains volcanism is best known for the formation of the Valles/Toledo calderas and emplacement of the Bandelier tuffs at ca. 1.2–1.6 Ma (Smith and Bailey, 1966; 1968), the calderas are constructed within a voluminous and complex sequence of earlier flows, domes and pyroclastic rocks (Bailey et al., 1969; Smith et al., 1970). Jemez volcanism began roughly 14–13 Ma with various mafic to silicic eruptions and continued more or less uninterrupted to ≤55 ka with effusion of the youngest post-caldera rhyolites (Gardner et al., 1986; Aldrich, 1986; Toyoda et al., 1995; Reneau et al., 1996; Phillips et al., 1997).

The primary object of this paper is to describe the geochronology, stratigraphy, and evolution of the JMVF and the Valles/Toledo calderas. The age of hydrothermal activity in the JMVF and the Valles/Toledo calderas is also summarized (WoldeGabriel, 1990; WoldeGabriel and Goff, 1989; 1992; Goff and Gardner; 1994). Minor attention is devoted to regional tectonics as it affects volcanism and volcanic stratigraphy. Magma generation and petrogenesis within the diverse eruptive products of the JMVF will not be reviewed but has been discussed previously by Smith (1979), Gardner et al. (1986), Loeffler et al. (1988), Stix et al. (1988), Spell and Kyle (1989), Stix and Gorton (1990), DePaolo et al. (1992), Dunbar and Hervig (1992), Perry et al. (1993), Wolff and Gardner (1995), Ellisor et al. (1996), Justet (1996), and Stimac (1996)

mong others.

STRATIGRAPHIC AND STRUCTURAL SETTING

The modern stratigraphic nomenclature of volcanic rocks in the emez Mountains was defined by Bailey et al. (1969) based most- y on geologic mapping published by Griggs (1964) and Smith et l. (1970), and on K/Ar dates obtained by Dalrymple et al. (1967) nd Doell et al. (1968). Additional dates were later presented by .uedke and Smith (1978). Kelley (1978) produced a regional map f the Española basin that includes the JMVF. The JMVF is divid- d into three groups, from oldest to youngest Keres, Polvadera, and ewa. Keres rocks are found primarily in the southern JMVF, olvadera rocks are found mostly in the northern JMVF, and Tewa ocks are focused in the central parts and flanks of the JMVF (Fig.). Mafic volcanic fields are found within the RGR peripheral to he main part of the JMVF, from north to south El Alto, Cerros del Rió, and Santa Ana Mesa (Fig. 3). The early radiometric dates indi- ate that the Keres Group was erupted from about 10.4–7.1 Ma, the Polvadera Group from about 9.6–2.0 Ma, and the Tewa Group from 1.37 Ma to <434 ka, but >45 ka. The peripheral volcanic fields were erupted from about 4.6–2.0 Ma (Bachman and Mehnert, 1978; Baldridge et al., 1980). Beginning in the early 1980s detailed mapping, radiometric dating and petrologic investigations were undertaken to refine our understanding of the stratigraphy and chronology of the JMVF. These studies, particularly that of Gardner et al. (1986), have shown that various units and formations in the three groups overlap in time and were erupted over a longer time interval than previously thought. These investigations will be referenced as appropriate in the sections below.

Geothermal and scientific drilling from 1959 to 1988 produced enormous amounts of information on the internal stratigraphy, structure, geophysical character, hydrothermal alteration, and hydrothermal fluids within the Valles caldera (Nielson and Hulen, 1984; Goff et al., 1989; Goff and Gardner, 1994). A generalized east-to-west cross section of the caldera region (Fig. 4) shows typical relations among the major stratigraphic groups of the JMVF and relations to Tertiary basin-fill rocks of the RGR, Paleozoic to Mesozoic rocks of the Colorado Plateau, and Precambrian basement. Drilling and geophysics have revealed that the caldera is structurally asymmetric, being much deeper on the east than on the west (a "trap door" caldera; Heiken and Goff, 1983). Miocene sedimentary rocks of the RGR thicken eastward toward the axis of the rift. Particularly noteworthy in the structure is the relative horst beneath the Sierra de los Valles between the eastern caldera and the deepest part of the RGR (Figs. 3, 4). This horst is bounded by the caldera ring fracture zone on the west and the Pajarito fault zone on the east. Structurally, the shallow western margin of the RGR underlies the JMVF and Valles caldera, but the caldera depression and the central and eastern portions of the RGR presently form separate hydrologic basins.

Figure 5 shows a correlation chart of stratigraphic units within various regions of the JMVF and RGR. This chart utilizes all radiometric dates known by the authors that are considered reliable as of the year 2000.

CHRONOLOGY OF VOLCANIC ROCKS

Inception of Jemez volcanism and basaltic volcanism in the Santa Fe Group, middle to late Miocene

Parts of the Keres Group and underlying rocks were mapped in detail and dated by K/Ar methods to determine the chemistry and petrogenesis of the units, and the inception of Jemez volcanism (Gardner, 1985; Goff et al., 1990). Gardner and Goff (1984) and Gardner et al. (1986) indicated that volcanism in the Jemez Mountains began >13 Ma. The oldest age determined from the JMVF is a basanite dated at 16.5 ± 1.4 Ma that is interbedded with Santa Fe Group sediments south of St. Peter's Dome (Figs. 3, 5, 6). A recent $^{40}Ar/^{39}Ar$ isochron age of the same unit is 17.7 ± 3.9 Ma (G. WoldeGabriel, *unpubl.*, 1999) The basanite is one of several alkali basalts in a discontinuous group of thin flows at this general stratigraphic horizon. The basanite occurs about 50 m below the contact of the main mass of overlying Keres Group.

The Santa Fe Group exposure mentioned above is part of the Tesuque Formation and is the oldest known exposure of Tesuque

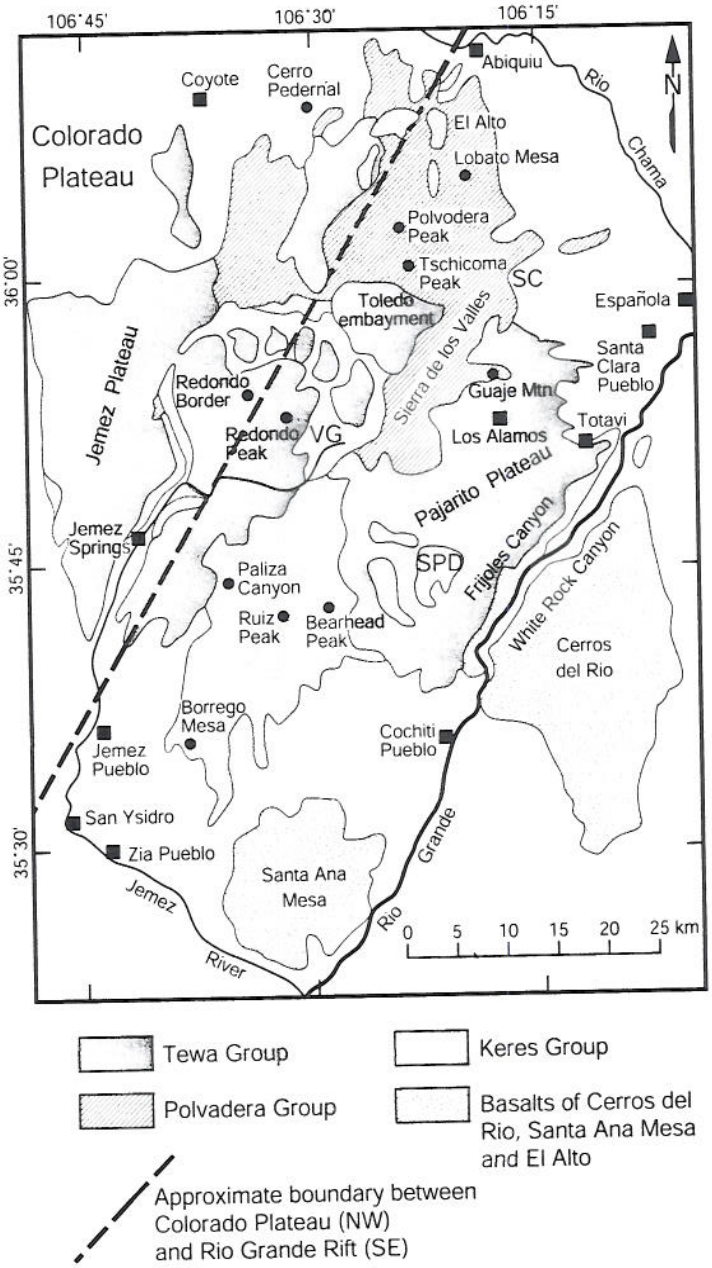

FIGURE 3. Schematic geologic map of the Jemez Mountains volcanic field showing the distribution of the major stratigraphic groups, the location of peripheral mafic volcanic fields, and the approximate boundary between the Colorado Plateau and Rio Grande rift. **SC** = Santa Clara Canyon area, **SPD** = St. Peter's Dome, **VG** = Valle Grande.

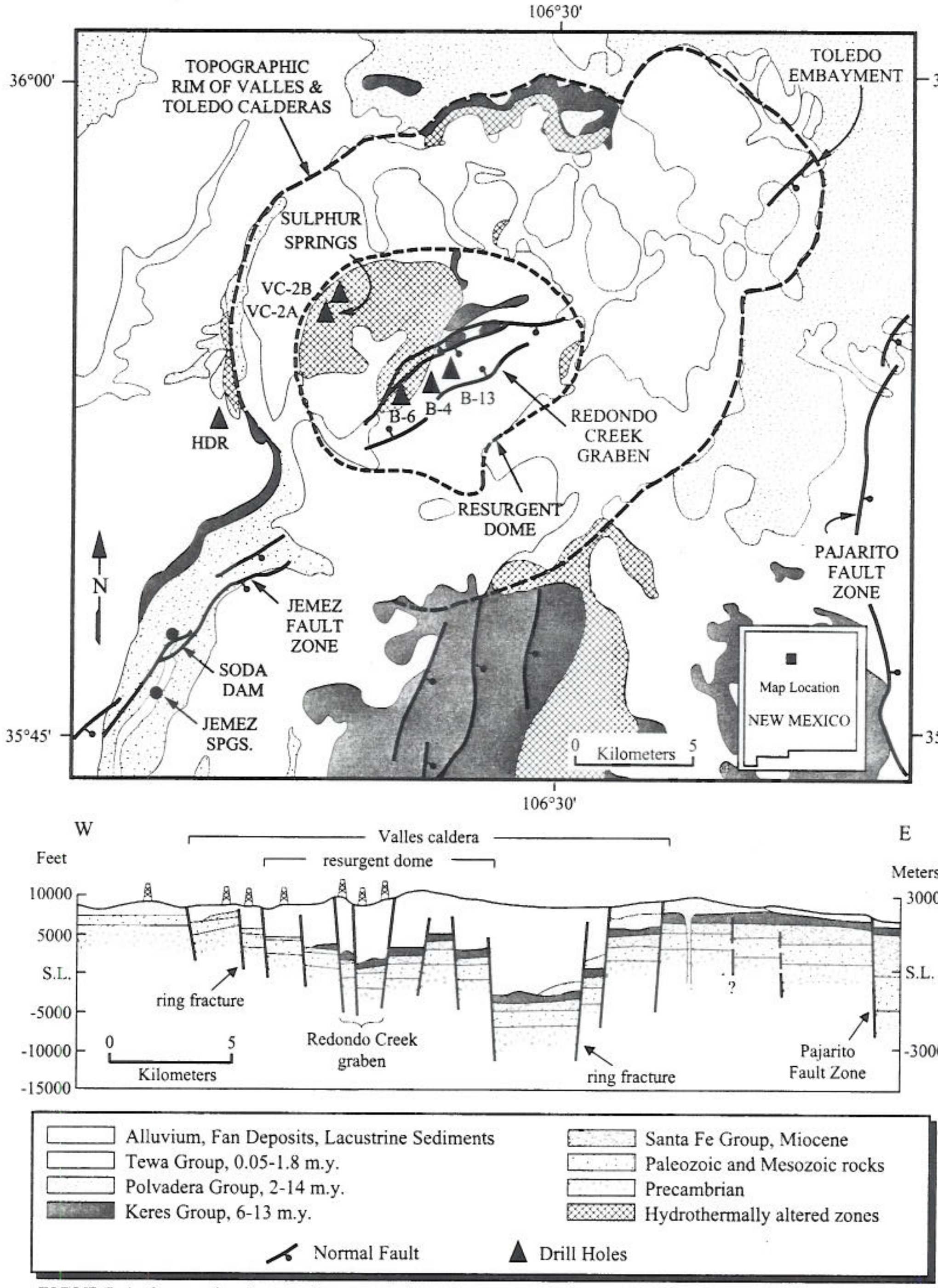

FIGURE 4. Generalized geologic map and east-west cross section of the Valles caldera region showing stratigraphic relations among various rocks and structural relations between the caldera and the RGR. Geothermal and scientific drilling combined with geophysical studies have revealed the "trap door" structure of the caldera and the relative horst between the caldera and the central RGR (modified from Goff and Gardner, 1994). **B-4**, **B-6**, and **B-13** show locations of three of the Baca geothermal wells, **HDR** marks location of the Los Alamos hot dry rock geothermal wells, and **VC-2A** and **VC-2B** locates two of the Continental Scientific Drilling Program core holes. The locations of the drill holes in the cross section are generalized.

within the JMVF (Goff et al., 1990, Cather, 1992). Other patches of Santa Fe Group and earlier Tertiary sediments occur in the northern, western, and southern JMVF, along the western caldera margin (Smith et al., 1970), along the northern caldera margin (Gardner and Goff, 1996), and beneath the caldera floor (Nielson and Hulen, 1984; Goff et al., 1987, Goff and Gardner, 1994). Because they have been little studied, these occurrences of Tertiary sediments are poorly identified and dated.

Aldrich (1986) determined a date of 14.05 ± 0.33 Ma on a lava flow mapped as part of the Lobato Basalt of the Polvadera Group in Santa Clara Canyon in the eastern JMVF (Fig. 3). This flow is interbedded with Tesuque Formation just below the main mass of

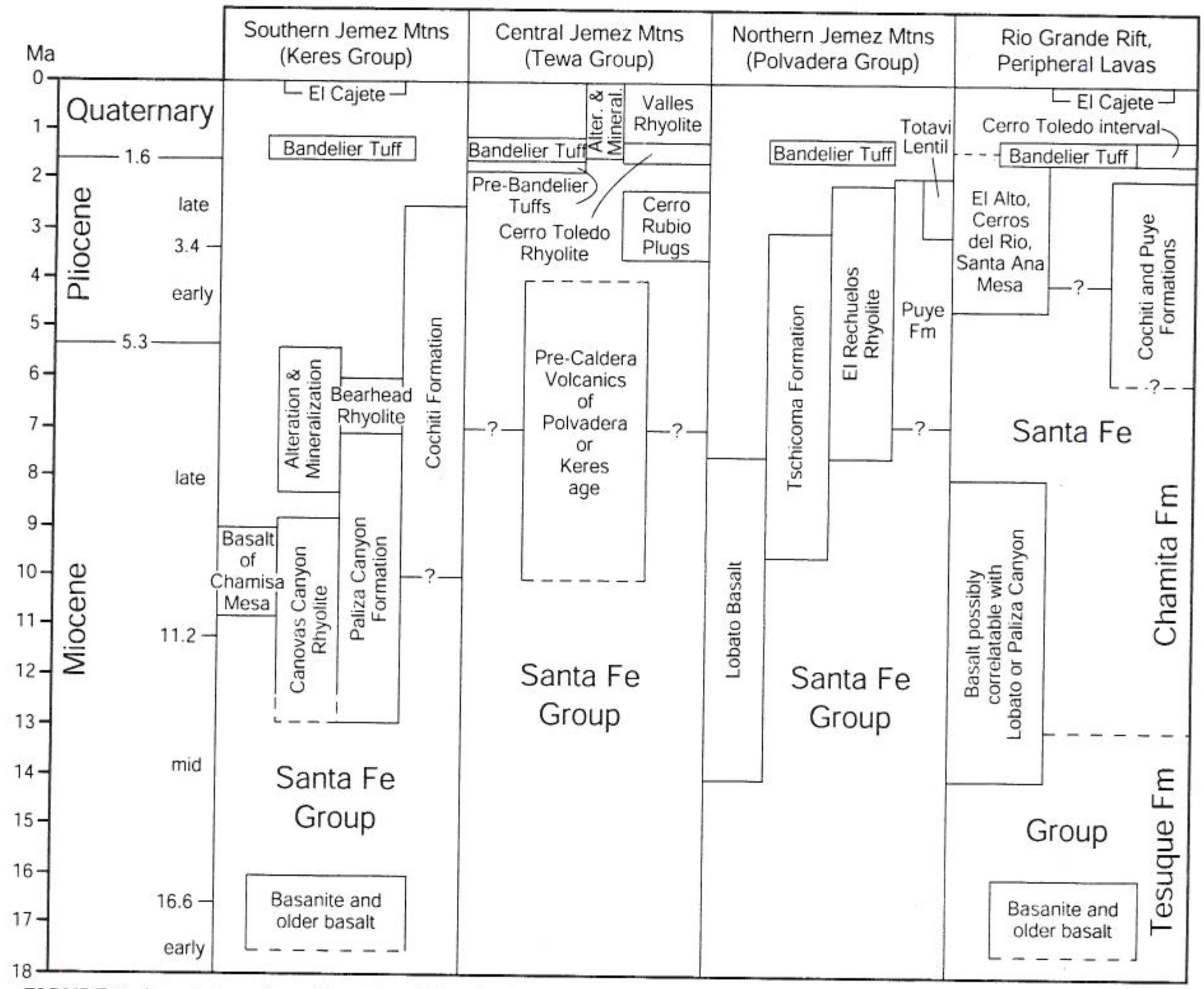

FIGURE 5. Correlation chart of stratigraphic units by subregion within the Jemez Mountains volcanic field. The chart utilizes all available radiometric dates that are considered to be reliable as of the yr 2000. The southern Jemez Mountains are dominated by rocks of the Kereš Group, the central Jemez Moutains are composed mostly of rocks of the Tewa Group, and the northern Jemez Mountains are constructed primarily of rocks of the Polvadera Group. In contrast, the RGR is filled mostly with basin-fill sedimentary rocks of the Santa Fe Group, subordinate volumes of mafic lavas from peripheral volcanic fields and earlier volcanism, and volcaniclastic units from the JMVF. The only widespread stratigraphic markers throughout the region are the Bandelier Tuff and the Santa Fe Group.

overlying Polvadera Group rocks. Aldrich and Dethier (1990) dated a similar basalt lava interbedded with Tesuque at 13.9 ± 0.4 Ma. Five other Lobato flows described by these authors have ages of 12.4 ± 0.4 to 9.6 ± 0.2 Ma and are interbedded in the overlying Chamita Formation. Additional Lobato dates reported in Goff et al. (1989) span a period from 11 to 9 Ma. Clearly volcanism in the Jemez Mountains region began as early as about 17 Ma and some eruptive products assigned to formal stratigraphic units erupted as early as 14 Ma. As pointed out by Gardner et al. (1986), inception of volcanism in the JMVF is a problem of semantics rather than a problem of geology.

Because Los Alamos National Laboratory is conducting detailed environmental investigations beneath the Pajarito Plateau (Fig. 3), many basaltic lavas from surface outcrops and drill holes have been recently dated that may or may not be correlated with the basalts in the northeast and southeast JMVF (i.e., the Lobato Basalt and basalts in the Paliza Canyon Formation, Fig. 5). Two recent $^{40}Ar/^{39}Ar$ dates on basalt lavas exposed on the northern Pajarito Plateau are 8.85 ± 0.03 and 8.77 ± 0.04 Ma (G. WoldeGabriel, *unpubl.*, 2000). These two lavas are also interbedded with sediments of the Santa Fe Group. Purtymun (1995) dated two basalt flows at 8–9 Ma that are interbedded with the Santa Fe Group at depths between 348 and 424 m in a well several kilometers east of Los Alamos. WoldeGabriel et al. (1996) dated a mugearite lava by $^{40}Ar/^{39}Ar$ at 9.3 ± 0.2 Ma in the bottom of White Rock Canyon. The lava is interbedded in the Santa Fe Group and overlain by the Puye Formation (Dethier, 1997). Although quite far from type areas of basalt in either the Keres or Polvadera groups, these dates indicate that basaltic volcanism was widespread in the western Española basin during mid- to late-Miocene time. The dates also seem to indicate that a lull in basaltic volcanism occurred beneath the Pajarito Plateau between about 8 and 4 Ma (see WoldeGabriel et al., 1996).

Keres Group, middle Miocene to late? Pliocene

Bailey et al. (1969) defined the Keres Group as being composed of three formations, Canovas Canyon Rhyolite, Paliza Canyon, and Bearhead Rhyolite, and an informal unit, the basalt of Chamisa Mesa. Compositions from basalt through high-silica rhyolite are found in the Keres Group, although rocks of basaltic andesite composition (52–56 wt.%) are rare (Gardner et al., 1986).

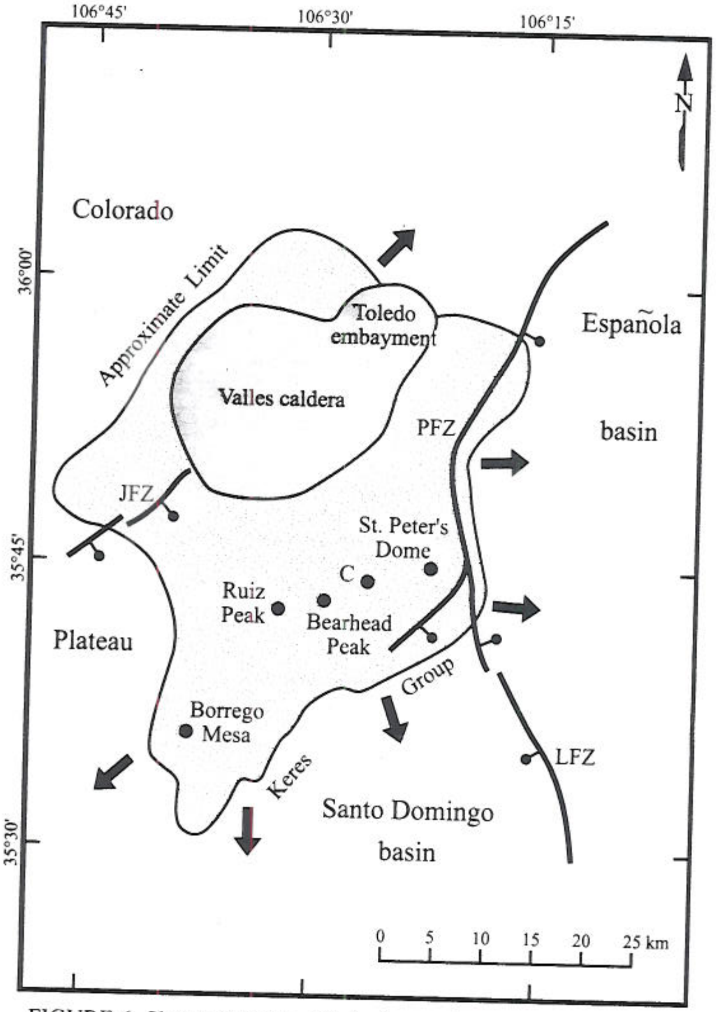

FIGURE 6. Sketch showing distribution and approximate limits of Keres Group rocks (13–6 Ma) with respect to the present position of Valles caldera and Toledo embayment. Most Keres rocks are found south of the present Valles caldera. During growth of the Keres complex, volcanic detritus was shed to the northeast, east, southeast, and south (shown by arrows), particularly into basins of the developing RGR. This detritus formed much of the Cochiti Formation (as defined by Bailey et al., 1969). Comparatively little Keres detritus was shed onto the Colorado Plateau. **JFZ** = Jemez fault zone, **PFZ** = Pajarito fault zone, **LFZ** = La Bajada fault zone, **C** = Cochiti mining district.

Volumetrically, andesite is the most common rock type. The total volume of preserved Keres Group rocks is estimated at about 1000 km^3 (Gardner et al., 1986). Keres Group rocks (Figs. 3, 5, 6) are found primarily in the southern JMVF, in the north and west walls of Valles caldera, as exotic blocks in intracaldera Bandelier Tuff, and as hydrothermally altered lavas beneath the caldera floor (Smith et al., 1970; Nielson and Hulen, 1984; Gardner and Goff, 1996; Gardner et al., 1996).

Basalt of Chamisa Mesa

Early basaltic lavas in the JMVF consist primarily of relatively thin flows and minor cinder deposits that form lava stacks and cap mesas. Bailey et al. (1969) indicated that the basalt of Chamisa Mesa is the oldest stratigraphic unit in the JMVF but dates were lacking. At Borrego Mesa (Figs. 3, 6), Chamisa Mesa basalt is separated from overlying Paliza Canyon basalt by an intervening sequence of Canovas Canyon rhyolitic tuffs. Luedke and Smith (1978) determined a date of 10.4 ± 0.5 Ma on Chamisa Mesa basalt lava beneath these tuffs. More recently, Chamberlin et al. (1999) obtained two $^{40}Ar/^{39}Ar$ dates of 10.8 ± 1.8 and 8.96 ± 0.76 Ma on the same flow of Chamisa Mesa basalt underlying Canovas Canyon tuff near the type area. Another $^{40}Ar/^{39}Ar$ date of 9.01 ± 0.14 Ma was obtained on a possible equivalent basalt in an area southeast of Borrego Mesa (G. Smith, *unpubl.*). These dates are equivalent to many determined for the Lobato Basalt (described above). Gardner (1985) described a basalt lava in the Paliza Canyon area dated at 13.2 ± 1.2 Ma that overlies a rhyolite tuff and Goff et al. (1990) mapped a basalt lava east of St. Peter's Dome dated at 11.3 ± 0.9 Ma that lies between the Santa Fe Group and the main mass of overlying Keres Group rocks. As a result, Chamisa Mesa basalt in the type area is not the oldest stratigraphic unit in the Keres Group or the oldest basalt in the JMVF. Nonetheless, it remains a useful stratigraphic unit within the type area (R. M. Chamberlin, personal commun., 2000).

Canovas Canyon Rhyolite

Bailey et al. (1969) indicated that Canovas Canyon Rhyolite occurs between basalt of Chamisa Mesa and overlying rocks of the Paliza Canyon Formation. Gardner et al. (1986) pointed out that small volumes of rhyolitic rocks are interbedded and intruded within much of the Paliza Canyon Formation. Canovas Canyon Rhyolite consists of domes, plugs, flows, and tuffs of mostly aphyric, high-silica rhyolite. Many of the lavas are perlitic and the tuffs are highly weathered. K/Ar dates range from 12.4 to 8.8 Ma (Luedke and Smith, 1978; Gardner et al. 1986). The oldest stratigraphic unit in the Canovas Canyon Rhyolite may be the ash flow tuff in the Paliza Canyon area described above (>13.2 Ma). It is similar in appearance to a widespread, pink, ash flow tuff resting on Santa Fe Group sediments south of St. Peter's Dome. The "pink tuff" is overlain south of St. Peter's Dome by rhyolite lava dated at 12.4 ± 2.0 Ma (Goff et al., 1990). The "pink tuff" has not been successfully dated by K/Ar due to the weathered nature of clasts and matrix; no date has been attempted on phenocrysts by $^{40}Ar/^{39}Ar$. Relatively voluminous Canovas Canyon lavas in the type area have K/Ar dates of 10.0 ± 0.3 and 10.2 ± 0.3 Ma (Luedke and Smith, 1978) and $^{40}Ar/^{39}Ar$ dates ranging from 9.7 to 9.5 Ma (n = 3, Chamberlin et al., 1999; Chamberlin, 1999). A sample of Canovas Canyon Rhyolite southeast of Borrego Mesa was recently dated by $^{40}Ar/^{39}Ar$ at 9.55 ± 0.34 Ma (G. Smith, *unpubl.*). The youngest dated Canovas Canyon unit (8.8 ± 0.7 Ma) is a dome in the Ruiz Peak area (Figs. 3, 6) that intrudes rocks of the Paliza Canyon Formation (Gardner and Goff, 1984; Gardner, 1985).

Paliza Canyon Formation

Rocks of the Paliza Canyon Formation consist of flows, domes, and minor pyroclastic rocks of basalt, andesite, and dacite composition. The unit includes thick sequences of flow breccia, dome-collapse breccia, debris flows, and minor stream deposits. The latter deposits were mapped as part of the Cochiti Formation by Goff et al. (1990; see discussion below). Generally speaking, the basaltic rocks are aphyric to slightly porphyritic, whereas the andesitic and dacitic rocks are porphyritic to coarsely porphyritic. K/Ar dates range from 13.2 to 7.1 Ma with basalts seeming to be slightly older as a group than intermediate composition units (Dalrymple et al., 1967; Luedke and Smith, 1978; Gardner et al., 1986; Chamberlin et al., 1999). Basal Paliza Canyon basalts of 13.2 and 11.3 Ma have been mentioned above. The oldest interme-

diate composition Paliza Canyon lava is dated at 10.6 ± 1.4 Ma but the majority of units (n = 9) are dated between 10.1 and 8.8 Ma (see Gardner et al., 1986). Three samples of basal Paliza Canyon andesitic rocks in the extreme southern JMVF have $^{40}Ar/^{39}Ar$ dates ranging from 9.2 to 9.0 Ma (Chamberlin et al., 1999). Chamberlin et al. (1999) mapped an andesitic lava underlying Peralta Tuff east of Borrego Mesa that was dated by $^{40}Ar/^{39}Ar$ at 7.1 ± 0.2 Ma. This is the youngest unit presently identified in the Paliza Canyon Formation.

The Cochiti mining district (Fig. 6) includes the ghost towns of Bland and Albermarle and consists primarily of hydrothermally altered, volcanic and hypabyssal rocks once thought to be Eocene in age (Smith et al., 1970). However, Stein (1983) obtained a K/Ar age of 11.3 ± 0.3 Ma on monzonite porphyry near dikes of andesite and rhyolite with Keres Group affinities. Thus, the Cochiti area probably represents the interior of a dissected Keres Group volcano (Gardner et al., 1986). If so, this date is the oldest so far obtained on an intermediate composition unit within the Paliza Canyon Formation.

Bearhead Rhyolite

The Bearhead Rhyolite consists of domes, shallow intrusions, flows, and pyroclastic rocks of generally aphyric to sparsely porphyritic rhyolite (Bailey et al., 1969). Some dome complexes, such as those at Bearhead Peak (Figs. 3, 6), are quite voluminous. A K/Ar date of 7.1 ± 0.2 Ma was obtained on a dome intruding Peralta Tuff southeast of the Cochiti mining district (Luedke and Smith, 1978). Gardner et al. (1986) reported six K/Ar ages ranging from 7.1 to 6.2 Ma on various Bearhead units. A $^{40}Ar/^{39}Ar$ age of 6.91 ± 0.06 Ma was obtained on a dome in lower Peralta Canyon (McIntosh and Quade, 1995). More recently, Justet (1996) obtained 19 $^{40}Ar/^{39}Ar$ dates on Bearhead lavas ranging from 7.06 ± 0.10 to 6.01 ± 0.05 Ma. She also determined that Bearhead eruptions were clustered in time, with the most voluminous main cluster occurring between 7.1 and 6.4 Ma.

The Peralta Tuff Member of the Bearhead Rhyolite includes major sequences of pyroclastic rocks consisting of fall, flow, surge, and hydromagmatic surge deposits that were erupted from different vents (Smith et al., 1991; Gay and Smith, 1996). The Peralta Tuff Member is thickest and most widespread in lower Peralta Canyon and adjacent canyons, but discontinuous patches of Peralta Tuff occur throughout the southeastern expanse of the Keres Group (Smith et al., 1970). A K/Ar date of 6.8 ± 0.1 was obtained by Goff et al. (1990) on a sanidine separate from a fall deposit in the type area. McIntosh and Quade (1995) determined $^{40}Ar/^{39}Ar$ ages of 6.96 ± 0.10 to 6.75 ± 0.09 Ma on five additional Peralta Tuff units near the type area. Chamberlin et al. (1999) dated a Peralta Tuff ash by $^{40}Ar/^{39}Ar$ at 6.25 ± 0.08 Ma that is interbedded in upper Cochiti Formation on the northwest flank of Santa Ana Mesa.

Cochiti Formation (volcaniclastic rocks of Keres Group)

Bailey et al. (1969) defined the Cochiti Formation as a thick sequence of volcanic gravel and sand derived from penecontemporaneous erosion of volcanic units of the Keres Group. These volcaniclastic units form coalesced but eroded alluvial fans directed east and south toward the RGR. On the southeast side of the JMVF the volcaniclastic rocks are abruptly terminated along and within the Pajarito fault zone (Fig. 6; Goff et al., 1990), the main fault bounding the west side of the deepest part of the Española basin. East of the Pajarito fault zone, the volcaniclastic debris equivalent in age to most of the Keres Group is buried beneath younger units and is presumably interfingered with Santa Fe Group.

Although the definition of the Cochiti Formation seems straightforward, geologic mapping of the Cochiti has been inconsistent, leading to much stratigraphic confusion. Smith et al (1970) mostly mapped Cochiti Formation as volcaniclastic units shed from and overlying Keres Group rocks in the southeastern Jemez Mountains. As such, some of the Cochiti Formation shown by Smith et al. (1970) occurs east of the Pajarito fault zone. In contrast, Goff et al. (1990), following Gardner et al. (1986), mapped Cochiti Formation as a unit of debris flows, various pyroclastic deposits, and stream deposits primarily interbedded within Canovas Canyon Rhyolite and Paliza Canyon Formation domes and lavas in the Keres Group. Smith and Lavine (1996) reviewed the issue and proposed that Cochiti Formation be restricted to units mapped more-or-less as shown by Smith et al. (1970). As defined by Bailey et al. (1969), the Cochiti Formation has a potential age range of <13 to <6 Ma whereas, as proposed by Smith and Lavine (1996, Fig. 2), the Cochiti Formation would be restricted to an age of about 6 to perhaps 2.5 Ma. The younger age is roughly time equivalent to the Puye and Totavi Formations in the northeast JMVF and western Española basin (Fig. 5).

Thick sequences of intermediate composition volcaniclastic rocks are well exposed in several deep canyons of the southeast JMVF (Goff et al., 1990; Lavine et al., 1996). Six stratigraphic sections from these canyon areas contain four dacitic tephra and pyroclastic flow deposits dated by $^{40}Ar/^{39}Ar$ at 9.47 ± 0.06 to 9.11 ± 0.05 Ma (Lavine et al., 1996). A fifth $^{40}Ar/^{39}Ar$ date of 9.48 ± 0.03 Ma was obtained on dacitic tephra from a 1-m-thick fall deposit exposed in a section of volcaniclastic rocks northeast of St. Peter's Dome (F. Goff, *unpubl.*, 1994). These dates are conformable with older K/Ar dates of Keres Group lavas presented by Dalrymple et al. (1967), Luedke and Smith (1978), Gardner et al. (1986), and Goff et al. (1990) and suggest that most of the volcaniclastic sequences were deposited in a relatively short time period. A basalt lava in a canyon east of St. Peter's dome dated at 11.3 ± 0.9 Ma underlies about 350 m of interbedded volcaniclastic rocks and subordinate lavas. Andesite lava at St. Peter's Dome dated at 8.7 ± 0.4 Ma caps this volcaniclastic section.

Polvadera Group, middle Miocene to late Pliocene

The Polvadera Group consists of three formations as follows: Lobato Basalt, Tschicoma Formation, and El Rechuelos Rhyolite (Bailey et al., 1969). Relations of the group to the Puye Formation are somewhat analogous to the relations of the Keres Group to the Cochiti Formation (Gardner et al., 1986; Waresback, 1986; Turbeville et al., 1989). Compositionally, the Polvadera Group consists of basaltic to high-silica rhyolitic rocks. The group is dominated by domes of dacite to rhyodacite composition and has a volume of about 500 km^3. Polvadera Group rocks (Figs. 3, 5, 7) are found primarily in the northern and eastern JMVF, in the north, west, and east walls of Valles caldera, as exotic blocks in intracaldera Bandelier Tuff, and as hydrothermally altered lavas beneath the caldera floor (Smith et al., 1970; Nielson and Hulen, 1984; Gardner and Goff, 1996; Gardner et al., 1996).

Lobato Basalt

The Lobato Basalt consists of multiple flows and associated cinder deposits of primarily olivine basalt. It forms prominent mesas in the northeastern Jemez Mountains and overlies the Abiquiu Tuff (Smith, 1938). Extensive dikes and lavas of Lobato Basalt intrude and are interbedded with the Santa Fe Group. A dacite flow of

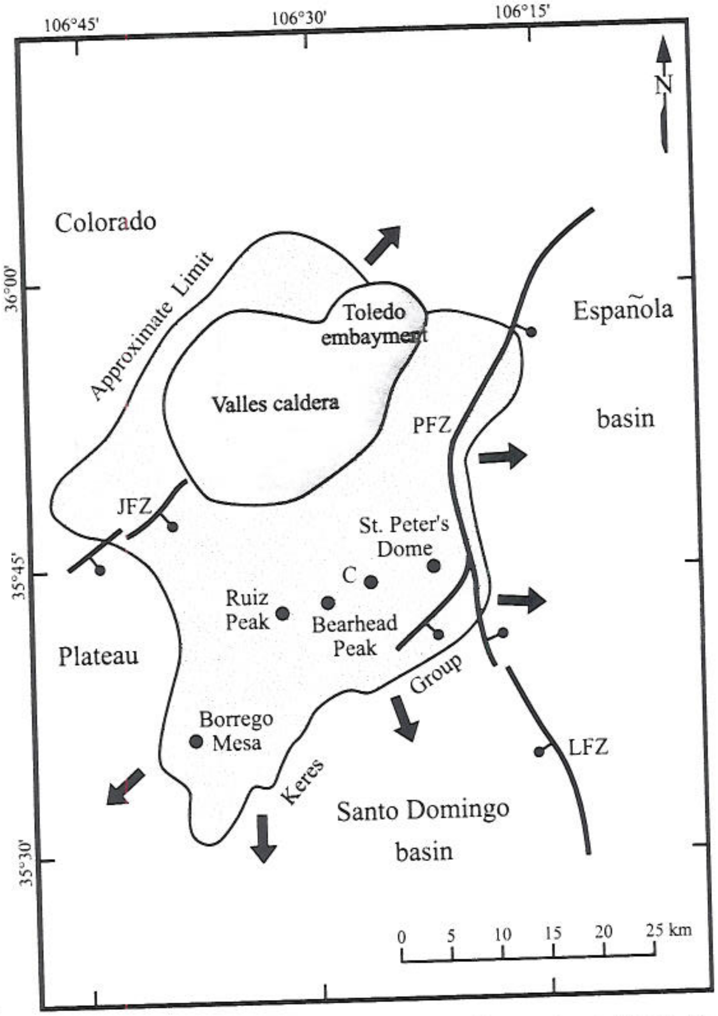

FIGURE 7. Sketch showing distribution and approximate limits of Polvadera Group rocks (14–2 Ma) with respect to the present position of Valles caldera and Toledo embayment. Most Polvadera rocks were erupted north and east of Valles caldera. During growth of the Polvadera complex, volcanic detritus was shed to the northeast and east into the developing Española basin. This detritus formed much of the Puye Formation. Also shown is the distribution of most of the Bearhead Rhyolite, Keres Group (7.1–6.0 Ma) which overlaps in time with much of the El Rechuelos Rhyolite of the Polvadera Group (7.5–2.0 Ma). Bearhead rocks, particularly the pyroclastic rocks, were shed southeast toward the developing Santo Domingo basin. Peripheral volcanic fields formed from about 4.6–1.6 Ma. Fault labels same as in Figure 6.

Tschicoma Formation is interbedded with Lobato Basalt east of Lobato Mesa (Bailey et al., 1969) but for the most part the Lobato underlies Tschicoma rocks. Rocks assigned to the Lobato Basalt have K/Ar ages ranging from 14.05 ± 0.33 to 7.6 ± 0.4 Ma (Dalrymple et al., 1967; Bachman and Mehnert, 1978; Luedke and Smith, 1978; Baldridge et al., 1980; Manley and Mehnert, 1981; Aldrich, 1986; Gardner et al., 1986). A voluminous pulse of Lobato volcanism apparently occurred from 10.8 ± 0.3 to 9.1 ± 0.2 Ma (15 of 22 Lobato dates reported in Gardner et al., 1986). Five more dates ranging from 11 to 9 Ma are described in Goff et al. (1989). Thirteen additional Lobato dates reported by Aldrich and Dethier (1990) have an age range of 13.9 ± 0.4 to 9.6 Ma. Most Lobato lavas correspond in age with older rocks of the Keres Group in the southern JMVF.

Tschicoma Formation

The Tschicoma Formation was first defined by Griggs (1964) and consists of voluminous domes and flows of porphyritic to coarsely porphyritic andesite, dacite, and rhyodacite. These domes are best exposed at Tschicoma and Polvadera Peaks, and in the Sierra de los Valles north and east of Valles caldera (Fig. 3). The Tschicoma unconformably overlies Abiquiu Tuff and the Santa Fe Group in the northern JMVF (Smith et al., 1970). Porphyritic lavas of Tschicoma Formation overlie hydrothermally altered lavas of the Keres Group and arkosic sediments resembling Santa Fe Group in the northern wall of Valles caldera (Gardner and Goff, 1996). Tschicoma rocks interfinger with deposits of the Puye Formation in the eastern JMVF. Twelve K/Ar dates on Tschicoma lavas display an age range of 6.9 ± 0.3 to 3.2 ± 0.3 Ma (Dalrymple et al., 1967; Luedke and Smith, 1978; Gardner et al., 1986) but the main volume of Tschicoma rocks was apprently erupted between 5 and 3 Ma (Goff et al., 1989). Subsequent work shows that some Tschicoma rocks are both older and younger than previously thought and include rhyolitic compositions. A dacite lava underlying Lobato Basalt near Lobato Mesa has a K/Ar date of 9.6 ± 0.2 Ma whereas a dacite dome east of Polvadera Peak has a date of 2.96 ± 0.27 Ma (Goff et al., 1989). Recent analyses show that some porphyritic domes in the Guaje Mountain area are compositionally equivalent to low-silica rhyolite. A porphyritic rhyolitic lava from this area has a K/Ar date of 4.55 ± 0.22 Ma (Goff et al., 1989).

El Rechuelos Rhyolite

This name is given to four small, aphyric to slightly porphyritic rhyolite domes and plugs, and a small pumice cone west and north of Polvadera Peak (Bailey et al., 1969). Stratigraphic relations suggest that El Rechuelos Rhyolite is younger than most Tschicoma rocks. Dalrymple et al. (1967) obtained a K/Ar date of 2.07 ± 0.06 Ma on obsidian from one of two glassy domes in the north part of the group. A second date on this dome came out 2.01 ± 0.06 Ma (Loeffler et al., 1988). However, the two southern domes have K/Ar dates of 7.5 ± 0.3 Ma and 5.8 ± 0.2 Ma, whereas the pumice cone is dated at 5.2 ± 0.2 Ma. Loeffler et al. (1988) revealed that the pumice cone is actually rhyodacite in composition, resembling average Tschicoma dacite. The older dates in El Rechuelos Rhyolite overlap with ages in the Tschicoma Formation and roughly correspond in age with Bearhead Rhyolite in the southern JMVF (Gardner et al., 1986).

Puye Formation

The Puye Formation is an extensive volcanogenic alluvial fan complex shed eastward from volcanic domes and flows of the Tschicoma Formation (Smith, 1938). The Puye was studied by Griggs (1964), defined by Bailey et al. (1969), and mapped by Smith et al. (1970). Waresback (1986) studied the sedimentological evolution of the Puye Formation while Turbeville et al. (1989) investigated volcanological origins of the unit. The Puye is well exposed north of the Pajarito Plateau and is intersected by all deep water supply wells in the northern plateau area (Dransfield and Gardner, 1985; Stoker et al., 1992; Purtymun et al., 1993).

The main mass of Puye Formation is distributed over an area of 200 km² and contains >15 km³ of volcaniclastic material deposited between about 3.5 and 1.9 Ma. It is mapped as a unit that overlies the Santa Fe Group. However, by original definition (Bailey et al., 1969; Gardner et al., 1986), Puye deposits may be as old as 7 Ma and as young as 1.6 Ma (the age of lower Bandelier Tuff). Olde

debris from Polvadera rocks was shed into the RGR and interfingers with Santa Fe Group rocks, primarily Chamita Formation. Most of the Puye conglomerates contain cobbles of dacitic to andesitic composition in a volcanic sand matrix. At least 25 ash beds of dacitic to rhyolitic composition are interbedded within the fanglomerates. Some of the dacitic ash beds have K/Ar dates of about 2.5 ± 0.1 Ma (Turbeville and Self, 1988; Goff et al., 1989) but, overall, the Puye Formation has few dates. Basaltic ash beds, pillow-palagonite complexes and lacustrine deposits are interbedded with Puye rocks on the east side of the deposit.

The fanglomerates display considerable lateral variation and are complex, intertonguing mixtures of stream flow, sheet flow, debris flow, block and ash flow, pumice fall, and ignimbrite deposits. Maximum thickness is about 220 m in Pueblo Canyon (Griggs, 1964) but thins to 15 m north of the Pajarito Plateau (Dethier and Manley, 1985). The Puye is as much as 183 m thick beneath the Pajarito Plateau (Goff, 1995). Interbedded Polvadera Group dacite and andesite flows, and Cerros del Rió basalt flows are common. The former relations are documented in water wells on the western side of the plateau whereas the latter relations are well exposed in White Rock Canyon.

Totavi Lentil

The Totavi Lentil is a coarse, poorly consolidated conglomerate that appears at the top of the Chamita Formation, Santa Fe Group. It contains cobbles and boulders of primarily quartzite, granite, pegmatite, and altered volcanics. Griggs (1964), who formalized the unit, defined the Totavi Lentil as the basal unit of the Puye Formation based on conformable bed relations with overlying fanglomerate layers. However, the lithologies of the cobbles and the arkosic sandy matrix argue that the Totavi is more akin to axial deposits of the Santa Fe Group. Present workers (Dethier, 1997; J. Hawley, personal commun., 1997) assume that the Totavi Lentil represents ancestral Rio Grande channel gravels; thus, it would be expected to show disconformable relations with finer-grained sediments beneath conglomerate layers. The Totavi Lentil is extremely distinctive due to the presence of well-rounded clasts such as the quartzite, granite, and pegmatite of Precambrian origin. It is intersected by no less than nine of the water wells and test holes studied by Griggs (1964) and is a key marker bed used for stratigraphic breakouts in supply wells drilled beneath the Pajarito Plateau.

The Totavi is exposed at several locations around the margins of the Pajarito Plateau but few dates exist to fully constrain the age. Manley (1979) obtained a fission track age of 2.9 Ma on an ash bed in the lower part of the Puye Formation, just above exposed Totavi conglomerate. In lower Los Alamos Canyon near Totavi (the type section, Fig. 3), it forms a layer of coarse conglomerate approximately 10 m thick that lies above pale buff Santa Fe Group rocks and beneath gray, bedded Puye fanglomerate deposits. Lacustrine beds and a Cerros del Rió basalt flow and pillow-palagonite complex dated at 2.4 ± 0.3 Ma overlie the Puye farther up canyon (Luedke and Smith, 1978). Just west of White Rock Canyon, the Totavi Lentil appears as a 8-m-thick conglomerate directly beneath an undated basalt flow of Cerros del Rió affinity. Flows further up section have dates of about 2.40 ± 0.06 Ma (WoldeGabriel et al., 1996). Underlying sedimentary rocks have been mapped as Puye fanglomerate by Dethier (1997); thus, this a location where exposed Totavi Lentil is interbedded in the Puye Formation. In lower Frijoles Canyon, two layers of Totavi Lentil pebble conglomerate about 5 m thick are interbedded in maar deposits of the Cerros del Rió volcanic field (F. Goff, *unpubl.*). The maar deposits lie beneath an undated basalt forming a ledge for a waterfall. The age of a benmorite lava overlying this basalt has a $^{40}Ar/^{39}Ar$ age of 2.75 ± 0.08 Ma (WoldeGabriel et al., 1996); thus, the Totavi is apparently bracketed between about 2.8 and 2.4 Ma. It is also apparent that the Totavi Lentil is not a precise time-stratigraphic marker and that it does not always occur at horizons like those in the type section.

Tewa Group, late Pliocene to late Pleistocene

According to Griggs (1964), Bailey et al. (1969), and Smith et al. (1970), the Tewa Group consists of four formations. From oldest to youngest, these are the Bandelier Tuff, Cerro Toledo Rhyolite, Cerro Rubio Quartz Latite, and Valles Rhyolite. However, more recent mapping and radiometric dating show that Cerro Rubio Quartz Latite predates the Bandelier Tuff (Gardner et al., 1986; Heiken et al., 1986; Stix et al., 1988; Gardner and Goff, 1996). In addition, at least three pre-Bandelier ignimbrites occur in the southwestern, eastern, and central JMVF that are not described by earlier workers (Self et al., 1986; Goff et al., 1987; Turbeville and Self, 1988; Hulen et al., 1991; Goff and Gardner, 1994). Thus, as originally defined, the Tewa Group spans a much greater time period than previously thought. Tewa units consist of domes, plugs, flows, and pyroclastic deposits of rhyodacite, rhyolite, and high-silica rhyolite. Tewa Group rocks unconformably overlie or intrude other units of the JMVF and are best exposed in Valles and Toledo calderas, the Toledo embayment, the Pajarito Plateau, and the Jemez Plateau (Figs. 3, 5, 8).

Cerro Rubio Quartz Latite

This unit consists of two small plugs with similar hypabyssal appearance that occur in the east side of the Toledo embayment (Gardner et al., 1986; Heiken et al., 1986; Stix et al., 1988; Gardner and Goff, 1996). Mapping shows that Cerro Rubio rocks are intruded by Cerro Toledo Rhyolite and overlain by the upper (Tshirege) member of the Bandelier Tuff (see Gardner and Goff, 1996). K/Ar dates are 3.6 ± 0.4 Ma for Cerro Rubio proper and 2.18 ± 0.09 Ma for the dome north of Cerro Rubio. Chemically, the Cerro Rubio rocks resemble average Tschicoma rhyodacite (Gardner et al., 1986). It is probable that the Cerro Rubio plugs represent remnants of former Tschicoma Formation domes and flows that have been modified by events that formed the Toledo embayment (Goff et al., 1984; Gardner and Goff, 1996).

Pre-Bandelier tuffs

A sequence of at least three tuffs older than, but chemically and petrographically similar to, the Bandelier Tuff occurs in the southwestern wall of Valles caldera and in San Diego Canyon (Fig. 8) for several kilometers southwest of the caldera (San Diego Canyon ignimbrites). These exposures consist of fall, flow and surge deposits of high-silica rhyolite tuff from 80 to <2 m thick below the Otowi Member, Bandelier Tuff (Self et al., 1986; Turbeville and Self, 1988). A similar pyroclastic deposit is found interbedded with fanglomerate in the upper Puye Formation in the northern Pajarito Plateau (Turbeville et al., 1989). Pre-Bandelier ignimbrites (the "Lower Tuffs") have also been identified inside the Valles caldera beneath the Redondo Peak area (Nielson and Hulen, 1984) and beneath the Sulphur Springs area (Goff et al., 1987; Hulen et al., 1991; Goff and Gardner, 1994). Although not recognized by Bailey et al. (1969) or shown on the map of Smith et al. (1970), the unit is designated as an "early leak" of the Bandelier magma chamber by Smith (1979). Two early K/Ar dates on these tuffs were too old

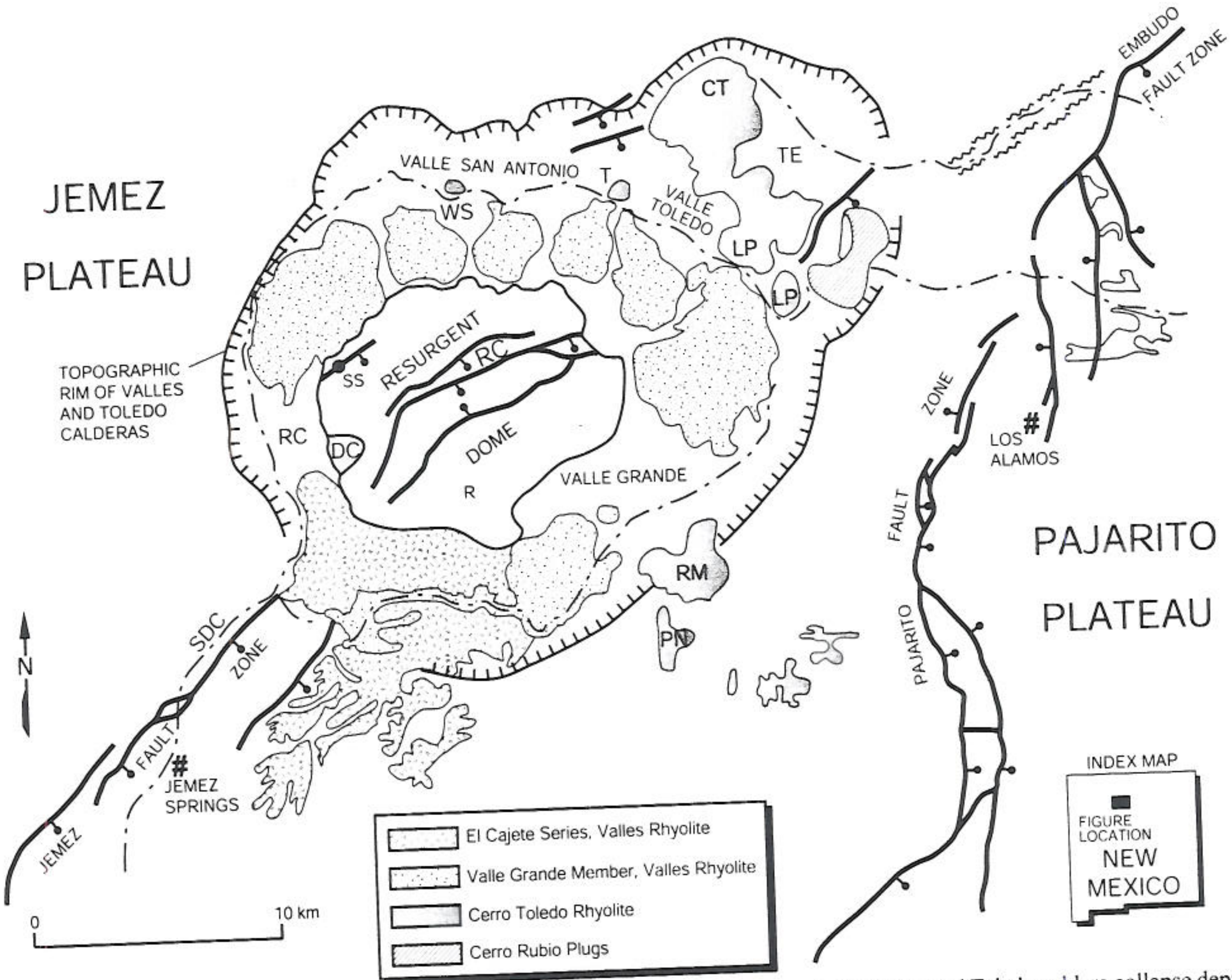

FIGURE 8. Sketch map showing location of Tewa Group rocks. Bandelier Tuff surrounds the Valles and Toledo caldera collapse depression but is best exposed on the Jemez and Pajarito Plateaus. The Cerro Rubio plugs occur in the Toledo embayment and pre-date the Toledo caldera and Bandelier Tuff. The Cerro Toledo Rhyolite post-dates Toledo caldera. Cerro Toledo rhyolite tuffs occur between the Otowi and Tshirege Members of the Bandelier Tuff east of the calderas. Near Los Alamos they are interbedded with other volcanic detritus shed from the Tschicoma Formation and form the Cerro Toledo interval (Broxton and Reneau, 1995). Cerro Toledo rhyolite domes are found within the Toledo embayment, at Rabbit Mountain and Paseo del Norte, and along an arc-remnant that originated in Toledo caldera (Goff et al., 1984). The Valles Rhyolite was erupted locally on the resurgent dome and within the moat zone of Valles caldera. **CT** = Cerro Toledo dome; **DC** = patch of Deer Canyon Member of Valles Rhyolite dated by Doell et al. (1968); **LP** = two Los Posos domes; **PN** = recently recognized patch of Cerro Toledo Rhyolite (Justet, 1996); **R** = Redondo Peak; **RC** = two locations of Redondo Creek Member of Valles Rhyolite dated by F. Goff (*unpubl.*); **RM** = Rabbit Mountain dome; **SDC** = San Diego Canyon and Jemez River; **SS** = Sulphur Springs; **T** = Cerro Trasquilar dome; **WS** = Warm Springs dome.

(3.64 and 2.84 Ma; Turbeville and Self, 1988) probably due to contamination of the samples. More recent $^{40}Ar/^{39}Ar$ dates on the units are 1.85 ± 0.07 Ma (Spell et al., 1996).

Bandelier Tuff

The Bandelier Tuff is the most famous rock unit of the JMVF (Smith and Bailey, 1966; 1968; Self et al., 1986; Heiken et al., 1990). It consists of two members, the lower (Otowi) member and the upper (Tshirege) Member. Each member contains a basal pyroclastic fall deposit, the Guaje Pumice beneath the Otowi and the Tsankawi Pumice beneath the Tshirege (Griggs, 1964; Bailey et al., 1969). Both members have been thoroughly studied and are exceptionally well exposed on the Pajarito and Jemez Plateaus (i.e., Eichelberger and Kock, 1979; Warshaw and Smith, 1988; Broxton and Reneau, 1995; Broxton et al., 1995; Caress, 1996; Stimac et al., 1996; Werner et al., 1996). The Tshirege Member is a compositionally zoned ash flow tuff composed of several flow units that form a compound cooling unit (Broxton and Reneau, 1995). The Otowi Member is also a compound cooling unit but generally displays less welding than the Tshirege Member. It is best exposed in the deeper canyons and edges of the two plateaus mentioned above. Compositionally, both members are porphyritic high-silica rhyolites, having distinctive phenocrysts of quartz and sanidine, inconspicuous tiny black phenocrysts of clinopyroxene, and large silky pumice clasts.

Because of its fame and stratigraphic position within the Valles caldera and the JMVF, the Bandelier Tuff has been radiometrically dated many times as new techniques and methods arise; thus, the "accepted" dates have become progressively older since the late1960s (Table 1). This has created conflicts with other dated units, as discussed below, but it also allows one to examine the variation resulting from dates on excellent samples. Radiometric dates on the Bandelier Tuff are usually performed on sanidine crystals extracted from pumice clasts in the basal fall deposits beneath outflow sheets. The first dates were presented by Doell et al. (1968) who obtained K/Ar ages of 1.37 ± 0.04 and 1.09 ± 0.03 Ma

on lower and upper members, respectively. With new decay constants (Steiger and Jäger, 1977), these dates changed to 1.45 ± 0.04 and 1.12 ± 0.03 Ma (Table 1). The first $^{40}Ar/^{39}Ar$ dates were obtained by Spell et al. (1990) who reported 1.51 ± 0.03 and 1.14 ± 0.02 for the lower and upper members, respectively. Izett and Obradovich (1994) reported a second pair of $^{40}Ar/^{39}Ar$ ages at 1.61 ± 0.01 and 1.22 ± 0.02 Ma. Spell et al. (1996) performed yet more $^{40}Ar/^{39}Ar$ dates that included adjustments of earlier ages based on standard comparisons, and got ranges of 1.64 to 1.57 Ma and 1.22 to 1.19 Ma. From all this analytical work the ages are apparently about 1.6 and 1.2 Ma, although the older ages of Spell et al. (1996) appear to correlate best with intracaldera rhyolite dates (discussed below). These dates also establish the formation times of Toledo and Valles calderas.

Cerro Toledo Rhyolite (Cerro Toledo Interval)

The Cerro Toledo Rhyolite consists of domes, flows, and pyroclastic deposits found within the Valles caldera and Toledo embayment, and as pyroclastic and contemporaneous volcaniclastic units found between the two members of Bandelier Tuff on the Pajarito Plateau (Griggs, 1964; Smith et al., 1970; Gardner et al., 1986; Heiken et al., 1986). Cerro Toledo Rhyolite represents post-collapse volcanism associated with formation of the Toledo caldera at ca. 1.6 Ma (Smith, 1979). Cerro Toledo rhyolites are primarily aphyric with sparse phenocrysts of quartz, sanidine, and biotite, and with very sparse phenocrysts of plagioclase, hornblende, and pyroxene. The aphyric character of Cerro Toledo tephras contrasts significantly with the highly porphyritic pumice of the Bandelier Tuff.

Smith et al. (1970) and Smith (1979) recognized that the Pajarito Plateau deposits were correlated with sources in the northeastern caldera. Izett et al. (1981) reported a combination of K/Ar and fission track ages on tephra layers in these deposits that ranged from 1.47 ± 0.04 to 1.23 ± 0.02 Ma. Stix et al. (1988) reported a K/Ar date of 1.52 ± 0.04 Ma on another tephra layer, at that time, significantly older than the accepted age of the Otowi Member, Bandelier Tuff. Spell et al. (1996) later obtained 13 $^{40}Ar/^{39}Ar$ ages ranging from 1.65 ± 0.03 to 1.21 ± 0.01 Ma. These recent dates correlate well with the presently accepted ages on the two members of the Bandelier Tuff and the two caldera-forming events.

Poorly sorted, coarse-grained volcaniclastic deposits composed [illegible]ily of Tschicoma andesite to rhyodacite detritus are locally intercalated with tephras of Cerro Toledo Rhyolite beneath the Pajarito Plateau (Heiken et al., 1986; Stix et al., 1988; Goff, 1995; Broxton and Reneau, 1995). Locally, these boulder to gravel deposits are rather thick (≤45 m), are volumetrically more significant than the tephras, and resemble volcaniclastic units of the Puye Formation. As a result, Broxton and Reneau (1995) have suggested that the interval of time between the two Bandelier Tuff members be called the Cerro Toledo interval.

Cerro Toledo Rhyolite domes were erupted in the northeastern part of present Valles caldera, within the Toledo embayment, and on the east edge of Valles caldera (Fig. 8). Smith et al. (1970) originally mapped a group of four domes in the northern caldera, from west-to-east, Warm Springs, Cerro Trasquilar, west Los Posos and east Los Posos, as Valles Rhyolite. Later mapping and radiometric dating by Goff et al. (1984) revealed that these domes were an arc remnant of post-Toledo caldera ring fracture volcanism (see also Heiken et al., 1986; Stix et al., 1988; Gardner and Goff, 1996). K/Ar dates on these four domes range from 1.50 ± 0.05 to 1.25 ± 0.04. Later weighted mean $^{40}Ar/^{39}Ar$ dates by Spell et al. (1996) span a time of 1.54 ± 0.02 to 1.26 ± 0.01 Ma. All these dates are consistent with the most recently accepted ages on formation of the two calderas.

The Toledo embayment was previously called Toledo caldera by Ross et al. (1961), Doell et al. (1968), and Smith et al. (1970), but more recent studies have presented evidence showing that the two calderas are nearly coincident (Potter and Oberthal, 1983; Self et al., 1986; Goff et al., 1989). Possible origins for the Toledo embayment are discussed by Heiken et al. (1986), Goff et al. (1989), Turbeville et al. (1989), Gardner and Goff (1996), and Nowell (1996). Most researchers argue that the Toledo embayment formed along a structurally controlled zone during collapse of the Toledo caldera. Rhyolite domes filling the Toledo embayment have K/Ar ages of 1.62 ± 0.02 to 1.20 ± 0.02 Ma (Stix et al., 1988) and weighted mean $^{40}Ar/^{39}Ar$ ages of 1.46 ± 0.02 to 1.34 ± 0.01 Ma. However, examination of the two data sets shows that the sample sites are not completely comparable.

Cerro Toledo rhyolite domes and pyroclastic deposits occur on the east edge and flank of present Valles caldera and consist of Rabbit Mountain (Smith et al., 1970) and the recently recognized unit of Paseo del Norte (Justet, 1996). The latter unit, formerly mapped as Bearhead Rhyolite, has a $^{40}Ar/^{39}Ar$ age of 1.47 ± 0.04 Ma. Rabbit Mountain has two K/Ar dates of 1.52 ± 0.06 and 1.43 ± 0.04 Ma (Stix et al., 1988). Block and ash flow and landslide

TABLE 1-Comparison of radiometric dates (Ma) on the Bandelier Tuff and San Diego Canyon ignimbrites, 1968 to 1996.

TIGATION[a]	D	G[b]	TS	S90	IO	S96
Method	K/Ar	K/Ar	K/Ar	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$
Tshirege Member	1.09 ± 0.03	1.12 ± 0.03	na	1.14 ± 0.02	1.22 ± 0.02	1.19 ± 0.02[c] 1.22 ± 0.1[d]
Otowi Member	1.37 ± 0.04	1.45 ± 0.04	na	1.51 ± 0.03	1.61 ± 0.01	1.57 ± 0.03[c] 1.62 ± 0.04[d] 1.64 ± 0.05[d]
San Diego B	na	na	2.84 ± 0.07	1.78 ± 0.04	na	1.85 ±0.04[c]
SanDeigo A	na	na	3.64 ± 1.64	1.78 ± 0.07	na	1.85 ± 0.07[c]

[a] **D** = Doell et al., 1968; **G** = Gardner et al., 1986; **TS** = Turbeville and Self, 1988; **S90** = Spell et al., 1990; **IO** = Izett and Obradovich, 1994; **S96** = Spell et al., 1996.

[b] Data of Doell et al., 1968 recalculated using decay constants and isotope abundances of Steiger and Jager (1977).

[c] Data of Spell et al. (1990) recalculated using different standard.

[d] Mean value of analyes on unique sample.

deposits from the west side of Rabbit Mountain are found between the two members of the Bandelier Tuff southeast of Valles caldera (Smith et al., 1970; Heiken et al., 1986; Goff et al., 1990).

Valles Rhyolite

The Valles Rhyolite was originally named by Griggs (1964) and was subdivided into six members by Bailey et al. (1969) and Smith et al. (1970). It properly includes all intracaldera rhyolites erupted after formation of Valles caldera. The group consists of domes, flows, and pyroclastic deposits of varied appearance, mineralogy, and chemistry. The circular arrangement of the "moat" domes around the central resurgent dome is striking (Fig. 8) and has lead to speculation that the vents are fed by ring-dikes (Smith et al., 1961). However, no ring dikes have been penetrated by the few deep wells drilled in the caldera ring-fracture zone (Goff et al., 1989; Goff and Gardner, 1994). As discussed below, earliest and latest members of the Valles Rhyolite have been difficult to date due to ambiguities caused by early Bandelier Tuff dates, post-caldera alteration, inherited argon problems, and youth.

The Deer Canyon Member is the oldest and consists of relatively small exposures of rhyolite lavas and tuffs exposed on the southwest and northeast flanks of the resurgent dome within Valles caldera. It is referred to as "early rhyolite" in Doell et al. (1968) and Smith and Bailey (1968). Field relations of Deer Canyon rocks are not resolvable at all outcrops but are interpreted as lavas that erupted soon after formation of the caldera. Thus, Deer Canyon rhyolites are apparently contemporaneous with early uplift of the resurgent dome. Petrographically, it is remarkably similar to the Bandelier Tuff and easily confused with the latter in outcrop. Because it is extensively altered there is little reliable chemistry but, apparently, it is a high-silica rhyolite resembling the Bandelier Tuff (Spell and Harrison, 1993). Only one K/Ar date at 1.25 ± 0.11 Ma has been reported (Fig. 8; Doell et al., 1968), which seemed unreasonably old compared to initial upper Bandelier ages but which now seems acceptable with the latest ages.

The Redondo Creek Member is considerably more extensive than the Deer Canyon and was erupted from multiple vents in the central and west resurgent dome, and in the western caldera moat. It is referred to as "middle rhyolite" in Doell et al. (1968) and Smith and Bailey (1968), and is contemporaneous with middle to late resurgence. Redondo Creek rhyolites are distinctive because they contain no quartz but have phenocrysts of plagioclase, biotite, and minor clinopyroxene. Chemically, they are rhyolites instead of high-silica rhyolites (Gardner et al., 1986). Some exposures of Redondo Creek rhyolite contain hydrothermally altered rock yet fresh material is relatively easy to find. Early K/Ar dates ranged between 3.25 and 1.28 Ma (Doell et al., 1968) and were thought to be affected by alteration. Later whole rock K/Ar dates of 1.34 ± 0.07 and 1.23 ± 0.02 obtained on two different flows in the mid-1980s were never reported (F. Goff, *unpubl.*) because they did not conform with the then accepted age of upper Bandelier Tuff (Fig. 8). However, the most recent Bandelier ages are more compatible with the younger Redondo Creek K/Ar dates. No $^{40}Ar/^{39}Ar$ dates on Redondo Creek rocks are known as of the yr 2000.

The Valle Grande Member consists of all post-Valles moat rhyolites in the northern sector of the caldera plus two units in the southeast sector. The various rhyolites of this group consist primarily of domes and thick flows, and have variable appearance and mineralogy, although most are highly porphyritic. Chemically, they are high-silica rhyolites (Gardner et al., 1986; Spell and Harrison, 1993). Early K/Ar dates obtained mostly on sanidine separates ranged from 1.15 ± 0.03 to 0.43 ± 0.02 Ma (Doell et al., 1968). Later $^{40}Ar/^{39}Ar$ dates by Spell and Harrison (1993) on the same units range from 1.13 ± 0.01 to 0.52 ± 0.01 Ma.

The youngest three members of Valles Rhyolite occur in the southern moat and were named, oldest to youngest, Battleship Rock, El Cajete, and Banco Bonito (Bailey et al., 1969). A rhyolite lava encountered only in the subsurface of the southern moat resembles rhyolites of the three youngest members and should be grouped with them (VC-1 Rhyolite, Goff et al., 1986). No other rocks in the JMVF have been as difficult to date as these, because of their youth and inherited argon problems. In addition, they have been the subject of several flawed stratigraphic assignments and geologic interpretations (Goff et al., 1986; Self et al., 1988, 1991; see discussion in Toyoda et al., 1995). Because they are chemically similar, originate from adjacent vent areas, and seem to be nearly co-magmatic, Self et al. (1988) proposed that they be grouped into the El Cajete Series (Fig. 8). Wolff et al. (1996) suggested that the El Cajete Series may be a sequence of three co-magmatic cycles beginning with pyroclastic activity and ending with lava effusions.

Chemically, the three youngest members (and VC-1 Rhyolite) contain roughly 73 wt.% silica. Petrographically they are characterized by lack of sanidine but with variable amounts of quartz, plagioclase, biotite, hornblende, and clinopyroxene (Gardner et al., 1986). Bailey et al. (1969) tried to date charcoal in the El Cajete by ^{14}C but the age was >42 ka, the upper age limit of the method at that time. Several fission track ages on the three members (summarized in Self et al., 1988) range from 170 ± 70 to 130 ± 100 ka. Most researchers accepted an age of roughly 130 ka throughout most of the 1980s. Goff et al. (1986) obtained a K/Ar date of 0.36 ± 0.06 on a biotite separate from the VC-1 rhyolite lava. A K/Ar date of 0.28 ± 0.05 was obtained on a feldspar separate from pumice in basal Battleship Rock tuff (F. Goff, *unpubl.*). Although these two dates are analytically precise, they are probably too old due to presence of xenocryst phases. Spell and Harrison (1993) reported similar problems with their $^{40}Ar/^{39}Ar$ measurements of these units (18 biotite ages >205 ka). An attempt to date the El Cajete by U/Th disequilibrium methods also failed (Self et al., 1991).

The Battleship Rock Member consists of rhyolitic ash flow tuffs whereas the El Cajete Member consists of rhyolitic falls with subordinate ash flows and surges. Fall deposits of El Cajete are found throughout the southeastern JMVF and out into the RGR whereas Battleship Rock ignimbrites are restricted to intracanyon environments in and near the southern caldera moat. Battleship and El Cajete Members share the same apparent vent (Bailey et al., 1969) and truly seem to be co-magmatic, representing different phases of the same eruption (Self et al., 1986,1988; Wolff et al., 1996). Although Bailey et al. (1969) claim that the Battleship Rock is older than the El Cajete, more recent work indicates that the reverse is true; i.e., fall deposits are precursors to predominately ash flow and surge deposits (Self et al., 1988; Wolff et al., 1996). Electron spin resonance (ESR) dates on quartz phenocrysts indicate that the Battleship and El Cajete Members have an age of about 55 ± 6 ka (Toyoda et al., 1995). Thermal luminescence dates obtained by Reneau et al. (1996) suggest a similar age. A second attempt to date carbon in the El Cajete came out >50 ka (Reneau et al., 1996).

The Banco Bonito Member undeniably represents the youngest eruption in Valles caldera and the JMVF due to stratigraphic relations (Smith et al., 1970). It is a porphyritic rhyolitic lava that varies in texture from pumice-breccia to vitrophyre. The flow orig-

inates from a vent about 0.5 km west of the El Cajete vent and flows roughly 8 km to the west and southwest, partially following preexisting drainage in the southwest moat. It has a very young geomorphic surface with deep, arcuate pressure ridges (Bailey et al., 1969) and consists of at least two flow units (Manley and Fink, 1987). Chemically and petrographically, the Banco Bonito is very similar to rhyolites of the Battleship Rock and El Cajete Members. Both Self et al. (1988, 1991) and Wolff et al. (1996) consider the Banco Bonito to be co-magmatic with the two earlier members, although their interpretations are quite different.

A hiatus in eruptive activity, represented by erosion and sedimentation, occurs between the Banco Bonito Member and the underlying two members (Goff et al., 1986; Self et al., 1988). Two paleocanyons more than 50 m deep cut into the Battleship Rock tuff are filled with thick flows of Banco Bonito rhyolite. In addition, an extensive debris flow deposit shed from the resurgent dome of the caldera underlies the Banco Bonito lava over a distance of several kilometers (F. Goff, *unpubl.* 1997). These relations suggest that Banco Bonito may be several thousand years or more younger than the Battleship Rock and El Cajete Members. Ogoh et al. (1993) obtained ESR dates of 45 ± 2 to 37 ± 6 ka on a sample of Banco Bonito rhyolite near the flow top. Phillips et al. (1997) reported a date of 37 ± 5 ka based on six Ne-21 exposure measurements. Nearby carbon-bearing deposits having a ^{14}C date of 29 ± 0.3 ka are overlain by terrace gravel containing cobbles of Banco Bonito rhyolite (F. Goff, *unpubl.*, 1998). These results suggest that the age of the Banco Bonito eruption may be between 45 and 35 ka.

Peripheral mafic volcanism, Pliocene to early Pleistocene

Three peripheral basalt fields of mostly Pliocene age occur in the JMVF (Smith et al., 1970) and are called, from north to south, the El Alto, Cerros del Rió, and Santa Ana Mesa volcanic fields (Figs. 3, 7). The Cerros del Rió field is the largest and best studied, and includes compositions ranging from tholeiitic to alkali basalt, as well as hawaiite, benmorite, mugearite, and dacite (Baldridge, 1979; Baldridge et al., 1980; Dunker et al., 1991; WoldeGabriel et al., 1996). The fields are dominated by low shield volcanoes, which produced lava flows and cinder deposits, but the Cerros del Rió field also includes considerable volumes of maar deposits in lower stratigraphic positions exposed along and near the Rio Grande (Aubele, 1978; Heiken et al., 1996). At least one plug (undated) is exposed along the Rio Grande in White Rock Canyon (Dethier, 1997). Gardner et al. (1986) listed 16 K/Ar dates from these three fields ranging from 4.62 ± 0.12 to 1.96 ± 0.06 Ma but 13 of these ages span 3.2–2.4 Ma. WoldeGabriel et al. (1996) reported $^{40}Ar/^{39}Ar$ dates ranging from 3.2 ± 0.4 to 2.33 ± 0.08 on 19 Cerros del Rió lavas and dikes exposed in and near White Rock Canyon.

Although the radiometric dates clearly argue that the greater volume of Cerros del Rió rocks were erupted in <1 Ma, most samples are from lavas overlying thicker sections of exposed maar deposits. Nonetheless, a thin basalt lava interbedded with the maar deposits along the Rio Grande is dated at 2.78 ± 0.04 Ma while the age of a thick benmorite lava overlying the maar deposits is 2.75 ± 0.08 Ma (WoldeGabriel et al., 1996). The geologic map of Smith et al. (1970) shows that at least some of the chemically evolved Cerros del Rió lavas were erupted after emplacement of the Otowi Member, Bandelier Tuff (1.6 Ma) but field relations with the Otowi are not always clear. A basaltic andesite vent and associated flows exposed a few kilometers south of Frijoles Canyon has a $^{40}Ar/^{39}Ar$ date of 1.62 ± 0.36 Ma (F. Goff, *unpubl.*, 2000). Although this complex underlies the Tshirege Member, Bandelier Tuff (1.2 Ma), relations with the Otowi Member are not exposed.

CHRONOLOGY OF HYDROTHERMAL ALTERATION

The age of hydrothermal alteration and mineralization in the JMVF and Valles caldera received considerable attention during the late 1980s and early 1990s because of the many investigations devoted to understanding the active Valles geothermal system. It was already known that alteration was quite pervasive in older rocks of the southeast JMVF (Stein, 1983; Wronkiewicz et al., 1984) but this alteration was not described by Bailey et al. (1969) or shown by Smith et al. (1970). Investigations since that time generally show that there are two periods of widespread and intense hydrothermal activity: A period from about 8.5–5.5 Ma correlated with Keres Group volcanism and a period ≤1.6 Ma associated with formation of Toledo and Valles calderas (WoldeGabriel and Goff, 1989; 1992). A period of hydrothermal activity related to Polvadera Group volcanism has never been recognized. Significantly, Polvadera and Keres Group rocks are in juxtaposition along the western and northern walls of Valles caldera. In both areas, Keres Group rocks show weak to intense alteration, whereas Polvadera Group rocks do not. During field mapping, alteration and primary textural differences contribute to determination of the boundary between the two groups (Gardner and Goff, 1996).

Keres Group alteration, late Miocene

Keres Group rocks display considerable argillic, phyllic, and propylitic hydrothermal alteration centered near the Cochiti gold mining district of the JMVF (Fig. 6; Stein, 1983; Wronkiewicz et al., 1984; Gardner et al., 1986; Goff et al., 1990). WoldeGabriel and Goff (1989) dated hydrothermal illite by the K/Ar method in various altered units at and near the Cochiti district. An altered rhyolite lava 10 m east of the Albermarle bonanza quartz vein gave an age of 8.1 ± 0.2 Ma while two other altered rhyolites yielded ages of 6.1 and 6.0 Ma. Presumably, the former unit is an altered Canovas Canyon lava whereas the latter two units are altered Bearhead Rhyolite. Hydrothermal illite from the quartz vein system is dated at 5.9 ± 0.2 Ma. Three altered Paliza Canyon andesites have dates ranging from 6.5 ± 1.0 to 5.6 ± 0.3 Ma. Chamberlin et al. (1999) found a hydrothermally altered tuff in middle Santa Fe Group sediments in the southern JMVF that provided a $^{40}Ar/^{39}Ar$ date of 5.3 ± 0.1 Ma.

Most of the alteration described above can be related to intrusive and hydrothermal activity contemporaneous with and post-dating the Bearhead Rhyolite. However, WoldeGabriel (1990) obtained hydrothermal illite ages ranging from 8.2 ± 0.3 to 7.0 ± 0.4 Ma in Keres Group rocks exposed along the northern and southern Valles caldera wall, suggesting that widespread hydrothermal activity was well established in Keres time before the Bearhead Rhyolite.

Alteration related to Toledo and Valles Calderas, Quaternary

Hydrothermal activity within the Toledo and Valles calderas has been widespread and intense due to the existence of a long-lived hydrothermal system that presently has measured temperatures ≤340°C (Hulen and Nielson, 1986; Goff and Shevenell, 1987; Goff and Gardner, 1994). Fumaroles and acid springs characterize surface features within the caldera and are associated with argillic to advanced argillic alteration (Charles et al., 1986). Travertine

deposits formed by bicarbonate-rich hot springs discharge near Jemez Springs (Fig. 8). These deposits were dated by U/Th disequilibrium and $^{234}U/^{238}U$ methods and were found to span a time interval of about 1 Ma to present (Goff and Shevenell, 1987). The dates were correlated with volcanic, hydrothermal, and geomorphic episodes in and near the Valles caldera. Subsurface activity within the caldera consists of a liquid-dominated geothermal reservoir in which alteration is characterized by argillic, phyllic, propylitic, and calc-silicate zones (Hulen and Nielson, 1988). WoldeGabriel and Goff (1989) studied alteration in the near-surface to moderate depth environment (10–527 m) at Sulphur Springs (Fig. 8). Four K/Ar dates on hydrothermal illite in veins and altered intracaldera Bandelier Tuff range from 0.83 ± 0.11 to 0.66 ± 0.21 Ma with a fifth sample producing a zero age.

WoldeGabriel and Goff (1992) presented a more detailed study that examined alteration in intracaldera and pre-caldera rocks from 48 to 1817 m depth. Six intracaldera samples yielded K/Ar dates on hydrothermal illite ranging from 1.09 ± 0.10 to 0.35 ± 0.05 Ma. A single sample of hydrothermal illite from a Keres Group andesite below the tuffs was dated at 0.59 ± 0.38 Ma. Three illite dates from underlying sandstones in the Santa Fe Group and Yeso and Abo Formations (Permian) range from 6.7 to 4.3 Ma. However, volcanic clasts from a conglomerate layer in the Yeso Formation produced three illite dates ≤1.1 Ma. Altered Precambrian quartz monzonite from beneath the caldera produced four dates ranging from 276 to 2.9 Ma. Obviously, Valles hydrothermal activity has a profound effect on all rock types within and below the caldera by forming K-rich minerals and resetting potassium-argon activities in existing minerals.

Post-caldera age alteration also affects pre-caldera rocks located outside of Valles caldera, especially along the Jemez fault zone (Fig. 8). WoldeGabriel (1990) dated hydrothermal illite in core from the VC-1 hole located near the Jemez fault zone just southwest of the structural margin of the caldera. Two illite samples from an argillic sandstone in the Pennsylvanian Madera Limestone at 479 m depth yielded ages of 1.34 ± 0.05 and 1.21 ± 0.08 Ma. Four illite dates from Mississippian Sandia Formation (817 m) and brecciated Precambrian rocks (843–854 m) yielded ages ranging from 17 to 11 Ma. While it could be argued that the latter group of illites was initially formed in Keres Group time, the hole contains hydrothermal fluids derived from the present Valles geothermal system (Goff and Gardner, 1994); thus, it is probable that Valles activity has partially reset these illites (see also Sasada, 1988; Sturchio and Binz, 1988; Hulen and Nielson, 1988).

FUTURE GEOCHRONOLOGY INVESTIGATIONS

The collective work of many researchers has unraveled the basic geochronology of volcanism and mineralization in the JMVF. However, the majority of dates have been obtained on rhyolites or their alteration products because they contain high-K_2O contents or K-rich minerals. Basalts are the second most commonly dated rock type while andesite and dacite dates are the least common. Because dating techniques inevitably become more precise and varied (if not more accurate), we feel compelled to identify a few subjects of special interest that remain for future investigators:

1. $^{40}Ar/^{39}Ar$ dates are needed on the oldest Keres Group rocks and underlying mafic lavas in the Santa Fe Group, particularly those exposed on the southeast side of St. Peter's Dome. There is still some ambiguity about the ages of these rocks and the possible time break between oldest Keres and Santa Fe Group in this well-exposed section. Because this area is a roadless wilderness, most investigators have ignored it.

2. $^{40}Ar/^{39}Ar$ dates are needed across the Polvadera Group-Keres Group boundary exposed in the north wall of Valles caldera and on the northwestern Pajarito Plateau. Recent maps now exist for these areas (i.e., Gardner and Goff, 1996), but few dates, other than alteration dates, have been obtained from rocks in key contacts. The presence of minor Santa Fe Group rocks in the caldera wall adds interest. Because Valles caldera is now part of the public domain, the formerly inaccessible slopes of the north caldera wall will soon be easily visited.

3. $^{40}Ar/^{39}Ar$ dates are needed on more ash beds and other stratigraphic layers in the Puye Formation, particularly in areas proximal to sources in the northeast Jemez Mountains. Because of environmental studies conducted on the Pajarito Plateau, it may be necessary to resolve the temporal, spatial, and compositional overlap of Cochiti Formation (as proposed by Smith and Lavine, 1996) and Puye Formation.

4. $^{40}Ar/^{39}Ar$ dates are needed on the youngest eruptions in the Cerros del Rió volcanic field. It would be interesting to quantify the amount of mafic volcanism that overlaps with early Tewa Group volcanism. These rocks are best exposed in the roadless areas of the southern Pajarito Plateau.

5. Reliable ages of any kind possible are needed on the El Cajete Series and associated volcaniclastic units in the southwestern caldera. These rocks have been incredibly difficult to date, yet they are the youngest in the JMVF. There is still no consensus on the overall stratigraphy and geologic history of these rocks.

6. Reliable dating and detailed mapping are needed on intracaldera sedimentary rocks to understand how they relate to caldera development, erosional history, and climate change. This subject has been barely touched because access to the caldera has been restricted.

CONCLUSIONS

The Jemez Mountains volcanic field consists of roughly 2000 km^3 of volcanic rocks erupted primarily from ca. 14 Ma to 55 ka. Compositions vary mostly from tholeiitic and alkali basalt to high-silica rhyolite but intermediate compositions (andesite and dacite) comprise about 75% of the volume of the volcanic pile. In a general way, compositions have evolved from mostly andesite to high-silica rhyolite through time, although basalts are erupted throughout most of the history of the field. The JMVF has developed contemporaneously with the middle to late evolution of the Española basin of the RGR; thus, considerable detritus from the JMVF partially fills the western side of the RGR.

Although it was originally thought that the Keres, Polvadera, and Tewa groups were more-or-less sequential (Bailey et al., 1969; Smith et al., 1970), subsequent dating reveals that there are considerable stratigraphic overlaps between various formations and compositional types within and among the groups. Nonetheless, the accepted stratigraphic nomenclature provides a useful and convenient basis for geologic mapping and petrologic study of most areas because the volcanic field is so large and diverse.

The JMVF also contains significant areas of hydrothermally altered and mineralized rocks that were produced during middle to late Keres Group time and after formation of Valles/Toledo calderas (during Tewa Group time). No hydrothermal episode has been identified that correlates with rocks of the Polvadera Group.

Geochronology of the JMVF has focused on rhyolites of the Tewa Group because they are products of the famous Valles/Toledo calderas and are relatively easy to date. Considerably fewer dates have been produced on volcanic rocks in the two earlier groups, except for their rhyolites. In spite of all the dates in the JMVF (probably more than 200 dates of all types), we have identified six research topics that would benefit from additional geochronology. These topics vary from better resolution on the volume, composition, and age of earliest volcanism to a full understanding of post-Valles caldera sedimentation and erosion.

ACKNOWLEDGMENTS

We thank the U.S. Forest Service, Bandelier National Monument, the U.S. Department of Energy, Los Alamos National Laboratory, and the now defunct Baca Land and Cattle Company for access to various parts of the Jemez Mountains and Valles caldera from 1978 to 2000. Long-time collaborations with Giday WoldeGabriel and other Los Alamos geologists have contributed greatly to our knowledge of the evolution of the JMVF. Gary Smith (University of New Mexico) provided several unpublished dates for this report and endless enlightenment during the last few years. Richard Chamberlin (NMBGMR) also provided several unpublished dates. We also wish to acknowledge many, many other Jemez and Valles collaborators, too numerous to name, who have contributed so much to Jemez and Valles geology. Much of our research was funded by the U.S. Department of Energy, Continental Scientific Drilling Program during the leadership of George Kolstad (deceased). The writing of this paper was funded by a Los Alamos Directed Research and Development grant (Remote Sensing of Volcanoes) and by the Los Alamos Seismic Hazards Program. Anthony Garcia (LANL) crafted the illustrations and Jim Aldrich and Scott Baldridge (LANL) reviewed the draft manuscript. Jon Spencer (Arizona Geological Survey) and Greg Mack (New Mexico State University) reviewed the final manuscript.

REFERENCES

Aldrich, M. J., 1986, Tectonics of the Jemez Lineament in the Jemez Mountains and Rio Grande rift: Journal of Geophysical Research, v. 91, p. 1753–1762.

Aldrich, M. J. and Dethier, D., 1990, Stratigraphic and tectonic evolution of the northern Española Basin, Rio Grande rift, New Mexico: Geological Society of America Bulletin, v. 102, p. 1695–1705.

Aubele, J., 1978, Geology of the Cerros del Rio volcanic field, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 136 p. (w/ 1:24,000 scale map).

Bachman, G. and Mehnert, H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283–292.

Bailey, R., Smith, R., and Ross, C., 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico: U.S. Geological Survey, Bulletin 1274-P, 19 p.

Baldridge, W. S., 1979, Petrology and petrogenesis of Plio-Pleistocene basaltic rocks from the central Rio Grande rift, New Mexico, and their relation to rift structure, *in* Riecker, R. E., ed., Rio Grande rift: Tectonics and magmatism: American Geophysical Union, Special Publication, p. 323–353.

Baldridge, W., Damon, P., Shafiqullah, M., and Bridwell, R., 1980, Evolution of the central Rio Grande rift: new potassium-argon ages: Earth and Planetary Science Letters, v. 51, p. 309–321.

Broxton, D. and Reneau, S., 1995, Stratigraphic nomenclature of the Bandelier Tuff for the environmental restoration project at Los Alamos National Laboratory: Los Alamos National Laboratory, Report LA-13010-MS, 21 p.

Broxton, D., Heiken, G., Chipera, S., and Byers, F., 1995, Stratigraphy, petrology, and mineralogy of Bandelier Tuff and Cerro Toledo deposits, *in* Broxton, D. and Eller, P., eds., Earth science investigations for environmental restoration—Los Alamos National Laboratory Technical Area 21: Los Alamos National Laboratory, Report LA-12934-MS, p. 33–63.

Caress, M., 1996, Zonation of alkali feldspar compositions in the Tshirege Member of the Bandelier Tuff in Pueblo Canyon, near Los Alamos, New Mexico: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 275–283.

Cather, S., 1992, Suggested revisions to the Tertiary tectonic history of north-central New Mexico: New Mexico Geological Society, 43rd Field Conference, Guidebook, p. 109–122.

Chamberlin, R. M., 1999, Partitioning of dextral slip in an incipient transverse shear zone of Neogene age, northwestern Albuquerque basin, Rio Grande rift, New Mexico (abs.): Geological Society of America, Abstracts with Programs, p. A-113.

Chamberlin, R. M., Pazzaglia, F., Wegmann, C., and Smith, G. A., 1999, Preliminary geologic map of the Loma Creston Quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Map OF-DM-25, scale 1:24,00.

Charles, R., Vidale, R., and Goff, F., 1986, An interpretation of the alteration assemblages at Sulphur Springs, Valles caldera, New Mexico: Journal of Geophysical Research, v. 91, p. 1887–1898.

Cordell, L., 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America Bulletin, v. 89, p. 1073–1090.

Dalrymple, G., Cox, A., Doell, R., and Grommé, C., 1967, Pliocene geomagnetic polarity epochs: Earth and Planetary Science Letters, v. 2, p. 163–173.

DePaolo, D., Perry, F., and Baldridge, W. S., 1992, Crustal versus mantle sources of granitic magmas: a two-parameter model based on Nd isotopic studies: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 83, p. 439–446.

Dethier, D., 1997, Geology of White Rock quadrangle, Los Alamos and Santa Fe Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Map 73, scale 1:24,000.

Dethier, D. and Manley, K., 1985, Geologic map of the Chile Quadrangle, Santa Fe and Los Alamos Counties, New Mexico. U.S. Geological Survey, Map MF-1814, scale 1:24,000.

Doell, R., Dalrymple, G., Smith, R. L., and Bailey R. A., 1968, Paleomagnetism, potassium argon ages, and geology of rhyolites and associated rocks of the Valles caldera, New Mexico: Geological Society of America, Memoir 116, p. 211–248.

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

Dunbar, N. W. and Hervig, R. L., 1992, Volatile and trace element composition of melt inclusions from the Lower Bandelier Tuff: Implications for magma chamber processes and eruptive style: Journal of Geophysical Research, v. 97, p. 15,151–15,170.

Dunker, K. Wolff, J., Harmon, R., Leat, P., Dicken, A., and Thompson, R., 1991, Diverse mantle and crustal components in lavas of the NW Cerros del Rio volcanic field, Rio Grande rift, New Mexico: Contributions to Mineralogy and Petrology, v. 108, p. 331–345.

Eichelberger, J. and Kock, J., 1979, Lithic fragments in the Bandelier Tuff, Jemez Mountains, New Mexico: Journal of Volcanology and Geothermal Research, v. 5, p. 115–134.

Ellisor, R., Wolff, J., and Gardner, J. N., 1996, Outline of the petrology and geochemistry of the Keres Group lavas and tuffs: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 237–242.

Gardner, J. N., 1985, Tectonic and petrologic evolution of the Keres Group: Implications for the development of the Jemez volcanic field, New Mexico [Ph.D. dissertation]: Davis, University of California, 293 p.

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

Gardner, J. and Goff, F., 1996, Geology of the northern Valles caldera and Toledo embayment, New Mexico: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 225–230.

Gardner, J., Goff, F., Garcia, S., and Hagan, R., 1986, Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico: Journal of

Geophysical Research, v. 91, p. 1763–1778.

Gardner, J., Goff, F., and Rogers, M.A., 1996, Second-day road log, from Los Alamos through Valles caldera and return: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 41–58.

Gay, K. and Smith, G. A., 1996, Simultaneous phreatomagmatic and magmatic rhyolitic eruptions recorded in the late Miocene Peralta Tuff, Jemez Mountains, New Mexico: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 243–250.

Goff, F., 1995, Geologic map of Technical Area 21, *in* Broxton, D., and Eller, P., eds., Earth science investigations for environmental restoration—Los Alamos National Laboratory Technical Area 21: Los Alamos National Laboratory, Report LA-12934-MS, p. 7–18.

Goff, F. and Grigsby, C., 1982, Valles caldera geothermal systems, New Mexico, USA: Journal of Hydrology, v. 56, p. 119–136.

Goff, F. and Shevenell, L., 1987, Travertine deposits of Soda Dam, New Mexico, and their implications for the age and evolution of the Valles caldera hydrothermal system: Geological Society of America Bulletin, v. 99, p. 292–302.

Goff, F. and Gardner, J. N., 1994, Evolution of a mineralized geothermal system, Valles caldera, New Mexico: Economic Geology, v. 89, p. 1803–1832.

Goff, F., Heiken, G., Tamanyu, S., Gardner, J., Self, S., Drake, R., and Shafiqullah, M., 1984, Location of Toledo caldera and formation of the Toledo embayment (abs.): EOS, Transactions, American Geophysical Union, v. 65, p. 1145.

Goff, F., Rowley, J., Gardner, J. N., Hawkins, W., Goff, S., Charles, R., Wachs, D., Maassen, L., and Heiken, G., 1986, Initial results from VC-1, first Continental Scientific Drilling Program corehole in Valles caldera, New Mexico: Journal of Geophysical Research, v. 91, p. 1742–1752.

Goff, F., Nielson, D., Gardner, J., Hulen, J., Lysne, P., Shevenell, L., and Rowley, J., 1987, Scientific drilling at Sulphur Springs, Valles caldera, New Mexico: Corehole VC-2A: EOS, Transactions, American Geophysical Union, v. 68, p. 649, 661–662.

Goff, F., Gardner, J., Baldridge, W., Hulen, J., Nielson, D., Vaniman, D., Heiken, G., Dungan, M., and Broxton, D., 1989, Excursion 17B: Volcanic and hydrothermal evolution of the Valles caldera and Jemez volcanic field: New Mexico Bureau of Mines and Mineral Resources, Memoir 46, p. 381–434.

Goff, F., Gardner, J., and Valentine, G., 1990, Geologic map of the St. Peter's Dome area, Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Map 69, scale 1:24,000.

Griggs, R., 1964, Geology and groundwater resources of the Los Alamos area, New Mexico: U.S. Geological Survey, Water Supply Paper 1753, 107 p. (w/1:24,000 scale map).

Heiken, G. and Goff, F., 1983, Hot dry rock geothermal energy in the Jemez volcanic field, New Mexico: Journal of Volcanology and Geothermal Research, v. 15, p. 223–246.

Heiken, G., Goff, F., Stix, J., Tamanyu, S., Shafiqullah, M., Garcia, S., and Hagan, R., 1986, Intracaldera volcanic activity, Toledo caldera and embayment, Jemez Mountains, New Mexico: Journal of Geophysical Research, v. 91, p. 1799–1815.

Heiken G., Goff, F., Gardner, J., Baldridge, W., Hulen, J., Nielson, D., and Vaniman, D., 1990, The Valles/Toledo caldera complex, Jemez volcanic field, New Mexico: Annual Reviews in Earth and Planetary Sciences, v. 18, p. 27–53.

Heiken, G., Wohletz, K., Fisher, R., and Dethier, D., 1996, Part II: Field guide to the maar volcanoes of White Rock Canyon, *in* Self, S., Heiken, G., Sykes, M., Wohletz, K., Fisher, R., and Dethier, D., eds., Field excursions to the Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 134, p. 56–72.

Hulen, J. and Nielson, D., 1986, Hydrothermal alteration in the Baca geothermal system, Redondo dome, Valles caldera, New Mexico: Journal of Geophysical Research, v. 91, p. 1867–1886.

Hulen, J. and Nielson, D., 1988, Hydrothermal brecciation in the Jemez fault zone, Valles caldera, New Mexico: Results from Continental Scientific Drilling Program corehole VC-1: Journal of Geophysical Research, v. 93, p. 6077–6091.

Hulen, J., Nielson, D., and Little, T., 1991, Evolution of the western Valles caldera complex, New Mexico: evidence from intracaldera sandstones, breccias, and surge deposits: Journal of Geophysical Research, v. 96, p. 8127–8142.

Iddings, J. P., 1890, On a group of rocks from the Tewan Mountains, New Mexico, and on the occurrence of primary quartz in certain basalts: U.S. Geological Survey, Bulletin 66, 34 p.

Izett, G. and Obradovich, J., 1994, $^{40}Ar/^{39}Ar$ age constraints for the Jaramillo Normal Subchron and the Matuyama-Bruhnes geomagnetic boundary: Journal of Geophysical Research, v. 99, p. 2925–2934.

Izett, G., Obradovich, J., Naeser, C., and Cebula, C., 1981, Potassium-argon and fission-track zircon ages of Cerro Toledo rhyolite tephra in the Jemez Mountains, New Mexico: U.S. Geological Survey, Professional Paper 1199-D, p. 37–43.

Justet, L., 1996, The geochronology and geochemistry of the Bearhead Rhyolite, Jemez volcanic field, New Mexico [M.S. thesis]: Las Vegas, University of Nevada, 152 p.

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

Lavine, A., Smith, G.A., Goff, F., and Gardner, J., 1996, Volcaniclastic rocks of the Keres Group: Insights into mid-Miocene volcanism and sedimentation in the southeastern Jemez Mountains: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 211–218.

Loeffler, B., Vaniman, D., Baldridge, W., and Shafiqullah, M., 1988, Neogene rhyolites of the northern Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 93, p. 6157–6167.

Luedke, R. and Smith, R. L., 1978, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Arizona and New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I-1091-A, scale 1:1,000,000.

Manley, C. R. and Fink, J., 1987, Internal textures of rhyolite flows as revealed by research drilling: Geology, v. 15, p. 549–552.

Manley, K., 1979, Stratigraphy and structure of the Española Basin, Rio Grande rift, New Mexico, *in* Riecker, R., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 71–86.

Manley, K. and Mehnert, H., 1981, New K-Ar ages of Miocene and Pliocene volcanic rocks in the northwestern Española Basin, and their relationships to the history of the Rio Grande rift: Isochron West, v. 30, p. 5–8.

Mayo, E., 1958, Lineament tectonics and some ore districts of the southwest: Mineral Engineering, v. 10, p. 1169–175.

McIntosh, W. and Quade, J., 1995, $^{40}Ar/^{39}Ar$ geochronology of tephra layers in the Santa Fe Group, Espanola Basin, New Mexico: New Mexico Geological Society, 46th Field Conference, Guidebook, p. 279–287.

Morgan, P., Sass, J., and Jacobson, R., 1996, Heat flow in VC-2A and VC-2B, and constraints on the thermal regime of the Valles caldera, New Mexico: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 231–236.

Nielson, D. and Hulen, J., 1984, Internal geology and evolution of the Redondo dome, Valles caldera, New Mexico: Journal of Geophysical Research, v. 89, p. 8695–8711.

Nowell, D., 1996, Gravity modeling of the Valles caldera: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 121–128.

Ogoh, K., Toyoda, S., Ikeda, S., Ikeya, M., and Goff, F., 1993, Cooling history of the Valles caldera, New Mexico using ESR dating method: Applied Radiation Isotropy, v. 44, p. 233–237.

Perry, F. V., DePaolo, D. J., and Baldridge, W. S., 1993, Neodymium isotopic evidence for decreasing crustal contributions to Cenozoic ignimbrites of the western United States: Implications for the thermal evolution of the Cordilleran crust: Geological Society of America Bulletin, v. 105, p. 872–882.

Phillips, W., Poths, J., Goff, F., Reneau, S., and McDonald, E., 1997, Ne-21 surface exposure ages from the Banco Bonito obsidian flow, Valles caldera, New Mexico, USA (abs.): Geological Society of America, Abstracts with Programs, p. A-307.

Potter, D. B. and Oberthal, C. M., 1983, Vent sites and flow directions of the Otowi ash flows (lower Bandelier Tuff), New Mexico: Geological Society of America Bulletin, v. 98, p. 66–76.

Powell, J., 1961, The exploration of the Colorado River and its canyons: Dover Publications, New York, 400 p. (Republication of Canyons of the Colorado, Flood and Vincent, 1885).

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

Purtymun, W., McLin, S., Stoker, A., Maes, M., and Hammock, B., 1993, Water supply at Los Alamos during 1990: Los Alamos National Laboratory, Report. LA-12471-PR, 50 p.

Reneau, S., Gardner, J., and Forman, S., 1996, New evidence for the age of the youngest eruptions in the Valles caldera: Geology, v. 24, p. 7–10.

Ross, C. S., 1938, Valles volcano, New Mexico: Journal of the Washington Academy of Sciences, v. 28, p. 417.

Ross, C. S., Smith, R. L., and Bailey, R. A., 1961, Outline of the geology of the Jemez Mountains, New Mexico: New Mexico Geological Society, 12th Field Conference, Guidebook, p. 139–143.

Sasada, M., 1988, Microthermometry of fluid inclusions from the VC-1 corehole in Valles caldera, New Mexico: Journal of Geophysical Research, v. 93, p. 6091–6096.

Segar, R., 1974, Quantitative gravity interpretation, Valles caldera area, Sandoval and Rio Arriba Counties, New Mexico: University of Utah Research Institute, Earth Science Laboratory, Open-file Report, NM/BACA-27, 12 p.

Self, S., Goff, F., Gardner, J., Wright, J., and Kite, W., 1986, Explosive rhyolitic volcanism in the Jemez Mountains: vent locations, caldera development, and relation to regional structure: Journal of Geophysical Research, v. 91, 1779–1798.

Self, S., Kircher, D., and Wolff, J., 1988, The El Cajete Series, Valles caldera, New Mexico: Journal of Geophysical Research, v. 93, p. 6113–6127.

Self, S., Wolff, J., Spell, T., Skuba, C., and Morrisey, M., 1991, Revisions to the stratigraphy and volcanology of the post-0.45 Ma units and the volcanic section of VC-1 corehole, Valles caldera, New Mexico: Journal of Geophysical Research, v. 96, p. 4107–4116.

Smith, G. A. and Lavine, A., 1996, What is the Cochiti Formation?: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 219–224.

Smith, G. A., Larsen, D., Harlan, S., McIntosh, W., Erskine, D., and Taylor, S., 1991, A tale of two volcaniclastic aprons: field guide to the sedimentology and physical volcanology of the Oligocene Espinaso Formation and Miocene Peralta Tuff, north-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 87–103.

Smith, H. T. U., 1938, Tertiary geology of the Abiquiu Quadrangle, New Mexico: Journal of Geology, v. 46, p. 933–965.

Smith, R. L., 1979, Ash-flow magmatism: Geological Society of America, Special Paper 180, p. 5–27.

Smith, R. L. and Bailey, R. A., 1966, The Bandelier Tuff: A study of ash-flow eruption cycles from zoned magma chambers: Bulletin of Volcanology, v. 29, p. 83–104.

Smith, R. L. and Bailey, R. A., 1968, Resurgent cauldrons: Geological Society of America, Memoir 116, p. 613–662.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1961, Structural evolution of the Valles caldera, New Mexico, and its bearing on the emplacement of ring dikes: U.S. Geological Survey, Professional Paper 424-D, p. 145–149.

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

Spell, T. and Kyle, P., 1989, Petrogenesis of Valle Grande Member rhyolites, Valles caldera, New Mexico: Implications for evolution of the Jemez Mountains magmatic system: Journal of Geophysical Research, v. 94, p. 10,379–10,396.

Spell, T. and Harrison, T., 1993, $^{40}Ar/^{39}Ar$ geochronology of post-Valles caldera rhyolites, Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 98, p. 8031–8051.

Spell, T., Harrison, T., and Wolff, J., 1990, $^{40}Ar/^{39}Ar$ dating of the Bandelier Tuff and San Diego Canyon ignimbrites, Jemez Mountains, New Mexico: temporal constraints on magmatic evolution: Journal of Volcanology and Geothermal Research, v. 43, p. 175–193.

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

Steck, L., Thurber, C., Fehler, M., Lutter, W., Roberts, P., Baldridge, W., Stafford, D., and Sessions, R., 1998, Crust and upper mantle P wave velocity structure beneath Valles caldera, New Mexico: Results from the Jemez teleseismic tomography experiment: Journal of Geophysical Research, v. 103, p. 24,301–24,320.

Steiger, R. and Jäger, E., 1977, Subcomission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.

Stein, H. L., 1983, Geology of the Cochiti Mining District, Jemez Mountains, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 122 p.

Stimac, J., 1996, Hornblende-dacite pumice in the Tshirege Member of the Bandelier Tuff: Implications for magma chamber and eruptive processes: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 269–274.

Stimac, J., Hickmott, D., Abell, R., Larocque, A., Broxton, D., Gardner, J., Chipera, S., Wolff, J., and Gauerke, E., 1996, Redistribution of Pb and other volatile trace metals during eruption, devitrification, and vapor-phase crystallization of the Bandelier Tuff, New Mexico: Journal of Volcanology and Geothermal Research, v. 73, p. 245–266.

Stix, J. and Gorton, M.P., 1990, Changes in silicic melt structure between the two Bandelier caldera-forming eruptions, New Mexico, USA: Evidence from zirconium and light rare earth elements: Journal of Petrology, v. 31, p. 1261–1283.

Stix, J., Goff, F., Gorton, M., Heiken, G., and Garcia, S., 1988, Restoration of compositional gradients in the Bandelier silicic magma chamber between two caldera-forming eruptions: Journal of Geophysical Research, v. 93, p. 6129–6147.

Sturchio, N. and Binz, C., 1988, Uranium-series age determination of calcite veins, VC-1 drill core, Valles caldera, New Mexico: Journal of Geophysical Research, v. 93, p. 6097–6102.

Stoker, A., McLin, S., Purtymun, W., Maes, M., and Hammock, B., 1992, Water supply at Los Alamos during 1989: Los Alamos National Laboratory, Report LA-12276-PR, 51 p.

Suppe, J., Powell, C., and Berry, R., 1975, Regional topography, seismicity, Quaternary volcanism, and the present-day tectonics of the western United States: American Journal of Science, v. 275-A, p. 397–436.

Toyoda, S., Goff, F., Ikeda, S., and Ikeya, M., 1995, ESR dating of quartz phenocrysts in the El Cajete and Battleship Rock Members of Valles Rhyolite, Valles caldera, New Mexico: Journal of Volcanology and Geothermal Research, v. 67, p. 29–40.

Turbeville, B. and Self, S., 1988, San Diego Canyon ignimbrites: Pre-Bandelier Tuff explosive rhyolitic volcanism in the Jemez Mountains, New Mexico: Journal of Geophysical Research, v. 93, p. 6148–6156.

Turbeville, B., Waresback, D., and Self, S., 1989, Lava-dome growth and explosive volcanism in the Jemez Mountains, New Mexico: Evidence from the Plio-Pleistocene Puye alluvial fans: Journal of Volcanology and Geothermal Research, v. 36, p. 267–291.

Waresback, D., 1986, The Puye Formation, New Mexico: Analysis of a continental rift-filling volcaniclastic alluvial fan sequence [M.S. thesis]: Arlington, University of Texas, 269 p.

Warshaw, C. and Smith, R. L., 1988, Pyroxenes and fayalites in the Bandelier Tuff, New Mexico: Temperatures and comparison with other rhyolites: American Mineralogist, v. 73, p. 1025–1037.

Werner, C., Stimac, J., and Hickmott, D., 1996, Trace element distributions in the upper Bandelier Tuff, New Mexico: Zircon zoning and implications for magmatic evolution of the Valles system: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 285–291.

WoldeGabriel, G., 1990, Hydrothermal alteration in the Valles caldera ring-fracture zone and corehole VC-1: evidence for multiple hydrothermal systems: Journal of Volcanology and Geothermal Research, v. 40, p. 105–122.

WoldeGabriel, G. and Goff, F., 1989, Temporal relations of volcanism and hydrothermal systems in two areas of the Jemez volcanic field, New Mexico: Geology, v. 17, p. 986–989.

WoldeGabriel, G. and Goff, F., 1992, K/Ar dates of hydrothermal clays from corehole VC-2B, Valles caldera, New Mexico and their relation to alteration in a large hydrothermal system: Journal of Volcanology and Geothermal Research, v. 50, p. 207–230.

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

Wolff, J. and Gardner, J. N., 1995, Is the Valles caldera entering a new cycle of activity?: Geology, v. 23, p. 411–414.

Wolff, J., Gardner, J.N., and Reneau, S., 1996, Field characteristics of the El Cajete

pumice deposit and associated southwestern moat rhyolites of the Valles caldera: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 311–316.

Wronkiewicz, D., Norman, D., Parkison, G., and Emanuel, K., 1984, Geology of the Cochiti Mining District, Sandoval County, New Mexico: New Mexico Geological Society, 35th Field Conference, Guidebook, p. 219–222.

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