ERID 204421

ENTERED

NEW MEXICO GEOLOGY — *BACK ISSUES*

Papers from back issues of *New Mexico Geology* are available as free downloads in PDF format. Back issues are generally also available in print for $4 each or $15 per volume (four issues). Contact us to purchase back issues as whole volumes.

Search Back Issue Papers:

Year (starting in 1979): 2010 OR **From** (Year): **To:** **Volume:** 32 **No.** (1-4): 1

Title: ANY **Author(s):** Gardner *(Enter a comma delimited list.)*

Keyword(s): ANY ☐ **Use All Keywords?**

(Enter a comma-delimited list for multiple keywords, time periods, or regions; check 'Use All' to limit results.)

Formation(s): ANY **County:** ANY

(Enter comma-delimited formation names.)

Your search returned **1** New Mexico Geology papers matching your criteria.
Displaying record: 1

Results ordered by Author, Year, Volume & Number:

Gardner, Jamie N.; Goff, Fraser; Kelley, Shari; Jacobs, Elaine, 2010, Rhyolites and associated deposits of the Valles-Toledo caldera complex (7.67 MB PDF), New Mexico Geology, v. 32, no. 1, pp. 3-18. [*See Issue*]

Geoscience e-Journals [http://paleopolis.rediris.es/geosciences/]			
Previous [http://www.univ-brest.fr/geosciences/ringlinks/cgi-bin/ringlink/prev.pl?ringid=journals;siteid=NMG]	Random [http://www.univ-brest.fr/geosciences/ringlinks/cgi-bin/ringlink/rand.pl?ringid=journals;siteid=NMG]	Next [http://www.univ-brest.fr/geosciences/ringlinks/cgi-bin/ringlink/next.pl?ringid=journals;siteid=NMG]	List [http://www.univ-brest.fr/geosciences/ringlinks/cgi-bin/ringlink/list.pl?ringid=journals;siteid=NMG]

New Mexico Bureau of Geology & Mineral Resources
New Mexico Institute of Mining & Technology
801 Leroy Place
Socorro, NM 87801-4796

information: (575) 835-5420
fax: (575) 835-6333

34806

http://geoinfo.nmt.edu

Revised: 5 April, 2011

Copyright © 2007 - 2008 New Mexico Bureau of Geology & Mineral Resources unless otherwise specified.

Rhyolites and associated deposits of the Valles–Toledo caldera complex

Jamie N. Gardner, 14170 Highway 4, Jemez Springs, New Mexico 87025, jamiengardner@yahoo.com; *Fraser Goff,* Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, candf@swcp.com; *Shari Kelley*, New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, New Mexico 87801, sakelley@ix.netcom.com; *Elaine Jacobs*, 3007 Villa Street, Los Alamos, New Mexico 87544, perkijacobs@gmail.com

Abstract

Several decades of focused studies on the Valles–Toledo caldera complex and the Jemez Mountains in northern New Mexico have brought about new understanding of the relations of stratigraphic units that record the complex's evolution. We present here a revision of the formal stratigraphic nomenclature for the Quaternary Tewa Group, an established stratigraphic unit that includes the volcanic and volcaniclastic deposits of the caldera complex. We propose 11 completely new units of member rank, with descriptions of lithology, contact relations, distribution, and type areas. These new members are parts of the Bandelier Tuff, Cerro Toledo, and Valles Rhyolite Formations, and serve to depict the magmatic and geomorphic evolution of the area during and following each of two major caldera-forming episodes. With results from mapping efforts in the Jemez Mountains revealing the broad implications and interrelations of some established units, we redefine one formation (Cerro Toledo Rhyolite) and demote three formal members (El Cajete, Battleship Rock, and Banco Bonito) to bed or flow rank. Because it has been shown repeatedly in published works that one formation (Cerro Rubio Quartz Latite) was originally defined based on erroneous relations, we propose its formal abandonment. Additionally, we propose formal abandonment of one established member (Valle Grande Member of the Valles Rhyolite) because of lack of utility and widespread disuse. Our proposed revisions embody the practices of geologic mappers, and serve to better clarify relations of volcanic and volcaniclastic rocks through the evolution of the Valles–Toledo caldera complex. The new formal stratigraphy that we propose will provide a flexible but robust framework for on-going and future research in the Valles–Toledo caldera complex.

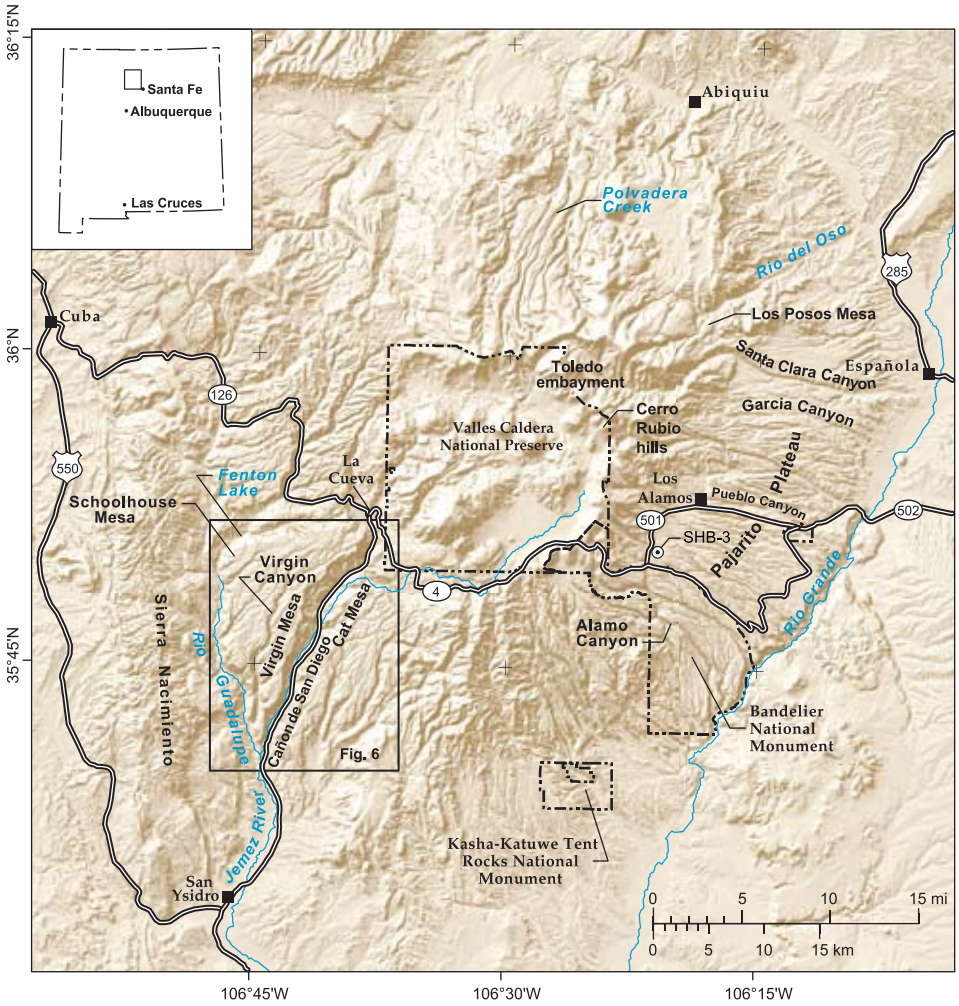

FIGURE 1—Maps showing the location of and shaded relief of the Jemez Mountains area. Box labeled Valles Caldera National Preserve covers most of the Valles–Toledo caldera complex. Some localities mentioned in text are shown.

Introduction

The centerpiece of the Jemez Mountains volcanic field of north-central New Mexico is the Valles–Toledo caldera complex (Fig. 1). Well known are the two voluminous eruptions of Bandelier Tuff, at about 400–475 km^3 (96–114 mi^3) each (Cook et al. 2006; Self 2009), that produced two major caldera-forming episodes at 1.25 Ma (the Valles caldera) and about 1.61 Ma (Toledo caldera; dates from Izett and Obradovich 1994; Phillips 2004; Phillips et al. 2007). The Tshirege Member is the name for Bandelier Tuff erupted with formation of the Valles caldera, and the Otowi Member is the name of the tuff erupted during formation of the Toledo caldera. Additionally renowned is the Valles caldera's resurgent dome, which preserves a record of more than 1,000 m (3,280 ft) of structural upheaval of the caldera floor within 54,000 yrs of caldera formation (Phillips et al. 2007). The volcanic rocks and associated deposits of the caldera complex are called the Tewa Group. Hence, all of the Tewa Group is Quaternary, and it includes many rhyolite lavas and domes, small- and large-volume pyroclastic flows, fallout tephras, and a variety of volcaniclastic deposits. Extensive new geologic mapping, new $^{40}Ar/^{39}Ar$ ages, and the impending publication of a series of new geologic maps of the Jemez Mountains necessitate a reevaluation of the stratigraphic relations and units that make up the Tewa Group (Fig. 2).

The Tewa Group and its component formations and members were originally defined (Griggs 1964; Bailey et al. 1969) to facilitate production of two geologic maps of the Jemez Mountains volcanic field. The geologic map of Griggs (1964; scale 1:31,680) was focused on the eastern part of the Valles caldera and the Pajarito Plateau (Fig. 1), and its purpose was for development of ground water supplies in the Los Alamos area. The second geologic map (Smith et al. 1970) was smaller scale (1:125,000) and provided a picture of and context for the volcanism that built the whole of the Jemez Mountains over a period spanning the Neogene (mid-Miocene) and Quaternary. Work in the intervening decades adds insights regarding the stratigraphic relations in the volcanic field, indicates significant temporal

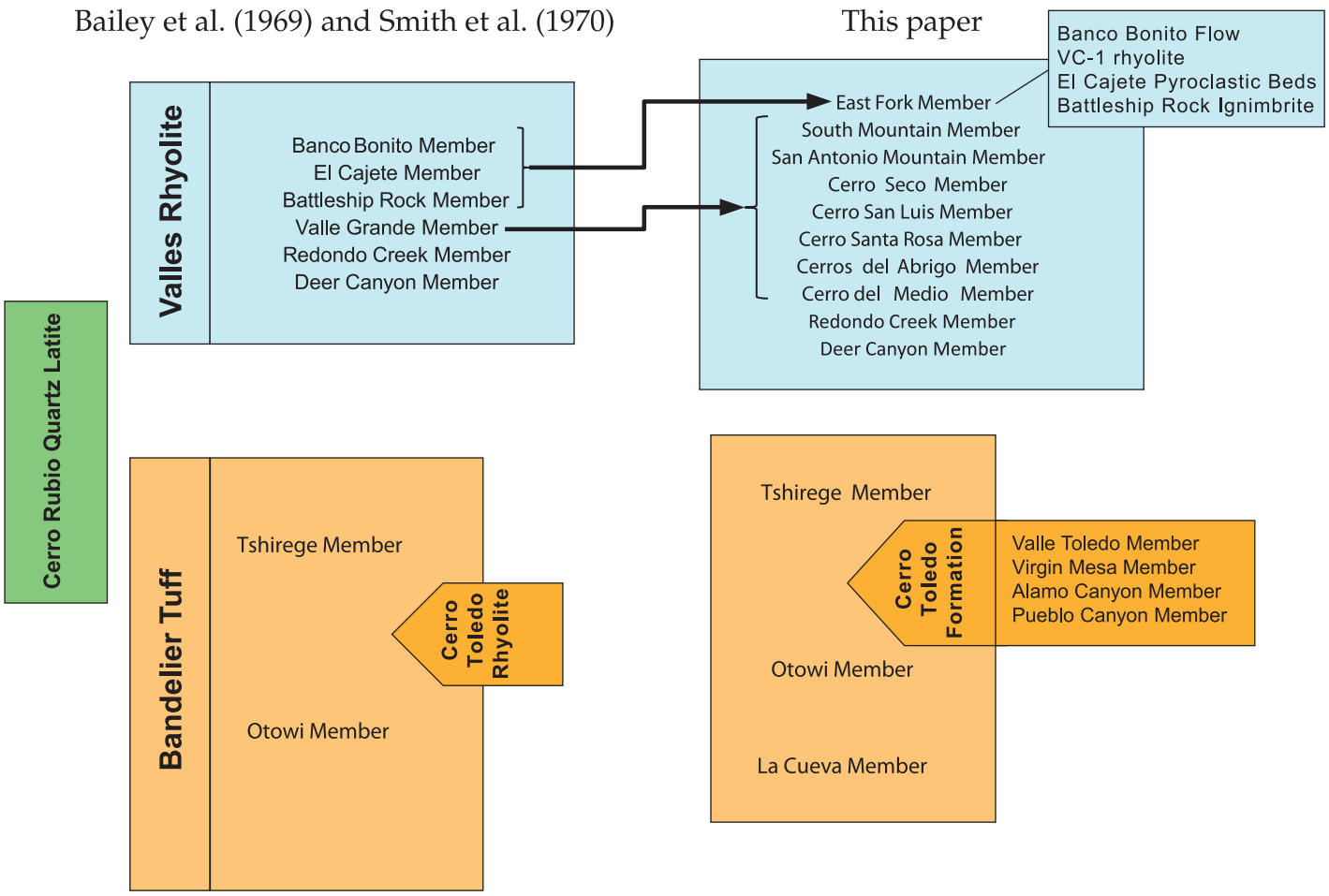

FIGURE 2—Stratigraphic charts comparing the stratigraphy of the Tewa Group before and after this revision. Colors are coded to formations in this figure only.

overlap among many formal stratigraphic groups, shows geographic utility for some established names, and raises questions regarding the validity of some formations (for example, Gardner et al. 1986; Goff et al. 1989; Broxton and Reneau 1995; Kelley et al. 2007a). Recent geologic mapping of the Jemez Mountains at 1:24,000 scale (for example, Goff et al. 2005a, 2005b, 2006; Kelley et al. 2003, 2004; Gardner et al. 2006; Kempter et al. 2004; Lawrence et al. 2004) has brought a greater level of detail and understanding of the stratigraphic significance of units, and a sound basis for abandoning some previously established names. In this paper we propose revisions to the formal stratigraphy of the Tewa Group that are consistent with the practices of the geologic mappers, and serve to clarify relations of volcanic and volcaniclastic rocks through the evolution of the Valles–Toledo caldera complex. We propose these revisions to bring the practical stratigraphic hierarchy more in line with accepted custom as established in the North American Stratigraphic Code (NACSN 2005). For example, member-level divisions are now appropriate among the dome clusters of the Valles Rhyolite, with each member being petrographically, geographically, and geochemically unique and identifiable, and with many of the new members defensibly divisible further into individual flows or beds. Thus, one formation (*Cerro Rubio Quartz Latite*) will be abandoned, four members (the *Valle Grande, El Cajete, Banco Bonito,* and *Battleship Rock Members*) will be abandoned or redesignated, nine new members (parts of the Valles Rhyolite and Bandelier Tuff) will be established, and one formation (the *Cerro Toledo Rhyolite*) will be redefined and renamed to become the **Cerro Toledo Formation** with four new members (Fig. 2). Please see the following section for explanation of the use of *italics* and **boldface** types in this paper.

Notes regarding terminology, definitions, and conventions

As much as is practical, the original names for units of the Tewa Group have been retained. New names are proposed for units with confusing usage, or with definitions that are too broad or too specific. Most established unit names have been retained even if the stature of the unit has been changed (for example, the former *El Cajete Member* now becomes the **El Cajete Pyroclastic Beds**). All names, according to the strictures of the North American Stratigraphic Code (NACSN 2005), are derived from geographic features that are shown on maps published by the U.S. Federal or local government, or have been established through precedents and long usage in the scientific literature. To add some clarity to discussions, former units whose rank, status, or name is to be changed are *italicized* and new units are in **boldface type**.

The NACSN (2005) states that age has no place in the definition of units. Lithostratigraphic units are intended to be diachronous, but stratigraphic position is part of the unit's definition. Although volcanic rocks will generally conform to expectations of superposition, high viscosity often prevents the rhyolitic lavas from overlapping. Thus, for separated volcanic centers, isotopic age has to be a surrogate for stratigraphic position. It should be noted, however, that much more work could be done on dating the members of the Valles Rhyolite. A single isotopic age from a given center may not represent the actual time span of that member's emplacement. For example, Spell and Harrison (1993) reported a "most reliable age" on the **Cerro del Medio Member** of 1.133 ± 0.011 Ma; however, subsequent work (Phillips et al. 2007; Gardner et al. 2007) has shown that **Cerro del Medio** volcanism may span 100,000 yrs.

The definitions of stratigraphic units in this paper are not intended to be restrictive. Many Tewa Group eruptive sequences

included pyroclastic activity. Where these pyroclastic phases have been recognized, we have included their descriptions as part of the definitions of the units. As additional units are discovered, such deposits should be included as part of the given formation or member, with appropriate descriptions and basis for correlation in published literature.

Locations are given in UTMs with respect to Zone 13. The datum is NAD27.

Formally abandoned units

Cerro Rubio Quartz Latite

This formation was defined by Griggs (1964), who described it as consisting of two domes that intruded *Cerro Toledo Rhyolite,* and were overlain by the Tshirege Member of the Bandelier Tuff. Bailey et al. (1969) adopted Griggs' definition without modification, but Smith et al. (1970) showed the formation as spanning a post-*Cerro Toledo Rhyolite* to post-Tshirege Member time frame (Fig. 2). Much argument, with implications for the development of the Toledo caldera, has centered on whether the Cerro Rubio hills are extrusive domes or shallow intrusive cores of older eroded volcanoes (Griggs 1964; Smith et al. 1970; Heiken et al. 1986; Gardner et al. 1986; Self et al. 1986; Goff et al. 1989; Gardner and Goff 1996; Goff and Gardner 2004). Textures and contact relations are equivocal and can be argued both ways. Geologic mapping (Gardner and Goff 1996; Gardner et al. 2006), however, has shown that *Cerro Toledo Rhyolite* tephra and Tshirege Member tuff overlie both Cerro Rubio mounds, indicating that they cannot be younger than the Valles caldera and probably pre-date the Toledo caldera. Both mounds are geochemically and petrographically similar to dacites of the Tschicoma Formation (see Fig. 3 for regional stratigraphy), and a number of isotopic ages indicate *Cerro Rubio* magmatism was contemporaneous with Tschicoma Formation volcanism. Finally, since the 1980s, many authors have included the Cerro Rubio hills (Figs. 1 and 4) as part of the Tschicoma Formation; moreover, geologic mappers show the hills as informal units of the Tertiary Tschicoma Formation, commonly called "Cerro Rubio dacite" or "dacite of Cerro Rubio" (Heiken et al. 1986; Self et al. 1986; Stix et al. 1988; Gardner and Goff 1996; Gardner et al. 2006; Goff et al. 2006). We propose, therefore, formal abandonment of *Cerro Rubio Quartz Latite.*

Valles Grande Member of the Valles Rhyolite

Bailey et al. (1969) defined the *Valle Grande Member*, part of the Valles Rhyolite (Fig. 2), to include "the morphologically young domes, flows, and pyroclastic rocks in the moat of the Valles caldera." They designate no type section or area because of "the isolated nature of the units forming the member and because of petrographic differences among them." Although they acknowledge substantial petrographic variations among the dome clusters, they assert "progressive mineralogical variation between…extremes and the annular distribution of the domes with the Valles caldera moat…indicate that they are petrologically related and are parts of a single geologic member." However, Spell and Kyle (1989) demonstrated the petrologic dissimilarity among the dome clusters of the *Valle Grande Member*. Furthermore, in practice the *Valle Grande Member* has been ignored because all workers have focused research and mapping on each of the post-caldera eruptive centers, treating them each as de facto members. The *Valle Grande Member* only served to separate syn-resurgence volcanism (Redondo Creek and Deer Canyon Members) from the youngest eruptive sequence (the new **East Fork Member**). Thus, we propose abandonment of the *Valle Grande Member* by replacing it with seven new members of the Valles Rhyolite (Fig. 2). The Valles Rhyolite will now include a total of ten members.

The Tewa Group

Griggs (1964) defined the Tewa Group as "rhyolite tuff and the rhyolite and quartz latite domes that constitute the latest eruptive rocks of the Jemez Mountains volcanic pile." As such the group contained the four formations: *Cerro Toledo Rhyolite*, Bandelier Tuff, *Cerro Rubio Quartz Latite*, and the Valles Rhyolite. Bailey et al. (1969) retained this structure of the Tewa Group, reiterating that the group is "a voluminous sequence of rhyolitic tuffs and lavas that represent the climactic and terminal stage of volcanism in the Jemez Mountains."

In our proposed revision of the stratigraphy, the Tewa Group includes the three formations: the Bandelier Tuff, the **Cerro Toledo Formation**, and the Valles Rhyolite. As discussed above, the formation *Cerro Rubio Quartz Latite* will be abandoned, and the *Cerro Toledo Rhyolite* more broadly redefined as the **Cerro Toledo Formation**. True to the intent and original definitions, in our revision the group and its three formations comprise the volcanic and volcaniclastic rocks and deposits directly associated with eruptions and evolution of the Toledo and Valles calderas.

Bandelier Tuff

The formation Bandelier Tuff has been long established in the geologic literature, and has proven useful in both surface and subsurface geologic mapping. The only change to the formation that we propose is subdivision of the Otowi Member to allow addition of the new **La Cueva Member** (Fig. 2). The term "Bandelier Rhyolitic Tuff" was first used by Smith (1938). The name was modified by Griggs (1964) to Bandelier Tuff, and he subdivided the formation into three members. Bailey et al. (1969) argued that a two-fold subdivision of the formation into the equally voluminous Tshirege and Otowi Members was more natural based on additional knowledge of the "overall character of the Bandelier, plus genetic considerations." Thus, it has been long recognized that the Otowi Member of the Bandelier Tuff, with a basal pyroclastic fallout deposit designated the Guaje Pumice Bed, represented eruptions that accompanied formation of the Toledo caldera at about 1.61 Ma, and the Tshirege Member of the Bandelier Tuff, with a basal fallout deposit called the Tsankawi Pumice Bed, represented eruptions associated with formation of the Valles caldera at 1.25 Ma. However, smaller-volume eruptions of ash flows, lithologically very similar to Bandelier Tuff, preceded the major caldera-forming events. These were informally referred to as "an early leak from the Bandelier magma chamber" (Smith 1979), and the "swept-under-the-carpet ash-flow tuffs" (R. L. Smith, pers. comm. 1980), and were included without mention as part of the Otowi Member of the Bandelier Tuff on the geologic map of the Jemez Mountains (Smith et al. 1970). Other workers recognized these older Bandelier-like tuffs and variously referred to them as "pre-Bandelier silicic tuffs," "pre-Bandelier ignimbrites," "San Diego Canyon tuffs," "San Diego Canyon ignimbrites," and "lower tuffs" (Nielson and Hulen 1984; Gardner and Goff 1984; Gardner et al. 1986; Self et al. 1986; Turbeville and Self 1988; and Spell et al. 1990; Kelley et al. 2007b). Geologic mapping at 1:24,000 scale (Osburn et al. 2002; Kelley et al. 2003, 2007b) has shown these ash-flow tuffs are mappable and occupy a specific stratigraphic position. Thus, to avoid further confusion from multiple names and inexact geographic references, in this paper we propose the formal designation "**La Cueva Member** of the Bandelier Tuff," with a type area for these ash-flow tuffs near the village of La Cueva (Fig. 4), as follows.

La Cueva Member

Two distinct, rhyolitic ignimbrites underlie the Otowi Member in the southwest caldera near La Cueva and can be traced southwest along the walls of Cañon de San Diego for a distance of nearly 20 km (12.5 mi) (Self et al. 1986; Kelley et al. 2003). Our proposed type locality is in a canyon known informally as "Cathedral Canyon," so named for the spectacular tent rocks developed in the Otowi and **La Cueva** Members. The type locality is the feature labeled "Tent Rocks" on the Jemez Springs 7.5-min topographic map near UTM: 350240E 3970260N, which corresponds to "section 100" described in Turbeville and Self (1988). Petrographically, pumice from ash-flow tuffs of the **La Cueva Member** closely resembles pumice from the later Otowi and Tshirege ash flows (Gardner et al. 1986), with bipyramidal or fragmental quartz and sanidine and sparse mafic phases. Geochemically, the **La Cueva Member** pumices are also similar to those of younger

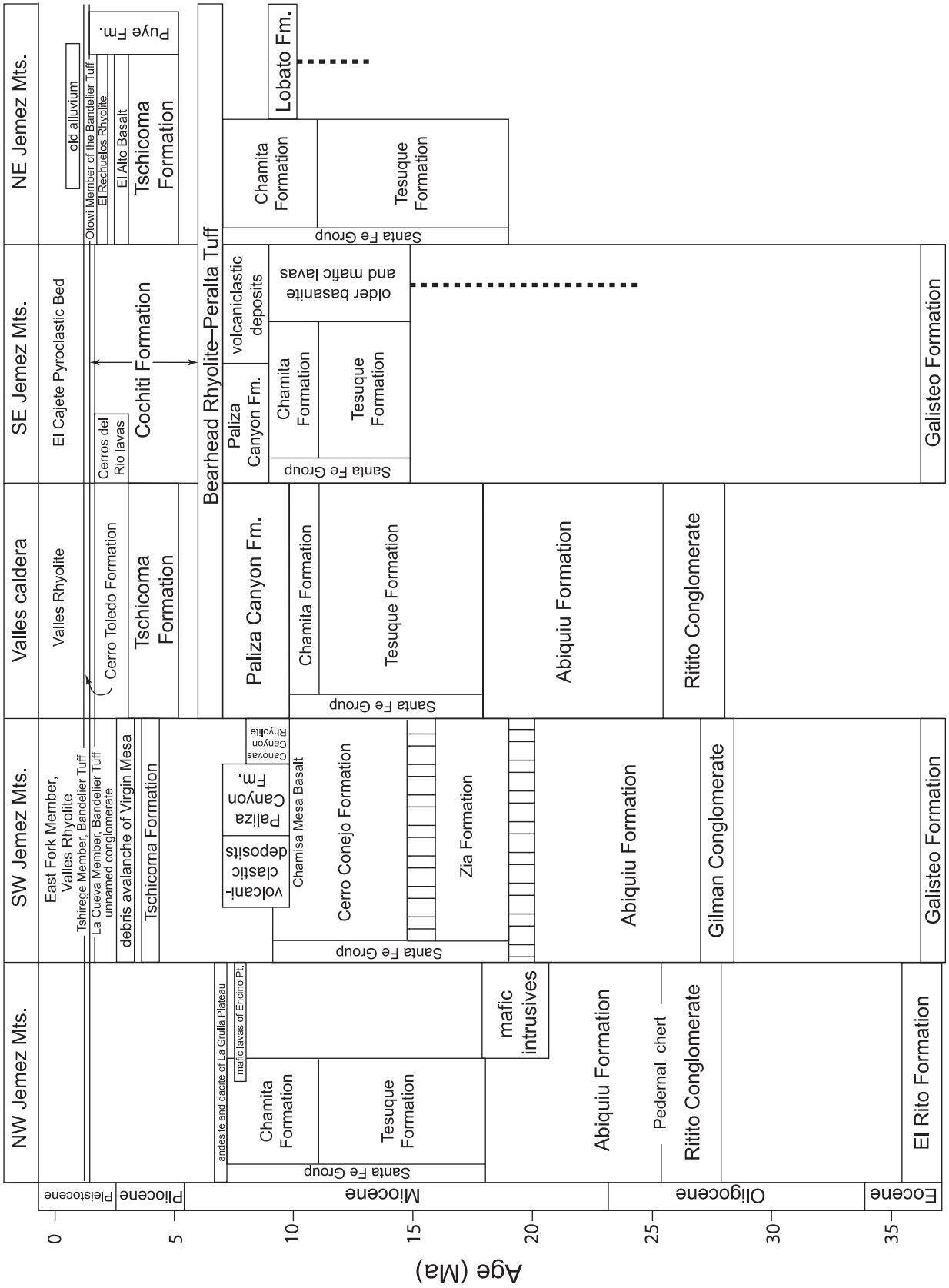

FIGURE 3—Chart showing regional and older stratigraphic units (modified from Kues et al. 2007).

Bandelier tuffs, with compositions for immobile trace elements identical to those of late-erupted Otowi Member (Gardner et al. 1986; Turbeville and Self 1988; Spell et al. 1990). Both **La Cueva Member** tuffs are more lithic rich (>30 wt-% in matrix) and the pumice is more crystal poor than younger Bandelier tuffs. Lithic fragments consist mostly of intermediate to mafic volcanics of the older Paliza Canyon Formation (Fig. 3). The upper **La Cueva** unit (unit B of Self et al. 1986) consists of multiple flow units and contains large pieces of gray pumice with well-developed tube vesicles. Both ash-flow tuffs are relatively nonwelded. The two ignimbrites are separated by reworked pumice and debris flows in areas proximal to the caldera complex, and by fluvial gravels and mudstones at more distal sites (Self et al. 1986; Kelley et al. 2003). The gravels interbedded within the **La Cueva Member**, and between the **La Cueva Member** and the overlying Otowi Member, have andesite, basalt, and dacite clasts of older Paliza Canyon Formation, rhyolite and obsidian from uncertain sources, reworked **La Cueva Member** tuff and pumice, Permian sandstone, Proterozoic granite and quartzite, and Pedernal chert (Fig. 3). The Proterozoic component of the gravels is absent in the vicinity of the type locality but is more common on the east side of Virgin Mesa south of Rincon Negro (Fig. 4). The **La Cueva Member** is separated from the overlying Otowi Member by an unconformity marked by fluvial gravels or a poorly developed soil (Self et al. 1986; Kelley et al. 2003). The **La Cueva Member** is underlain by a debris avalanche composed of Paliza Canyon Formation andesite (debris avalanche of Virgin Mesa; Fig. 3) in the northern part of the area and by sandstone and conglomeratic sandstone that may correlate with Cochiti Formation (Fig. 3) in the southern part of the area. Spell et al. (1996b) determined an $^{40}Ar/^{39}Ar$ date of 1.85 ± 0.07 Ma for the **La Cueva Member**. Total thickness of the **La Cueva Member** is about 80 m (262 ft) near La Cueva to ≤ 2 m (≤ 6.5 ft) at distal locations in Cañon de San Diego. The **La Cueva Member** has been tentatively correlated with hydrothermally altered drill cuttings of "lower tuffs" identified beneath the Otowi Member within the Valles caldera (Self et al. 1986; Hulen et al. 1991).

Tephras correlative to the **La Cueva Member** have been found elsewhere in the Jemez Mountains. Turbeville and Self (1988) report similar, distinctive pumice textures for tephras overlying Puye Formation tuff and basaltic cinders dated at 2.5–2.6 Ma on the Pajarito Plateau; furthermore, these pumices are geochemically identical to those from the type area, described above (J. A. Wolff, pers. comm.). Lynch et al. (2004) report $^{40}Ar/^{39}Ar$ ages of 1.87 ± 0.01 Ma and 1.84 ± 0.02 Ma for primary and reworked tephra beds in the upper Cochiti Formation east of Kasha-Katuwe Tent Rocks National Monument in the southeastern Jemez Mountains (Fig. 1). Additionally, we have observed **La Cueva Member** tephra beneath the Otowi Member in the lower reaches of Alamo Canyon in Bandelier National Monument (Fig. 1), suggesting that the **La Cueva Member** is of widespread stratigraphic significance.

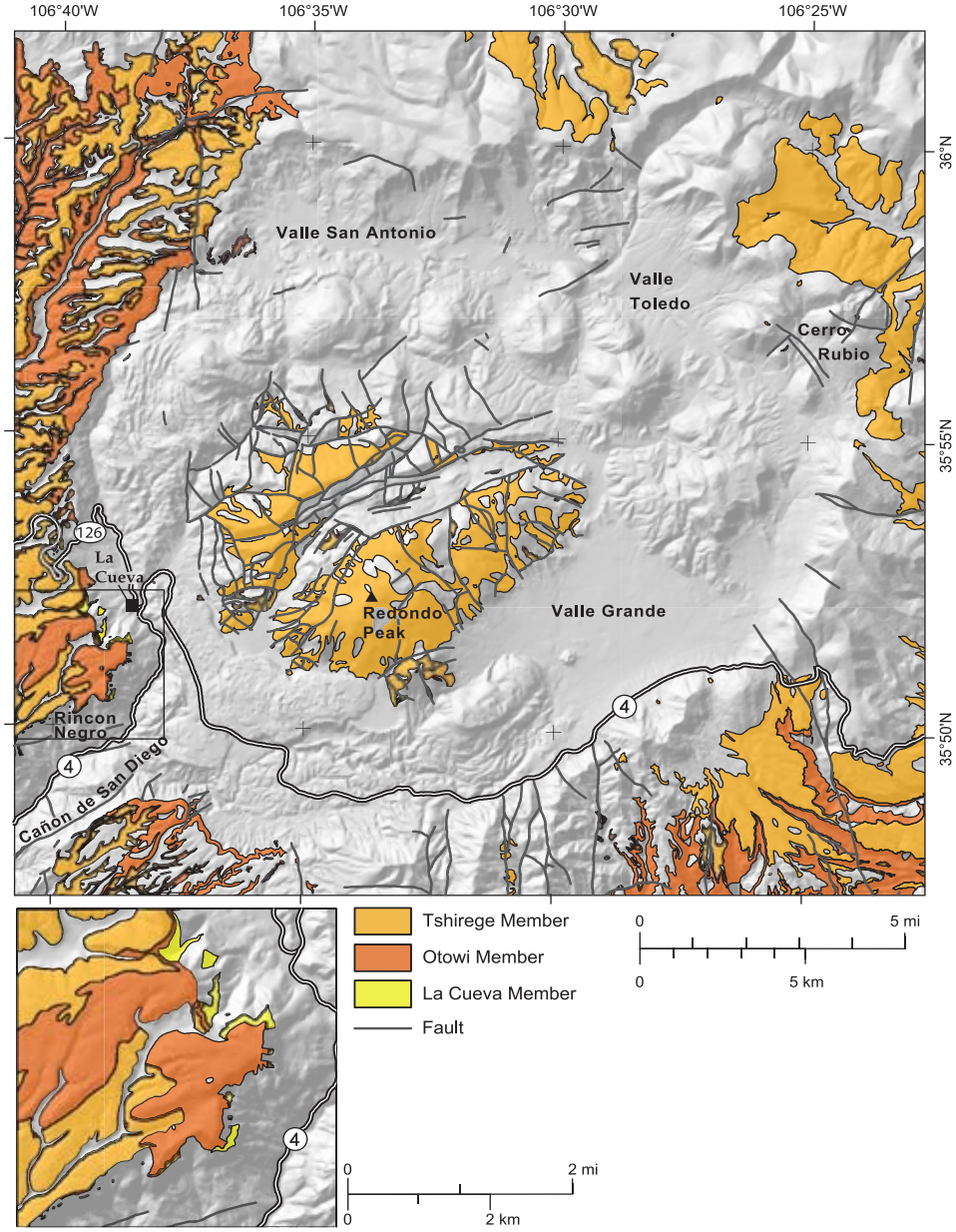

FIGURE 4—Shaded relief map of Valles–Toledo caldera complex showing members of the Bandelier Tuff (formation) and some features mentioned in text. Black box is area near village of La Cueva shown blown up in inset (data from Goff et al. in prep.).

Cerro Toledo Formation

The **Cerro Toledo Formation** is a new name that replaces and broadens the definition of the former *Cerro Toledo Rhyolite.* Considerable time elapsed between the major caldera-forming eruptions of the Otowi and Tshirege Members of the Bandelier Tuff. During this interval, intra-Toledo caldera volcanism produced rhyolitic domes and pyroclastic rocks that have long been recognized as the *Cerro Toledo Rhyolite*; however, substantial erosion and topographic modification of the caldera's margins and deposition by fluvial systems also occurred in this interval, and the stratigraphic assignment of these deposits has been problematic.

Griggs (1964) defined the *Cerro Toledo Rhyolite* as a "group of extrusive volcanic domes" that was "extruded after the cycle of eruptions that produced…the Otowi Member of the Bandelier." Bailey et al. (1969) made no changes to Griggs' definition, but Smith et al. (1970) added an informal subdivision that included "tuffs and associated sediments," as well as "hot avalanche deposits from the Rabbit Mountain center," that are to the east and southeast of the caldera complex, between the Otowi and Tshirege Members of the Bandelier Tuff. An arc of rhyolite domes, including the informally named Los Posos, Trasquilar, and Warm Springs domes in the northern part of the caldera complex

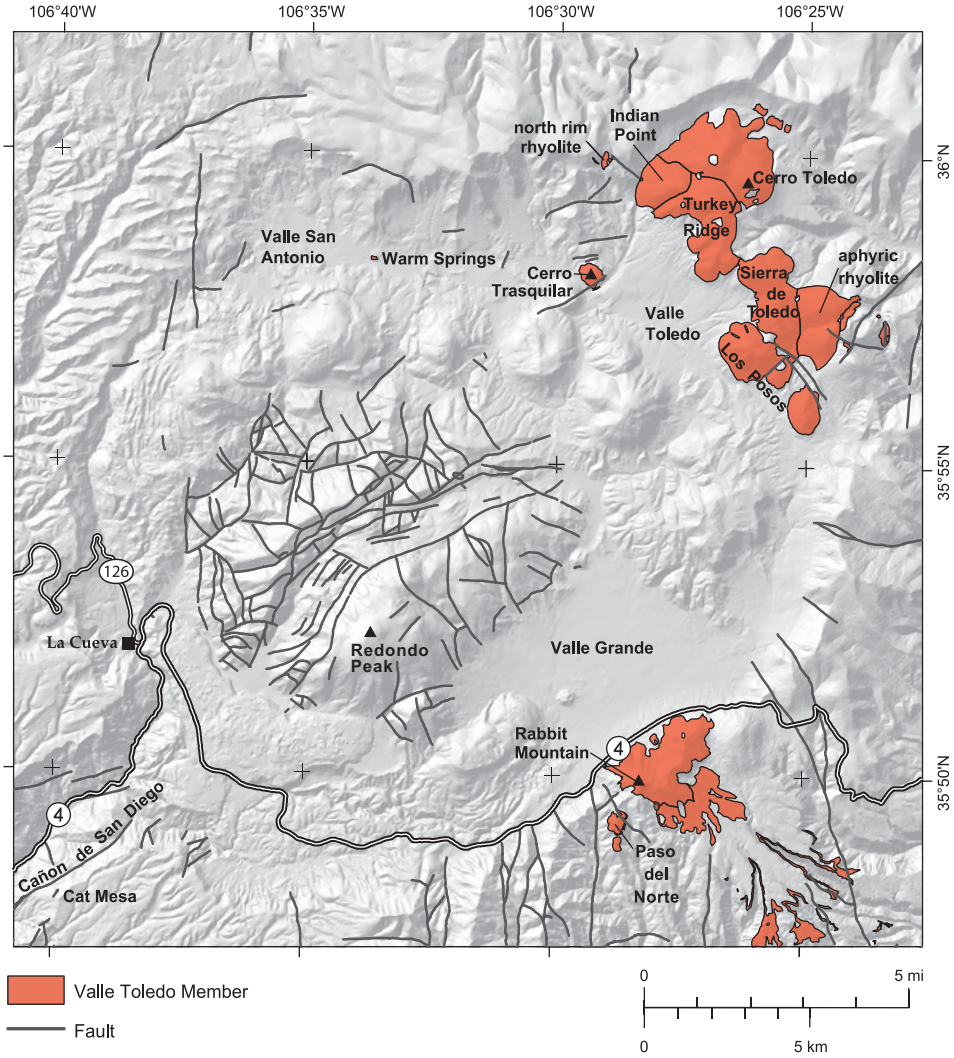

FIGURE 5—Shaded relief map of Valles–Toledo caldera complex showing Valle Toledo Member and some features mentioned in text (data from Goff et al. in prep.).

(Fig. 5), was originally assigned to the *Valle Grande Member* of the Valles Rhyolite (Smith et al. 1970), but later mapping, geochronology, and petrology indicated they are part of the *Cerro Toledo Rhyolite* (Heiken et al. 1986; Stix et al. 1988; Gardner and Goff 1996; Spell et al. 1996b). The revised stratigraphic assignment of these domes was part of what contributed to the recognition of and the redefinition of the position of the Toledo caldera (Goff et al. 1984; Heiken et al. 1986; Self et al. 1986). Heiken et al. (1986) studied extracaldera pyroclastic deposits of the *Cerro Toledo Rhyolite*, and noted that some of the deposits were reworked and interbedded with "epiclastic" sediments with a dacitic clast content similar to the Puye Formation. Gardner et al. (1993) reported thick sequences of dacitic-composition sands and gravels, with minor primary pyroclastic interbeds, between the Otowi and Tshirege Members of the Bandelier Tuff in two core holes on the Pajarito Plateau. Broxton and Reneau (1995) called this sedimentary sequence the "Cerro Toledo interval." Recent mapping has shown that the pyroclastic and sedimentary deposits between the Otowi and Tshirege Members vary systematically around the Jemez Mountains. Furthermore, these deposits contain a record of the landscape and volcanic evolution of the area in the period between formation of the Toledo and Valles calderas. Consequently, we propose revision of the *Cerro Toledo Rhyolite* to the **Cerro Toledo Formation**, broadening the definition of the formation beyond the original restriction to a "group of extrusive volcanic domes." The **Cerro Toledo Formation** consists of four members: the volcanic **Valle Toledo Member**, and the dominantly sedimentary **Pueblo Canyon Member**, **Alamo Canyon Member**, and **Virgin Mesa Member** (Fig. 2).

Valle Toledo Member

The new name simply replaces the former *Cerro Toledo Rhyolite* as defined by Griggs (1964) and mapped by Smith et al. (1970). The new name is necessary to allow some form of nomenclatural continuity while avoiding duplicative use of the same geographic designators. The type area of Griggs (1964) remains the same, although the new name expands the area to the vicinity of Valle Toledo (Fig. 5). As such, included in the **Valle Toledo Member** are informally named domes that cluster in the northeast part of the caldera complex and along an arc in the northern caldera complex, Rabbit Mountain and Paso del Norte domes and tuffs on the southeast topographic rim of the complex (Fig. 5), and extracaldera sequences dominated by primary pyroclastic deposits. Published descriptions and delineation of the informal units within the **Valle Toledo Member** can be found in Heiken et al. (1986), Stix et al. (1988), Spell et al. (1996a, 1996b), Goff et al. (2000, 2005b, 2006), and Gardner et al. (2006) and are briefly summarized in Table 1. The stratigraphic position, between the Otowi and Tshirege Members of the Bandelier Tuff, fixes the age of these units between 1.61 and 1.25 Ma, and Spell et al. (1996a, 1996b) report many isotopic dates on domes and tephras of the **Valle Toledo Member** that fall in this range.

Virgin Mesa Member

The new name applies to fluvial conglomerate and sandstone deposits on the west and south flanks of Valles caldera that underlie the Tsankawi Pumice Bed of the Tshirege Member of the Bandelier Tuff and overlie the Otowi Member of the Bandelier Tuff (Kelley et al. 2003; Goff et al. 2005a). The informally named "S3 sandstone," beds of sandstone, sandstone breccia, and volcanic breccia found between the Tshirege and Otowi Members within Valles caldera (Nielson and Hulen 1984; Hulen et al. 1991), is included in the **Virgin Mesa Member**. The type area is designated to be on the east side of Virgin Mesa between outcrops located southwest of Sino Spring and outcrops located northwest of Agua Durme Spring in Cañon de San Diego (Stations 11–14, Table 2, Fig. 6). The conglomerates in the **Virgin Mesa Member** contain rock types from a variety of source regions, including clasts of Otowi and **La Cueva** (?) member tuffs, Proterozoic granitic and metamorphic rocks, Pennsylvanian limestone, Permian sandstone, and Paliza Canyon Formation andesite and basalt. Considerable paleotopography developed during the 400,000 yrs between the Bandelier eruptions, and these sedimentary deposits are localized in paleovalleys. Thus, at any locality, the member also contains clasts derived from subjacent units and colluvial wedges shed from the paleocanyon walls. The **Virgin Mesa Member** has a maximum thickness of 15 m (49 ft).

One of the most remarkable outcrops of this unit is located in Virgin Canyon at UTM: 342800E 3958770N (star in Fig. 6). Here, a south-flowing stream cut a paleo-Virgin Canyon into the Otowi Member that is offset just west of the present-day drainage; this paleocanyon was nearly as deep as the modern Virgin Canyon. Clasts in the fluvial gravels in the paleocanyon include rounded Paliza Canyon Formation andesite,

TABLE 1—Informal names, ages, and brief descriptions of Valle Toledo Member rhyolite domes, Cerro Toledo Formation.

Dome name	Age (Ma)	Method	Description
Toledo embayment domes			
Pinnacle Peak	1.20 ± 0.02	K-Ar[2]	aphyric, microphenocrysts of quartz, sanidine, and biotite
Unnamed aphyric dome	1.33 ± 0.02	K-Ar[2]	sparsely porphyritic, phenocrysts quartz, sanidine, biotite, magnetite
Sierra de Toledo	1.34–1.38	Ar/Ar[1]	porphyritic, phenocrysts quartz, sanidine, biotite, magnetite
Turkey Ridge	1.34 ± 0.02	Ar/Ar[1]	porphyritic, phenocrysts quartz, sanidine, biotite, magnetite, sanidine large and chatoyant
Cerro Toledo	1.38 ± 0.05	K-Ar[2]	aphyric, microphenocrysts of quartz, sanidine, and biotite
Indian Point	1.46 ± 0.01	Ar/Ar[1]	sparsely porphyritic, phenocrysts quartz and sanidine, rare biotite
North Rim	1.61 ± 0.03	Ar/Ar[4]	sparsely porphyritic, phenocrysts quartz, sanidine, and biotite
Toledo caldera ring fracture domes			
Warm Springs	1.26 ± 0.01	Ar/Ar[1]	porphyritic, phenocrysts quartz, sanidine, and biotite
Cerro Trasquilar	1.36 ± 0.01	Ar/Ar[1]	sparsely porphyritic, phenocrysts quartz, sanidine, clinopyroxene, and rare biotite
Rabbit Mountain	1.43 ± 0.04	K-Ar[2]	aphyric to sparsely porphyritic, few phenocrysts quartz and sanidine
East Los Posos	1.45 ± 0.01	Ar/Ar[1]	porphyritic, phenocrysts quartz, sanidine, biotite, hornblende
Paso del Norte	1.47 ± 0.04	Ar/Ar[3]	sparsely porphyritic, phenocrysts quartz, sanidine, and biotite
West Los Posos	1.54 ± 0.01	Ar/Ar[1]	porphyritic, phenocrysts quartz, sanidine, plagioclase, and biotite

[1]Spell et al. (1996b); [2]Stix et al. (1988); [3]Justet (2003); [4]Kelley et al. (in prep.).

recycled lithic fragments from the Otowi Member, and sparse flow-banded rhyolite. The Tshirege Member of the Bandelier Tuff subsequently filled this paleocanyon. Impressive colluvial wedges that mark the eastern edge of the paleovalley are preserved between the Otowi and Tshirege Members. An equally spectacular outcrop is located at UTM: 342040E 3955860N in the middle reaches of Virgin Canyon (Station 6 in Fig. 6). A colluvial wedge composed of Otowi Member blocks is interbedded with fluvial gravel that is also between the Otowi and Tshirege Members. The meandering paleo-Virgin Canyon seems to have been oriented east-west at this locality.

Sandstone and conglomerate of the **Virgin Mesa Member** are preserved discontinuously below the Tsankawi Pumice Bed of the Tshirege Member on the west side of Garcia Mesa east of the Rio Guadalupe (Fig. 6). Although the Otowi Member and **La Cueva Member** ignimbrites do not crop out in this particular area, the gravels contain lithic-rich tuff clasts and overlie a tephra that is trough crossbedded at its base and interbedded with conglomerate with rounded clasts of lithic-rich tuff toward the south end of the mesa. This tephra is most likely the Guaje Pumice Bed, based on the crystal content and texture of the pumice lapilli. Toward the north end of the mesa, the tuff-bearing fluvial gravels rest on an orange-red siltstone with a few lenses of Paliza Canyon Formation andesite clasts. Other clasts in the conglomerate are Proterozoic granitic and metamorphic rocks, Pennsylvanian limestone, Permian sandstone, Paliza Canyon Formation andesite and basalt.

The provenance of the clasts in the **Virgin Mesa Member** in the southwestern Jemez Mountains (Table 2) indicates that the Sierra Nacimiento, a basement-cored Laramide highland located to the west of the Jemez Mountains (Fig. 1), was the likely source of much of the conglomerate exposed in Guadalupe Canyon, Virgin Canyon, and southern Cañon de San Diego (Fig. 6). Proterozoic clasts are a dominant component and Pennsylvanian limestone clasts are common in the conglomerates of the **Virgin Mesa Member** in this area (brown and blue circles on Fig. 6); these components are absent to the north and are less common to the east. Paleocurrents derived from imbricated pebbles in **Virgin Mesa Member** conglomerates indicate flow toward the south to southwest in most of the exposures in Cañon de San Diego. Similarly, southwest-striking paleocanyons cut in the Otowi Member are preserved on Cat Mesa and northern Virgin Mesa between La Cueva and Rincon Negro (Fig. 6); these paleocanyons contain gravels with Permian Abo and Yeso Formation sandstone and Paliza Canyon Formation andesite cobbles. Combined, the provenance and paleocurrent data from the **Virgin Mesa Member** and the elevation of the Otowi/Tshirege contact can be used to reconstruct the paleogeography of the western Jemez Mountains before the eruption of the Tshirege Member at 1.25 Ma (Fig. 7).

The Otowi Member formed rugged highlands in the northwestern Jemez Mountains during the interval between eruptions, due, in part, to the fact that the Otowi Member is welded in this area (Fig. 7). The Tshirege Member did fill in an eroded topography with relief on the order of tens to hundreds of meters, but the younger tuff typically rests directly on the Otowi Member. The Otowi Member thickly buried the underlying units, so exotic material in streams was not readily available for preservation in the paleocanyons of the northwestern Jemez Mountains (Fig. 7). The **Virgin Mesa Member** is found at only two localities in the western Jemez Mountains. A small colluvial wedge composed of blocks of Otowi Member is preserved beneath the Tsankawi Pumice Bed northwest of Fenton Lake, and rounded clasts of Permian Abo Formation sandstone are present between the tuffs in Schoolhouse Canyon near the western limit of the Bandelier Tuff (Figs. 1 and 7).

Pueblo Canyon Member

The type sections for this member are sections 14 (UTM: 384340E 3971900N) and 15 (UTM: 384340E 3971900N) of Stix (1989) in Pueblo Canyon in the community of Los Alamos on the Pajarito Plateau (Figs. 1 and 7). The new name is applied to the sedimentary deposits of fluvial systems in the northern and eastern Jemez Mountains that drained highlands composed mostly of Tschicoma Formation dacites in the period between eruption of the Otowi and Tshirege Members of the Bandelier Tuff. As such, sandstone and conglomerate of the **Pueblo Canyon Member**, in places, resemble those of the Puye Formation, but the unit also contains significant components of reworked Otowi Member tuff and **Valle Toledo Member** tephra (Broxton and Vaniman 2005). The sedimentary rocks are interbedded with primary pyroclastic deposits of the **Valle Toledo Member** on the northern and central Pajarito Plateau. Generally, the unit consists of sandstone beds that are tabular to crossbedded intercalated with lenses and beds of pebble- to boulder-sized rounded clasts of porphyritic dacite and rhyodacite. The degree of lithification of deposits of the **Pueblo Canyon Member** is variable, and for simplicity, we commonly refer to nonindurated deposits as sandstone and conglomerate too.

The relative amount of sandstone versus conglomerate and the provenance of the unit changes from north to south across

TABLE 2—Dominant rock types in Virgin Mesa Member gravels, southwestern Jemez Mountains. Rock types listed in order of relative abundance at each locality. Location of stations shown in Figure 6.

Station number	NAD27 UTM Location	Clast rock type
1	342028 3952045	Proterozoic granite and quartzite Paliza Canyon Formation andesite and basalt Rhyolite Permian Abo Formation sandstone Pennsylvanian limestone Pedernal chert
2	341951 3951931	Proterozoic granite Paliza Canyon Formation andesite Permian Abo Formation sandstone Pennsylvanian limestone
3	342003 3951566	Proterozoic granite Paliza Canyon Formation andesite Pennsylvanian limestone and sandstone Pedernal chert
4	342100 3951407	Proterozoic granite Otowi Member, Bandelier Tuff Paliza Canyon Formation andesite Permian Abo and Yeso sandstone
5	342310 3951094	Permian Glorieta and Yeso sandstone Paliza Canyon Formation andesite and basalt Proterozoic granite Pennsylvanian limestone Otowi Member, Bandelier Tuff
6	342040 3955860	Otowi Member, Bandelier Tuff Paliza Canyon Formation andesite Permian Abo and Yeso sandstone Proterozoic granite
7	342035 395650	Permian Abo and Yeso sandstone Paliza Canyon Formation andesite Pennsylvanian limestone Proterozoic granite
8	347324 3956281	Permian Abo and Yeso sandstone Proterozoic quartzite Paliza Canyon Formation andesite, dacite, and basalt Rhyolite Obsidian
9	347566 3956686	Paliza Canyon Formation andesite, dacite, and basalt Rhyolite Permian Abo and Yeso sandstone Otowi Member, Bandelier Tuff pumice Proterozoic granite
10	347495 3957769	Otowi Member, Bandelier Tuff lithics and pumice Permian Abo and Yeso sandstone
11	347313 3964557	Otowi Member, Bandelier Tuff
12	347255 3964636	Otowi Member, Bandelier Tuff Paliza Canyon Formation andesite and dacite Rhyolite
13	347610 3965010	Otowi Member, Bandelier Tuff
14	347908 3965171	Otowi Member, Bandelier Tuff
15	350371 3970368	Paliza Canyon Formation andesite and dacite Permian Abo sandstone Otowi Member, Bandelier Tuff

the Pajarito Plateau. The **Pueblo Canyon Member** on the northern Pajarito Plateau in Garcia Canyon is primarily a fine-grained sandstone derived from reworked **Valle Toledo Member**. Lenses of conglomerate eroded from the Tschicoma Formation and contributions from the Otowi Member are more common toward the south in Pueblo Canyon. Broxton and Vaniman (2005) used both outcrop and borehole data from the area south of Pueblo Canyon and north of Bandelier National Monument (Fig. 1) to document that the relative proportions of detritus from the Tschicoma Formation, Otowi Member of the Bandelier Tuff, and **Valle Toledo Member** in the **Pueblo Canyon Member** vary considerably across the southern Pajarito Plateau. For example, the **Pueblo Canyon Member** in the southwestern part of this area is composed of reworked Otowi Member sandwiched between beds of Tschicoma-derived conglomerate at the base and top of the unit (Broxton et al. 2002; Kleinfelder 2005). In contrast, just 5 km (3 mi) to the northeast, **Valle Toledo Member** tephra and Tschicoma Formation are the main components of the **Pueblo Canyon Member** (Broxton and Vaniman 2005; Kleinfelder 2006a, 2006b).

Primary **Valle Toledo Member** interbedded with the **Pueblo Canyon Member** on the northern Pajarito Plateau consists of pyroclastic-flow and fallout deposits with aphyric to crystal-poor pumice lapilli. The crystal-poor pumices have < 1% phenocrysts of potassium feldspar and pyroxene. Reworked crystal-rich pumice in this unit is derived from the underlying Otowi Member. The bulk of tephras on the northern Pajarito Plateau were erupted from the **Valle Toledo Member** domes located to the west of the Pajarito Plateau in the Toledo embayment (Figs. 1 and 5). Six to seven explosive cycles of phreatomagmatic tuff overlain by fallout deposits have been identified (Heiken et al. 1986). Spell et al. (1996a, 1996b) determined $^{40}Ar/^{39}Ar$ ages for the **Valle Toledo Member** tephras in section 15 (Stix 1989) that range from 1.65 Ma to 1.25 Ma. Early tephras are thickest in Pueblo Canyon, and the later tephras are more uniformly thick between Pueblo Canyon on the south and Santa Clara Canyon on the north (Fig. 1). South from Pueblo Canyon, interbedded primary tephras of the **Valle Toledo Member** decrease in abundance, ultimately giving way to sequences tens of meters thick of interbedded sandstones and conglomerate with no interbedded tephras (e.g., Gardner et al. 1993; "Cerro Toledo interval" of Broxton and Reneau 1995). Broxton and Vaniman (2005) report that primary **Valle Toledo Member** fall deposits are interbedded with the **Pueblo Canyon Member** as far south as Mortandad Canyon. The **Pueblo Canyon Member** in core hole SHB-3 near the junction of NM–4 and NM–501 (West Jemez Road; Fig. 1) consists of more than 30 m (98 ft) of dacitic-composition sands and boulder-bearing gravels, with only one thin interbed of **Valle Toledo Member** pumice lapilli, likely derived from Rabbit Mountain (Gardner et al. 1993).

Heiken et al. (1986) noted an isolated outcrop of **Valle Toledo Member** tephra on the south side of Rio del Oso (Figs. 1 and 7). In addition, we found rounded, reworked tephra derived from the **Valle Toledo Member** (based on pumice chemistry, N. Dunbar, unpubl. data) in a paleochannel cut into Tshicoma Formation dacite and Guaje Pumice Bed (Otowi Member of the Bandelier Tuff) tephra on Los Posos Mesa in

the northeastern Jemez Mountains (UTM: 381920E 3987660N, Figs. 1 and 7). Similarly, **Valle Toledo Member** tephra and **Pueblo Canyon Member** gravel deposits with clasts of locally derived Tschicoma Formation dacite and El Rechuelos Rhyolite obsidian are preserved between the Otowi Member and the Tshirege Member in the northern Jemez Mountains along Polvadera Creek (Figs. 1 and 7). Thus, the bulk of the **Pueblo Canyon Member** in the northeastern and north-northeastern Jemez Mountains is interbedded with material erupted from the **Valle Toledo Member** domes in the Toledo embayment (Figs. 1, 5, and 7).

Alamo Canyon Member

The **Alamo Canyon Member** is named for exceptional exposures of this unit in Alamo Canyon in Bandelier National Monument on the southeastern Pararito Plateau (Figs. 1 and 7). The section described by Jacobs and Kelley (2007) is designated as the type section. The deposit in Alamo Canyon is composed of a basal fluvial sandy conglomerate with several thin tephras near the top of the conglomerate, a **Valle Toledo Member** pyroclastic-flow deposit containing aphyric obsidian breccia derived from collapse of the Rabbit Mountain dome to the west, and an upper fluvial sandy conglomerate with tephra. The provenance of the **Alamo Canyon Member** is in the southeastern Jemez Mountains, in contrast to the **Pueblo Canyon Member**, which is sourced in the northeastern Jemez Mountains. Thus, the **Alamo Canyon Member** fluvial deposits include clasts of Paliza Canyon Formation andesite and dacite, Canovas Canyon Rhyolite, Bearhead Rhyolite, and aphyric **Valle Toledo Member** obsidian (Rabbit Mountain obsidian). The tephras from the basal conglomerate and the pyroclastic flow yield $^{40}Ar/^{39}Ar$ ages in the 1.65–1.56 Ma range and appear to contain abundant xenocrystic sanidine derived from the underlying Otowi Member of the Bandelier Tuff (Jacobs 2008). A tephra in the upper conglomerate yielded a 1.42 ± 0.03 Ma $^{40}Ar/^{39}Ar$ sanidine age (Jacobs 2008). **Alamo Canyon Member** fluvial gravel is present, but has not been described in detail, in the Colle Canyon area just north of Kasha-Katuwe Tent Rocks National Monument in the southern Jemez Mountains (Fig. 1).

Valles Rhyolite

Changes that we propose to the Valles Rhyolite leave the Deer Canyon and Redondo Creek Members (Fig. 8) unaffected, and these units will be discussed no further. With abandonment of the *Valle Grande Member* (discussed above), our proposed seven new members and consolidation of the former *El Cajete, Battleship Rock,* and *Banco Bonito Members* into the new **East Fork Member** will be the focus of discussion here (Fig. 2).

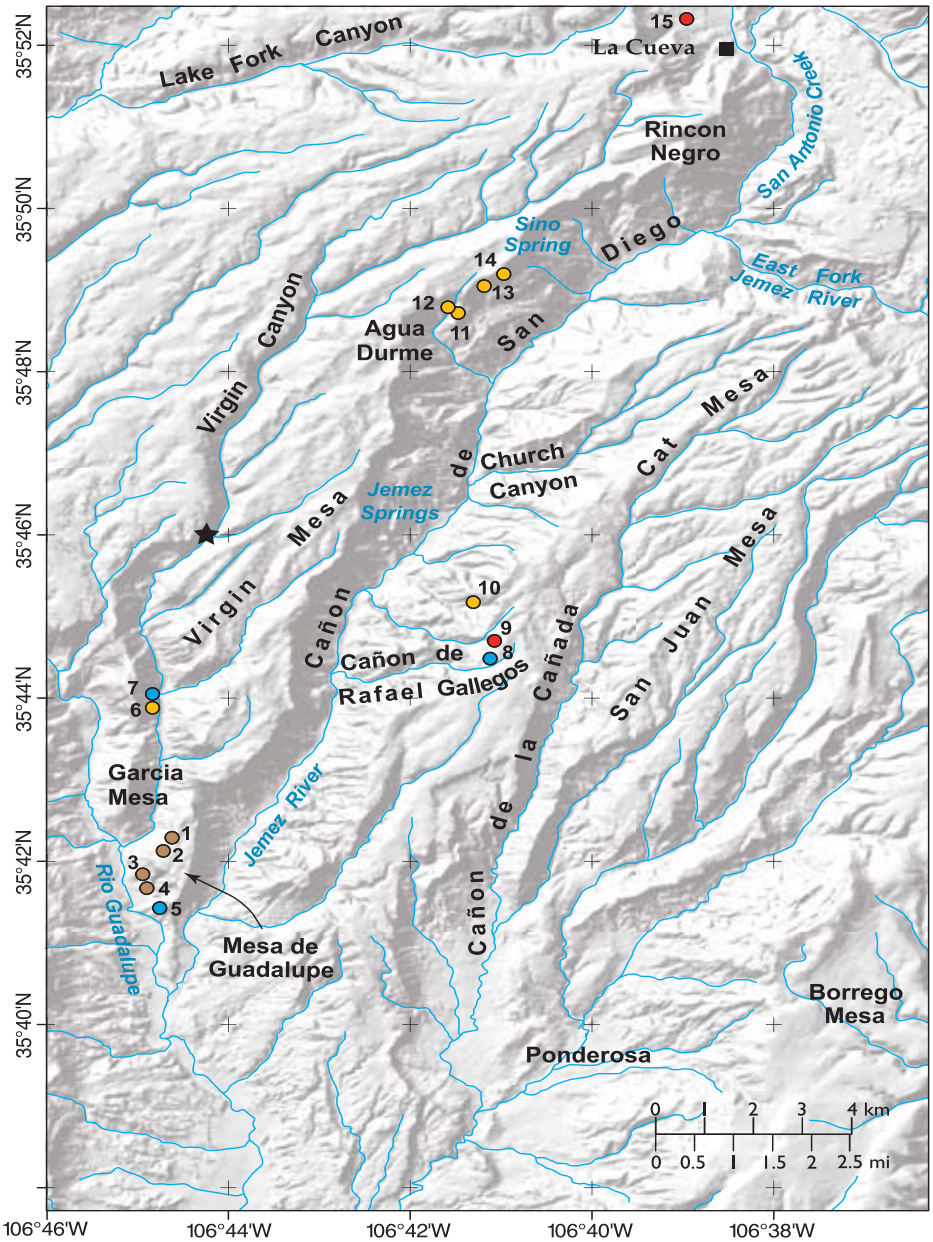

FIGURE 6—Location of exposures of the Virgin Canyon Member in Cañon de San Diego and Virgin Canyon in the southwestern Jemez Mountains. The numbered dots are localities keyed to Table 2. The color of each dot reflects the dominant rock type of clasts in each fluvial deposit: brown = Proterozoic granite and metamorphic rocks, blue = Paleozoic sedimentary rocks, red = Paliza Canyon Formation volcanic rocks, yellow = recycled Otowi Member lithic fragments, pumice, and tuff. The star is the location of the outcrop of paleo-Virgin Canyon.

Cerro del Medio Member

The name for this new member is derived from the cluster of hills and mountains so labeled on Valle Toledo 7.5-min topographic quadrangle. The type area is established as an area of 2–3 km (~ 1–2 mi) radius about UTM: 368800E 3974250N. The **Cerro del Medio Member** is a rhyolite flow and dome complex of at least six distinctive phases of eruptive activity, distinguished petrographically and morphologically, that have a composite volume of about 5 km^3 (1 mi^3) (Fig. 8; Gardner et al. 2007). The complex consists of a crude partial ring of older rhyolite flow remnants, intruded by an upheaved dome whose margins, where exposed, are vertically foliated breccias. A final eruption at the summit gave rise to a small-volume lava flow that caps the mountain. Doell et al. (1968) presented a figure that inaccurately divides the complex into three units, and this, together with Bailey et al.'s (1969) description of Cerro del Medio rhyolite as "nearly free of phenocrysts," has led to some confusion regarding samples used for determining isotopic ages on the complex (see Izett and Obradovich 1994 and Spell and Harrison 1993).

Pyroclastic activity accompanied much **Cerro del Medio** volcanism, and primary

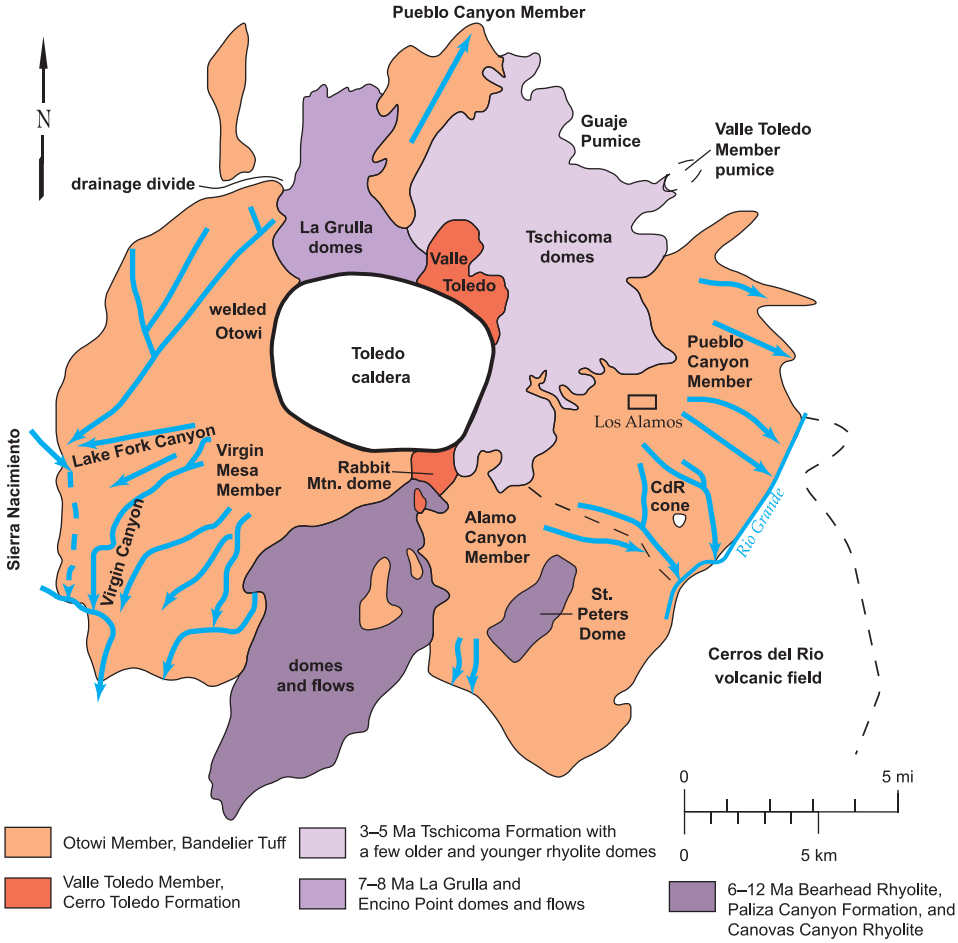

FIGURE 7—Simplified geologic map of the Jemez Mountains before eruption of the Tshirege Member of the Bandelier Tuff at 1.25 Ma. Blue arrows show paleovalleys cut into the Otowi Member of the Bandelier Tuff. Purple areas were highlands during this time frame. Paleocanyons on the east side of the Jemez Mountains near Los Alamos are modified from Dethier and Kampf (2007), Broxton and Vaniman (2005), and Jacobs (2008). CdR = Cerros del Rio.

pyroclastic fall deposits as thick as 4 m (13 ft) are on the complex's north flank. Additionally, **Cerro del Medio** tephra fragments are included in sedimentary deposits within the caldera, and **Cerro del Medio Member** pyroclastic flows are mappable on the Valle San Antonio 7.5-min quadrangle (Goff et al. 2006). Tephras of the **Cerro del Medio Member** have also been recognized as pumice lapilli, reworked in alluvial deposits east of the Valles caldera on the Pajarito Plateau (Reneau and MacDonald 1996; McCalpin 1998; Reneau et al. 2002).

Flows and deposits of the **Cerro del Medio Member** range from truly aphyric, to 1–3% phenocrysts, to around 5% phenocrysts. Rocks are glassy obsidian, pumiceous rhyolite, devitrified rhyolite, and vitrophyre. Local zones of flow banding and spherulite development are common. Phenocrysts (≤ 2 mm) of sanidine and glomerocrysts of sanidine and other phases are most common, with sparse hornblende, opaque oxides, and embayed quartz, rare plagioclase, and extremely rare clinopyroxene and zircon. Feldspars are weakly zoned and largely inclusion free to moderately zoned with some phenocryst cores and zones riddled with inclusions of mostly glass.

Some obsidian of the **Cerro del Medio Member** is so clean and free of inclusions and crystals that it was a highly desired material for tool and point making for ancient peoples. Ancient quarry sites are common within the type area of the member, and lithic scatters include exotic rocks, such as rounded quartzite cobbles from axial river deposits near the Rio Grande, that were used as hammerstones. Ancient peoples quarried the **Cerro del Medio Member** aphyric obsidian so extensively that true outcrops can be difficult to find.

Thicknesses of flows of the **Cerro del Medio Member** range from 30 m to 120 m (98–394 ft), with the upheaved part of the complex attaining a thickness of about 260 m (853 ft). Basal contacts of the member are not exposed, but the unit presumably overlies early caldera-fill sedimentary deposits. Assorted sedimentary deposits of poorly constrained ages also overlie portions of the complex, but no other useful contact relations are evident. Spell and Harrison (1993) determined a composite $^{40}Ar/^{39}Ar$ date of 1.133 ± 0.011 Ma (one sigma error) for the entire **Cerro del Medio** complex. However, detailed work by Phillips (2004, unpubl), Phillips et al. (2007), and Gardner et al. (2007) has yielded very high precision dates on one of the older flows and obsidian from the stratigraphic middle of the sequence that indicate the **Cerro del Medio** eruptions spanned at least 40,000–80,000 yrs, with the top of the **Cerro del Medio** sequence remaining undated. Phillips (unpubl.) determined an $^{40}Ar/^{39}Ar$ age of 1.169 ± 0.005 Ma (two sigma error) for the middle of the **Cerro del Medio** sequence, and Phillips (2004; Phillips et al. 2007) dated the southern lobe of the complex by $^{40}Ar/^{39}Ar$ at 1.229 ± 0.017 Ma. The magnetic polarity of the **Cerro del Medio Member** is reversed (Doell et al. 1968).

Cerros del Abrigo Member

The name for this new member is from the hills so named on the Valle Toledo 7.5-min quadrangle that are a complex of four dome and flow sequences of finely porphyritic rhyolite with subtle petrographic variations among them. The type area is established as an area of about 1–2 km (~ 0.5–1 mi) radius (Fig. 9) about UTM: 366475E 3977650N. An apron of an older rhyolite flow skirts the complex on the south and is apparently intruded by several younger, petrographically similar domes. The dome and flow rocks of the **Cerros del Abrigo Member** comprise about 2 km^3 (0.5 mi^3) of rhyolite. Rocks are white to gray, glassy to perlitic to devitrified porphyritic rhyolite. Phenocrysts in the member range from 10 to 20% and are dominantly sanidine with subordinate plagioclase and sparse pale-pink quartz, biotite, and opaque oxides. Euhedral, embayed, and fragmented bipyramidal forms of quartz are present as well as trace phenocrysts of hornblende.

Contact relations of the **Cerros del Abrigo Member** with other units are covered or obscured by younger sedimentary deposits, although a portion of the south part of the complex overlies pyroclastic flows that belong to the **Cerro del Medio Member**. The older flow on the south side of the complex has maximum exposed thickness of about 65 m (213 ft), and an apparently exogenous dome in the complex is as much as 405 m (1,329 ft) thick. Spell and Harrison (1993) give a composite $^{40}Ar/^{39}Ar$ date of 0.973 ± 0.010 Ma for the entire complex. Magnetic polarity is normal (Doell et al. 1968).

Cerro Santa Rosa Member

The name for this new member derives from long-standing usage on geologic maps and in the published literature (for example, Doell et al. 1968; Bailey et al. 1969; Smith et al. 1970; Spell and Kyle 1989; Spell and Harrison 1993; Gardner and Goff 1996; Gardner et al. 2006; Goff et al. 2006). Singer and Brown (2002) have even named the geomagnetic "Santa Rosa Event" based on work on this member. Unfortunately, recently revised topographic maps restrict the name Cerro Santa Rosa to the northern hill of the type area (see below), and label a chain of hills, including the **Cerro Santa Rosa Member**, "Cerros de

Trasquilar." The type area is hereby designated as the north-northeast-trending chain of hills, about 3.5 km (2.2 mi) long and less than 2 km (1.25 mi) wide (Fig. 9), centered at UTM: 3664350E and 3979000N. The **Cerro Santa Rosa Member** consists of about 1.2 km^3 (0.25 mi^3) of at least two domes and flows and pyroclastic deposits of petrographically and chemically similar rhyolite. The rocks of the member are white to gray, porphyritic rhyolite with glassy, pumiceous textures. Phenocrysts (as large as 4 mm) constitute 10–20% of the rocks and comprise abundant pink quartz, subordinate sanidine, and biotite. Sanidine in some flows exhibits chatoyance. The southern dome of the member is apparently exogenous, exhibiting a breccia apron around the summit, and yields $^{40}Ar/^{39}Ar$ dates of 0.914 ± 0.004 Ma (one sigma error, Spell and Harrison 1993) and 0.936 ± 0.008 Ma (two sigma error, Singer and Brown 2002). The maximum thickness is more than 240 m (787 ft). The northern dome has been dated by $^{40}Ar/^{39}Ar$ at 0.787 ± 0.015 Ma (one sigma error, Spell and Harrison 1993), and is about 150 m (492 ft) thick. The southern dome of the type area overlies a pyroclastic flow of the **Cerro del Medio Member**, and a flow of the northern dome underlies terrace deposits along San Antonio Creek in Valle Toledo and Valle San Antonio (Fig. 9). Pyroclastic flows of the **Cerro Santa Rosa Member** underlie lavas of the **Cerro San Luis Member**, to the west, and are apparently beneath Santa Rosa lavas on the southeast side of the type area. The **Cerro Santa Rosa Member** pyroclastic flow underlying the **Cerro San Luis Member** has been dated by $^{40}Ar/^{39}Ar$ at 0.91 ± 0.03 Ma (Kelley et al. in prep.) and is about 15 m (49 ft) thick. Magnetic polarity of the older south dome is transitional (Doell et al. 1968; Singer and Brown 2002), but polarity of the younger north dome is normal.

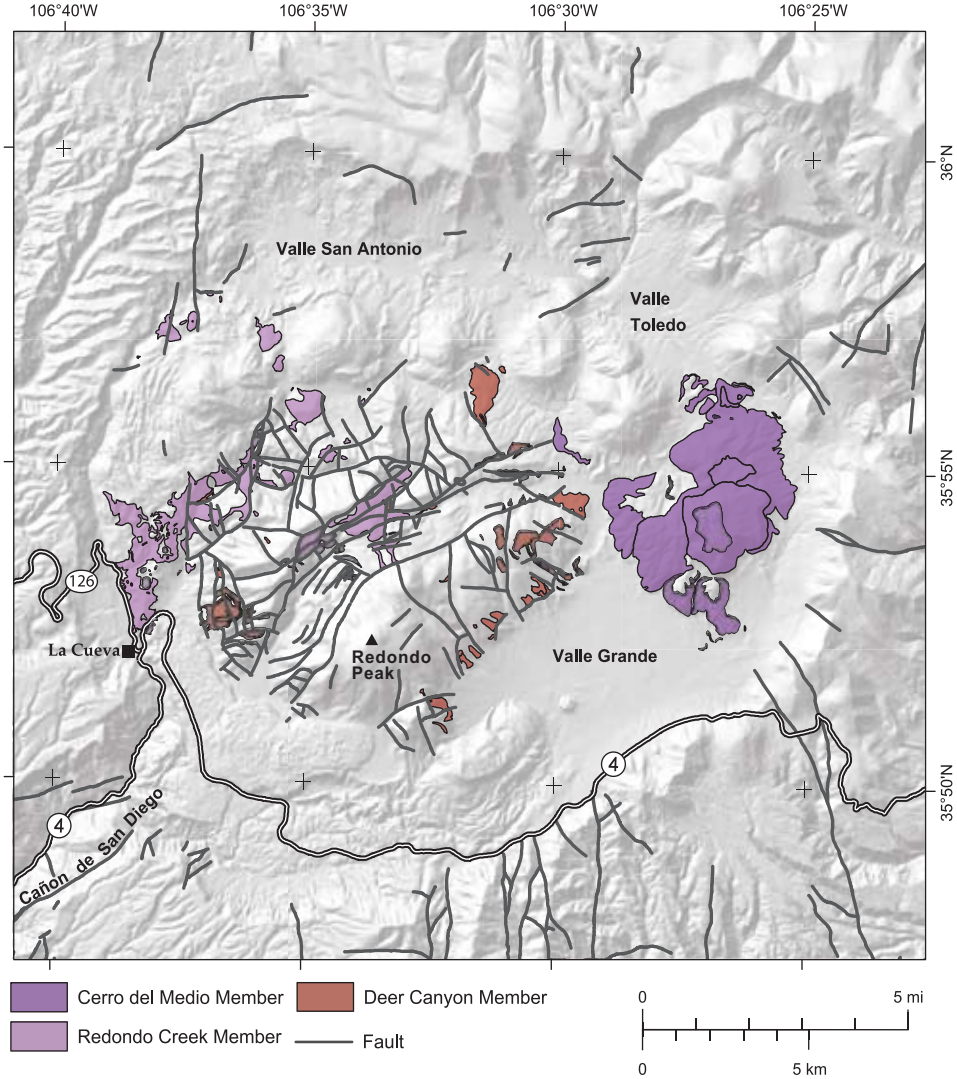

FIGURE 8—Shaded relief map of Valles–Toledo caldera complex showing Deer Canyon, Redondo Creek, and Cerro del Medio Members of the Valles Rhyolite (formation) and some features mentioned in text. This map shows a pulse of post-Valles caldera volcanism from roughly 1.25 to 1.1 Ma (data from Goff et al. in prep.).

Cerro San Luis Member

The name for this member does not appear on topographic maps but enjoys long-standing usage on geologic maps and in the published literature (Doell et al. 1968; Bailey et al. 1969; Smith et al. 1970; Spell and Kyle 1989; Spell and Harrison 1993; Goff et al. 2006). The type area of the **Cerro San Luis Member** is the area of about 1.5 km (1 mi) radius (Fig. 9) around UTM: 361400E and 3979100N. The **Cerro San Luis Member** is about 1 km^3 (0.25 mi^3) and consists of two main eruptive pulses, with a broad ring of lava intruded by a younger dome of about 325 m (1,066 ft) thickness. Rocks are typically flow-banded, pumiceous, porphyritic rhyolite. Phenocrysts of sanidine, quartz, and biotite make up about 10% of the rocks and are set in a gray to pale-pink devitrified groundmass. Primary glass is rare. Pyroclastic deposits associated with the **Cerro San Luis Member** eruptions have not been identified, but Goff et al. (2006) suspect they underlie **San Luis** lavas on the north and east sides of the type area. **Cerro San Luis** lavas overlie and fill a paleocanyon cut into early caldera-fill sedimentary units on the west side of, and overlie a pyroclastic flow of the **Cerro Santa Rosa Member** on the east side of, the type area. Pyroclastic deposits of the **Cerro Seco Member** overlie **Cerro San Luis** lavas. Spell and Harrison (1993) report an $^{40}Ar/^{39}Ar$ date of 0.800 ± 0.003 Ma (one sigma error) from the **Cerro San Luis Member**. Magnetic polarity is reversed.

Cerro Seco Member

The name for this new member comes from long-standing usage in the published literature (Doell et al. 1968; Bailey et al. 1969; Smith et al. 1970; Spell and Kyle 1989; Spell and Harrison 1993; Goff et al. 2006), but it does not appear on topographic maps. The type area for the **Cerro Seco Member** is designated as the rectangular area defined with the northwest corner at UTM: 356050E 3981750N, and the southeast corner at UTM: 359600E 3977300N. The **Cerro Seco Member** consists of about 1.5–2 km^3 (0.25–0.5 mi^3) of porphyritic rhyolite and pyroclastic deposits (Fig. 9). As is common with some members of the Valles Rhyolite, the **Cerro Seco Member** has a partial, remnant ring of an older lava, intruded by a younger dome. A radiating apron of **Cerro Seco Member** ignimbrite, dry surge, and hydromagmatic surge lies in the north part of the type area. The pyroclastic deposits underlie the lavas of the member, and runout of pyroclastic flows was at least 2 km (1.25 mi), assuming a vent location within the area of the dome and flow. White laminated mudstone with desiccation cracks is interbedded with the pyroclastic deposits, and some pyroclastic deposits have been reworked into intercalated sedimentary beds. Pyroclastic deposits also contain angular fragments of cognate rhyolite. Rocks are commonly flow banded, devitrified, or vitrophyric and contain 5–10% phenocrysts of quartz and sanidine, with sparse biotite and rare hornblende. Sanidine is commonly chatoyant, and quartz can have a vague pinkish tint.

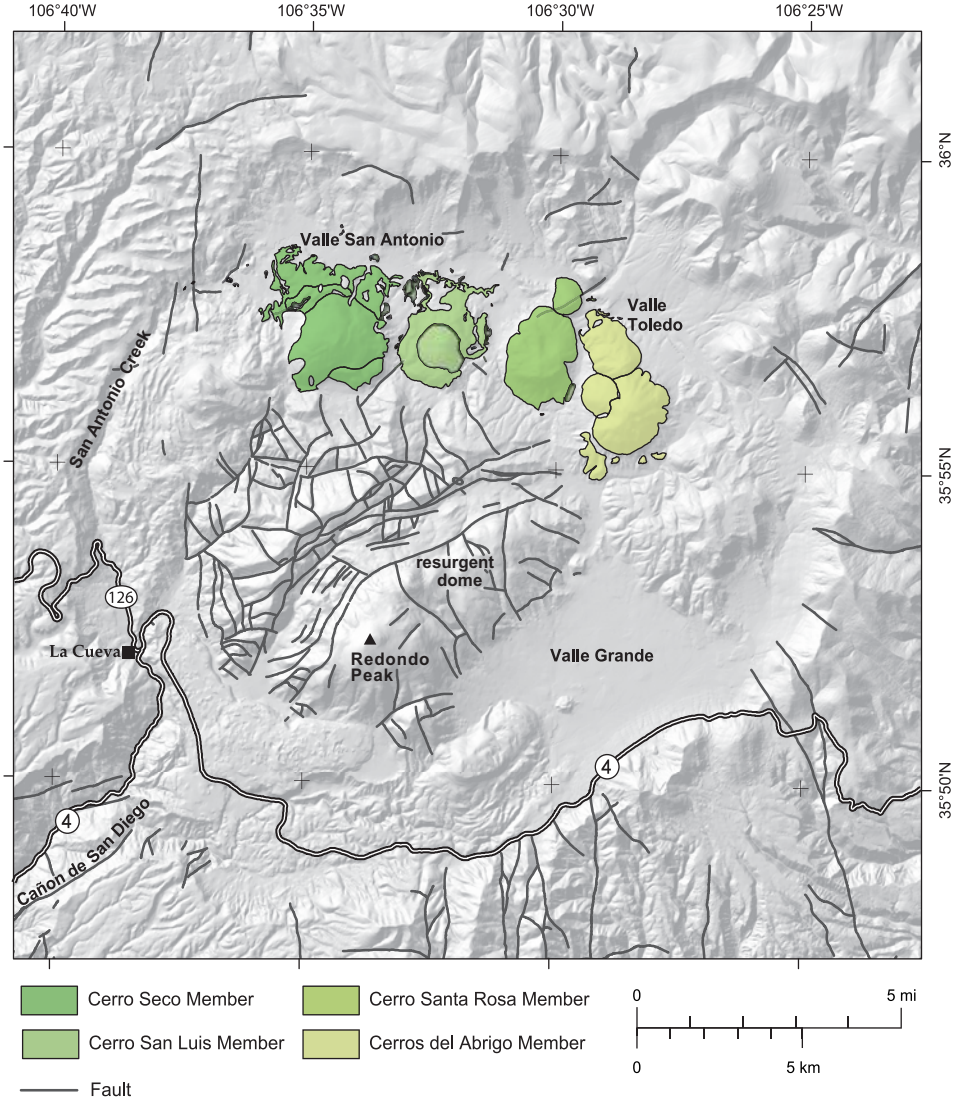

FIGURE 9—Shaded relief map of Valles–Toledo caldera complex showing Cerros del Abrigo, Cerro Santa Rosa, Cerro San Luis, and Cerro Seco Members of the Valles Rhyolite (formation) and some features mentioned in text. These members form a pulse of post-Valles caldera volcanism from roughly 1.0 to 0.8 Ma (data from Goff et al. in prep.).

Pyroclastic deposits of the **Cerro Seco Member** overlie **Cerro San Luis Member** lava and cover portions of the Warm Springs dome of the **Valle Toledo Member** (Figs. 5 and 9). Additionally, **Cerro Seco** units overlie debris-flow deposits from the resurgent dome of Valles caldera, caldera-fill deposits, fluvial units, and some flat-lying lacustrine deposits in the northern caldera moat. Contact relations with the **San Antonio Mountain Member**, to the west and southwest, have been obscured by erosion. Spell and Harrison (1993) report an $^{40}Ar/^{39}Ar$ date of 0.800 ± 0.007 Ma on a sample that is probably from the dome of the member. $^{40}Ar/^{39}Ar$ sanidine dates on the **Cerro Seco** pyroclastic deposits are 0.77 ± 0.03 Ma for a large pumice clast from an ignimbrite bed, and 0.78 ± 0.04 Ma from pumice in a hydromagmatic bed (Kelley et al. in prep.). The **Cerro Seco Member** dome attains a thickness of 375 m (1,230 ft), whereas lava and pyroclastic flows have a maximum thickness of about 75 m (246 ft). Magnetic polarity is reversed.

San Antonio Mountain Member

The name for this member is taken from San Antonio Mountain, as labeled on the Valle San Antonio 7.5-min quadrangle. The type area is designated as the area defined by roughly a 3 km (1.86 mi) radius (Fig. 10) about UTM: 354180E 3978100N. The **San Antonio Mountain Member** consists of a porphyritic rhyolite flow and dome center that exhibits at least three eruptive pulses. A partial ring of older lavas is centrally intruded by younger domes, with a total volume for the member of about 4 km^3 (1 mi^3). Rocks exhibit 15–30% felsic phenocrysts of sandine, plagioclase, and pink quartz, with as much as 5% mafic phenocrysts of biotite, hornblende, and rare clinopyroxene. The groundmass is typically devitrified or perlitic, and rocks are commonly flow banded. **San Antonio Mountain Member** lavas buried an ancestral San Antonio Creek and abutted the west topographic wall of the caldera, forming a substantial dam (Rogers 1996; Rogers et al. 1996; Reneau et al. 2004). The resultant lake ponded in the Valle San Antonio and in the adjacent Valle Toledo, with major arms extending up San Luis Creek and Valle Santa Rosa (Fig. 10). Lacustrine deposits associated with this lake are well exposed in the Valle San Antonio and Valle Toledo quadrangles, and generally consist of finely laminated to more thickly bedded clay, silt, and sand, and are variably diatomaceous. Inferred deltaic sediments are also exposed near the east side of the Valle San Antonio and in Valle Santa Rosa, recording partial filling of the lake with coarser fluvial sediment (Gardner et al. 2006; Goff et al. 2006). **San Antonio Mountain Member** rhyolites overlie debris-flow deposits from the caldera's resurgent dome, Redondo Creek Member rhyolite, and lacustrine deposits in the north caldera moat. Spell and Harrison (1993) report a composite $^{40}Ar/^{39}Ar$ date of 0.557 ± 0.004 Ma on one of the central domes. Thickness of the member exceeds 510 m (1,673 ft). Magnetic polarity is normal.

South Mountain Member

The name for the new **South Mountain Member** comes from long-standing usage on geologic maps and in the published literature (Doell et al. 1968; Bailey et al. 1969; Smith et al. 1970; Spell and Kyle 1989; Spell and Harrison 1993; Goff et al. 2005a, 2005b). The name does not appear on topographic maps. The type area for the **South Mountain Member** is a northeast-trending rectangular area about 5 km (3 mi) long and 2 km (1.35 mi) wide (Fig. 10), centered on UTM: 361850E 3966750N. It should be noted that **South Mountain** lavas flowed for at least 10 km (6 mi) west of the type area, and a satellite dome of the member, called Cerro La Jara (Fig. 10), lies about 1 km (.05 mi) east-northeast of the type area. The domes, lavas, and pyroclastic deposits of the **South Mountain Member** record at least five eruptive episodes of porphyritic rhyolites from the center in the southwestern part of the Valle Grande. Because of extensive burial by younger deposits, a volume estimate for the member of about 6 km^3 (1.5 mi^3) is probably a minimum. Rocks are typically flow banded, pumiceous, and devitrified, although fresh groundmass glass is not uncommon. Dominantly felsic phases, such as sanidine, plagioclase, and pale-pink quartz, and as much as 5% mafic phases of mostly biotite, hornblende, and minor clinopyroxene constitute 10–20% phenocrysts in the rocks. **South Mountain Member** lavas fill a paleocanyon through the southwestern moat of Valles caldera, and a pyroclastic flow beneath the lavas of the member is exposed in roadcuts along NM–4 at the southwestern end of the type area. The Cerro La Jara dome intrudes caldera-fill sedimentary deposits, and is onlapped by lacustrine and beach deposits from a lake formed during eruption of the **East Fork Member**. **South Mountain Member** lavas are extensively covered with fallout deposits from the **East Fork Member** eruptions and younger alluvial units. A

sequence of alluvial sediments also overlies **South Mountain** lavas in the VC-1 core hole (Fig. 11; Gardner et al. 1987; Goff and Gardner 1987). Lower contacts of the member are generally not exposed, but in the type area the lavas no doubt overlie caldera-fill sediments, and far to the west **South Mountain** lavas overlie older landslide deposits and a layer of fluvial and minor lacustrine rocks, which in turn overlie older andesite and Paleozoic and Mesozoic rocks in ravines west of Jemez Falls (Fig. 10). Spell and Harrison (1993) report $^{40}Ar/^{39}Ar$ dates of 0.52 ± 0.01 Ma on South Mountain proper, and 0.53 ± 0.01 Ma on Cerro La Jara. Thicknesses in the member are extremely variable with Cerro La Jara about 75 m (246 ft), the westward extending lava about 100 m (328 ft), and South Mountain itself at least 450 m (1,476 ft). Magnetic polarity is normal.

East Fork Member

The name for this new member is an abbreviation from the East Fork Jemez River (Fig. 11). The river cuts through the heart of the exposed beds and flows of the member, and the area exemplifies the textural variety of the member imparted by differing eruptive styles. The **East Fork Member** includes the former *Battleship Rock*, *El Cajete*, and *Banco Bonito Members* of Bailey et al. (1969) and Smith et al. (1970) as the **Battleship Rock Ignimbrite**, **El Cajete Pyroclastic Beds**, and the **Banco Bonito Flow**. The type areas for the flows and beds of the **East Fork Member** designated by Bailey et al. (1969) are retained. Bailey et al. (1969) established the Battleship Rock, El Cajete, and Banco Bonito units, giving each member status within the stratigraphic hierarchy of the Valles Rhyolite. The *Battleship Rock Member* was defined as a "sequence of local rhyolitic ash-flow deposits," the *El Cajete Member* as "a mantle-bedded air-fall deposit of rhyolitic pumice lapilli and blocks," and the *Banco Bonito Member* as "the porphyritic obsidian flow that fills the southwestern moat of Valles caldera" (Bailey et al. 1969). Because they found densely welded tuff lithic fragments, identical to the welded tuffs at Battleship Rock, in the El Cajete deposits, Bailey et al. (1969) and Smith et al. (1970) inferred the Battleship Rock as the oldest of the three members, followed in turn by the El Cajete, and capped with the effusive Banco Bonito. Bailey et al. (1969) acknowledged the petrographic similarities among the three members, and Self et al. (1988, 1991) recognized the three members represented products of the same eruption sequence, which they called the "El Cajete Series," with differences imparted only by eruptive style. Wolff and Gardner (1995) established the common petrogenesis of the units, referring to them collectively as the "southwestern moat rhyolites."

The VC-1 core hole (Fig. 11) penetrated about 298 m (978 ft) of the **East Fork Member**, which consisted of several vitrophyric lavas, at least four welded tuffs, and relatively minor pyroclastic fallout beds. One of the vitrophyric lavas, called the VC-1 rhyolite (Gardner et al. 1987; Goff et al. 1986), clearly is not present in surface exposures. Because of the sequence and petrologic similarities of Bailey et al.'s (1969) original three members, correlations to VC-1 became immediately problematic. Additionally, Wolff et al. (1996) identified yet another effusive event in the sequence that was previously unrecognized, and they pointed out that the true complexity of the sequence, eruptive behavior of the units, the effects of paleotopography, and the petrologic kinship of the units rendered correlations of widely separated localities tenuous, at best. In that the units of Bailey et al. (1969) represent the youngest eruptions from the Valles caldera area, and are superficially individually distinguishable, they have been the focus of a fair amount of attention that, although revealing in some respects, has led to controversy and confusion (Kelley et al. 1961; Smith et al. 1970; Bailey and Smith 1978; Goff et al. 1986; Gardner et al. 1987; Self et al. 1988, 1991, 1996). In the words of Wolff et al. (1996): "the published works on these units can be best described as a history of conflicting interpretations" with respect to stratigraphic sequence and correlations.

Thus, we propose establishment of the new **East Fork Member**, which includes the **El Cajete Pyroclastic Beds, Battleship Rock Ignimbrite, Banco Bonito Flow**, and VC-1 rhyolite. The broadened definition of the **East Fork Member** serves to highlight its importance as the most recent eruptive sequence within the Valles caldera with implications for possible renewed volcanic hazards to the region (Wolff and Gardner 1995; Reneau et al. 1996; Wolff et al. 1996). We retain the original three units of Bailey et al. (1969) as beds or flows because of their local utility in geologic mapping (Kelley et al. 2003; Goff et al. 2000, 2005a, 2005b) and their long-standing usage. Published descriptions and delineation of the units that make up the **East Fork Member** can be found in Bailey et al. (1969), Wolff and Gardner (1995), Wolff et al. (1996), Kelley et al. (2003), and

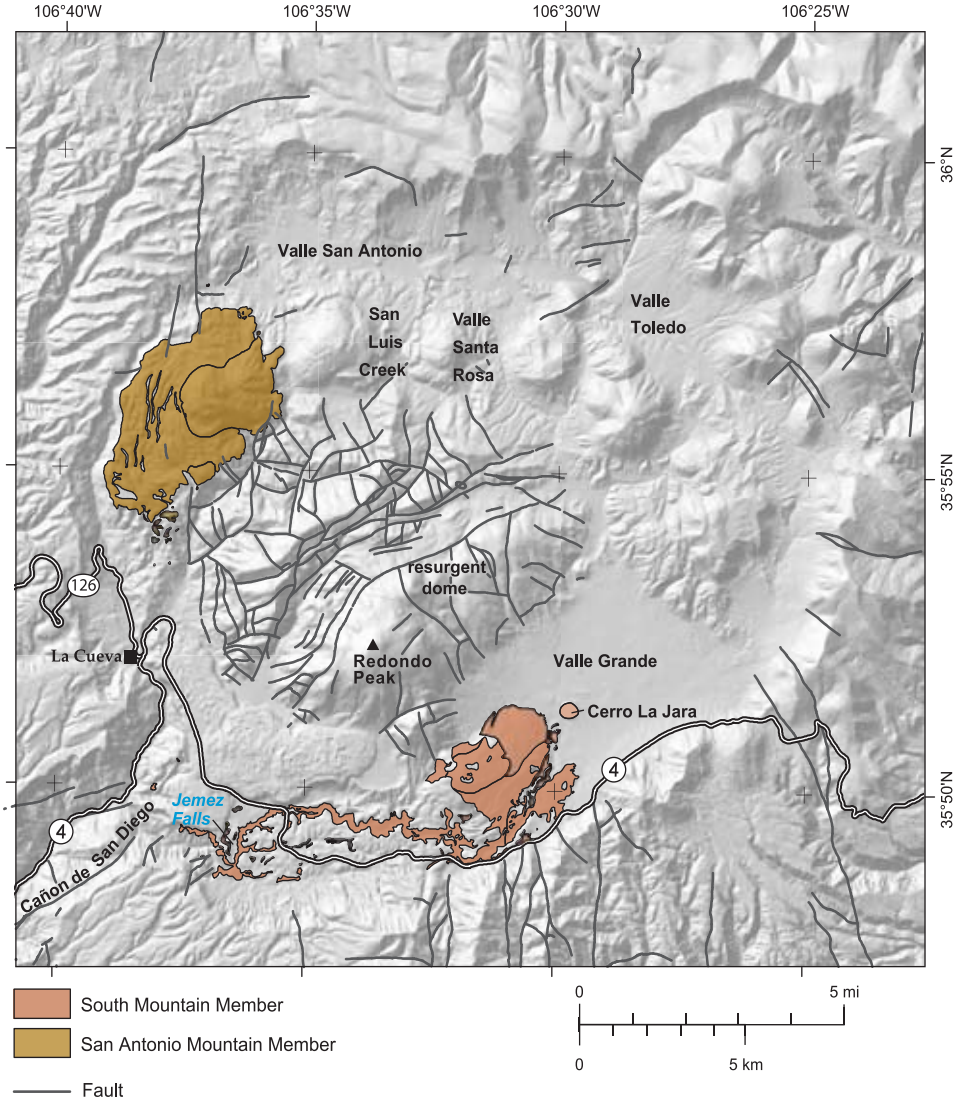

FIGURE 10—Shaded relief map of Valles–Toledo caldera complex showing San Antonio Mountain and South Mountain Members of the Valles Rhyolite (formation) and some features mentioned in text. These members form a pulse of post-Valles caldera volcanism from about 0.56–0.52 Ma (data from Goff et al. in prep.).

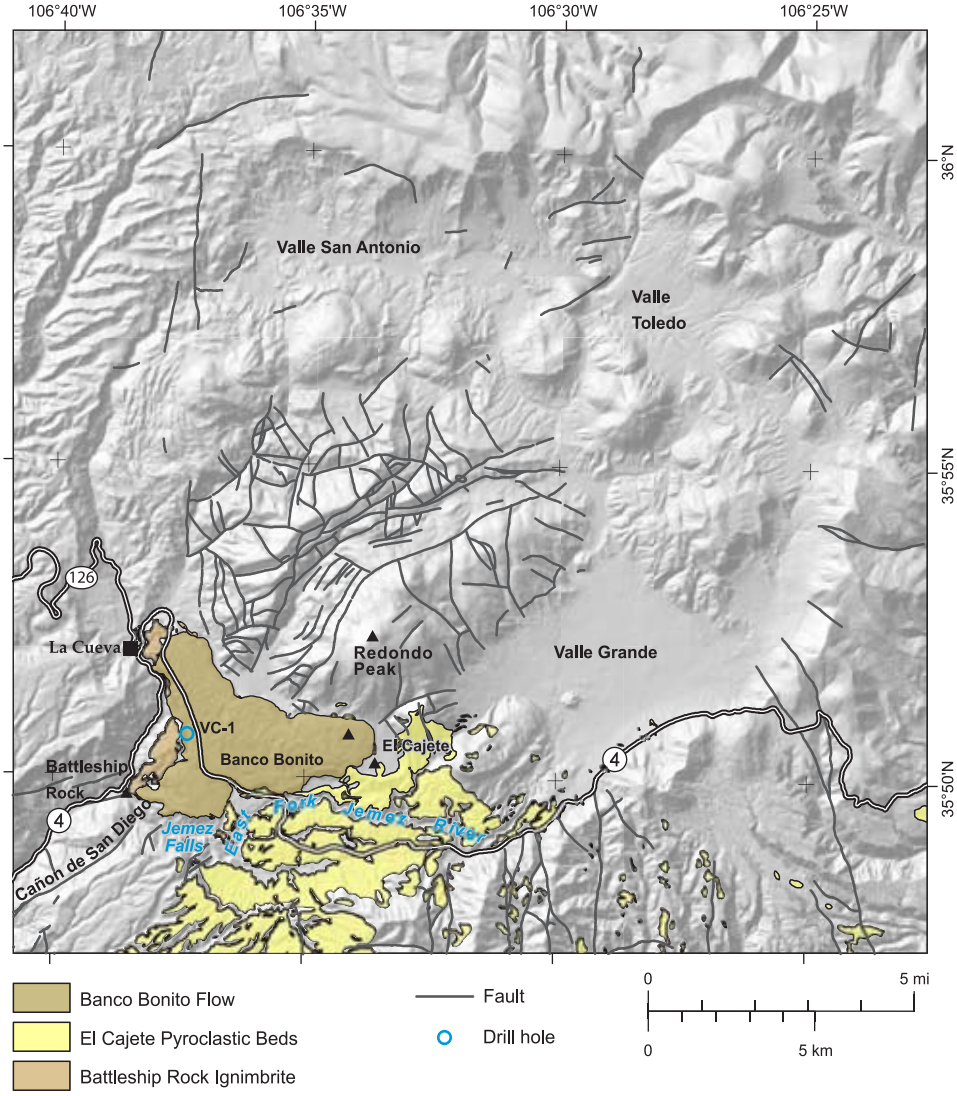

FIGURE 11—Shaded relief map of Valles–Toledo caldera complex showing flows and beds of the East Fork Member of the Valles Rhyolite (formation) and some features mentioned in text. The East Fork Member is the youngest pulse of post-Valles caldera volcanism from about 0.06 to 0.04 Ma (data from Goff et al. in prep.).

Goff et al. (2000, 2005a, 2005b) and will not be repeated here. Recent work indicates the **East Fork Member** spans about 60–40 ka (Reneau et al. 1996; Toyoda et al. 1995; Phillips et al. 1997). A recent attempt to date the **Banco Bonito Flow** by optically stimulated luminescence (OSL) dating provided no resolution to the age of this unit (Lepper and Goff 2007). Magnetic polarity of **Banco Bonito Flow** is normal.

Conclusions

Data gathered during many studies in the decades following the original establishment and definition of the Tewa Group precipitate the need for, and form the basis for, revisions to the formal stratigraphic nomenclature. The formation *Cerro Rubio Quartz Latite* is abandoned because geochronologic and petrologic studies show it is most appropriately part of the Tschicoma Formation. Furthermore, field relations indicate that the stratigraphic position of the *Cerro Rubio Quartz Latite*, originally inferred to span the formation and resurgence of Valles caldera (Griggs 1964; Smith et al. 1970), is simply not valid. The *Valle Grande Member* of the Valles Rhyolite is abandoned because of long-standing disuse, and collection of sufficient field, petrologic, and temporal data to establish seven individually distinctive new members to replace it. The Bandelier Tuff has been expanded to include the **La Cueva Member**, previously called a variety of names, which is a pair of ignimbrites with Bandelier Tuff-like petrography and chemistry that underlies the Otowi Member of Bandelier Tuff. The *Cerro Toledo Rhyolite* has been expanded into the **Cerro Toledo Formation** that includes four members: the volcanic **Valle Toledo Member,** and the dominantly sedimentary **Virgin Canyon Member, Pueblo Canyon Member,** and **Alamo Canyon Member**. This new designation provides insight into the distribution of highlands and river valleys before the eruption of the Tshirege Member of the Bandelier Tuff at 1.25 Ma (Fig. 7). A new **East Fork Member** is created that contains the VC-1 rhyolite, the **El Cajete Pyroclastic Beds**, the **Battleship Rock Ignimbrite**, and the **Banco Bonito Flow**. It is our sincere intention that this new stratigraphy for the Tewa Group will provide a robust, but flexible, framework that facilitates future studies.

Acknowledgments

We thank Steve Reneau and Grant Heiken (LANL), Steve Self (Nuclear Regulatory Commission), John Wolff (Washington State University), John Stix (University of Montreal), Terry Spell (University Nevada-Las Vegas), and Kirt Kempter for their discoveries and hard work on various stratigraphic issues of the Tewa Group. A huge cast of geologic mappers, graduate students, and field assistants too numerous to name contributed to our evolving understanding of the Tewa Group from 1978 to 2009. Funding and/or assistance during this time period came from the Office of Basic Energy Sciences (U.S. Department of Energy), Los Alamos National Laboratory's Community Relations Office, the Valles Caldera National Preserve, the U.S. Forest Service, and the STATEMAP program, which is jointly sponsored by the U.S. Geological Survey and the New Mexico Bureau of Geology and Mineral Resources. We appreciate the ongoing support of STATEMAP program managers Paul Bauer and J. Michael Timmons. Rick Kelley helped with preparation of many of the figures. Jane Love and Greer Price (NMBGMR) provided invaluable help pulling the manuscript together. We are grateful for insightful reviews by Dave Broxton, John Wolff, and Nelia Dunbar that greatly improved aspects of the draft manuscript.

References

Bailey, R. A., and Smith, R. L., 1978, Guide to the Jemez Mountains and Española Basin: New Mexico Bureau of Mines and Mineral Resources, Circular 163, pp. 184–196.

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

Broxton, D. E., and Reneau, S. L., 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, 18 pp.

Broxton D. E., and Vaniman, D. T., 2005, Geologic framework of a groundwater system on the margin of a rift basin, Pajarito Plateau, north-central New Mexico: Vadose Zone Journal, v. 4, pp. 522–550.

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

Cook, G. W., Wolff, J. A., and Self, S., 2006, The Otowi Member of the Bandelier Tuff, Valles caldera, New Mexico: A new volume and evidence of vent site evolution during eruption (abs.): Transactions of the American Geophysical Union (EOS), #V53C-1773.

Dethier, D. P., and Kampf, S. K., 2007, Reconstructing pyroclastic flow dynamics and landscape evolution using the upper Bandelier Tuff, Puye quadrangle, New Mexico; *in* Kues, B. S., Kelley, S. A., and Lueth, V. W. (eds.), Geology of the Jemez region II: New Mexico Geological Society, Guidebook 58, pp. 344–353.

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

Gardner, J. N., and Goff, F., 1984, Potassium-argon dates from the Jemez volcanic field: implications for tectonic activity in the north-central Rio Grande rift; *in* Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, Z. (eds.), Rio Grande rift: northern New Mexico: New Mexico Geological Society, Guidebook 35, pp. 75–81.

Gardner, J. N., and Goff, F., 1996, Geology of the northern Valles caldera and Toledo embayment, New Mexico; *in* Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N. (eds.), The Jemez Mountains region: New Mexico Geological Society, Guidebook 47, pp. 225–230.

Gardner, J. N., Kolbe, T., and Chang, S., 1993, Geology, drilling, and some hydrologic aspects of Seismic Hazards Program core holes, Los Alamos National Laboratory: Los Alamos National Laboratory, Report LA-12460-MS, 19 pp.

Gardner, J. N., 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, pp. 1763–1778.

Gardner, J. N., Sandoval, M. M., Goff, F., Phillips, E., and Dickens, A., 2007, Geology of the Cerro del Medio moat rhyolite center, Valles caldera, New Mexico; *in* Kues, B. S., Kelley, S. A., and Lueth, V. W. (eds.), Geology of the Jemez region II: New Mexico Geological Society, Guidebook 58, pp. 367–372.

Gardner, J. N., Goff, F., Goff, S., Maassen, L., Mathews, K., Wachs, D., and Wilson, D., 1987, Core lithology, Valles Caldera #1, New Mexico: Los Alamos National Laboratory, Report LA-10957-OBES, 273 pp.

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

Goff, F., and Gardner, J. N., 1987, Jemez volcanics cored in second DOE hole: Geotimes, v. 32, no. 3, pp. 11–12.

Goff, F., and Gardner, J. N., 2004, Late Cenozoic geochronology of volcanism and mineralization in the Jemez Mountains and Valles caldera, north-central New Mexico; *in* Mack, G., and Giles, K. (eds.), The Geology of New Mexico; New Mexico Geological Society, Special Publication 11, pp. 295–312.

Goff, F., Gardner, J. N., and Reneau, S. L., 2000, Geology of the Frijoles 7.5-minute quadrangle: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 42, scale 1:24,000.

Goff, F., Gardner, J. N., Reneau, S. L., and Goff, C. J., 2005a, Preliminary geologic map of the Redondo Peak quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 111, scale 1:24,000.

Goff, F., Reneau, S. L., Goff, C. J., Gardner, J. N., Drakos, P., and Katzman, D., 2006, Preliminary geologic map of the Valle San Antonio quadrangle, Sandoval and Rio Arriba Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 132, scale 1:24,000.

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

Goff, F., Reneau, S. L., Lynch, S., Goff, C. J., Gardner, J. N., Drakos, P., and Katzman, D., 2005b, Preliminary geologic map of the Bland quadrangle, Los Alamos and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 112, scale 1:24,000.

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

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 Core Hole in Valles caldera, New Mexico: Journal of Geophysical Research, v. 91, pp. 1742–1752.

Griggs, R., 1964, Geology and groundwater resources of the Los Alamos area, New Mexico: U.S. Geological Survey, Water Supply Paper 1753, 107 pp., (1:31,680-scale map).

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, pp. 1799–1815.

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, pp. 8127–8142.

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

Jacobs, E. P., 2008, Buried landscapes: The paleotopography of the Cerro Toledo interval in Bandelier National Monument, Jemez Mountains volcanic field, New Mexico: Unpublished M.S. thesis, Colorado State University, Ft. Collins, 215 pp.

Jacobs, E. P., and Kelley, S. A., 2007, The time between the tuffs: Deposits of the Cerro Toledo interval in Bandelier National Monument, New Mexico; *in* Kues, B. S., Kelley, S. A., and Lueth, V. W. (eds.), Geology of the Jemez region II: New Mexico Geological Society, Guidebook 58, pp. 308–315.

Justet, L., 2003, Effects of basalt intrusion on the multi-phase evolution of the Jemez volcanic field, New Mexico: Unpublished Ph.D. dissertation, University of Nevada, Las Vegas, 246 pp.

Kelley, V. C., Baltz, E. H., and Bailey, R. A., 1961, Jemez Mountains and vicinity; *in* Northrop, S. A. (ed.), Guidebook of the Albuquerque country: New Mexico Geological Society, Guidebook 12, pp. 47–62.

Kelley, S. A., Kempter, K., and Lawrence, J. R., 2007a, Stratigraphic nomenclature and trends in volcanism in the northern Jemez Mountains; *in* Kues, B. S., Kelley, S. A., and Lueth, V. W. (eds.), Geology of the Jemez region II: New Mexico Geological Society, Guidebook 58, pp. 48–49.

Kelley, S. A., Osburn, G. R., and Kempter, K. A., 2007b, Geology of Cañon de San Diego, southwestern Jemez Mountains, north-central New Mexico; *in* Kues, B. S., Kelley, S. A., and Lueth, V. W. (eds.), Geology of the Jemez region II: New Mexico Geological Society, Guidebook 58, pp. 169–181.

Kelley, S. A., Osburn, G. R., Ferguson, C.A., Kempter, K., and Osburn, M., 2004, Preliminary geologic map of the Seven Springs 7.5-minute quadrangle, Rio Arriba and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 88, scale 1:24,000.

Kelley, S. A., Kempter, K., Goff, F., Rampey, M., Osburn, G. R., and Ferguson, C. A., 2003, Geology of the Jemez Springs 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 73, scale 1:24,000.

Kempter, K. A., Kelley, S. A., Kelley, S., and Rampey, M., 2004, Preliminary geologic map of the Polvadera Peak 7.5-minute quadrangle, Rio Arriba and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 96, scale 1:24,000.

Kleinfelder, Inc., 2005, Final well R-26 completion report: Unpublished consulting report for Los Alamos National Laboratory, Project number 37151, Revision 1, 27 pp.

Kleinfelder, Inc., 2006a, Final completion report intermediate well I-6: Unpublished consulting report for Los Alamos National Laboratory, Project number 49436, 19 pp.

Kleinfelder, Inc., 2006b, Final completion report intermediate well I-8: Unpublished consulting report for Los Alamos National Laboratory, Project number 48436, 16 pp.

Kues, B. S., Kelley, S. A., and Lueth, V. W. (eds.), 2007, Geology of the Jemez region II: New Mexico Geological Society, Guidebook 58, 499 pp.

Lawrence, R., Kelley, S. A., and Rampey, M., 2004, Preliminary geologic map of the Cerro del Grant 7.5-minute quadrangle, Rio Arriba and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 87, scale 1:24,000.

Lepper, K., and Goff, F., 2007, Yet another attempt to date the Banco Bonito rhyolite, the youngest volcanic flow in the Valles caldera, New Mexico: New Mexico Geology, v. 29, pp. 117–121.

Lynch, S. D., Smith, G. A., and Kuhle, A. J., 2004, Preliminary geologic map of the Cañada 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 85, scale 1:24,000.

McCalpin, J. P., 1998, Late Quaternary faulting on the Pajarito fault, west of Los Alamos National Laboratory, north-central New Mexico: Results from the seven-trench transect excavated in summer of 1997: GEO-HAZ Consulting, Inc., Estes Park, CO, unpublished consulting report for Los Alamos National Laboratory.

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

North American Commission on Stratigraphic Nomenclature (NACSN), 2005, North American stratigraphic code: American Association of Petroleum Geologists, Bulletin, v. 89, no. 11, pp. 1547–1591.

Osburn, G. R., Kelley, S., Rampey, M., Ferguson, C. A., Frankel, K., and Pazzaglia, F., 2002, Geology of the Ponderosa 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 55, scale 1:24,000.

Phillips, E. H., 2004, Collapse and resurgence of the Valles caldera, Jemez Mountains, New Mexico: $^{40}Ar/^{39}Ar$ age constraints on the timing and duration of resurgence and ages of megabreccia blocks: Unpublished M.S. thesis, New Mexico Institute of Mining and Technology, Socorro, 200 pp.

Phillips, E. H., Goff, F., Kyle, P. R., McIntosh, W. C., Dunbar, N. W., and Gardner, J. N., 2007, The $^{40}Ar/^{39}Ar$ age constraints on the duration of resurgence at the Valles caldera, New Mexico: Journal of Geophysical Research, v. 112, B08201, doi:10.1029/2006JB004511.

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, v. 29, no. 6, p. A-419.

Reneau, S. L., and MacDonald, E. V., 1996, Landscape history and processes on the Pajarito Plateau, northern New Mexico: Rocky Mountain Cell of the Friends of the Pleistocene; Los Alamos National Laboratory, Report LA-UR-96-3035, 195 pp.

Reneau, S. L., Drakos, P. G., and Katzman, D., 2004, Post-resurgence lakes of the Valles caldera, New Mexico (abs.): New Mexico Geology, v. 26, p. 63.

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

Reneau, S. L., Gardner, J. N., Lavine, A., McDonald, E. V., Lewis, C., Katzman, D., WoldeGabriel, G., Krier, D., Bergfeld, D., Heikoop, J., 2002, Paleoseismic investigation of trench EOC-2, Pajarito fault zone, Los Alamos National Laboratory, New Mexico: Los Alamos National Laboratory, Report LA-13939-MS, 65 pp.

Rogers, J. B., 1996, The fluvial landscape evolution of San Diego Canyon, Jemez Mountains, New Mexico: Unpublished M.S. thesis, University of New Mexico, Albuquerque, 123 pp.

Rogers, J. B., Smith, G. A., and Rowe, H., 1996, History of formation and drainage of Pleistocene lakes in the Valles caldera; *in* Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N. (eds.), The Jemez Mountains region: New Mexico Geological Society, Guidebook 47, pp. 14–16.

Self, S., 2009, Defining super-eruptions and exploring the limits of super-eruption size (abs.): Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 57.

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

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, pp. 1779–1798.

Self, S., Wolff, J. A., Spell, T. L., Skuba, C. E., and Morrissey, M. M., 1991, Revisions to the stratigraphy and volcanology of the post-0.5 Ma units and the volcanic section of VC-1 core hole, Valles caldera, New Mexico: Journal of Geophysical Research, v. 96, pp. 4107–4116.

Self, S., Heiken, G., Sykes, M. L., Wohletz, K., Fisher, R. V., and Dethier, D. P., 1996, Field excursions to the Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 134, 72 pp.

Singer, B., and Brown, L., 2002, The Santa Rosa event: $^{40}Ar/^{39}Ar$ and paleomagnetic results from the Valles Rhyolite near Jaramillo Creek, Jemez Mountains, New Mexico: Earth and Planetary Science Letters, v. 197, pp. 51–64.

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

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

Smith, R. Bailey, R., and Ross, C., 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. L., and Harrison, T. M., 1993, $^{40}Ar/^{39}Ar$ geochronology of post-Valles caldera rhyolites, Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 98, pp. 8031–8051.

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

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

Spell, T., Kyle, P. R., and Baker, J., 1996a, Geochronology and geochemistry of the Cerro Toledo Rhyolite; *in* Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N. (eds.), The Jemez Mountains region: New Mexico Geological Society, Guidebook 47, pp. 263–268.

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

Stix, J., 1989, Physical and chemical fractionation processes in subaerial and subaqueous pyroclastic rocks: Unpublished Ph.D. dissertation, University of Toronto, 420 pp.

Stix, J., Goff, F., Gorton, M. P., Heiken, G., and Garcia, S. R., 1988, Restoration of compositional zonation in the Bandelier silicic magma chamber between two caldera-forming eruptions: Geochemistry and origin of the Cerro Toledo Rhyolite, Jemez Mountains, New Mexico: Journal of Geophysical Research, v. 93, pp. 6129–6147.

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

Turbeville, B. N., 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, pp. 6148–6156.

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

Wolff, J. A., Gardner, J. N., and Reneau, S. L., 1996, Field characteristics of the El Cajete pumice deposit and associated southwestern moat rhyolites of the Valles caldera; *in* Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N. (eds.), The Jemez Mountains region: New Mexico Geological Society, Guidebook 47, pp. 311–316.