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Intracaldera Volcanic Activity, Toledo Caldera and Embayment, Jemez Mountains, New Mexico

GRANT HEIKEN,[1] FRASER GOFF,[1] JOHN STIX,[2] SHIRO TAMANYU,[3] MUHAMMAD SHAFIQULLAH,[4] SAMMY GARCIA,[1] AND ROLAND HAGAN[1]

The Toledo caldera was formed at 1.47 ± 0.06 Ma during the catastrophic eruption of the lower member, Bandelier Tuff. The caldera was obscured at 1.12 ± 0.03 Ma during eruption of the equally voluminous upper member of the Bandelier Tuff that led to formation of the Valles caldera. Earlier workers interpreted a 9-km-diameter embayment, located NE of the Valles caldera (Toledo embayment), to be a remnant of the Toledo caldera. Drill hole data and new K-Ar dates of Toledo intracaldera domes redefine the position of Toledo caldera, nearly coincident with and of the same dimensions as the younger Valles caldera. The Toledo embayment may be of tectonic origin or a small Tschicoma volcanic center caldera. This interpretation is consistent with distribution of the lower member of the Bandelier Tuff and with several other field and drilling-related observations. Explosive activity associated with Cerro Toledo Rhyolite domes is recorded in tuff deposits located between the lower and upper members of the Bandelier Tuff on the northeast flank of the Jemez Mountains. Recorded in the tuff deposits are seven cycles of explosive activity. Most cycles consist of phreatomagmatic tuffs that grade upward into Plinian pumice beds. A separate deposit, of the same age and consisting of pyroclastic surges and flows, is associated with Rabbit Mountain, located on the southeast rim of the Valles-Toledo caldera complex. These are the surface expression of what may be a thicker, more voluminous intracaldera tuff sequence. The combined deposits of the lower and upper members of the Bandelier Tuff, Toledo and Valles intracaldera sediments, tuffs, and dome lavas form what we interpret to be a wedge-shaped caldera fill. This sequence is confirmed by deep drill holes and gravity surveys. This fill accumulated in depressions formed during precaldera rifting and episodes of caldera collapse. We interpret the Toledo-Valles caldera complex to be a pair of nearly coincident trapdoor calderas, with the hinge on the west side and thick caldera fill in the east.

INTRODUCTION

The Toledo and Valles calderas are the most obvious volcanic landforms of the Jemez Mountains volcanic field, which has erupted basaltic through rhyolitic rocks since 13 Ma [*Smith et al.*, 1970; *Gardner and Goff*, 1984]. Formation of the calderas, 1.45 and 1.12 Ma, occurred during eruptions of the lower and upper members of the Bandelier Tuff, which is a deposit of high-silica rhyolitic tephra with an approximate volume of 600 km^3 [*Doell et al.*, 1968; *Izett et al.*, 1981].

Although the Toledo caldera was mostly obliterated by the younger Valles caldera, rhyolitic domes were erupted, and resurgence may have occurred following its collapse [*Smith and Bailey*, 1968]. The Valles caldera is a circular, 22-km-diameter topographic depression that was deformed by a resurgent structural dome located slightly west of center and surrounded by a ring of moat rhyolite lavas (Figure 1).

During the last 15 years, the caldera complex has been a locus for geothermal exploration and research because of its relative youth and abundant geothermal manifestations [*Dondanville*, 1971; *Laughlin*, 1981; *Goff and Grigsby*, 1982; *Heiken and Goff*, 1983]. Drilling by Union Oil Company of California has revealed temperatures of 200°–300°C in an active hydrothermal system that circulates to depths of 1–3 km beneath the resurgent dome. The Los Alamos hot dry rock (HDR) geothermal experiment has encountered temperatures of 325°C, at a depth of 4.5 km, in Precambrian igneous and metamorphic rocks at Fenton Hill, located on the west flank of the caldera. The Valles caldera has been repeatedly chosen as a prime site for deep drilling as part of the Continental Scientific Drilling Program (CSDP) because it is representative of an economically important and scientifically interesting active magma-hydrothermal system, analogous to eroded, ore-bearing caldera complexes [*U.S. Geodynamics Committee*, 1979: *Continental Scientific Drilling Committee*, 1984].

These research and development interests have spawned a multitude of recent geologic, geophysical, and hydrogeochemical studies in the Jemez Mountains. Because Valles caldera is considered by many to be a classic resurgent caldera and because a large data base is available from drilling, some of the fundamental research objectives are to investigate the subsurface structure of the caldera complex [*Heiken and Goff*, 1983; *Goff*, 1983], structure of the resurgent dome and mechanisms of resurgence [*Nielson and Hulen*, 1984], and location of the earlier Toledo caldera [*Goff et al.*, 1984]. The purpose of this paper is to emphasize the post-Toledo intracaldera pyroclastic volcanism and ages of intracaldera dome lavas and to discuss their significance with regard to evolution and structure of the Toledo caldera.

PREVIOUS GEOLOGIC WORK

The Jemez volcanic field and the Valles and Toledo calderas were a focus of many field studies by *Ross and Smith* [1961], *Bailey et al.* [1969], and *Smith et al.* [1970]. These authors show the Toledo caldera as an arcuate structure, 10 km in diameter, located on the northeastern edge of Valles caldera (Figure 1). Rhyolitic pyroclastic rocks and domes partly filling the arcuate depression have been formally named the Cerro Toledo Rhyolite [*Bailey et al.*, 1969]. *Smith et al.* [1970] include in this unit (1) pyroclastic deposits that crop out between the upper and lower members of the Bandelier Tuff and (2) the Rabbit Mountain rhyolite dome and pyroclastic deposits, which are located on the eastern caldera rim. On the

[1] Los Alamos National Laboratory, Los Alamos, New Mexico.
[2] Department of Geology, University of Toronto, Ontario, Canada.
[3] Geothermal Research Department, Geological Survey of Japan, Ibaraki.
[4] Department of Geosciences, University of Arizona, Tucson.

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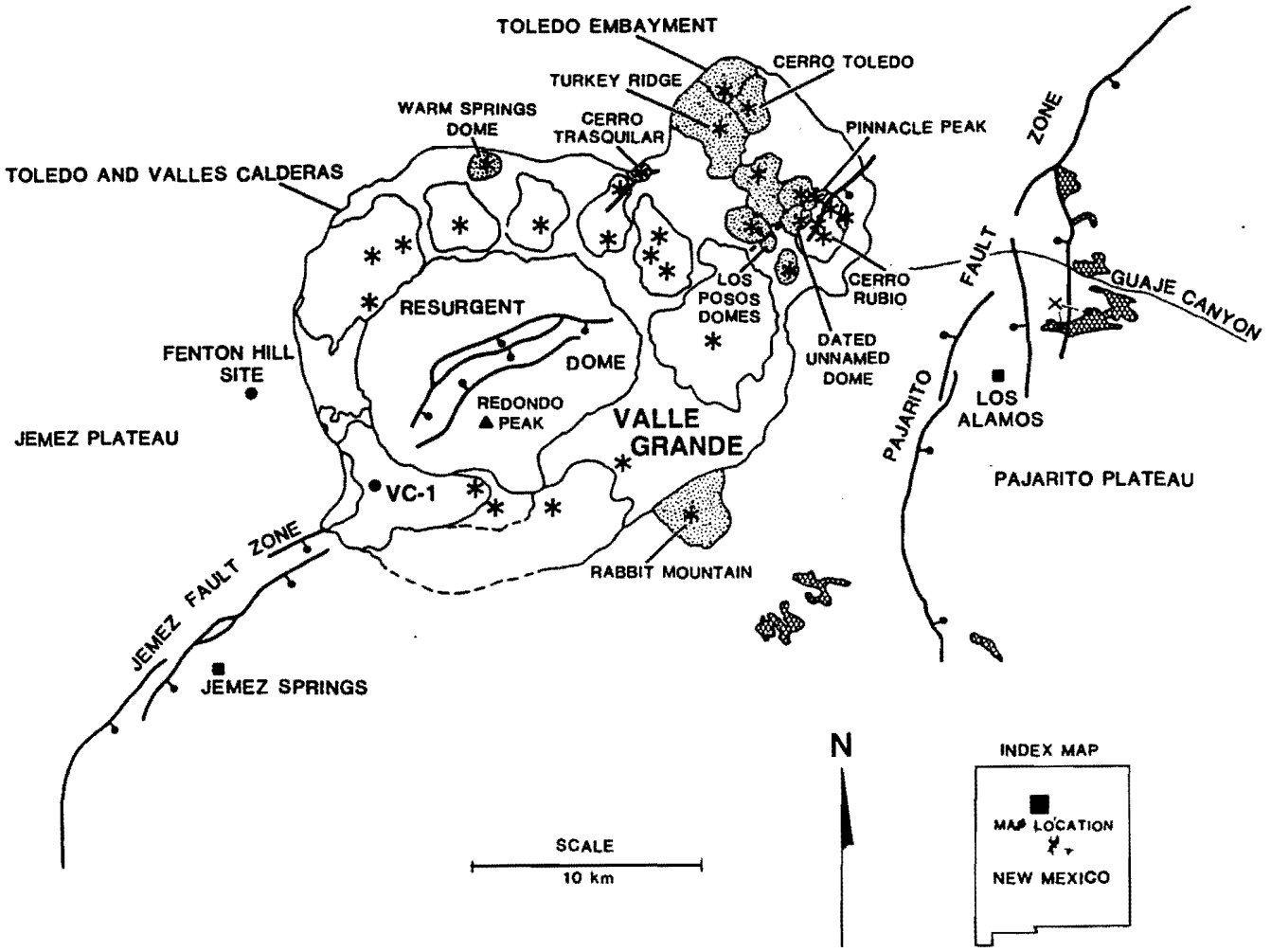

Fig. 1. Generalized map of the Toledo and Valles calderas, Jemez Mountains volcanic field, New Mexico. Cerro Toledo Rhyolite domes and lavas are represented by stippled pattern; distal tuff deposits are present in areas with cross-hatched pattern. Asterisks are vent locations for intracaldera domes and flows.

basis of stratigraphic position and petrologic similarities, the domes, lavas, and tephra deposits of the Cerro Toledo Rhyolite make up a single stratigraphic unit. Although the domes were never dated, *Izett et al.* [1981] dated pyroclasts from the tephras and obtained ages of 1.47 ± 0.04 Ma and 1.23 ± 0.02 Ma from two of the many tephra layers (Table 1). These ages are stratigraphically consistent with reported ages of upper and lower members of the Bandelier Tuff (1.45 ± 0.06 and 1.12 ± 0.03 Ma, respectively) [*Doell et al.*, 1968] (recalculated by *Izett et al.* [1981]).

Two quartz latitic domes (Cerro Rubio Quartz Latite) occur on the eastern side of the arcuate structure presently named Toledo embayment (Figure 1). These domes were not previously dated, but their approximate age was estimated at 1.1 Ma by *Smith et al.* [1970] and *Smith* [1979].

Toledo Caldera and Toledo Embayment

Recent geologic mapping and age dating in the northeastern sector of the Toledo-Valles caldera complex indicates that Toledo caldera is nearly coincident with Valles caldera rather than being confined to its northeast margin [*Goff et al.*, 1984]. Details of this work must wait until a later paper because all age determinations for this project have not been completed. Information on six new K-Ar age dates not previously published is presented in Table 2. However, a list of all ages of rock units associated with the "Toledo caldera" as previously mapped is given in Table 1 to support this reinterpretation. We have used the name "Toledo embayment" for the arcuate depression on the northeast margin of the Valles caldera [*Goff et al.*, 1984].

Redefinition of the position of the Toledo caldera is based, in part, on the ages of an arcuate line of four domes located along the northern side of Valles caldera (Figure 1) that were mapped previously as part of the Valles Rhyolite [*Smith et al.*, 1970]. New dates show that these four domes are between 1.45 and 1.12 Ma and are here designated as part of the Cerro Toledo Rhyolite (Table 1 and stippled pattern on Figure 1). Warm Springs dome was previously discussed by *Doell et al.* [1968], who did not realize the significance of the 1.22 Ma age and concluded that the age was incorrect. The age of Cerro Trasquilar [*Tamanyu and Goff*, 1985], which was obtained while more recent mapping was in progress, caused us to reevaluate the stratigraphic position of these domes. Subsequent mapping revealed that small outcrops of upper Bandelier Tuff lie on top of the West and East Los Posos domes. New age determinations demonstrate that the Los Posos domes are also of Cerro Toledo age.

We propose that the arcuate chain of Warm Springs, Cerro Trasquilar, and Los Posos domes are remnants of Toledo age intracaldera volcanoes. If this is correct, at least the northern

TABLE 1. Ages of Stratigraphic Units in the Toledo Caldera and Toledo Embayment

Unit	Age,[a] Ma	Material[b]	Reference of Laboratory[c]	Comment
Upper Bandelier Tuff	1.12 ± 0.03	san	I	weighted mean of three age determinations
Cerro Toledo Rhyolite, pyroclastic Units				
Upper fall unit[d]	1.23 ± 0.02	san	I	
Lower fall unit[d]	1.47 ± 0.04		I	isochron age from sanidine, plagioclase and hornblende dates
	1.43 ± 0.11	zir		average of two fission track ages
Cerro Toledo Rhyolite, Toledo Embayment domes				
Pinnacle Peak	1.20 ± 0.03	glass	T	average of two dates
Turkey Ridge	1.24 ± 0.03	san	Dr	
Unnamed dome	1.33 ± 0.02	obsid	T	average of two dates
Cerro Toledo	1.38 ± 0.05	san + glass	S	
	1.62 ± 0.03	obsid	T	average of two dates
Cerro Toledo Rhyolite, Toledo Calera moat domes				
Warm Springs dome	1.25 ± 0.04	san	Do	weighted mean of two age determinations
Cerro Trasquilar	1.27 ± 0.02	glass	T	average of two dates
East Los Posos dome	1.47 ± 0.05	san + plag	S	
West Los Posos dome	1.50 ± 0.05	san	Dr	
Lower Bandelier Tuff	1.45 ± 0.06	san	I	weighted mean of three age determinations
Cerro Rubio Quartz Latite				
Cerro Rubio	3.59 ± 0.36	plag	Dr	
Dome north of Cerro Rubio	2.18 ± 0.09	plag	S	

All age determinations are by potassium-argon method unless noted.
[a]Method of reporting error varies from lab to lab.
[b]san, sanidine; zir, zircon; obsid, obsidian; plag, plagioclase.
[c]Do, *Doell et al.* [1968]; Dr, R. Drake, University of California at Berkeley; I, *Izett et al.* [1981]; S, M. Shafiqullah, University of Arizona; T, *Tamanyu and Goff* [1985].
[d]Upper fall unit corresponds with unit c of this paper (Fig. 2); lower fall unit corresponds with unit b.

part of Toledo caldera is nearly coincident with and of the same dimensions as Valles caldera. Several additional lines of evidence support this hypothesis.

1. Distribution of the lower member of Bandelier Tuff is symmetrical about a vent or vents located near the center of the Valles caldera [*Smith et al.*, 1970; *Self et al.*, this issue].

2. Thickness of basal pumice fall beds and characteristics of lag breccias within pyroclastic flow deposits of the lower member of Bandelier Tuff suggest that the source is below the Valles caldera [*Self et al.*, this issue].

3. Flow direction indicators in pyroclastic flows of the lower Bandelier Tuff indicate that the source is below the Valles caldera [*Potter*, 1983].

4. Studies of cuttings from 20 deep geothermal wells located in the resurgent dome, western Valles caldera, has revealed that the thickness of lower Bandelier Tuff exceeds 400 m and is believed to be an intracaldera fill [*Nielson and Hulen*, 1984].

5. The thickness, degree of welding, and lithic clast content of the lower member of the Bandelier Tuff in corehole VC-1 suggest that this unit is an intracaldera facies beneath the southwestern Valles caldera [*Goff et al.*, this issue].

6. Pre-Toledo domes in the Toledo embayment are overlain only by a thin deposit of Bandelier Tuff, implying little or no collapse of the embayment during the Toledo and Valles eruptions.

Ages of Cerro Toledo Rhyolite domes within the Toledo embayment are compatible with those of pyroclastic deposits dated by *Izett et al.* [1981] (Table 1). Separate age determinations of high analytical quality on different samples from Cerro Toledo dome (1.62 and 1.38 Ma) straddle the age of Toledo caldera (1.45 Ma). The two domes of Cerro Rubio

TABLE 2. New Potassium-Argon Age Data From Table 1

Unit	Sample	Location[a] Latitude	Longitude	Rock Type	Material	Percentage	Radiogenic ^{40}AR, $\times 10^{-12}$ mol/g	Percentage Radiogenic ^{40}AR	Age[b], 10^6 years
Turkey Ridge dome	PC-81-13	35°59.2'N	106°26.5'W	rhyolite	sanidine	5.881	12.6	40.9	1.24 ± 0.03
Cerro Toledo dome	F84-9	35°59.6'N	106°26.2'W	rhyolite	sanidine and glass	3.870	9.236	30.2	1.38 ± 0.05
East Los Posos dome	F84-12	35°55.8'N	106°25.2'W	rhyolite	sanidine and plagioclase	2.537	6.46	41.0	1.47 ± 0.05
West Los Posos dome	F83-27	35°56.8'N	106°25.8'W	rhyolite	sanidine	5.595	14.6	45.0	1.50 ± 0.05
Cerro Rubio dome	F83-245	35°56.8'N	106°24.0'W	quartz latite	plagioclase	0.353	2.20	26.4	3.59 ± 0.36
Dome north of Cerro Rubio	614-84-8	35°57.0'N	106°24.2'W	quartz latite	plagioclase	0.428	1.618	44.1	2.18 ± 0.09

$\lambda_e = 0.581 \times 10^{-10}$ yr^{-1}, $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}, ^{40}K/K = 1.167×10^{-4}.
[a]All samples located on Valle-Toledo 7.5 min topographic quadrangle.
[b]1σ error reported.

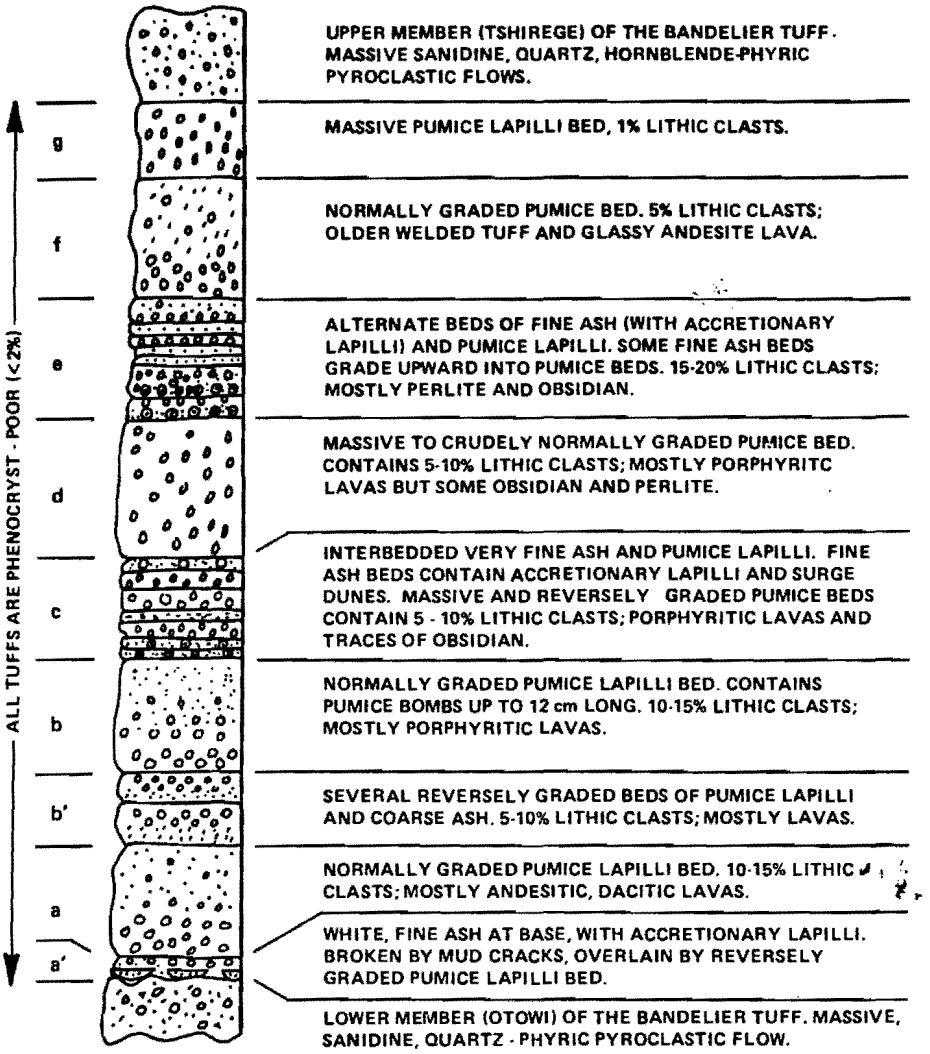

Fig. 2. Composite stratigraphic section, Cerro Toledo tuffs.

Quartz Latite are considerably older than the 1.1 Ma suggested by *Smith* [1979] (Table 1). These domes appear to be quartz latite plugs of earlier Tschicoma age (6.5–2.0 Ma) because detailed mapping reveals that Cerro Toledo Rhyolite intrudes the plugs. Possible origins for the Toledo embayment include (1) an earlier but smaller caldera that erupted silicic tuffs (4–1.5 Ma) that are interbedded within the Puye Formation [*Self et al.*, this issue] (the distribution and volume of these tuffs supports this interpretation), (2) a scallop-shaped slump on the edge of Toledo caldera (by analogy, the north wall of Valles caldera is a mass of these large slide blocks [*Smith et al.*, 1970]), (3) a part of the Toledo caldera, and (4) formed, in part, by collapse that accompanied pyroclastic eruptions, followed by extrusion of large domes of Cerro Toledo Rhyolite.

It is most probable that a combination of the above hypotheses will best explain the origin of Toledo embayment. There also may have been some control of the shape and trend of the embayment by faults associated with the Jemez lineament, which passes through the resurgent dome of Valles caldera, the Toledo embayment, and the northeast flank of the volcanic field [*Aldrich*, this issue; *Self et al.*, this issue].

TUFFS AND EPICLASTIC SEDIMENTARY ROCKS OF THE CERRO TOLEDO RHYOLITE

We have identified six pyroclastic eruption sequences within the Cerro Toledo Rhyolite (Figure 2). All tuff sequences from Toledo intracaldera activity are separated by epiclastic sedimentary rocks that represent periods of erosion and deposition in channels. All consist of rhyolitic tephra and most contain Plinian pumice falls and thin beds of very fine grained ash of phreatomagmatic origin. Most Toledo deposits are thickest in paleocanyons cut into lower Bandelier Tuff and older rocks. Some of the phreatomagmatic tephra flowed down canyons from the caldera as base surges. A summary of the intracaldera eruption sequence is shown in Figures 2 and 3. The tuffs are limited to two zones: (1) a 20-km-wide band that trends east to northeast of the Toledo-Valles caldera complex (from the northern edge of the Valle Grande to the northern rim of the Toledo embayment) and (2) a southeast trending, 4-km-wide tuff blanket from Rabbit Mountain (Figure 3). There are no Cerro Toledo tuffs exposed elsewhere around the Jemez Mountains.

Most eruptions began with deposition of very fine grained phreatomagmatic tephra (Table 3) that make up 10–60% of each eruptive unit. These tuffs are overlain by pumice fall beds or interbedded pumice falls and fine-grained tephra beds. Many of the fine-grained tephra beds contain accretionary lapilli and, in some units, are broken by desiccation cracks. Most were deposited as plane beds, but some contain small surge dunes. They consist of mostly angular, blocky shards, 1–60 μm long, scattered throughout the fine matrix are 200- to 400-μm-long, angular pumice pyroclasts (with 30–50% vesicles) (Figure 4). There are only traces of K-feldspar and

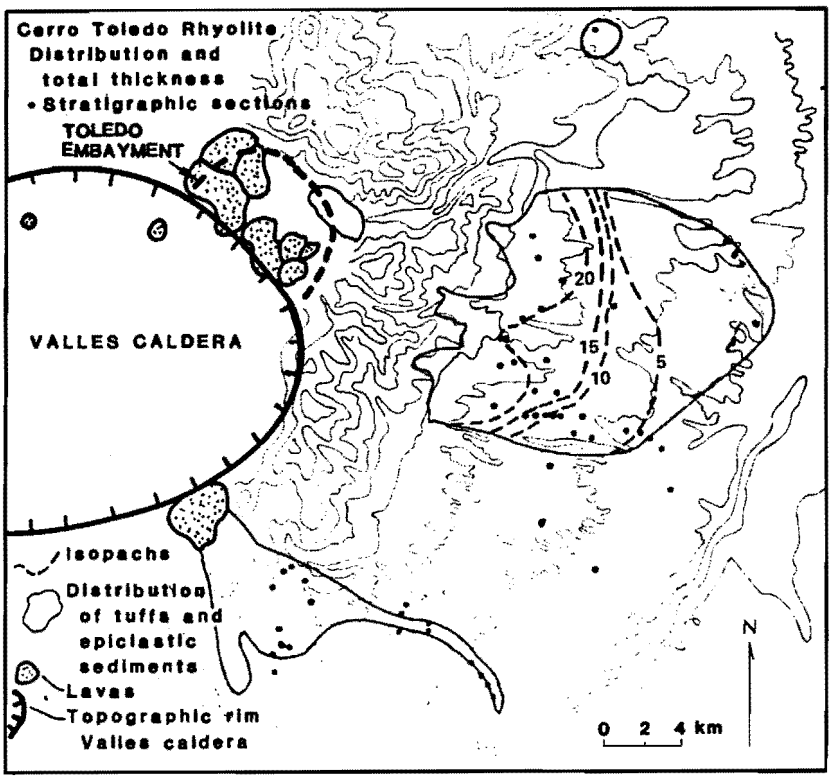

Fig. 3*a*. Total thickness of Cerro Toledo Rhyolite tuffs. Base is pre-Toledo paleotopography; contour interval is 500 ft (152 m).

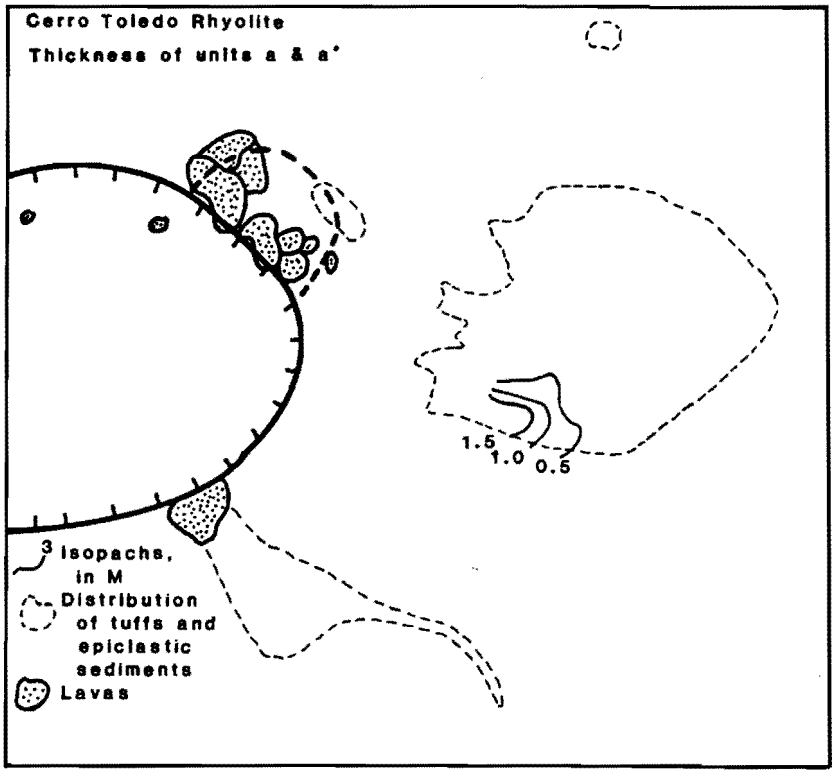

Fig. 3*b*. Distribution and thickness of units a and a'.

Fig. 3. Distribution of Cerro Toledo Rhyolite tuffs. Isopach maps, in meters.

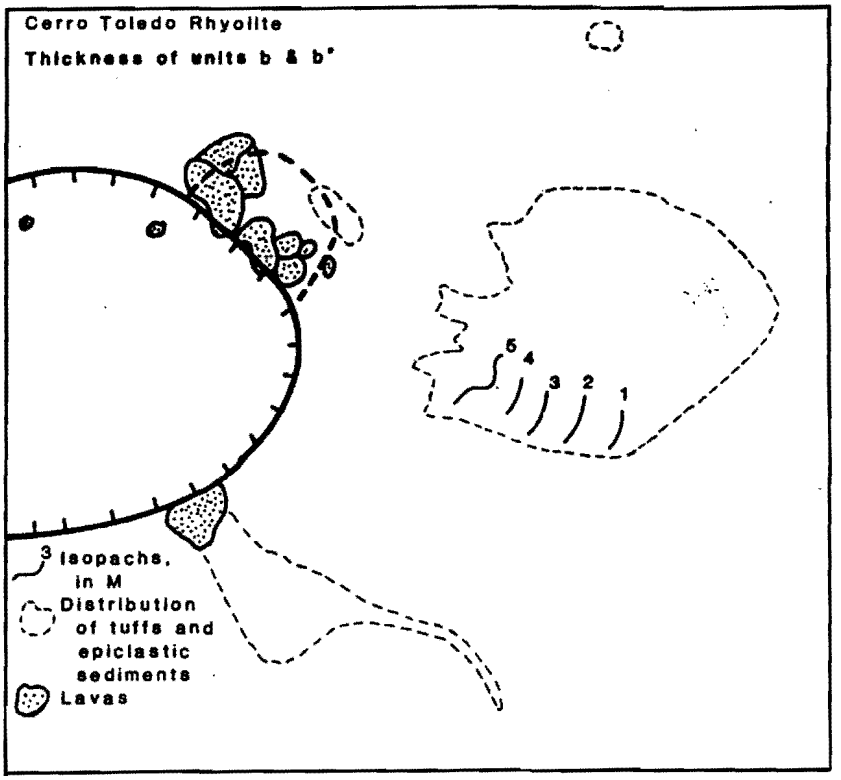

Fig. 3*c*. Distribution and thickness of units b and b'.

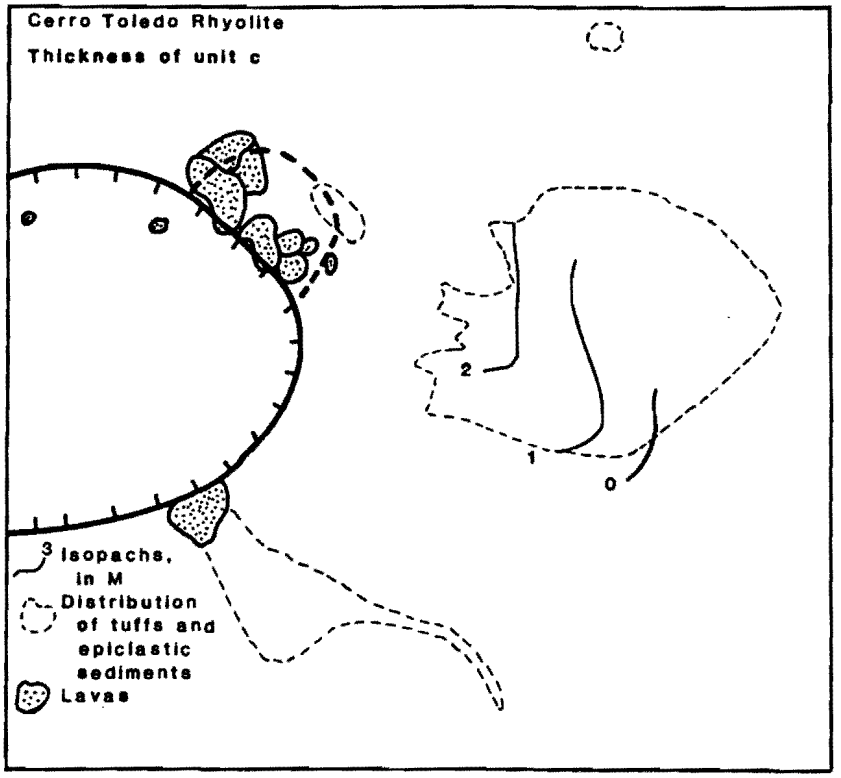

Fig. 3*d*. Distribution and thickness of unit c.

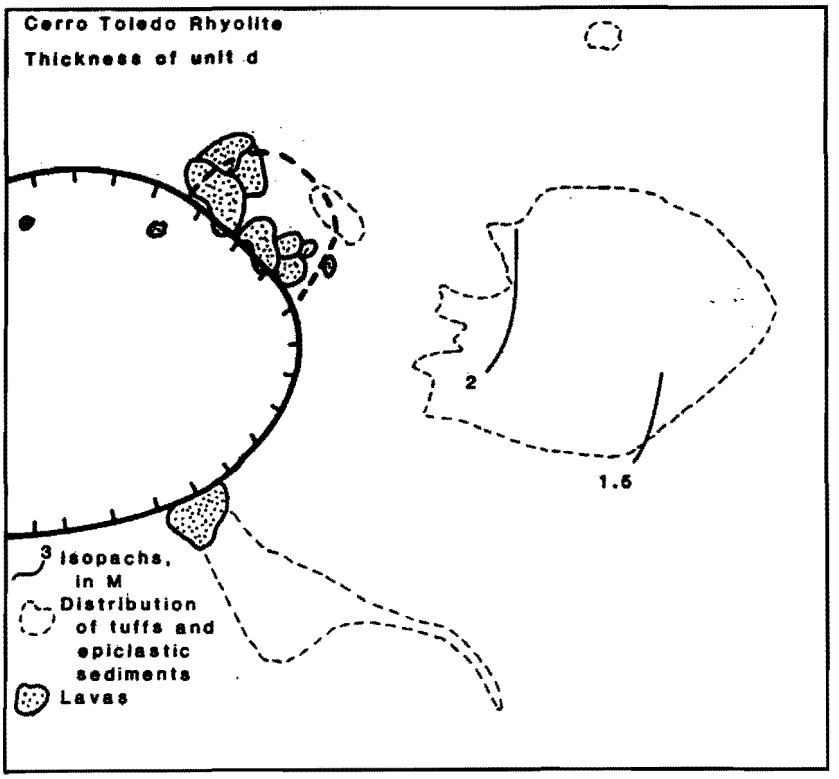

Fig. 3*e*. Distribution and thickness of unit d.

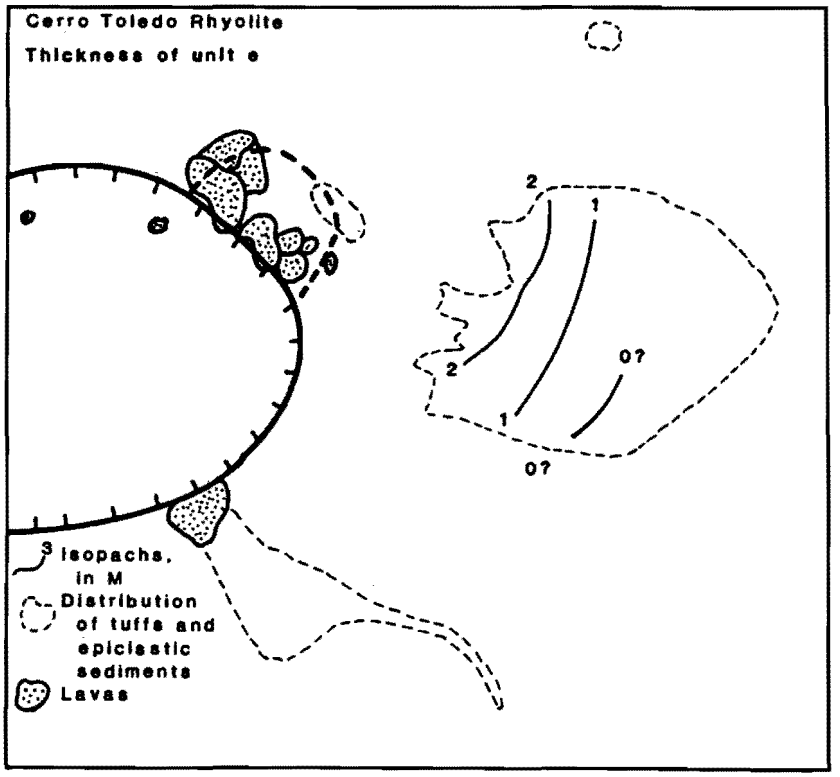

Fig. 3*f*. Distribution and thickness of unit e.

TABLE 3. Typical Cerro Toledo Rhyolite Pyroclastic Eruption Sequence

	Field Description	Petrographic Description	Grain Count
Top pumice fall	massive pumice bed; crudely graded fine pumice lapilli and coarse ash	elongate pumice pyroclasts with a heterogeneous distribution of vesicles; 100–500 μm wide, ovoid to highly elongate vesicles (lensoid in cross-section), subrounded to subangular pumice lapilli with 50–60% vesicularity; <1% K-feldspar phenocrysts	pumice, 100%
Base, phreato-magmatic tephra	well-bedded, very fine grained ash containing 40% accretionary lapilli grades into overlying pumice fall	coarse ash to lapilli pumice in fine ash matrix <1- to 100-μm-long shards are angular, equant to elongate; pumice pyroclasts have 20–30% vesicularity	shards, 77% pumice, 22% K-feldspar, 1%

Unit e is used here as an example.

plagioclase phenocrysts in these tephra. Pumice beds within the Cerro Toledo Rhyolite are composed of framework-supported pumice lapilli and lithic clasts; most beds are normally graded or massive. The angular, blocky pumice pyroclasts are heterogeneous, consisting of elongate, flattened pockets of coalesced vesicles that are surrounded by highly elongate, flattened vesicles. Many pumices are aphyric, but some contain traces of K-feldspar, plagioclase, orthopyroxene, and Fe-Ti oxides.

When compared with the lower and upper members of the Bandelier Tuff, the Toledo intracaldera tuffs are easily identified by the absence of or only traces of phenocrysts. Only one pair of Cerro Toledo domes (Indian Point and Turkey Ridge) contain abundant phenocrysts. Both members of the Bandelier Tuff contain 10–20% sanidine (commonly chatoyant) and quartz phenocrysts—a very distinctive feature that is useful in field identifications.

Units a and a'

These tuffs overlie the lower (Otowi) member of the Bandelier Tuff or epiclastic sedimentary rocks that overlie the lower member. Units a and a' are discontinuous and range in thickness from 0.2 to 1.8 m (Figure 3*b*).

The lowest bed is 8–10 cm thick, consisting of light gray, fine ash with accretionary lapilli and small pumice pyroclasts. In many outcrops this tuff is broken into discontinuous polygons by mud cracks. This tuff is a very fine grained ash; there are 200- to 400-μm-long, angular pumice pyroclasts in a matrix of 5- to 40-μm long, angular shards. There are only traces of small, angular phenocrysts of K-feldspar, Fe-Ti oxides, clinopyroxene, and plagioclase No lithic fragments were observed in this tuff.

Unit a' ("mud crack" unit) is overlain by a 20- to 50-cm-thick, reversely graded tephra fall, consisting of coarse ash and fine lapilli. It contains heterogeneous pumice lapilli and coarse ash (with highly elongate vesicles). There are only rare phenocrysts of K-feldspar, augite, Fe-Ti oxides, and a trace of allanite. Lithic clasts make up 10–15% of the deposit and consist of weathered, subrounded porphyritic basalt and andesitic clasts and muddy graywacke.

Unit a is a 1- to 1.5-m thick, normally graded, white pumice fall bed. It consists of mostly fine to coarse pumice lapilli and 10–15% lithic clasts. Pumice clasts are heterogeneous, containing "pockets" of coalesced vesicles and ovoid to spherical vesicles (vesicularity is 60%). As in the lower beds, there are only traces of phenocrysts.

Deposition of units a and a' was followed by a major erosional interval. Immature epiclastic sandstones, conglomerates, and siltstones make up a deposit 0–5 m thick. These tuffaceous sedimentary rocks are mostly massive, with concentrations of boulders and cobbles throughout. Boulders and cobbles consist mostly of dacite and quartz latite that are derived from the Tschicoma Formation, with source areas upslope, whereas smaller clasts consist mostly of rounded pumice.

Units b and b'

These units consist of a pair of Plinian pumice fall beds, sometimes separated by a thin erosional interval (Figure 2); they range in total thickness from 0.2 to 4.8 m and form an east to ESE trending deposit.

The lowest subunit (b') consists of one or two reversely graded pumice beds; these beds consist of framework-supported coarse to fine lapilli and coarse ash. They appear to mantle the paleotography. Most pumice pyroclasts are nearly aphyric, with only traces of very small K-feldspar, hornblende, and Fe-Ti oxide phenocrysts. These pumice beds contain 5–10% lithic clasts that consist of perlitic, spherulitic glass, welded tuff, and porphyritic lavas.

Unit b is a thick (over 2 m in places), normally graded pumice bed. It is the thickest of all Toledo tuff units but is not very well preserved in the northern part of the Pajarito Plateau. It consists of mostly pumice lapilli and coarse ash and pumice bombs of up to 12 cm diameter. The unit contains 10–15% lithic clasts, mostly porphyritic lavas.

Unit b was dated by *Izett et al.* [1981] at 1.47 ± 0.04 Ma (K-Ar mineral isochron age) and 1.43 ± 0.11 Ma (the average of two fission track ages of zircon). The sample selected by them for dating is from a well-exposed cliff section in Pueblo Canyon.

Unit b is generally overlain by unit c. In places, however, they are separated by 1- to 2-m-thick tuffaceous gray sandstones consisting of very immature, massive beds that contain rounded pumice lapilli.

Unit c

Although not the thickest of the Cerro Toledo tuffs, unit c is one of the most widespread and is exposed in canyons throughout much of northern Pajarito Plateau (Figure 3*d*). It consists of four to nine beds of very fine grained tuff and massive, reversely graded pumice fall. The unit ranges in thickness from 0.4 to 2 m.

The fine-grained tuff beds consist of traces to 30% pumice and accretionary lapilli in a matrix of very fine white ash. Beds within these subunits are 0.5–8 cm thick. They are massive

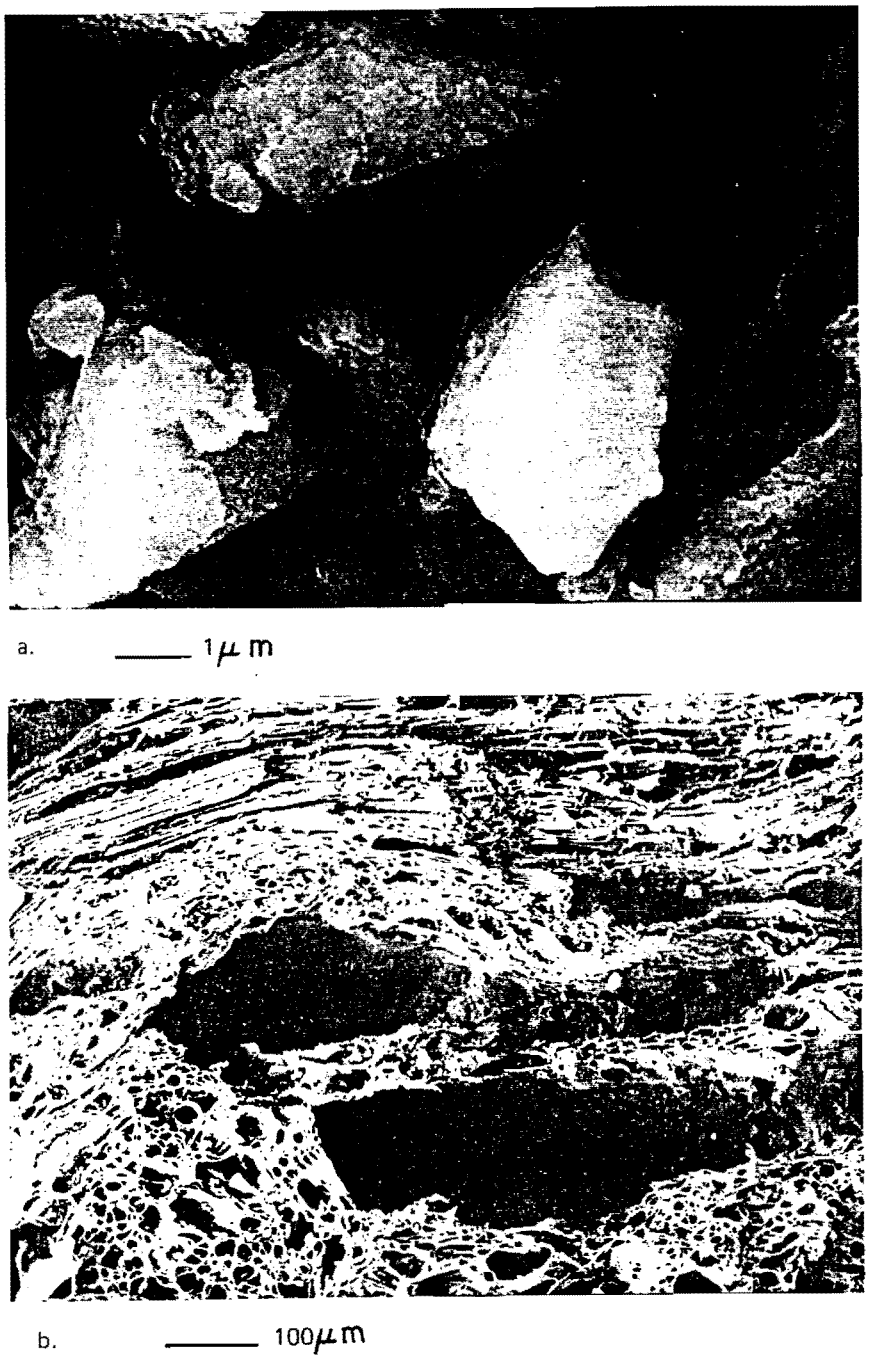

Fig. 4. Scanning electron micrographs of rhyolitic tephra from unit e, typical of variations from the base to top of most of the eruption sequences. (*a*) Fine-grained vitric tephra; 5–10 μm long, angular, and blocky pyroclasts of phreatomagmatic origin. Grain surfaces are hydrated and have irregular flakes of glass peeling away from the pyroclasts. This sample is from the fine-grained, accretionary lapilli-bearing base of unit e. (*b*) Surface of a pumice pyroclast from the upper pumice bed of unit e. There is a bimodal distribution of vesicles: ovoid pockets of coalesced vesicles are surrounded by parallel, thin, highly elongate vesicles.

and well laminated and, in a few locations closer to source, contain small surge dunes. Inclusion of rip-ups from underlying beds in the tuffs also supports a surge origin for many of these fine-grained beds. Most of the tuff consists of 5- to 50-μm-long colorless glass shards; these were derived from a pumiceous melt with highly elongate vesicles. Pumice pyroclasts, which make up less than 20% of the tuff, are mostly 100–200 μm long; some have accretionary rinds of fine shards. Accretionary lapilli, consisting entirely of fine ash, are up to 0.5 cm in diameter and make up to 40% of some beds. There are about 2% mineral pyroclasts, including K-feldspar, quartz, hornblende, hypersthene, and Fe-Ti oxides. Only traces of fine-grained lithic clasts are present (brown pumice).

The other type of deposit in unit c consists of massive and reversely graded pumice lapilli and coarse ash beds of Plinian origin. These beds contain 5–10% clasts of porphyritic lavas and lesser amounts of obsidian flakes.

This distinctive sequence of tuffs has been used throughout the Pajarito Plateau as a stratigraphic marker and was dated by *Izett et al.* [1981] at 1.23 ± 0.02 Ma (K-Ar date on sani-

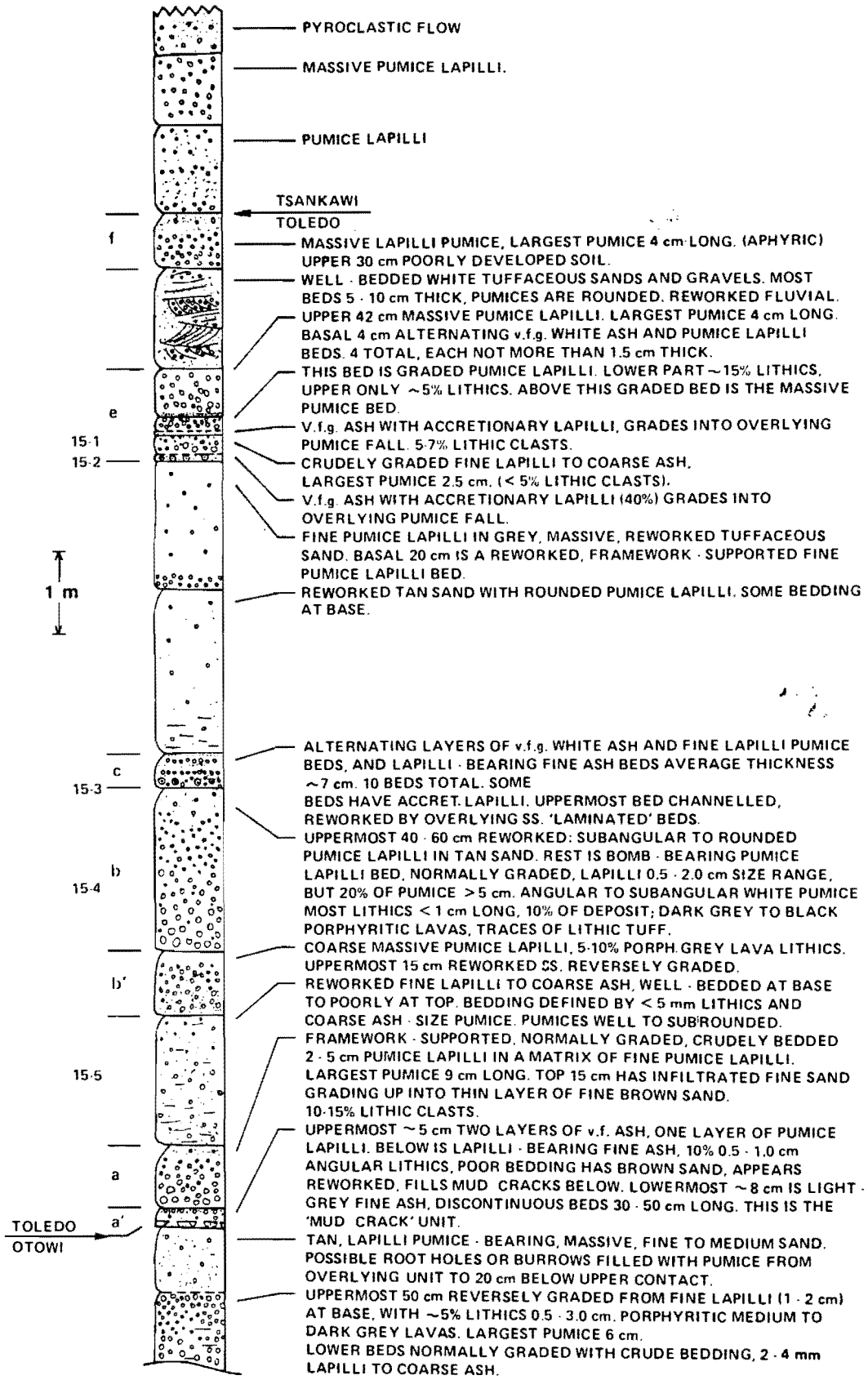

Fig. 5. "Typical" stratigraphic section of the Cerro Toledo tuffs, northeastern Pajarito Plateau. Location, Guaje Mountain Quadrangle, SW1/4, T19N R6E Sec. 11. This section was chosen to illustrate the erosional intervals present between explosive eruption sequences.

TABLE 4a. Major, Minor, and Trace Element Analyses of Glasses From Cerro Toledo Rhyolite Pyroclastic Rocks and Bandelier Tuff

	Lower Member, Bandelier Tuff (Pumice)[a]	Cerro Toledo Rhyolite—Tuffs										Upper Member Bandelier Tuff (Pumice)[a]
		Unit a', Phreato-magmatic Base	Unit a', Pumice Bed	Unit a, Pumice Bed	Unit b, Pumice Bed	Unit c Phreato-magmatic	Reworked Unit c, Epiclastic Sandstone	Unit d, Pumice Bed	Unit e, Phreato-magmatic	Unit e, Pumice Bed	Unit f, Pumice Bed	
	Electron Microprobe Analyses—(Pumice and Shards), Normalized, Volatile Free[b]											
SiO_2	77.3	78.1	78.0	78.0	78.1	77.9	77.8	77.7	77.7	77.8	77.7	76.6
TiO_2	0.11	0.16	0.04	0.16	0.10	0.11	0.04	0.06	0.06	0.02	0.09	0.05
Al_2O_3	12.6	12.2	12.1	12.0	12.1	12.0	12.2	12.2	12.2	12.2	12.1	12.5
FeO	1.17	0.95	0.91	0.90	0.74	0.89	0.77	1.01	0.90	1.00	0.94	1.42
MnO	n.d.	0.05	0.07	0.10	0.07	0.03	0.01	0.07	0.11	0.06	0.12	n.d.
MgO	0.04	0.02	0.04	0.03	0.04	0.04	0.05	0.03	0.02	0.04	0.03	n.d.
CaO	0.30	0.32	0.32	0.32	0.37	0.37	0.43	0.29	0.25	0.26	0.29	0.15
Na_2O	3.40	3.24	3.74	3.81	3.57	3.38	3.54	3.68	3.50	3.59	3.40	3.78
K_2O	4.89	4.58	4.66	4.50	4.87	5.19	5.05	4.61	5.14	4.61	5.23	5.57
Number of Analyses	6	5	6	8	7	6	8	7	8	7	6	1
	Instrumental Neutron Activation Analyses[c], *ppm*											
Cl	2800	920	970		1310	950			1100	1380	1380	2200
Sc	0.58	2.2	1.7		1.4	1.8			2.0	1.1	1.3	1.01
Cr	5.0	4.8	2.8		4.0	2.2			6.3	2.5	4.9	n.d.
Zn	20	83	65		64	73			88	89	86	33
Rb	330	120	120		130	140			160	190	190	330
Zr	190	135	165		140	130			130	90	115	350
Cs	10.5	3.4	3.0		3.7	3.9			5.5	6.2	5.6	18.0
La	52	50	49	n.d.	43	45	n.d.	n.d.	36	33	31	91
Ce	109	107	95		86	101			81	75	71	117
Nd	47	31	33		28	28			26	24	21	60
Sm	13.9	6.5	7.8		5.9	6.5			5.9	6.6	6.8	16.5
Eu	2.4	0.2	0.1		0.2	0.2			0.1	n.d.	0.1	n.d.
Dy	18.5	6.7	6.9		6.5	5.4			9.6	9.2	9.9	28.0
Yb	12.2	4.3	4.4		4.5	4.2			5.9	6.5	6.6	15.4
Hf	12.0	6.0	5.4		5.5	6.0			6.9	7.5	7.2	14.0
Th	43.0	17.0	17.0		17.7	17.8			20.0	22.0	22.0	40.0
U	15.9	5.1	5.5		5.8	5.6			6.9	8.0	7.4	11.8
	Mode Volume Percent											
Shards and pumice	87.4	98.2	83.7	99.3	99.6	99.3	92.5	100.0	98.7	99.5	79.9	78.6
Sanidine	8.7	1.0	3.4	Tr	Tr	0.3	1.5	...	1.3	0.5	Tr	13.7
Quartz	4.0	...	...	...	...	Tr	...	...	...	...	0.2	6.3
Hornblende	...	...	...	...	0.3	Tr	1.0	...	...	...	...	...
Lithic clasts	...	0.3	10.4	...	...	Tr	3.5	...	...	...	18.7	1.3
Other	...	0.3	2.3	0.7	...	0.3	1.5	...	...	...	1.0	...

n.d., not determined.
[a]Data for the Bandelier Tuff are from *Crowe et al.* [1978].
[b]Analyses of glasses were by Cameca electron microprobe, Model Camebax, 10-μm raster, 15 kV, 0.01 μA, and count time of 50 s or precision of 1%. Most samples are >90% glass (see modes).
[c]Analyses were done at Omega Site reactor, Los Alamos National Laboratory.

dine). Such a marker horizon is useful, as there are so many partial stratigraphic sections.

Within paleovalleys, the interval between unit c and overlying pyroclastic units is one of major erosion and deposition (Figure 5). Mostly massive, tan tuffaceous sandstones and conglomerates and cross-bedded fluvial deposits fill channels cut into the older Toledo tuffs. The matrix in these deposits consists of mostly subangular to subrounded pumice pyroclasts; each is coated with brown silt that fills the outermost vesicles. In one of the southeasternmost stratigraphic sections there is evidence of erosion within unit c; a mud-cracked fine ash bed is underlain and overlain by brown epiclastic sedimentary rocks.

Unit d

Unit d is a crudely normally graded pumice bed, 0.6–1.8 m thick and consisting of mostly white pumice lapilli at the base, grading upward into coarse ash. It contains 5–10% lithic clasts; slightly over half consist of porphyritic lavas and the remainder are obsidian and perlite. This unit is similar to unit e, based on lithic clast populations; both contain numerous obsidian clasts.

Unit e

The sequence in this unit of alternating fine ash and pumice lapilli beds is very similar to that of unit c; the two units can, however, be separated on the basis of abundant perlite clasts in unit e. As in unit c, unit e is relatively thin (0.2–2.2 m thick) and is widespread over the northern Pajarito Plateau (Figure 3*f*). Most of the beds within this unit are 1–4 cm thick.

These beds form sets, with a fine-grained ash grading upward into fine pumice lapilli and coarse ash. The fine-grained basal portions consist of up to 40% accretionary lapilli in a matrix of very fine ash. The matrix consists mostly of

TABLE 4b. Cerro Toledo Rhyolite: Dome Lavas

	East Los Posos	Cerro Toledo	Rabbit Mountain	Pinnacle Peak
Electron Microprobe Analyses—(Glass)—Normalized, Volatile Free[a]				
SiO_2	76.7	77.5	77.2	77.3
TiO_2	0.12	0.06	0.08	0.07
Al_2O_3	12.6	12.3	12.4	12.7
FeO	1.17	1.11	1.15	0.93
MnO	0.06	n.d.	n.d.	0.07
MgO	0.08	n.d.	n.d.	0.03
CaO	0.43	0.24	0.26	0.20
Na_2O	4.46	4.31	4.38	4.18
K_2O	4.42	4.48	4.72	4.58
Number of analyses	6	2	2	6
Instrumental Neutron Activation Analyses[b], *ppm*				
Cl	860	790	2100	2100
Sc	1.58	1.09	1.22	1.10
Cr	n.d.	n.d.	n.d.	n.d.
Zn	57	60	70	70
Rb	150	205	220	215
Zr	135	130	180	150
Cs	3.8	4.6	6.9	7.8
La	44	31	43	41
Ce	91	72	83	73
Nd	31	18	23	28
Sm	5.8	7.0	8.7	9.0
Eu	0.19	n.d.	0.10	0.08
Dy	6.9	10.2	10.9	11.7
Yb	5.1	5.7	7.9	7.7
Hf	6.0	8.6	8.9	7.8
Th	17.8	24.0	26.0	24.0
U	6.1	8.0	8.5	8.1
Mode Volume Percent				
Glass	90.0	100.0	100.0	77.0
Anorthoclase	...	...	...	...
Hypersthene	...	...	...	...
Plagioclase	7.0	...	...	15.0
Hornblende	...	...	...	5.0
Sanidine	...	...	...	2.0
Quartz	2.0	...	...	...
Biotite	1.0	...	...	1.0

Most samples are >90% glass (see modes).

[a]Analyses of glasses were by Cameca electron microprobe, Model Camebax, 10-μm raster, 15 kV, 0.01 μA, and count time of 50 s or precision of 1%.

[b]Analyses were done at Omega Site reactor, Los Alamos National Laboratory.

angular shards, ranging in length from 1 to 100 μm. Most beds are planar, grading up into overlying pumice bed, but one section contains convolute laminae.

The pumice fall parts of these bedding sets consist of massive pumice lapilli and coarse ash. They contain 15–20% lithic clasts. The lithic clast population is distinctive and consists of mostly perlite and obsidian with lesser amounts of aphanitic lavas. Irregular, elongate pumice clasts are characterized by a heterogeneous vesicle population, with pockets of coalesced vesicles surrounded by highly elongate, curved vesicles.

In contrast with unit c, unit e is thickest in the northern half of the area covered by Cerro Toledo tuffs. Both appear to have been deposited in part by surges; those in unit e swept across the northern half of the area.

A strong candidate as the source of unit e is a tuff ring located within the Toledo embayment. Bedded rhyolitic tuffs form a tuff crescent with quaquaversal dips; they overlie the 2–3.5 Ma Cerro Rubio Quartz Latite domes and an unnamed rhyolite dome of Cerro Toledo Rhyolite age (Table 1) and are overlain by the upper member of the Bandelier Tuff. Basal tuffs are poorly bedded, fine-grained white tuffs containing pumice, obsidian, and perlite lapilli as well as gray andesite and dacite lithic clasts. There are some accretionary lapilli in these fine-grained tuffs. The tuff matrix has been replaced mostly by smectites with traces of a zeolite, but relict glass shards range in size from 20 to 80 μm. Near the base of the sequence the tuffs are nonwelded. These tuff beds grade upward into normally graded ash fallout beds that are rich in lithic clasts that are partly to densely welded. The proportion of obsidian (and perlite) clasts increases from 16% (in the underlying nonwelded tuffs) to 35–50% in the welded fallout tuffs.

Units f and g

Both units f and g crop out only in a few places, near the western edge of the Cerro Toledo tuff deposit. Both beds are normally graded pumice falls composed of aphyric pumice lapilli.

Unit f contains less than 5% lithic clasts, including older, spherulitic welded tuffs and a hornblende-pyric glassy andesitic lava. The subequant pumice pyroclasts contain only traces of aegerine-augite, K-feldspar, albitic plagioclase, quartz, and biotite.

Unit g was identified in only two locations. It consists of pumice lapilli with 1–2% lithic clasts.

Rabbit Mountain

Contemporaneous with, but separate from the main NE to east trending tuff deposits of the Cerro Toledo Rhyolite, are the dome, lava flows, and pyroclastic deposits of Rabbit Mountain, which are located on the southeastern rim of the Valles caldera. The pyroclastic deposits trend southeast from Rabbit Mountain, forming a 4-km-wide, 7-km-long deposit that is interbedded with rhyolite flows (Figures 1 and 3). Patches of this deposit (mostly reworked epiclastic sediments) are present as narrow channel fillings. These deposits overlie the lower and underlie the upper members of the Bandelier Tuff.

The clastic deposit is a massive breccia, consisting of angular, light gray, aphyric, flow-banded rhyolite blocks in a matrix of gray, medium- to fine-grained lithic ash. The matrix is a finer-grained version of the rhyolite fragments. This monolithologic breccia is greater than 20 m thick and is overlain by a 20-m-thick banded rhyolite flow that is, in turn, overlain by 3–6 m of breccia that also contains abundant obsidian fragments and blocks. It is the presence of obsidian clasts that allows much of this unit to be mapped in surrounding areas of poor outcrop. Along most of Obsidian Ridge, Rabbit Mountain deposits are overlain by the upper member of Bandelier Tuff.

Surge deposits are exposed immediately SE of Rabbit Mountain. Over 3 m of the deposits overlie a 1-m-thick, lithic-rich massive pyroclastic flow deposit. The surge deposits consist of dunes with wavelengths of 5 m, amplitudes of 0.6 m, and current directions trending SW. The dunes consist of medium to coarse ash that contains up to 30% lithic clasts, including abundant perlitic obsidian.

COMPARATIVE PETROCHEMISTRY OF CERRO TOLEDO DOMES AND TUFFS

Analytical Methods

Major and minor element analyses of Cerro Toledo lavas and tuffs were determined primarily by electron microprobe;

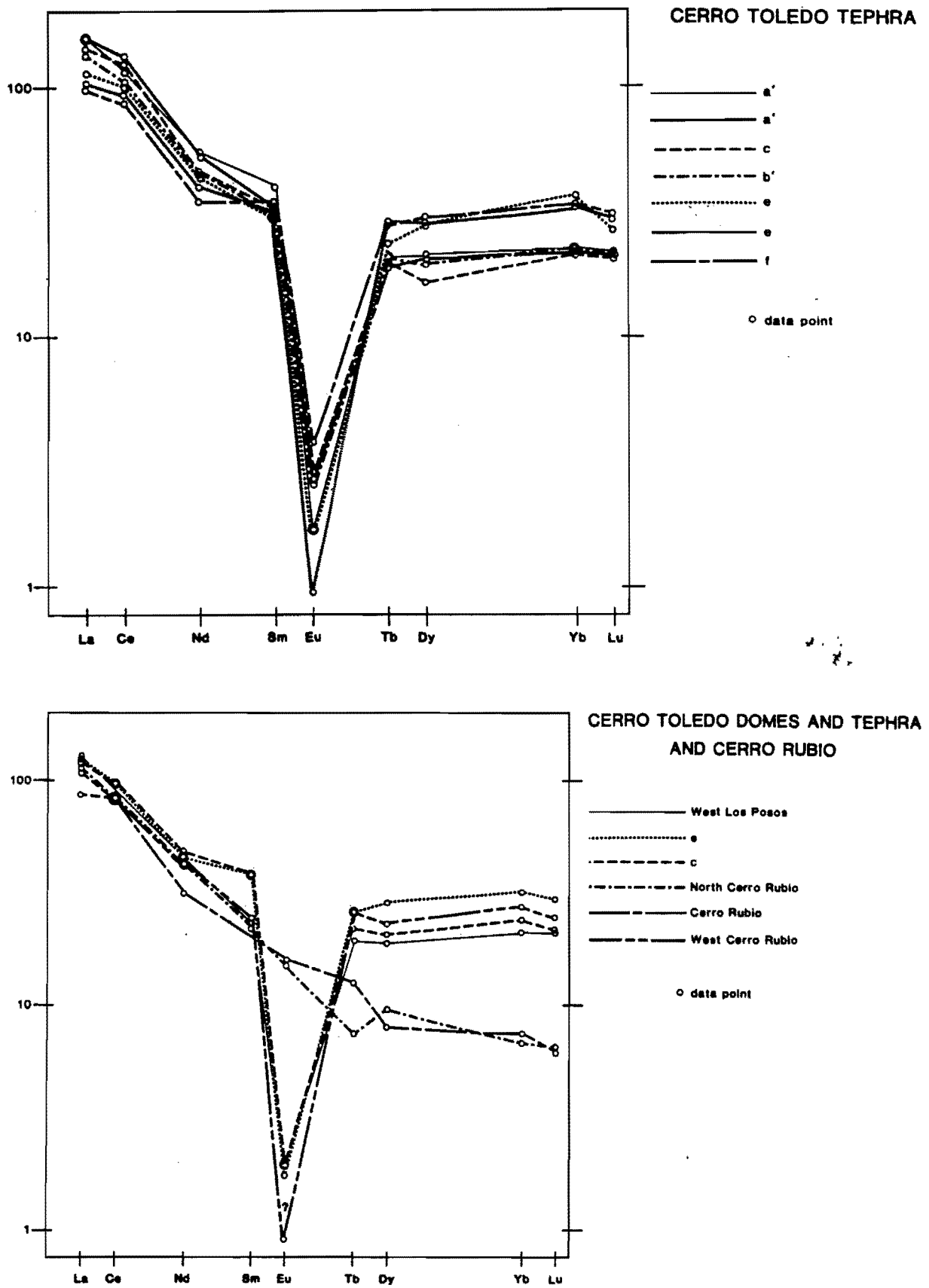

Fig. 6. Chondrite-normalized REE patterns of Cerro Toledo Rhyolite domes and tuffs and the Cerro Rubio Quartz Latite lavas.

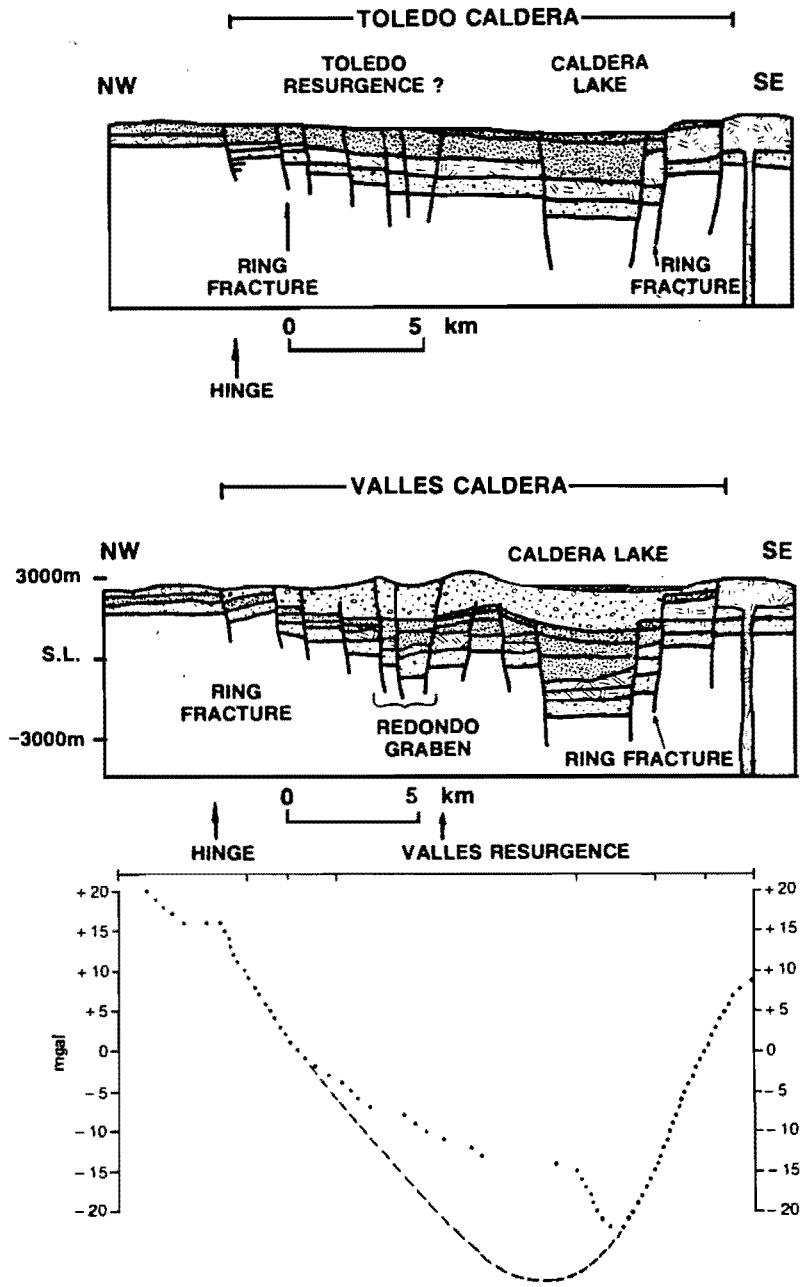

Fig. 7. Schematic cross sections illustrating structural development of the Toledo and Valles calderas (upper and middle illustrations) as proposed in this paper and by *Nielson and Hulen* [1984]. The lower illustration is a residual Bouguer gravity profile along the line of the cross sections; it is from *Nielson and Hulen* [1984], based upon a gravity survey by *Segar* [1974]; present gravity signature (dots) and the gravity signature postulated for the caldera complex immediately after eruption of the upper member of the Bandelier Tuff (dashed line). Patterns are white, Precambrian "basement" and Paleozoic and Mesozoic sedimentary rocks; fine stipple, sedimentary rocks of the Rio Grande rift; double dashes, pre-Bandelier Tuff volcanic rocks; dark short dashes, lower member, Bandelier tuff; coarse stipple and cross hatch, intracaldera tuffs and lake deposits; dots and circles, upper member, Bandelier Tuff.

polished thin sections of glass shards and pumice (tephras) and rhyolitic glass (lavas). Whole rock samples of the East Los Posos dome and welded tuff of Pinnacle Peak were analyzed by XRF according to procedures of *Hagan* [1982]. Selected trace elements were analyzed on aliquots of the same samples by instrumental neutron activation analysis, following the methods of *Garcia et al.* [1982] and *Minor et al.* [1982].

Chemistry of Cerro Toledo Tuffs and Lavas

All pyroclasts (shards and pumice) and lavas of Cerro Toledo Rhyolite from inside and outside the Toledo caldera and embayment are of high-silica rhyolite composition; CaO is relatively low, and K_2O is greater than Na_2O (Table 4). The two lavas that contain feldspar phenocrysts are slightly less silicic and more aluminous than the aphyric rocks. By comparison, pumice from the Bandelier Tuff contains slightly more FeO and Al_2O_3 and slightly less SiO_2 than Cerro Toledo pumices. Differences in major and minor element concentrations between Cerro Toledo tuffs and dome lavas are so small that correlation, based on major element compositions, of any tuff with a dome is uncertain.

Trace element concentrations within these rhyolites are

more distinctive than the major element compositions. There are significant differences in concentrations of Zn, Rb, Cs, Nd, Sm, Dy, Yb, Hf, Th, and U between samples of Cerro Toledo Rhyolite and Bandelier Tuff. There are subtle differences in these elements among the domes of Cerro Toledo Rhyolite. Certain trace elements change systematically in successively younger Cerro Toledo tuff units, as noted by *Smith* [1979] for Nb. In particular, Rb, Cs, Hf, Th, U, and the heavy rare earths Dy and Yb increase with decreasing age, whereas Zr, Sc, and the light rare earths La, Ce, and Nd decrease upward through the tuff section (Table 4 and Figure 6). *Smith* [1979] proposed that these trace element patterns document systematic chemical evolution of the Bandelier magma chamber before catastrophic eruption of the upper member of Bandelier Tuff.

Three main conclusions can be based on these data:

1. Chemical trends within the Cerro Toledo Rhyolite tephras are opposite to those documented in some pyroclastic flow deposits [*Hildreth*, 1979; *Smith*, 1979].
2. The Toledo intracaldera Plinian and phreatomagmatic deposits may represent eruptions that removed only the uppermost part of the magma chamber. These eruptions may have had little or no influence on deeper magmatic processes that controlled the compositional gradients within the magma chamber. In contrast, Bandelier pyroclastic flow deposits appear to have been derived from deeper levels in the chamber.
3. Chemical trends within the Cerro Toledo Rhyolite tephras may document the reestablishment of compositional zonation over a period of 0.4 m.y. In contrast, the large volumes of tephra erupted during the upper Bandelier Tuff event record a chemical section through the magma chamber.

Correlation of Cerro Toledo Tuffs and Domes

Correlations between individual Cerro Toledo domes and tuff units have been extremely difficult because of the uniformity of petrographic and chemical characteristics. Correlations based on phenocryst populations are not possible because of the nearly aphyric nature of most of the rocks (Turkey Ridge is a notable exception) (Table 3). Isopach maps have been useful to tie tuffs to the general cluster of Cerro Toledo domes but not to identify single sources for tephra. The best means of correlation has been by comparison of trace element compositions and age dates. On the basis of these data, the most likely sources of fall units a and b (> 1.43 Ma) would be the East and West Los Posos domes or the pair of domes comprising Cerro Toledo (1.62–1.38 Ma). The trace element composition of East Los Posos dome compares well with that of tephra units a and b, particularly in the elements Sc, Zr, Cs, La, Ce, Nd, Dy, Hf, Th, and U. Tephra units c through f, which are < 1.23 Ma are most likely correlated with tuffs of Pinnacle Peak (1.20 Ma); trace element compositions are similar. Other possible sources for the younger tephra units could be Turkey Ridge or Warm Springs domes but both of these domes are phenocryst-bearing, whereas the tephras are aphyric.

DISCUSSION

Cerro Toledo Rhyolite tuffs and associated epiclastic sediments provide evidence indicating that Toledo intracaldera pyroclastic activity was very limited in extent, with the exception of a deposit below Rabbit Mountain; this assumes that all intracaldera rhyolite domes had associated explosive activity, which is likely [*Newhall and Melson*, 1983]. The contact between upper and lower members of the Bandelier Tuff was examined throughout the field for presence or absence of the Cerro Toledo Rhyolite tuffs. The main body of tuffs are distributed to the east and northeast of the Valles-Toledo caldera complex and are exposed nowhere else in the Jemez volcanic field. Based on distribution of these deposits, explosive intracaldera activity was limited mostly to the northeast quadrant of the Toledo caldera and Toledo embayment. Explosive activity associated with the rhyolite domes consisted of a mixture of Plinian pumice eruptions and surges and falls associated with phreatomagmatic activity. This activity implies that intracaldera activity was in or near a caldera lake and that the lake was located in a depression on the eastern side of the caldera.

Nielson and Hulen [1984] correlate the S_3 sandstone identified in drill holes on the Baca location with the Cerro Toledo Rhyolite tuffs and epiclastic sediments. This distinctive sandstone occurs between the upper and lower Bandelier tuffs. The western edge of the S_3 deposit is located just west of Redondo graben and thickens toward the east, reaching a maximum thickness of 40 m. It is possible that the edge of this deposit lies on the western rim of the Toledo caldera. *Nielson and Hulen* [1984] suggest that the S_3 sandstone was deposited on an erosion surface sloping toward the east; it was not in a caldera lake but was perhaps on an erosion surface sloping into a lake.

A gravity survey of the caldera complex by *Segar* [1974] is the basis for several interpretations of the thickness of the caldera fill in the eastern half of the caldera complex [*Segar*, 1974; *Goff and Grigsby*, 1982; *Heiken and Goff*, 1983; *Goff*, 1983]. In these interpretations, the total caldera "fill" thickens from 1500 m in the Redondo Creek area (west central part of the caldera complex) to 3400 m below Valle Grande in the east. "Fill" includes (1) lower tuffs, older silicic welded and nonwelded tuffs (pre-Bandelier ignimbrites of *Self et al.* [this issue]), (2) lower (Otowi) member of the Bandelier Tuff, (3) Cerro Toledo Rhyolite, (4) upper (Tshirege) member of the Bandelier Tuff, and (5) intracaldera rhyolitic lavas and tuffs (Valles Rhyolite), epiclastic sediments, and lake sediments. If caldera fill does indeed thicken greatly toward the east, as is interpreted from the gravity data and the stratigraphy of caldera fill deposits [*Nielson and Hulen*, 1984], then there are implications as to the nature of caldera collapse for the Toledo and Valles calderas.

Caldera Model

The Toledo and Valles calderas appear to have a trapdoor origin, hinged on the west. Eruption of the lower member of Bandelier Tuff caused asymmetric collapse to form Toledo caldera, filled with a wedge of tuff that thickens toward the east (Figure 7). Interpretation is based on drill hole records and gravity models of the caldera complex. The proposed tuff wedge is bounded on the east by a major, NE trending rift-related fault (parallel to the Jemez lineament) that cuts the precursor dacite domes and andesitic composite cones of the Tschicoma and Paliza Canyon formations. The thickest part of the wedge has remained topographically low and was the site of the Toledo caldera lake(s) and intracaldera eruptions. This lake may have occasionally extended into the Toledo embayment. Inference of the eruption of Cerro Toledo Rhyolite through a lake can be made on presence of phreatomagmatic tuffs within the Cerro Toledo Rhyolite deposits. It is not known if there was structural resurgence of the Toledo caldera.

Later eruption of the upper member of the Bandelier Tuff also resulted in asymmetric collapse to form the Valles caldera; a tuff wedge, believed to be thickest in the east, partly

filled the caldera (Figure 7). An intracaldera lake in Valles caldera may have been located in the north and east [*Griggs*, 1964], with lacustrine deposits exceeding 360 m in the eastern Valles caldera, less than 100 m in the northeastern Valles caldera [*Griggs*, 1964] and absent in the western Redondo Peak area [*Nielsen and Hulen*, 1984]. Interbedded with moat sediments are the Valles intracaldera rhyolite domes that are inferred to have erupted along the ring-fracture system [*Smith et al.*, 1970].

A similar trapdoor caldera is Cerro Galan, Argentina [*Francis*, 1978], where there is considerable asymmetry, resurgence limited to the shallower side of the caldera, and a caldera lake on the lower (and thicker?) side of the depression. Cerro Galan is also astride the edge of a rift. Other examples of trapdoor calderas include Silverton, Cochetopa, Ute Creek and Bonanza calderas, Colorado, and Three Creeks caldera, Utah [*Lipman*, 1984]. A smaller, historic example is that of the 1968 eruption of Fernandina, Galapagos, where, after an explosive eruption, the southeastern caldera floor subsided 300 m over a 12-day period, tilting the old caldera floor [*Simkin and Howard*, 1970].

A trapdoor hypothesis for the Toledo and Valles calderas was also suggested by *Nielson and Hulen* [1984], an interpretation based on the thickening of the Bandelier Tuff toward the southeast in the Redondo Creek geothermal wells and on interpretation of a gravity survey by *Segar* [1974]. A trapdoor would also be consistent with caldera collapse across the western edge of the Rio Grande rift, with rift-bounding faults and an eastward thickening wedge of rift sediments underlying the eastern half of the caldera complex and structurally high Paleozoic sedimentary rocks and Precambrian igneous-metamorphic complex underlying the "hinge."

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S. Garcia, F. Goff, R. Hagan, and G. Heiken, Los Alamos National Laboratory, ESS-1, MS/D 462, Los Alamos, NM 87545.

M. Shafiqullah, Department of Geosciences, University of Arizona, Tucson, AZ 85721.

J. Stix, Department of Geology, University of Toronto, Toronto, Ontario M5S 1A1 Canada.

S. Tamanyu, Geothermal Research Department, Geological Survey of Japan, 1-1-3, Higashi, Yatabe, Ibaraki, 305, Japan.

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