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GEOCHRONOLOGY AND GEOCHEMISTRY OF THE CERRO TOLEDO RHYOLITE

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Abstract—The Cerro Toledo Rhyolite (CTR) comprises domes and tephra erupted during the interval between two caldera-forming ignimbrites, the Tshirege Member (TMBT) and Otowi Member (OMBT) of the Bandelier Tuff, in the Jemez volcanic field, New Mexico. The $^{40}Ar/^{39}Ar$ ages for the OMBT (1.608 ± 0.010 Ma) and the TMBT (1.225 ± 0.008 Ma) yield a repose interval of 380 ± 20 ka between caldera collapse events. $^{40}Ar/^{39}Ar$ dates on pumice fall units within the CTR tephra indicate that eruptive activity occurred at >1.59, 1.54, 1.48, 1.37 and 1.22 Ma. $^{40}Ar/^{39}Ar$ dating of CTR domes indicates these were erupted within the caldera at 1.54, 1.45, 1.38-1.34 and 1.27 Ma. Analyzed crystal populations range from being fairly homogenous juvenile material to very heterogeneous mixed magmatic and xenocrystic assemblages. The dates obtained indicate that CTR eruptive activity producing both tephra and domes occurred during discrete intervals at approximately 1.54 Ma, 1.48-1.45 Ma, 1.37-1.35 Ma, and 1.27 Ma. The interval from 1.34-1.38 Ma was particularly active as 7 of 16 units dated are constrained to these ages. All CTR samples are high-silica rhyolites that are extremely depleted in minor elements such as Fe and Mg. In contrast to relatively constant major and minor element compositions, trace elements such as Nb vary widely, reflecting distinct differences in differentiation. CTR tephra samples generally exhibit lower $(^{87}Sr/^{86}Sr)_i$ for sanidine than for whole pumice and may reflect Rb loss and Sr exchange with meteoric water during hydration of glass. Sanidine $(^{87}Sr/^{86}Sr)_i$ ranges between 0.70482 to 0.70593, except for one sample with an $(^{87}Sr/^{86}Sr)_i$ of 0.74821. This sample may be contaminated by Precambrian xenocrysts, although $^{40}Ar/^{39}Ar$ data indicates complete equilibration of the argon isotopic system. e_{Nd} values for CTR tephra range from -0.2 to -2.6 and show an irregular decrease with decreasing age. The isotopic data indicate a significant mantle-derived component in CTR magmas. Geochemical data suggests the oldest CTR tephra is closely related to the OMBT and probably represents residual material left in the OMBT magma chamber. The youngest tephra has an $^{40}Ar/^{39}Ar$ date indistinguishable from the TMBT and is geochemically similar and probably represents the earliest phase of the TMBT eruption. Although geochemical trends suggest CTR tephra and domes from 1.54 to 1.22 Ma record differentiation producing TMBT magmas the variable e_{Nd} values for CTR tephra samples precludes this simple interpretation. These data suggest that the CTR represents a sequence of eruptions that either tapped several separate magma bodies during the 380 ka interval between the OMBT and TMBT, or tapped an open system magma chamber which was replenished prior to 1.55, 1.46, 1.38 and 1.22 Ma, rather than progressive evolution of a single closed system magma chamber.

INTRODUCTION

The Valles-Toledo caldera complex, located near the center of the Jemez volcanic field (Fig. 1), provides an ideal opportunity for studying the evolution of large epicontinental silicic magma systems. This is because the products of several large ignimbrite eruptions producing caldera collapse events as well as postcollapse rhyolite domes and tephra are well preserved and exposed. When precise and accurate $^{40}Ar/^{39}Ar$ dates of eruptions are integrated with geochemical data the combination provides a powerful means of examining the rates of magmatic differentiation and timing of magma recharge/emplacement events. In this study we examine the $^{40}Ar/^{39}Ar$ geochronology of the Cerro Toledo Rhyolite (CTR), a sequence of small volume pyroclastic rocks and associated domes that erupted during a 380 ka interval between two large caldera-forming ignimbrites, the Otowi Member of the Bandelier Tuff (OMBT) (1.61 Ma) and the Tshirege Member of the Bandelier Tuff (TMBT) (1.23 Ma). These rocks thus record the development of the magma system following caldera collapse until immediately prior to the next, and as such offer a unique insight into magmatic evolution of a large rhyolitic magma chamber.

GEOLOGIC OUTLINE

The Jemez volcanic field is located in north-central New Mexico on the western margin of the Rio Grande rift (Fig. 1). The overall structure of the present volcanic field is dominated by basaltic to rhyolitic volcanic rocks of the Polvadera and Keres Groups, which form the broad shield upon which younger silicic volcanic rocks of the Tewa Group were erupted (Bailey et al., 1969; Gardner and Goff, 1984; Gardner et al., 1986). Beginning at ~1.85 Ma a series of explosive silicic eruptions occurred. The first of these produced the San Diego Canyon (SDC) ignimbrites which consist of two small (<10 km^3) units vented from a source area beneath the Valles Caldera (Self et al., 1986; Turbeville and Self, 1988; Spell et al., 1990). These were followed by the OMBT, which was erupted at 1.608 ± 0.010 Ma and resulted in collapse of the Toledo caldera, after which the TMBT was erupted at 1.225 ± 0.008 Ma and resulted in formation of the Valles caldera at a nearly coincident location (Smith and Bailey, 1968; Bailey et al., 1969; Heiken et al., 1986; Self et al., 1986). The volumes of the OMBT and TMBT were each 300–400 km^3. During the interval between the Bandelier Tuffs, rhyolite domes and associated tephra of the Cerro Toledo Rhyolite (CTR) were erupted (Bailey et al., 1969; Stix et al., 1988). Preserved CTR domes (some were likely destroyed during the collapse of the Valles caldera) are situated in the northeastern half of the Valles caldera and within the Toledo embayment, whereas the tephra fall deposits are exposed in canyons to the east of the caldera (Fig. 1). Postcollapse rhyolites of the Valles caldera are included in the Valles Rhyolite Formation and consist dominantly of high-silica rhyolite domes and lavas (Griggs, 1964; Bailey et al., 1969; Spell and Kyle, 1989; Spell et al., 1993), which range in age from ~1.13 to <.30 Ma (Spell and Harrison, 1993; Reneau et al., 1996).

ANALYTICAL METHODS AND DATA TREATMENT

Representative whole rock samples of the CTR domes and pumice clasts from the CTR tephra fall units were analyzed at N.M. Tech by X-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA) using standard procedures described by Hallett and Kyle (1993). Strontium and neodymium isotope ratios were determined on whole-rock powders and sanidine mineral separates at Royal Holloway and Bedford New College using a VG354 mass spectrometer and a multidynamic five collector method (Thirlwall, 1991). $^{87}Sr/^{86}Sr$ ratios were normalized to $^{87}Sr/^{86}Sr = 0.1194$. The value of $^{87}Sr/^{86}Sr$ for SRM 987 was 0.710245 at the time the samples were analyzed. $^{143}Nd/^{144}Nd$ ratios were normalized to $^{143}Nd/^{144}Nd = 0.7219$. The recommended $^{143}Nd/^{144}Nd$ value for CHUR is 0.512646. An interlaboratory standard gave $^{143}Nd/^{144}Nd = 0.511421 \pm 9$ (2s, n = 40) equivalent to a La Jolla standard $^{143}Nd/^{144}Nd = 0.511859$.

Cerro Toledo Rhyolite tephra samples were dated at the Australian National University (Table 1). Cerro Toledo Rhyolite dome samples were dated at the University of Houston (Table 2). Details of analytical procedures are described by Spell et al. (in press). These two data sets can be compared without concern for differences in calibration between the two

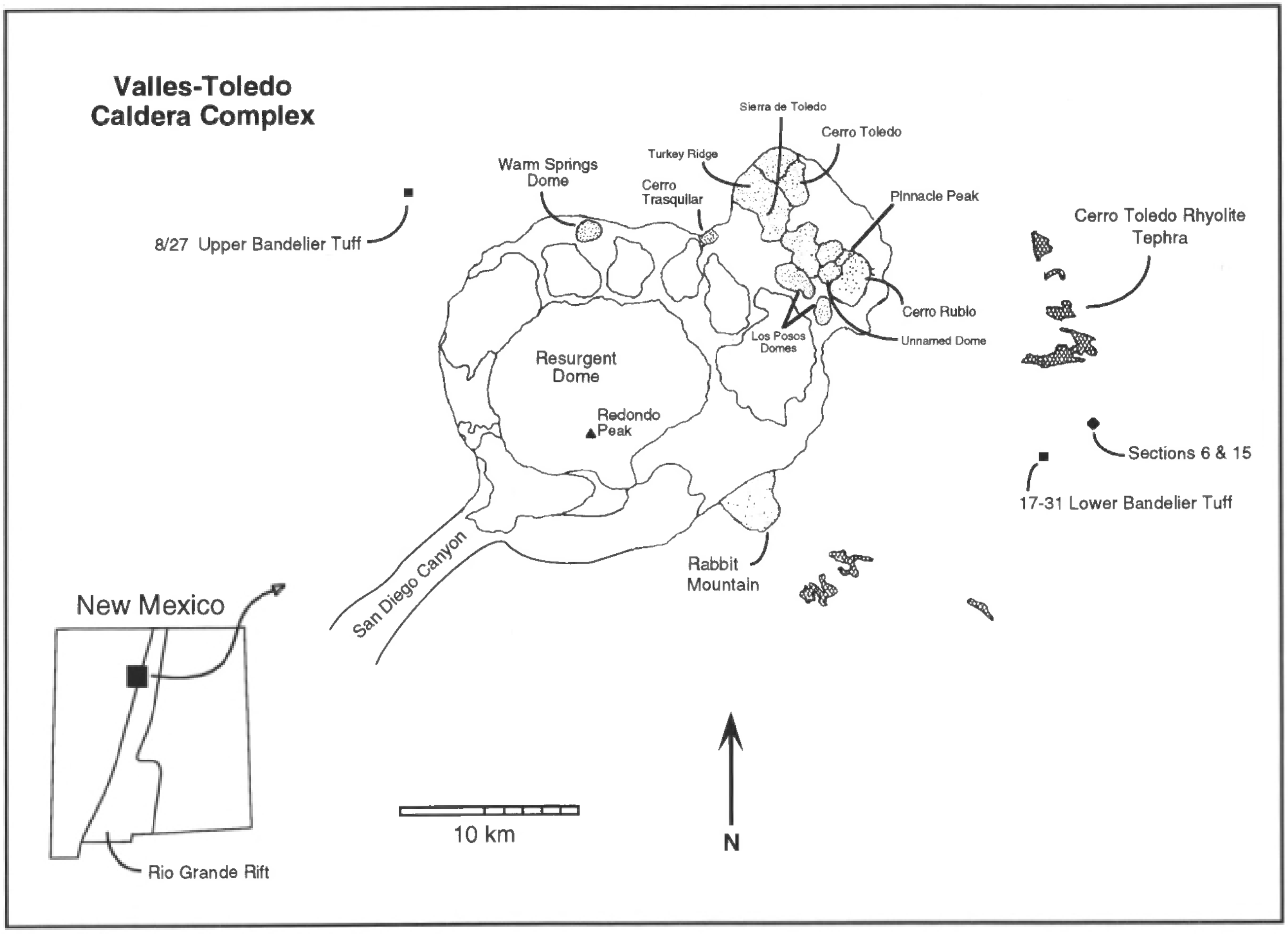

FIGURE 1. Geologic map of Jemez volcanic field showing location of Cerro Toledo Rhyolite domes and tephra (partly after Smith et al., 1970; Heiken et al., 1986; Stix and Gorton, 1993). Ring fracture post-Valles Caldera domes are shown as unpatterned. CTR domes shown with speckled pattern. Major CTR tephra outcrops indicated by cross hatched pattern. Bandelier Tuff is exposed in large outcrop areas to the east and west of the caldera with smaller outcrops to the north, south, and within the Valles Caldera and Toledo embayment (not shown for clarity). Location of CTR tephra sections 6 and 15 in Pueblo canyon and sample localities for the Bandelier Tuff samples (Kuentz, 1986; Balsley, 1988) are indicated.

TABLE 1. Geochronology of Cerro Toledo Rhyolite tephra and associated units. Australian National University data.

Sample ID	K/Ar	$^{40}Ar/^{39}Ar$ (Ma ± σ)		
	Ma ± σ	Isochron	Mean	Weighted Mean
8/27 (TM)	1.12 ± 0.03[a]	1.225 ± 0.008*	1.220 ± 0.007	1.212 ± 0.006
CT-9	1.23 ± 0.02[b]	1.212 ± 0.009*	1.213 ± 0.010	1.212 ± 0.007
CT-6	—	1.362 ± 0.016*	1.404 ± 0.124	1.389 ± 0.011
CT-5	—	1.376 ± 0.018*	1.387 ± 0.012	1.384 ± 0.008
CT-8	1.52 ± 0.04[c]	1.479 ± 0.020*	1.457 ± 0.016	1.459 ± 0.008
CT-7	1.47 ± 0.04[b]	n.d.o. (s)	1.543 ± 0.066 (s)	1.520 ± 0.016 (s)
		n.d.o. (p)	1.324 ± 0.215 (p)	1.205 ± 0.024 (p)
CT-4	—	1.474 ± 0.023* (s)	1.488 ± 0.024 (s)	1.491 ± 0.009 (s)
		n.d.o. (p)	1.370 ± 0.143 (p)	1.287 ± 0.019 (p)
CT-3	—	1.451 ± 0.022	1.531 ± 0.032	1.542 ± 0.008*
CT-2	—	1.536 ± 0.018*	1.558 ± 0.033	1.550 ± 0.008
CT-1	—	n.d.o.	1.653 ± 0.032	1.652 ± 0.008
17-31 (OM)	1.45 ± 0.06[a,b]	1.608 ± 0.010*	1.611 ± 0.008	1.609 ± 0.008

All ages are based on the Fish Canyon Tuff sanidine standard with a K/Ar age of 27.9 Ma. Asterisks indicate preferred ages. Samples arranged in stratigraphic order. TM, Tshirege Member Bandelier Tuff; OM, Otowi Member Bandelier Tuff. Isochron ages calculated using inverse isochron York (1969) fit routine and omitting outliers until MSWD <2.5, errors include J and MSWD. Weighted mean ages use weighting by the inverse of the variance, errors include 0.5% J factor error. Mean ages are sample mean ± population standard deviations. Means and weighted means are calculated using model apparent ages and exclude analyses greater than 2σ from the mean. n.d.o., no date obtained. All $^{40}Ar/^{39}Ar$ analyses are sanidine unless otherwise indicated. For samples where both sanidine and plagioclase were analyzed, s = sanidine, p = plagioclase. Decay constants and isotopic compositions are those recommended by (Steiger and Jäger, 1977).

a) Doell et al., 1968., b) Izett et al., 1981, c) Stix et al., 1988.

TABLE 2. Geochronology of Cerro Toledo Rhyolite Domes and associated units. University of Houston data.

Sample ID	Dome	K/Ar Ma ± σ	$^{40}Ar/^{39}Ar$ (Ma ± σ) Isochron	Mean	Weighted Mean
WS-2	Warm Springs	1.25 ± 0.04[c]	1.265 ± 0.011*	1.267 ± 0.025	1.263 ± 0.011
TE-9	Sierra de Toledo	——	1.336 ± 0.018*	1.326 ± 0.027	1.336 ± 0.012
TE-15	Turkey Ridge	1.24 ± 0.03[c]	1.343 ± 0.015*	1.351 ± 0.026	1.348 ± 0.021
TE-1	Unnamed dome	1.33 ± 0.02[a]	1.348 ± 0.010*	1.356 ± 0.011	1.357 ± 0.013
TE-26	Cerro Trasquilar	1.27 ± 0.02[c]	1.351 ± 0.015*	1.368 ± 0.048	1.369 ± 0.011
TE-13	Sierra de Toledo	——	1.379 ± 0.012*	1.367 ± 0.030	1.380 ± 0.011
TE-20	Los Posos East	1.47 ± 0.05[c]	1.446 ± 0.009*	1.481 ± 0.027	1.477 ± 0.009
TE-18	Indian Point	——	1.463 ± 0.011*	1.457 ± 0.018	1.464 ± 0.009
TE-25	Los Posos West	1.50 ± 0.05[c]	1.540 ± 0.012*	1.548 ± 0.018	1.545 ± 0.016
17-31 BT	Otowi Member	1.45 ± 0.06[a,b]	1.618 ± 0.011*	1.644 ± 0.053	1.625 ± 0.009

All ages are based on the Fish Canyon Tuff sanidine standard with a K/Ar age of 27.9 Ma. Asterisks indicate preferred ages. Isochron ages calculated using inverse isochron York (1969) fit routine and omitting outliers until MSWD <2.5, errors include J and MSWD. Weighted mean ages use weighting by the inverse of the variance, errors include 0.5% J factor error. Mean ages are sample mean ± population standard deviations. Means and weighted means are calculated using model apparent ages and exclude analyses greater than 2σ from the mean. BT, Bandelier Tuff. All $^{40}Ar/^{39}Ar$ analyses are on sanidine. Decay constants and isotopic compositions are those recommended by (Steiger and Jäger, 1977).

a) Doell et al., 1968., b) Izett et al., 1981, c) Stix et al., 1988.

laboratories. Intercalibration of the Australian National University $^{40}Ar/^{39}Ar$ data with that from the University of Houston was accomplished by analyzing sample 17-31 (OMBT) at both laboratories. The flux monitor for samples run in both labs was 92-176, sanidine from the Fish Canyon Tuff, with an age of 27.9 Ma (Steven et al., 1967; Hurford and Hammerschmidt, 1985; Cebula et al., 1986). The identical results obtained for the age of sample 17-31 (Tables 1, 2) indicates that the two data sets are directly comparable.

Mixed crystal populations of juvenile phenocrysts, altered crystals, and xenocrysts in explosively erupted volcanic rocks were identified by laser fusion dating of individual crystals. Ages reported here have been obtained by three methods. Sample means and population standard deviations are calculated. Any samples greater than 2s from the mean are excluded and a new mean calculated. Weighted means of these refined data sets are also calculated using the inverse of the variance as the weighting factor (Young, 1962). Isochron ages are calculated using a method outlined in previous studies (Deino and Potts, 1990; Spell and Harrison, 1993). Briefly, all analyses are regressed on an isochron using the York (1969) routine. If MSWD is greater than ~2.5 (indicating geologic scatter in the data) the analysis contributing the most to the MSWD is omitted and the remaining data regressed again. This process was repeated if necessary until a homogeneous crystal population was defined.

$^{40}AR/^{39}AR$ AGES OF CERRO TOLEDO RHYOLITE TEPHRA AND DOMES

The $^{40}Ar/^{39}Ar$ ages obtained in this study (Tables 1, 2) are in some cases consistent with previously reported K/Ar and fission track data (Izett et al., 1981). Tephra samples CT-9 and CT-8 and dome samples WS-2, TE-1, TE-20 and TE-25 yield $^{40}Ar/^{39}Ar$ ages similar to previous K/Ar ages (Tables 1, 2; Izett et al., 1981; Stix et al., 1988). Sample TE-15 from the Turkey Ridge dome and TE-26 from Cerro Trasquilar, however, have significantly older $^{40}Ar/^{39}Ar$ ages than previous K/Ar ages (Table 2). These older ages likely reflect incomplete degassing of radiogenic argon during K/Ar dating (Webb and McDougall, 1967; McDowell, 1983).

For tephra samples CT-4 and CT-7, feldspars are dominantly plagioclase and the samples are nearly aphyric so that both plagioclase and sanidine crystals were analyzed. Although radiogenic yields as high as ~81% were obtained for the plagioclase analyses the data generally are discordant with coexisting sanidine and with stratigraphic relations (Table 1). All mineral separates analyzed appeared pristine under the binocular microscope, although unrecognized mm scale alteration cannot be ruled out (e.g., Kelley et al., 1994). In general, our experience is that total fusion plagioclase ages may not be reliable and should be interpreted with caution (cf., Pringle et al., 1992).

There is good agreement between the $^{40}Ar/^{39}Ar$ ages, including those of the bracketing Bandelier Tuffs, and stratigraphic level in the CTR tephra sequence (Table 1). There is a regular progression of decreasing age with higher stratigraphic level. The new dates indicate that the major CTR eruptive activity (as recorded by the large pyroclastic pumice units sampled) during the 380 ka interval between the OMBT and TMBT occurred during discrete periods at >1.59, 1.54, 1.48, 1.37 and 1.22 Ma (Fig. 2). These pulses of volcanic activity are separated by quiescent intervals of 60 to 140 ka.

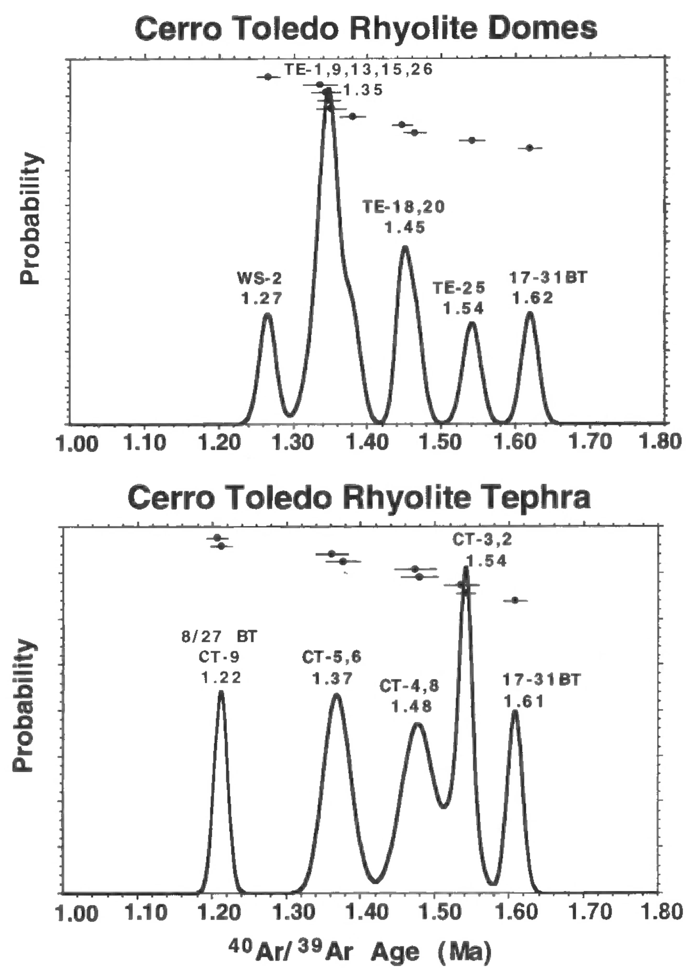

FIGURE 2. Probability distribution spectra for Cerro Toledo Rhyolite domes (top diagram) and tephra (lower diagram). $^{40}Ar/^{39}Ar$ ages are those marked as preferred in Tables 1 and 2. Ages and 1s errors indicated.

Cerro Toledo Rhyolite domes dated in this study are within the Toledo embayment with the exception of Warm Springs dome, Cerro Trasquilar, and possibly the Los Posos domes (Fig. 1). There is no apparent regular progression of ages with geographic locality within what remains of the Toledo caldera. Two samples of Sierra de Toledo, a previously undated dome, yield ages of 1.336 ± 0.018 Ma (TE-9) and 1.379 ± 0.012 Ma (TE-13), which are different at the 1s confidence level. The Sierra de Toledo dome may be a composite unit produced by multiple eruptions. Turkey Ridge (1.343 ± 0.015 Ma) and the Sierra de Toledo dome form a continuous morphological feature and thus may represent a single eruptive event between 1.336 and 1.379 Ma. An obvious aspect of the dates on CTR domes is that dates for 5 of the 9 samples fall between the dates on the two Sierra de Toledo samples TE-9 and TE-13. This is also an interval during which two of the CTR tephra samples (CT-5, CT-6) were erupted (Table 1, Fig. 2). The previously undated Indian Point dome gave a $^{40}Ar/^{39}Ar$ age of 1.463 ± 0.011Ma. As with CTR tephra samples, the domes dated were erupted during discrete periods separated by longer quiescent intervals. Eruptions occurred at 1.54, 1.45, 1.38-1.34, and 1.27 Ma. Quiescent intervals of 70-80 ka separate these periods of volcanic activity.

The new $^{40}Ar/^{39}Ar$ dates place constraints on a magma chamber recharge event (Stix and Gorton, 1993), which is recorded in samples stratigraphically equivalent with units between our samples 17-31 (OMBT) and CT-2. Ages of 1.608 ± 0.010 Ma (OMBT) and 1.536 ± 0.018 Ma (CT-2) suggest that this event occurred within ~70 ka of eruption of the OMBT and collapse of the Toledo caldera.

^{40}AR/^{39}AR CORRELATIONS BETWEEN TEPHRA AND DOMES

Both CTR tephra and dome samples record periodic volcanic activity with nearly identical timing. Based on the $^{40}Ar/^{39}Ar$ dates (Tables 1, 2) chronologic correlations between CTR tephra and domes may be made. Tephra samples CT-2 and CT-3 (1.536 and 1.542 Ma, respectively) from near the base of the section yield similar ages to that obtained on Los Posos West dome sample TE-25 (1.540 Ma). Farther upsection, tephra samples CT-4 and CT-8 (1.474 and 1.479 Ma, respectively) correlate with the Indian Point and Los Posos East dome samples TE-18 and TE-20 (1.463 and 1.446 Ma, respectively). Tephra samples CT-5 and CT-6 (1.376 and 1.362, respectively) correlate temporally with samples from Sierra de Toledo, Cerro Trasquilar, Unnamed Dome, and Turkey Ridge; samples TE-13 (1.379 Ma), TE-26 (1.351 Ma), TE-1 (1.348 Ma), TE-15 (1.343 Ma), and TE-9 (1.336 Ma). There is no correlative tephra for the Warm Springs dome (WS-2, 1.265 Ma). Finally, tephra sample CT-9 at 1.212 Ma has an age which is indistinguishable from the TMBT (1.225 Ma).

GEOCHEMISTRY AND ISOTOPE SYSTEMATICS

All CTR samples are high-silica rhyolites that are extremely depleted in elements such as Fe and Mg (Tables 3, 4). In contrast to relatively constant major and minor element compositions, trace elements such as Nb vary widely, reflecting varying degrees of differentiation and magmatic evolution (Fig, 3, Tables 3, 4). Elements such as Nb, Cs and La vary by 100-200% among the samples, reflecting significant differences in differentiation.

The geochemical evolution of the CTR tephra and domes and comparison with the OMBT and TMBT is shown on Figure 3. The CTR domes and tephra have a well-defined trend that shows a rapid decrease in Zr/Nb, which correlates with a decrease in age from 1.61 Ma to ~1.46 Ma. Two samples of 1.54 Ma dome (Los Posos West) fall off this trend. For tephra and domes between 1.46 and 1.22 Ma, Zr/Nb remains constant but Nb shows an ~2.5x increase in abundance, which also correlates with decreasing age. Samples of a 1.45 Ma dome (Los Posos East) show higher Nb than would be predicted from the trends shown by the other dome and tephra samples.

TABLE 3. Major and trace element geochemical data for Cerro Toledo Rhyolite tephra samples.

	CT-1	CT-2	CT-3	CT-4	CT-5	CT-6P	CT-7	CT-8	CT-9
SiO_2	73.89	73.4	73.76	73.23	73.06	73.22	73.42	73.46	73.94
TiO_2	0.14	0.1	0.11	0.11	0.07	0.09	0.11	0.10	0.06
Al_2O_3	11.72	11.78	11.78	12	11.71	11.91	11.93	11.75	11.46
Fe_2O_3	1.52	1.18	1.09	0.96	1.14	1.23	0.91	0.9	1.57
MnO	0.05	0.05	0.05	0.05	0.07	0.06	0.05	0.05	0.08
MgO	0.15	0.12	0.14	0.11	0.08	0.15	0.1	0.13	0.04
CaO	0.41	0.41	0.46	0.45	0.36	0.44	0.45	0.47	0.29
Na_2O	3.42	3.43	3.19	3.18	3.61	3.33	3.44	3.23	3.63
K_2O	4.82	4.98	4.69	4.89	4.65	4.75	4.73	4.79	4.46
P_2O_5	0.03	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.01
LOI	3.83	4.75	4.74	5.11	5.09	4.85	4.82	5.04	4.39
Total	99.98	100.22	100.03	100.11	99.85	100.05	99.98	99.94	99.93
Rb	100	131	138	140	198	198	138	148	317
Sr	18	13	26	25	12	10	25	18	7
Y	34	61	41	42	65	65	40	44	119
Zr	261	159	142	134	162	164	132	127	277
Nb	49	49	62	61	91	90	61	66	160
Ba	81	51	111	130	25	0	134	55	0
Pb	18	24	26	30	39	38	29	30	54
Sc	2.03	1.79	1.59	1.50	1.27	1.49	1.44	1.34	0.69
Cr	3	2	2	1	2	3	1	1	1
Zn	61	53	54	54	84	82	50	52	130
Cs	2.19	3.46	3.73	3.75	5.85	7.31	3.66	4.21	11.98
La	61.4	52.7	43.5	39.9	33.3	33.7	40.5	35.7	55.1
Ce	114.8	103.1	87.4	80.2	71.3	71.1	81.6	74.9	115.8
Nd	36.3	35.1	29	27.4	28.5	28.5	26.5	25.3	44.1
Sm	7.0	7.2	6.5	6.4	7.5	7.7	6.3	6.4	11.5
Eu	0.23	0.13	0.15	0.20	0.07	0.09	0.19	0.14	0.06
Tb	0.94	1.04	1.01	1.03	1.48	1.47	0.99	1.10	2.44
Yb	3.33	4.09	4.01	4.00	6.14	6.08	3.91	4.31	10.91
Lu	0.485	0.616	0.583	0.573	0.842	0.851	0.568	0.619	1.52
Hf	8.21	6.37	5.75	5.74	7.95	7.79	5.60	5.83	14.14
Ta	4.63	4.58	4.46	4.32	6.60	6.35	4.27	4.67	10.70
Th	14.27	16.99	17.1	17.51	21.86	21.77	17.32	18.58	33.90
U	4.0	5.8	5.8	5.7	8.0	7.8	5.6	6.2	12.3

Notes: Fe_2O_3 - total Fe as Fe_2O_3; LOI - loss on ignition
Major element oxides in wt. %, trace elements in ppm

TABLE 4. Major and trace element geochemical data for Cerro Toledo Rhyolite dome samples.

	TE-1	TE-9	TE-13	TE-15	TE-18	TE-20	TE-22	TE-25	TE-26	WS-2
SiO_2	77.08	74.48	77.36	76.92	74.62	77.07	77.16	76.16	77.11	77.1
TiO_2	0.07	0.08	0.07	0.05	0.09	0.07	0.07	0.12	0.07	0.06
Al_2O_3	12.32	12.05	12.56	12.4	11.96	12.51	12.46	12.68	12.27	11.2
Fe_2O_3	1.13	1.09	1.07	1.49	1.02	1.11	1.14	1.24	1.13	1.52
MnO	0.06	0.07	0.07	0.02	0.06	0.07	0.07	0.04	0.04	0.02
MgO	0.08	0.54	0.08	0.07	0.35	0.08	0.07	0.53	0.07	0
CaO	0.21	0.29	0.09	0.06	0.32	0.11	0.12	0.37	0.13	0.08
Na_2O	4.21	3.83	4.23	4.17	4.21	4.2	4.29	4.14	4.24	4.1
K_2O	4.58	4.62	4.59	4.59	4.6	4.6	4.6	4.55	4.63	4.17
P_2O_5	0.01	0.01	0	0.01	0.02	0	0.01	0.03	0.01	0.03
LOI	0.24	2.86	0.16	0.24	3.18	0.23	0.09	0.65	0.38	0.85
Total	99.75	97.06	100.10	99.78	97.25	99.82	99.99	99.86	99.70	98.30
Rb	202	191	199	229	178	200	205	140	196	282
Sr	0	2	0	1	1	0	0	19	1	5
Y	48	65	45	27	56	48	51	41	66	62
Zr	169	165	171	224	146	175	172	154	166	244
Nb	97	93	95	119	81	97	95	67	93	145
Ba	0	40	0	0	0	40	0	90	0	0
Pb	37	37	43	25	47	40	28	28	26	34
Sc	1.02	1.07	0.95	0.74	1.14	1.12	1.09	1.05	1.02	0.67
Cr	2	0	1	2	1	1	0	1	1	0
Zn	69	72	61	39	74	60	60	46	74	103
Cs	4.98	5.62	3.41	4.67	5.06	4.09	4.37	2.56	4.36	4.68
La	31.7	35.5	26.5	14.7	33.3	34.2	23.1	42.4	37.7	48.4
Ce	67.7	73.3	70.7	68.6	69	73.5	81.5	80.6	67.6	106
Nd	0	24.0	27.4	20.8	25.0	28.7	32.0	25.0	36.2	34.0
Sm	7.1	7.7	6.3	4.0	6.9	7.6	5.9	6.3	8.1	10.5
Eu	0.06	0.07	0.07	0.04	0.07	0.09	0.06	0.16	0.09	0.05
Tb	1.21	1.52	1.08	0.73	1.37	1.31	1.12	0.93	1.46	1.98
Yb	5.18	6.00	5.05	3.86	5.24	5.52	5.68	3.86	6.35	7.00
Lu	0.71	0.87	0.65	0.55	0.74	0.71	0.79	0.52	0.88	0.96
Hf	8.55	7.9	8.44	11.08	7	8.56	8.87	6.48	8.34	13.5
Ta	6.77	6.39	6.62	8.06	5.85	6.80	6.69	4.74	6.61	10.60
Th	23.05	22.40	23.30	27.70	20.20	23.18	22.80	19.00	22.12	32.20
U	8.2	7.9	7.8	7.5	7.2	8.3	7.9	5.8	8.1	11.6

Notes: Sample locations are given in Table 2 except for sample TE-22 which is from Cerro Rubio.
Fe_2O_3 - total Fe as Fe_2O_3; LOI - loss on ignition
Major element oxides in wt. %, trace elements in ppm

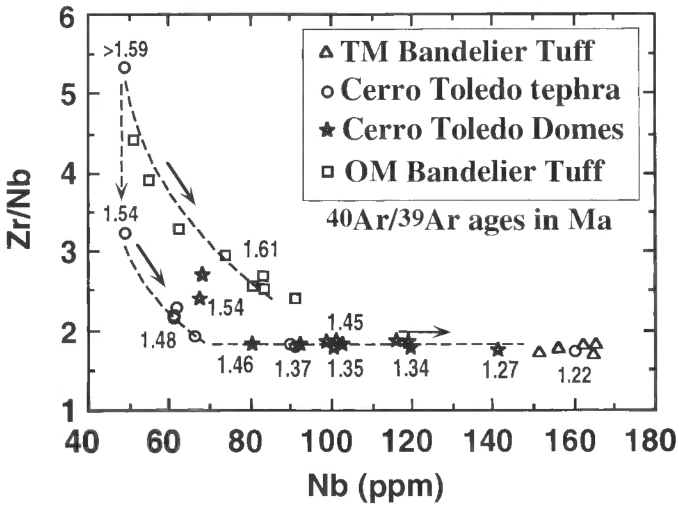

FIGURE 3. Zr/Nb versus Nb (ppm) for Cerro Toledo Rhyolite tephra and domes. The $^{40}Ar/^{39}Ar$ ages in Ma are those marked as preferred from Tables 1 and 2. Arrows indicate apparent differentiation trends. For clarity only the least differentiated OMBT samples (data from Kuentz, 1986) and most evolved TMBT samples (data from Balsley, 1988) are plotted.

CTR tephra samples generally exhibit lower $(^{87}Sr/^{86}Sr)_i$ for sanidine than for whole pumice samples (Table 5). There is a rough correlation between the increase in $(^{87}Sr/^{86}Sr)_i$ and degree of hydration of the pumice samples. The differences between the sanidine and whole pumice Sr isotopic analyses is probably due to Rb loss and Sr exchange with meteoric water during hydration of the pumice glass. Sanidine $(^{87}Sr/^{86}Sr)_i$ ranges between 0.70526 to 0.70593, with the exception of CT-5 for which sanidine $(^{87}Sr/^{86}Sr)_i$ is 0.74821, significantly higher than that of the whole pumice. This may reflect contamination by Precambrian xenocrysts, although $^{40}Ar/^{39}Ar$ data indicates complete equilibration of the argon isotopic system. e_{Nd} values for CTR tephra range from -0.2 to -2.6 and show a irregular decrease with decreasing age. The isotopic data differ substantially from local Precambrian basement rocks and indicate a significant mantle-derived component in CTR magmas (Spell et al., 1993).

The oldest CTR tephra sample (CT-1) did not give an isochron age (Table 1) and the mean and weighted mean ages are slightly older than the OMBT. The youngest laser fusion single crystal feldspar age is 1.59 Ma, suggesting that the age of this tephra unit is 1.59 Ma. CT-1 stratigraphically overlies the OMBT and the age data suggest no statistical difference between the two. Geochemical analyses of the OMBT show a well defined trend on the Zr/Nb vs Nb plot (Fig. 3), with the most primitive (least differentiated) rhyolites having the highest Zr/Nb ratio and lowest Nb contents. Tephra sample CT-1 lies on an extrapolation of the trend shown by the OMBT and isotopically is within the range shown by OMBT samples (Table 5). These data suggest that the CT-1 tephra is part of the OMBT magmatic system and probably sampled residual magma remaining in the magma chamber following the OMBT eruption. Stix et al. (1988) and Dunbar and Hervig (1992) also noted the close relationship between the first CTR tephra and the OMBT.

Although geochemical trends suggest CTR tephra and domes from 1.54 to 1.22 Ma record differentiation that produced the TMBT magmas, the variable e_{Nd} values for CTR tephra samples precludes this simple interpretation. These data suggest that the CTR represents a sequence of eruptions that either tapped separate magma bodies during the 380 ka interval between the OMBT and TMBT, or tapped an open system magma chamber that was replenished prior to 1.55, 1.46, 1.38 and 1.22 Ma. Our preliminary interpretation suggests that the CTR magmas are not the products of a progressive evolution of a single closed system magma chamber.

The youngest tephra (CT-9) has the same age and geochemical characteristics as the overlying TMBT (Tables 1, 3–5). No dome correlative for this tephra has been identified. This eruption resulted in deposition of at least a meter of tephra and the age and geochemical data suggest that the eruption was tapping the TMBT magma chamber. Significant volcanism was therefore occurring within the CTR sequence immediately prior to the cataclysmic TMBT eruption and collapse of the Valles caldera.

SUMMARY

The Cerro Toledo Rhyolite records volcanism during the ~380 ka interval between eruption of the caldera forming the Tshirege and Otowi Members of the Bandelier Tuff in the Jemez volcanic field. They thus contain important geochemical information about the evolution of this large crustal silicic magma system during the transition from and to caldera collapse events.

$^{40}Ar/^{39}Ar$ dating of nine major pumice fall units within the CTR tephra yields a detailed chronology of eruptive activity, with seven of these units having reliable and stratigraphically consistent ages. With a few exceptions, reliable sanidine isochrons were obtained from multiple laser fusions of individual phenocrysts. Plagioclase dates were generally discordant with coexisting sanidine and inconsistent with stratigraphic constraints. The dates obtained suggest that major CTR tephra-producing eruptions occurred in pulses at approximately 1.59, 1.54, 1.48, 1.37 and 1.23 Ma. $^{40}Ar/^{39}Ar$ dates of CTR rhyolite domes (1.54, 1.45, 1.38–1.34 and 1.27 Ma) show that many can be correlated with the tephra sequence. The oldest and youngest CTR tephra are identical to the OMBT and TMBT, respectively, and provide insight into the final products of the OMBT magma chamber and the earliest phases of the TMBT magma chamber.

This eruptive chronology, when tied to geochemical and isotopic data, indicates that evolution of the Bandelier silicic magma system during this interval is more complex than previously thought. Although all CTR samples are virtually homogeneous in terms of major and minor element chemistry, wide variation exists in trace element chemistry, reflecting large variations in the differentiation of the magmas erupted. Evidence

TABLE 5. Nd and Sr isotope data for Cerro Toledo Rhyolite tephra samples.

Sample	$^{87}Rb/^{86}Sr$	$(^{87}Sr/^{86}Sr)_m \pm 2\sigma$	$(^{87}Sr/^{86}Sr)_i \pm 2\sigma$	$^{143}Nd/^{144}Nd \pm 2\sigma$	ε_{Nd}
TMBT			0.70413-0.70906	0.512490-0.512505	-2.9 to -2.6
CT-9wr	57.589	0.708850 ± 12	0.707859 ± 20	0.512514 ± 4	-2.6
CT-9fspar	33.660	0.706510 ± 20	0.705931 ± 22		
CT-5wr	65.373	0.710741 ± 13	0.709464 ± 37	0.512559 ± 4	-1.7
CT-5fspar	19.426	0.748590 ± 14	0.748210 ± 17		
CT-8wr	12.450	0.706523 ± 14	0.706262 ± 16	0.512512 ± 7	-2.6
CT-8fspar	1.899	0.705820 ± 12	0.705780 ± 12		
CT-2wr	40.534	0.709575 ± 13	0.708691 ± 25	0.512614 ± 5	-0.6
CT-2fspar	2.843	0.705765 ± 14	0.705703 ± 14		
CT-1wr	19.471	0.707533 ± 12	0.707093 ± 17	0.512634 ± 4	-0.2
CT-1fspar	6.788	0.705421 ± 14	0.705268 ± 15		
OMBT			0.70645-0.73043	0.512617-0.512664	-0.4 to 0.5

Rb, Sr determined by isotope dilution; wr, data on whole rock sample; fspar, data on sanidine separates
Errors on isotope ratios given for the last significant decimal places
TMBT, Tshirege Member Bandelier Tuff
OMBT, Otowi Member Bandelier Tuff
TMBT and OMBT data from Skuba (1990) and John Wolff (personal commun. 1996)

for a magma chamber replenishment event recorded in CTR tephra immediately above the OM Bandelier Tuff (Stix and Gorton, 1993), combined with stratigraphic and age constraints, suggest that this occurred within ~70 ka of caldera collapse. The combined trace element and Nd isotopic data on tephra samples suggest that CTR eruptions tapped several separate magma bodies during the 380 ka interval between the OMBT and TMBT, or tapped an open system magma chamber that was replenished prior to 1.55, 1.46, 1.38 and 1.22 Ma.

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