$^{40}Ar/^{39}Ar$ dating, sanidine chemistry and potential sources of the Las Tablas Tuff, northern New Mexico

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^{40}AR/^{39}AR DATING, SANIDINE CHEMISTRY, AND POTENTIAL SOURCES OF THE LAS TABLAS TUFF, NORTHERN NEW MEXICO

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Abstract—The age and geochemistry of sanidine from the Las Tablas tuff was determined to investigate the source of this unit. A total of thirty Las Tablas tuff sanidine crystals from two geographically different locations were analyzed using the single-crystal laser-fusion ^{40}Ar/^{39}Ar dating technique. Two samples of the Las Tablas tuff yielded ages of 28.27±0.05 and 28.29±0.05 Ma. The weighted mean age of these samples is 28.28±0.07 Ma. The Las Tablas tuff is indistinguishable in age to two regional ignimbrites. The 28.201±0.046 Ma Fish Canyon Tuff was emplaced during the formation of the La Garita Caldera in the central San Juan volcanic field. The 28.22±0.05 Ma Tuff of Tetilla Peak was erupted during precaldera volcanism related to the Questa caldera in north-central New Mexico. Electron microprobe analyses were conducted to geochemically characterize sanidine from the three ignimbrites to determine if the Las Tablas tuff is correlative to either the distal outflow of the Fish Canyon Tuff, the Tuff of Tetilla Peak, or neither. Las Tablas tuff sanidine crystals exhibit oscillatory zoning, which precludes a correlation to the nonzoned sanidine of the Tetilla Peak Tuff. Though sanidine in the Fish Canyon Tuff are also zoned, there are subtle differences in Na_2O and K_2O content between the Fish Canyon Tuff and Las Tablas tuff. This prevents a simple correlation and suggests previously unrecognized geochemical variation of the Fish Canyon Tuff. Preliminary geochronology and geochemistry of the Las Tablas tuff indicate that this unit may represent distal outflow of the Fish Canyon Tuff or is related to a source that has yet to be identified.

INTRODUCTION

The Las Tablas tuff is an enigmatic tuff located near the base of the Los Pinos Formation in the Tusas Mountains, northern New Mexico. The tuff was first recognized during reconnaissance mapping of the Las Tablas quadrangle (Manley and Wobus, 1982). Recent mapping by Aby et al. (2010) has shown that the tuff is more extensive than previous thought. The Las Tablas tuff is crystal-rich, containing 25-35% phenocrysts of quartz, sanidine, plagioclase, biotite and very sparse hornblende. The tuff contains lenses or megabreccia blocks of fluvial, volcanic, and basement debris (see Aby et al., this volume for further description of the tuff matrix and clast lithologies). Though breccias are commonly found within intracaldera ignimbrites (Lipman, 1976), typical intracaldera facies features lacking in the Las Tablas tuff include very thick (> 1km), densely welded, commonly altered tuff that is delineated by topographic margins and ring faults. The Las Tablas tuff was most likely deposited within a paleovalley and the breccia lenses represent syn-deposition debris flows originating from the valley walls. The Las Tablas tuff was sampled to determine the ^{40}Ar/^{39}Ar age, which could potentially identify the source for this tuff.

^{40}AR/^{39}AR DATING METHODS AND RESULTS

Two samples (MZQ-42 and MZQ-44) of the Las Tablas tuff were collected from geographically different locations in the Tusas Mountains during the summer of 2009. Sanidine crystals were separated using heavy liquid, acid washing, and frantz magnetic separation, and then optically picked using a binocular microscope to insure a high-purity separate. Sanidine were dated at the New Mexico Geochronology Research Laboratory using the single-crystal laser-fusion technique, a method proven useful for identifying altered and/or xenocrystic grains (Deino and Potts, 1992). Fifteen crystals from each of the two samples were fused to release argon. Liberated gas was cleaned in an all-metal extraction line. Argon isotopic concentrations were measured using a MAP 215-50 mass spectrometer. Ages were calculated relative to the FC-2 interlaboratory standard (28.201 Ma; Kuiper et al., 2008). A more detailed description of analytical techniques is provided in McIntosh et al. (2003).

Sanidine from MZQ-42 and MZQ-44 yielded indistinguishable weighted mean ages of 28.29±0.05 and 28.27±0.05 Ma, respectively (Figs. 1A and B; Table 1). Both samples display single age populations, indicating that xenocrystic grains or altered grains were not analyzed. Radiogenic ^{40}Ar yields are ~100%, which also indicates that pristine, non-altered grains were dated. The K/Ca value for MZQ-42 is 67.9±34.9 and 83.6±26.0 for MZQ-44. Because of the similarity in age and composition of the two samples, the samples are interpreted to be the same volcanic unit. The weighted mean age of these samples is 28.28±0.07 Ma, which is interpreted to be the eruption age of the Las Tablas tuff.

The age of the Las Tablas tuff is indistinguishable from the age of two regional ignimbrites in northern New Mexico and southern Colorado. The Tuff of Tetilla Peak is associated with precaldera volcanic activity at the Questa caldera, located ~40 km to the east of the Tusas Mountains in the Sangre de Cristo Mountains (Lipman et al.,1986). The sanidine single-crystal laser-fusion age of the Tuff of Tetilla Peak is 28.22±0.05 Ma (Fig. 1C, and Table 1). The K/Ca value for this ignimbrite is 95.4±73.8, similar to the Las Tablas tuff. The Tuff of Tetilla Peak contains quartz, sanidine, plagioclase, and biotite, which is a similar mineral assemblage to that of the Las Tablas tuff. Hornblende was not found in the Tetilla Peak Tuff handsample or during the mineral separation process.

The dacitic Fish Canyon Tuff, the largest known volcanic eruption on earth (5000 km^3; Lipman et al., 1997), was emplaced at 28.201±0.046 Ma (Kuiper et al., 2008) during the collapse of the La Garita Caldera, located in the central San Juan Mountains of southwestern Colorado (Stevens and Lipman, 1976). The Fish Canyon Tuff is a widely-used interlaboratory standard for the

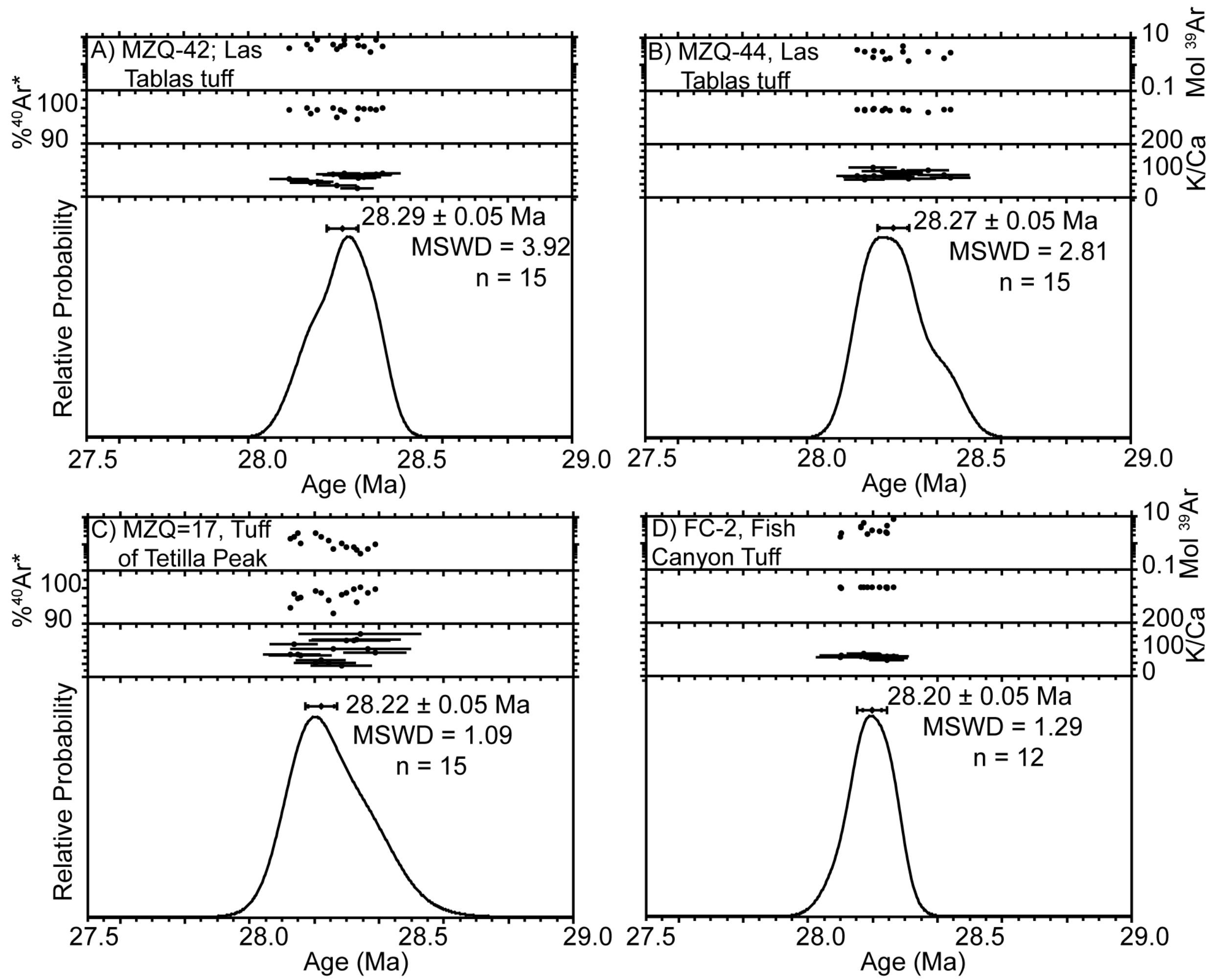

FIGURE 1 – Age probability distribution plot (Deino and Potts,1992) for the samples dated in this study. All errors are reported at 2σ and the data is plotted at 1σ. Also included are auxillary K/Ca, radiogenic yield (%^{40}Ar*), and moles of ^{39}Ar (x 10^{-14}) plots. Plot D is of the interlaboratory standard FC-2 and was chosen to display a "typical" Fish Canyon age distribution, K/Ca values, and radiogenic yields. MSWD = Mean Standard Weighted Deviation.

^{40}Ar/^{39}Ar dating technique. A representative ideogram is plotted in Figure 1D. The closest outcrop of the Fish Canyon tuff is located 30 km north of the Colorado-New Mexico border in Hot Creek, CO (Peter Lipman, personal communication, 2011), approximately 80 km from the sampled outcrops. In addition to being temporally indistinguishable from the Las Tablas tuff, Fish Canyon Tuff sanidine K/Ca values are similar to the Las Tablas tuff. Intracaldera and proximal outflow deposits of Fish Canyon Tuff contains 35-50% phenocrysts consisting of quartz, sanidine, plagioclase, biotite, hornblende, sphene, apatite, and zircon. (Lipman et al., 1997; Bachmann et al., 2002). Though the Fish Canyon Tuff contains mineral phases that are were not observed in the handsamples of the Las Tablas tuff (i.e., sphene, apatite, and zircon), the petrology of the Las Tablas tuff has yet to be fully evaluated.

Because the age of the Las Tablas tuff is analytically indistinguishable from two regional ignimbrites, the dating results do not indicate a definitive source for this tuff. To further investigate the source of the Las Tablas tuff, the chemistry of sanidine phenocrysts from each of the three ignimbrites was investigated using electron microprobe analyses. Particularly important are trace element (e.g., Sr and Ba) contents of phenocrysts, which previous studies have shown to be useful for correlating large volume ignimbrites (de Silva and Francis, 1989, Bachmann et al., 2002).

ELECTRON MICROPROBE ANALYSES

Sanidine separates for electron microprobe analysis were mounted in epoxy in 1" round disks, ground, and then diamond polished. The sample disks were first ground on metal plates embedded with diamond to expose cross-sections of feldspar crystals, then polished using 15, 6 and 1 micron pure diamond grit suspended in distilled water. This process yielded a smooth, flat sample surface, ideal for high quality electron microprobe analysis.

Samples were analyzed using a Cameca SX-100 electron microprobe located at New Mexico Institute of Mining and Technology. Samples were examined using backscattered-electron (BSE) imagery, and selected areas on sanidine were quantitatively analyzed. BSE imaging provided useful information about

TABLE 1- Summary of $^{40}Ar/^{39}Ar$ data.

Sample	Unit	Location (13S; Nad 27)	Mineral	Analysis*	n**	MSWD#	K/Ca†	±2σ	Age (Ma)ζ	±2σ
MZQ-17	Tuff of Tetilla Peak	467502 4076711	Sanidine	SCLF	15	1.1	95.4	73.8	28.22	0.05
MZQ-42	Las Tablas tuff	407923 4046346	Sanidine	SCLF	15	3.9	67.9	34.9	28.29	0.05
MZQ-44	Las Tablas tuff	409324 4048995	Sanidine	SCLF	15	2.8	83.6	26.0	28.27	0.05
FC-2	Fish Canyon Tuff	349463 4163793	Sanidine	SCLF	12	1.3	70.9	12.9	28.20	0.05

Notes:
* SCLF – Single Crystal Laser Fusion
** n refers to number of analysis used to calculate an age
# MSWD – Mean Square Weighted Deviate
† K/Ca is determined from the K-derived ^{39}Ar and Ca-derived ^{37}Ar.
ζ All ages are calculated relative to the Fish Canyon Tuff interlaboratory standard FC-2 equal to 28.201 Ma (Kuiper et al, 2008) and the corresponding ^{40}K decay constant equal to 5.463×10^{-10} yr^{-1} (Min et al., 2000)

the chemical zonation in the sanidine crystals. Elements analyzed include Na, Al, Si, K, Ca, Fe, Sr, and Ba (Table 2). An accelerating voltage of 15 kV was used, with a probe current of 20 nA, and a beam size of 10 micrometers (in order to avoid Na volatilization). Peak count times of 20 seconds were used for all elements with the exception of Sr and Ba, which were both counted for 60 seconds. Background counts were obtained using one half the times used for peak counts. Standard reference feldspars were run as unknowns during the analytical session to evaluate calibration accuracy and precision (reported in Table 2).

BSE images indicate that sanidine from both the Fish Canyon Tuff (Fig. 2A) and Las Tablas tuff (Figs. 2C and 2D) are chemi-

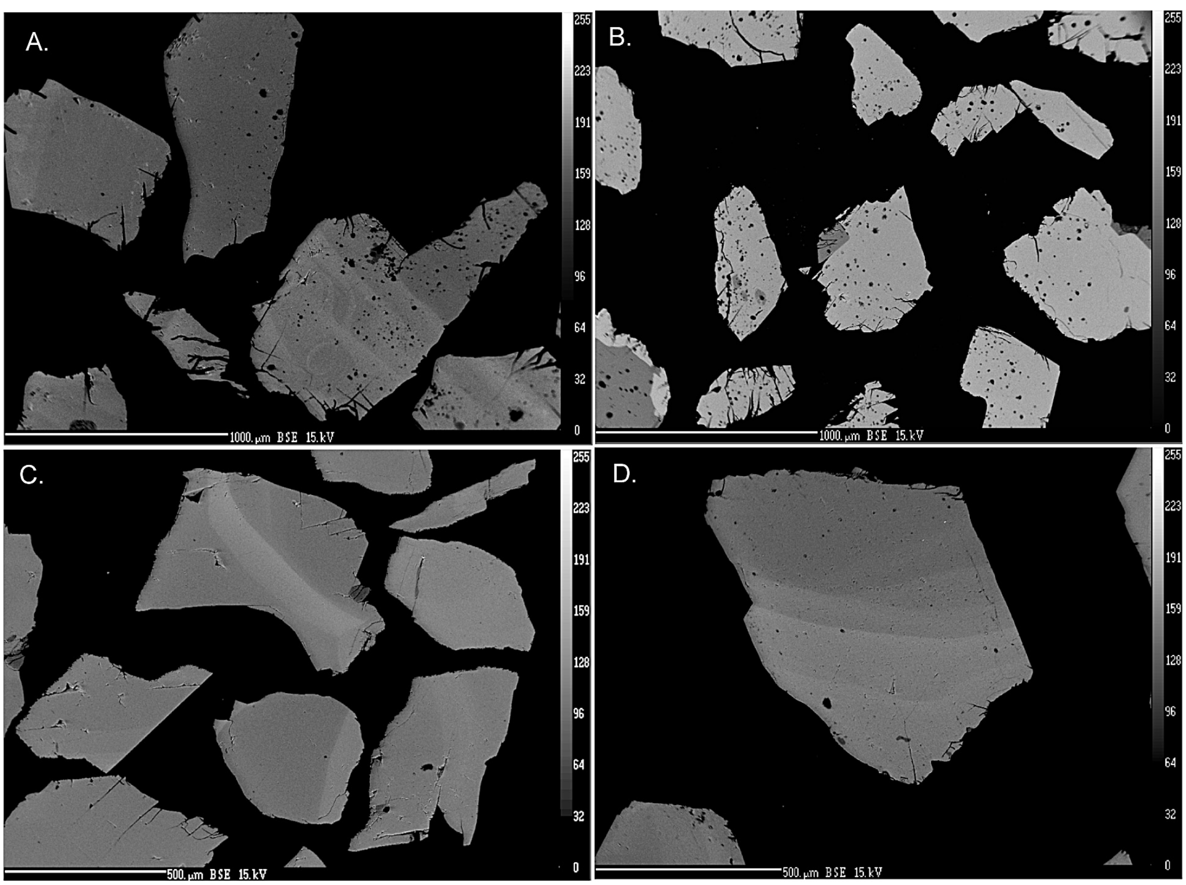

FIGURE 2 – Backscatter electron (BSE) microprobe images of sanidine separates from the three ignimbrites. A – Fish Canyon Tuff. Samples displays oscillatory zonation. Small polishing pits are common. B – Tuff of Tetilla Peak. Lack of observed zonation suggests the sample is chemically homogenous. Some grains contains small quartz inclusions. Some polishing pits are apparent. C and D – Las Tablas tuff. Oscillatory zonation is common in these sanidine.

cally zoned with respect to K and Ba, whereas the Tuff of Tetilla Peak sanidine (Fig. 2B) are compositionally uniform. Zoning suggests that the Las Tablas tuff is not distal outflow of the Tuff of Tetilla Peak. However, the Fish Canyon Tuff and Las Tablas tuff are potentially correlative. Ba and K zoning in Fish Canyon Tuff sanidine was described in detail in two previous studies (Lipman et al.,1997; Bachmann et al.,2002). These studies suggested that oscillatory Ba zoning originates from either repeated mixing of Ba-poor and Ba-rich magmas (Lipman et al., 1997) or multiple stages of K-feldspar growth (Bachman et al., 2002). These proposed mechanisms may explain the similar oscillatory zonation observed in the Las Tablas tuff sanidine.

Quantative element compositions of sanidine from the three ignimbrites provides additional information useful for correlating the Las Tablas tuff. Variations in Na_2O, K_2O, SrO, and BaO content of the sanidine are displayed in Figures 3A and B. As suggested by BSE images, sanidine from the Tuff of Tetilla Peak have a restricted range of BaO and SrO content (0.00-0.20 and 0.00-0.05 wt%, respectively), whereas sanidine from the Las Tablas and Fish Canyon Tuff contain large variations. In general, the SrO content for the Las Tablas tuff and Fish Canyon Tuff are very similar (Fig. 3A). The BaO content is slightly higher in the Fish Canyon sanidine (0.30-1.71 wt%) compared to the Las Tablas tuff (0.04-1.09 wt%)(Fig. 3A). Though BaO and SrO contents are similar, there are subtle difference in Na_2O and K_2O content (expressed as a ratio in wt%; Fig. 3B). Fish Canyon sanidine crystals have the lowest Na/K ratios of the three ignimbrites. Whole rock geochemistry of the Tuff of Tetilla Peak indicates 70-72 wt% SiO_2 (Lipman et al., 1986), whereas the Fish Canyon Tuff whole rock geochemistry is less silicic (67.5-68.5 wt% SiO_2; Lipman et al., 1997). Because the Las Tablas tuff sanidine have Na/K ratios similar to the Tuff of Tetilla Peak, this may suggest that the Las Tablas tuff is also more silicic than the Fish Canyon Tuff, although whole-rock major element geochemistry has yet to be completed.

SOURCE OF THE LAS TABLAS TUFF

Preliminary geochronology and geochemistry of the Las Tablas tuff provides useful information for investigating the source of this tuff. The age of this tuff, 28.28±0.07 Ma, is indistinguishable from two regional ignimbrites, the Fish Canyon Tuff and Tuff of Tetilla Peak. BSE images and electron microprobe elemental analyses indicate that the Las Tablas tuff is not related to the Tuff of Tetilla Peak. The Las Tablas tuff sanidine crystals exhibit oscillatory zoning and have BaO and SrO contents that are unique to the Fish Canyon Tuff (Bachmann et al., 2002). One discrepancy between the Fish Canyon Tuff and Las Tablas tuff are the Na_2O and K_2O contents. In addition to its large volume, the Fish Canyon Tuff is known for its distinctly uniform composition (Lipman, 1997). However, many large volume ignimbrites are compositionally and mineralogically zoned (Hildreth and Wilson, 2007; Bachmann and Bergantz, 2008). If the Las Tablas tuff represents distal outflow of the Fish Canyon Tuff, variation in Na_2O and K_2O contents between the units indicates pre-eruptive magma chamber zonation that was not previously recognized, possibly because of incomplete sampling of the outflow sheet. Alternatively, variation in Na_2O and K_2O content may suggest that the Las Tablas tuff is not distal outflow of the Fish Canyon Tuff and that the source for this tuff is buried beneath younger rift-related sediments or lava flows of the Taos Plateau.

Additional work will continue to help determine the source of the Las Tablas tuff. Because the Fish Canyon sanidine crystals that were analyzed as part of this project are from within the La Garita caldera, geochemical analyses of distal outflow of the Fish Canyon Tuff, perhaps from Hot Creek, CO, may provide a better comparison. Whole-rock elemental and isotopes analyses could potentially clarify the relationship of the Fish Canyon Tuff and Las Tablas tuff. Bachmann et al. (2002) described major element variability and chemical zoning in hornblende and pla-

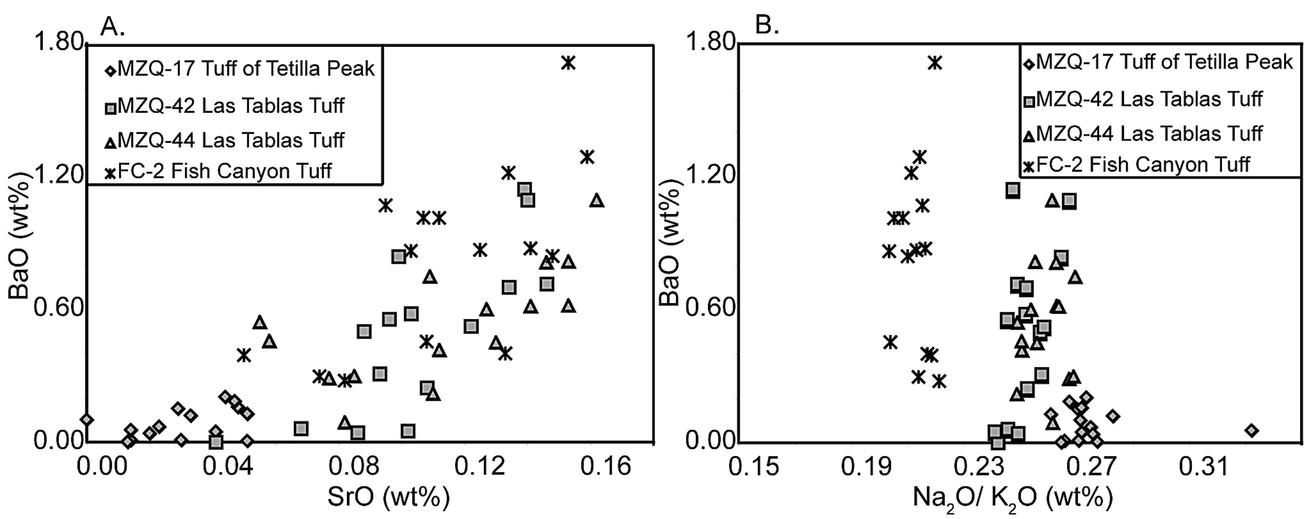

FIGURE 3 – Compositional variation of sanidine in the Tuff of Tetilla Peak, Las Tablas tuff, and Fish Canyon Tuffs. A –SrO vs BaO content (in wt%). B- Na_2O/K_2O vs BaO content (in wt%).

gioclase, which could be used for correlating the Las Tablas and Fish Canyon Tuff. Another common method that could also be used for correlating the Las Tablas tuff to other regional ignimbrites is through the use of geomagnetic remanance (McIntosh et al., 1992). Continued mapping in northern New Mexico will be important for determining the source of the Las Tablas tuff.

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TABLE 2. Element composition of sanidine from the Las Tablas tuff, Fish Canyon Tuff, and Tuff of Tetilla Peak.

Sample	SiO2#	Al_2O_3	CaO	FeO	SrO	BaO	Na_2O	K_2O
MZQ-42 Las Tablas tuff	65.02	19.46	0.13	0.11	0.15	0.72	3.02	12.13
	65.06	19.55	0.15	0.11	0.10	0.58	3.09	12.27
	65.11	19.35	0.12	0.11	0.09	0.50	3.13	12.16
	64.82	19.45	0.11	0.10	0.10	0.56	3.04	12.38
	65.00	19.57	0.14	0.04	0.12	0.52	3.15	12.19
	65.17	19.30	0.20	0.12	0.11	0.25	3.09	12.25
	65.65	19.52	0.19	0.12	0.09	0.31	3.16	12.27
	65.44	19.29	0.14	0.12	0.04	0.00	3.02	12.49
	64.14	19.69	0.20	0.11	0.14	1.14	2.99	12.08
	65.44	19.34	0.13	0.12	0.10	0.05	3.05	12.64
	64.14	19.58	0.16	0.10	0.14	1.09	3.16	11.81
	64.54	19.62	0.25	0.11	0.10	0.84	3.16	11.94
	65.44	19.79	0.12	0.09	0.13	0.70	3.09	12.27
	65.55	19.40	0.15	0.08	0.07	0.06	3.08	12.52
	65.35	19.32	0.13	0.10	0.09	0.04	3.09	12.41
MZQ-44 Las Tablas tuff	64.68	19.25	0.12	0.12	0.06	0.54	3.01	12.07
	64.93	19.37	0.13	0.08	0.11	0.42	3.08	12.30
	65.01	19.26	0.14	0.08	0.08	0.29	3.25	12.16

TABLE 2. Element composition of sanidine from the Las Tablas tuff, Fish Canyon Tuff, and Tuff of Tetilla Peak - Cont.

Sample	SiO2[#]	Al_2O_3	CaO	FeO	SrO	BaO	Na_2O	K_2O
	65.00	19.35	0.16	0.09	0.13	0.45	3.14	12.27
	64.82	19.31	0.15	0.08	0.15	0.81	3.14	11.93
	65.06	19.40	0.18	0.05	0.06	0.46	3.07	12.26
	64.98	19.47	0.20	0.11	0.15	0.62	3.17	12.06
	65.21	19.40	0.21	0.06	0.11	0.22	3.06	12.28
	64.56	19.55	0.18	0.10	0.15	0.82	3.07	12.00
	64.18	19.69	0.15	0.10	0.16	1.09	3.12	11.93
	64.82	19.29	0.15	0.01	0.13	0.60	3.08	12.12
	65.11	19.22	0.12	0.05	0.08	0.09	3.21	12.26
	64.97	19.45	0.18	0.07	0.09	0.30	3.27	12.14
	63.98	19.19	0.14	0.07	0.11	0.75	3.20	11.88
	64.69	19.41	0.20	0.10	0.14	0.61	3.18	12.06
MZQ-17 Tuff of Tetilla Peak	65.62	19.31	0.14	0.09	0.00	0.10	3.31	12.20
	65.60	19.35	0.12	0.11	0.05	0.00	3.40	12.25
	65.87	19.37	0.09	0.10	0.05	0.13	3.26	12.49
	65.95	19.42	0.12	0.06	0.01	0.01	3.24	12.18
	66.02	19.30	0.09	0.10	0.02	0.07	3.35	12.17
	65.95	19.37	0.10	0.12	0.03	0.15	3.30	12.20
	66.07	19.39	0.08	0.08	0.05	0.16	3.33	12.26
	65.72	19.52	0.15	0.10	0.04	0.20	3.30	12.07
	65.79	19.44	0.17	0.09	0.03	0.12	3.39	11.97
	66.30	19.51	0.09	0.03	0.01	0.05	3.85	11.60
	65.90	19.34	0.07	0.08	0.05	0.18	3.28	12.27
	65.72	19.21	0.09	0.06	0.04	0.05	3.29	12.11
	66.10	19.46	0.12	0.11	0.02	0.04	3.40	12.30
	65.76	19.36	0.12	0.10	0.03	0.01	3.28	12.10
	65.97	19.41	0.09	0.09	0.01	0.00	3.27	12.36
FC-2 Fish Canyon Tuff	64.70	19.38	0.18	0.10	0.13	0.40	2.77	12.75
	64.36	19.63	0.17	0.12	0.16	1.29	2.68	12.48
	64.80	19.77	0.23	0.12	0.14	0.87	2.70	12.49
	65.15	19.34	0.24	0.14	0.08	0.28	2.83	12.78
	64.82	19.39	0.18	0.10	0.11	0.45	2.62	12.83
	64.62	19.52	0.22	0.11	0.15	0.84	2.63	12.53
	64.21	19.62	0.21	0.10	0.10	1.07	2.74	12.73
	64.09	19.80	0.25	0.10	0.15	1.71	2.70	12.30
	64.69	19.65	0.18	0.14	0.11	1.01	2.61	12.54

TABLE 2. Element composition of sanidine from the Las Tablas tuff, Fish Canyon Tuff, and Tuff of Tetilla Peak - Cont.

Sample	$SiO2^{\#}$	Al_2O_3	CaO	FeO	SrO	BaO	Na_2O	K_2O
	63.97	19.57	0.20	0.13	0.13	1.22	2.65	12.51
	64.08	19.36	0.17	0.11	0.13	0.87	2.72	12.77
	65.08	19.30	0.20	0.09	0.05	0.39	2.83	12.93
	63.96	19.52	0.18	0.17	0.11	1.01	2.59	12.63
	64.67	19.28	0.16	0.12	0.10	0.86	2.58	12.69
	65.17	19.37	0.19	0.12	0.07	0.30	2.71	12.68

- Geochemical quantities are in wt%. Fifteen analyses were used to characterize each of the samples. Analytical precision, based on replicate analyses of standard reference material similar in composition to the unknown samples, are: SiO_2±0.23, Al_2O_3±0.05, CaO±0.01, FeO±0.06, SrO±0.01, BaO±0.05, Na_2O±0.02, and K_2O±0.10 (wt%).