The eruptive and magmatic history of the youngest pulse of volcanism at the Valles caldera: Implications for successfully dating late Quaternary eruptions

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ABSTRACT

New ⁴⁰Ar/³⁹Ar and U/Th ages provide insight into the youngest eruptions at the Valles caldera and also reveal previously unknown pulses of magmatism. The youngest eruptive units, collectively termed the East Fork Member of the Valles Rhyolite, include the El Cajete pyroclastic beds and co-erupted Battleship Rock ignimbrite, and the disconformably overlying Banco Bonito lava flow. Previous attempts to date these units using a variety of techniques yielded ages ranging from < 40 ka to > 1 Ma. New ⁴⁰Ar/³⁹Ar ages were generated using the high-sensitivity, multi-collector ARGUS VI mass spectrometer, which provides more than an order of magnitude increase in precision compared to most single-detector mass spectrometers. ⁴⁰Ar/³⁹Ar dating of single crystals yields a range of ages, of which the youngest populations are interpreted to represent the eruption age. Sanidine ages indicate that the El Cajete pyroclastic beds and Battleship Rock ignimbrite erupted at 74.4 ± 1.3 ka, whereas the Banco Bonito lava erupted at 68.3 ± 1.5 ka. Populations of older crystals represent variably degassed xenocrysts, explaining

23 why previous $^{40}\text{Ar}/^{39}\text{Ar}$ bulk step-heating analyses yielded spuriously old and irreproducible
24 results. U/Th dating of unpolished zircon surfaces also yield multiple age populations, which
25 range from the eruption age to >350 ka, indicating protracted magmatism during the 453-ka-long
26 eruptive hiatus prior to the eruption of the East Fork Member. $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Th ages indicate
27 that the East Fork Member represents a short (6.1 ± 2.8 ka) eruptive cycle, from a longer-lived
28 magmatic system beneath the southern caldera. Equally short repose periods, similar to the
29 interval between the El Cajete-Battleship Rock and Banco Bonito eruptions, are possible during
30 future volcanism at the Valles caldera. Results demonstrate that detailed geochronology using
31 single-crystal and in-situ techniques is necessary for understanding the eruptive history and
32 magmatic evolution at some young volcanic systems.

1. Introduction

The timescales of magmatism and ages of eruptions are vital for understanding the history and hazards of active and dormant volcanic fields. Eruption ages are used to calculate hazard parameters such as recurrence rates and repose periods, as well as to identify vent migration patterns that are crucial to eruption forecasting (Tanaka et al., 1986; Connor and Hill, 1995; Condit and Conner, 1996; Heizler et al., 1999). Timescales of crystallization, typically calculated from U/Th or U/Pb zircon dating, determine the duration of magma assembly, sources of melting, role of assimilation, and transport of magma through the crust (Miller et al., 2007; Claiborne et al., 2010). Both eruption and crystallization ages provide a temporal framework to assess related geothermal systems and to evaluate the implications of low-velocity zones (i.e., crustal melts) and related seismic events beneath volcanic fields.

Despite the geologic and societal importance, the chronologies for many late Quaternary vent loci are poorly understood. Single-crystal $^{40}\text{Ar}/^{39}\text{Ar}$ dating of <100 ka samples with previous generation, less-sensitive single-collector mass spectrometers often yields imprecise ages, and thus requires fusing or step-heating multi-grain aliquots in order to obtain large signals for precise measurements. Samples with abundant xenocrysts or that have grains with excess ^{40}Ar will yield anomalously old ages (Deino and Potts, 1990). Likewise, analyses of whole zircons with temporally complex domains, such as those with protracted crystallization histories (i.e., 10 to >100 ka) or inherited cores, will yield an integrated age that neither dates the eruption nor documents the crystallization history (Miller et al., 2007; Lipman and Bachmann, 2015). The high spatial-resolution of in-situ measurements of sectioned zircons using the LA-ICPMS or SIMS techniques can identify unique domains. However, some distinct age domains within

zircon are too fine to measure individually (Corfu et al., 2003), including the outermost rims that document the youngest phase of zircon growth prior to the eruption.

The published ages for the youngest series of eruptions at the Valles caldera (Fig. 1A) are not sufficiently precise or reproducible to develop a conclusive eruption chronology useful for hazard assessment. The youngest eruptions at the Valles caldera are collectively known as the East Fork Member of the Valles Rhyolite, which includes the El Cajete pyroclastic beds and co-erupted Battleship Rock ignimbrite, and the overlying Banco Bonito lava flow (Gardner et al., 2010). Previous attempts to date these units using numerous dating techniques (Fig. 2) have yielded widely-varying ages, from < 40 ka to > 1 Ma (Miyachi et al., 1985; Self et al., 1988; Spell and Harrison, 1993; Ogoh et al., 1993; Toyoda et al., 1995; Reneau et al., 1996, Phillips et al., 1997; Lepper and Goff, 2007), although the most commonly cited ages for the two eruptions are 55 and 40 ka (Goff and Gardner, 2004) based on electron spin resonance (Ogoh et al., 1993; Toyoda et al., 1995), ^{14}C (Reneau et al., 1996), and ^{21}Ne dating (Phillips et al., 1997). In particular, the range of $^{40}\text{Ar}/^{39}\text{Ar}$ ages for K-bearing minerals is likely due to the abundance of xenocrystic material and presence of excess ^{40}Ar (Spell and Harrison, 1993). In addition to constraining the last pulse of volcanic activity, the ages of these units are particularly important because the vents are located above low-velocity structures (Fig. 1B) interpreted to be zones of partial melt at ~5-15 km and ~39 km depth (Lutter et al., 1995; Steck et al., 1998; Aperia et al., 2002).

In order to better assess the timing of the youngest eruptions at the Valles caldera, new $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Th ages were determined for the East Fork Member. $^{40}\text{Ar}/^{39}\text{Ar}$ ages were generated using the newest generation ARGUS VI mass spectrometer, which permits precise dating of late Quaternary samples at the single-crystal level. Unpolished zircon crystal faces,

rather than sectioned grains, were dated using the U/Th method to investigate the youngest pulse of zircon growth, further constraining the eruption ages and crystallization history. The combination of $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Th ages provides insight into the timescales of eruptions and magmatic pulses during postcaldera volcanism at the Valles caldera.

2. Geology of the East Fork Member of the Valles Rhyolite

Numerous studies have investigated the temporal and spatial trends of volcanism at the Valles caldera. (e.g., Spell and Harrison, 1993; Phillips et al., 2007; Kelley et al., 2013). The Valles caldera, located in the Jemez Mountain volcanic field of north-central New Mexico (Fig. 1A), is a classic example of a resurgent caldera (Smith and Bailey, 1968). The Jemez field is located at the intersection of the Rio Grande rift, a major east-west extensional feature extending from central Colorado to northern Mexico, and the Jemez lineament, a northeast trending zone of crustal weakness that has concentrated tectonic, magmatic, and volcanic activity (Chapin et al., 2004). Compositionally diverse magmas were erupted from widely scattered centers beginning as early as ca. 16 Ma and continuing to ca. 2 Ma (Gardner and Goff, 1996; Kelley et al., 2015), when magmas evolved to more rhyolitic compositions during the Quaternary (Self et al., 1988; Gardner et al., 2010). The Toledo caldera formed during the 1.651 ± 0.011 Ma¹ eruption of the Otowi Member of the Bandelier Tuff (Izett and Obradovich, 1994). Located in nearly the same location as the Toledo caldera is the morphologically well-preserved Valles caldera. The Valles caldera formed at 1.264 ± 0.010 Ma during the eruption of Tshirege Member of the Bandelier Tuff (Phillips et al., 2007). Within 57 ka after the eruption of the Tshirege Member the caldera floor was resurgently uplifted more than 1000 m to form Redondo Peak (Phillips et al., 2007).

¹ All published ages are recalculated relative to 28.201 Ma Fish Canyon sanidine

Volumetrically minor rhyolitic lavas and pyroclastics (Redondo Peak and Deer Canyon units) were erupted on the flanks of the resurgent dome during uplift. Following resurgence, numerous high-silica rhyolitic domes, referred to as the Valle Grande Member of the Valles Rhyolite (Gardner et al., 2010), were erupted along the structural margin of the caldera between 1.24 Ma and 527 ka (Spell and Harrison, 1993; Phillips et al., 2007).

The youngest pulse of post-Valles caldera volcanism occurred along the southwestern ring-fault zone (Wolff and Gardner, 1995; Goff et al., 2011). El Cajete pyroclastic beds (bedded pumice interlayered with thin nonwelded ignimbrites) and Battleship Rock ignimbrite (non to densely welded) were erupted from the El Cajete crater (Self et al., 1991). Both units contain lithics of precaldern andesites and dacites, as well as some pre-volcanic sedimentary rocks.

These two units were co-erupted during an eruption episode estimated to have lasted less than one year (Wolff et al., 2011). The total volume of the El Cajete-Battleship Rock eruption series is $\sim 10 \text{ km}^3$. The Banco Bonito lava flow, comprised of mostly vitrophyric lava and minor pumiceous deposits, is the youngest eruption in the Jemez field. Large-scale ($\sim 20 \text{ m}$ of relief) pressure ridges are still preserved on the flow surface (Goff et al., 2011). The total volume is estimated to be $\sim 4 \text{ km}^3$ (Wolff et al., 2011). Small outcrops of debris-flow units between the El Cajete-Battleship Rock deposits and Banco Bonito lava flow indicate a temporal hiatus between the two eruptions. All units contain the same mineral assemblage of plagioclase, quartz, biotite, hornblende, clinopyroxene, Fe-Ti oxides, occasional orthopyroxene and olivine, and very rare sanidine (Goff et al., 2011). Accessory minerals include zircon and apatite. Wolff and Gardner (1995) suggested that the abundance of disequilibrium textures among phenocrysts in the East Fork Member, coupled with the presence of seismically imaged low-velocity zones (Fig. 1B) beneath much of the western caldera (Steck et al., 1998; Aprea et al., 2002), indicates that these

units represent a new phase of postcaldera volcanism. The low-silica rhyolites of the East Fork Member are mineralogically, petrographically, and geochemically distinct from the older, high-silica ring-fault domes (Spell et al., 1993; Wolff and Gardner, 1995), further supporting the hypothesis that these units mark a new cycle of postcaldera volcanism.

3. Methods

Samples of the El Cajete pyroclastic beds, Battleship Rock ignimbrite, and Banco Bonito lava flow were collected from multiple locations within and near the Valles caldera (Fig. 1A). Outcrops with any significant alteration were avoided. Pyroclastic rocks with abundant lithics were also avoided. As much as 20 kg of material was collected and processed from each selected sampling site in order to assure that zircon and the very sparse sanidine could be concentrated. K-bearing minerals and zircon were separated using standard separation techniques. Data repository A contains information regarding sample locations.

$^{40}\text{Ar}/^{39}\text{Ar}$ ages were determined at the New Mexico Geochronology Research Laboratory. Sanidine, plagioclase, and biotite were irradiated with the 28.201 Ma FC-2 sanidine standard (Kuiper et al., 2008). Calcium and potassium correction factors were determined using CaF_2 and K-glass from longer irradiations that bracketed the short irradiation used for this study. Single crystals were fused using a focused CO_2 laser. Extracted gas was expanded into and cleaned by an all-metal, fully automated, extraction line containing a SAES D-50 getter pump operated at 450°C.

Isotopic ratios were measured using the multi-collector ARGUS VI mass spectrometer. The ARGUS VI mass spectrometer provides more than an order of magnitude increase in precision and sensitivity compared to most single-detector mass spectrometers (Phillips and

Matchan, 2013; Matchan and Phillips, 2014). The ARGUS VI permits precise dating of <100 ka single crystals, allowing xenocrystic grains and crystals with excess ^{40}Ar to be distinguished from crystals that record the eruption age. Additional $^{40}\text{Ar}/^{39}\text{Ar}$ analytical details, procedures, and data tables are in [data repository B](#).

U/Th ages were determined using the high-spatial resolving power of the SHRIMP-RG [secondary ion](#) mass spectrometer at the Stanford-USGS facility. Zircons were imaged using cathodoluminescence techniques to assess geochemical variation. Whole zircon crystals were pressed into [a polished](#) indium mount and euhedral crystal faces were analyzed for ^{238}U - ^{230}Th - ^{232}Th compositions using methods of Vazquez and Lidzbarski (2012). Between 50 and 60 crystals were mounted for each sample. U/Th model ages were calculated using the initial ^{238}U - ^{232}Th and ^{230}Th - ^{232}Th values (0.56 ± 0.03 and 0.82 ± 0.04 , respectively) of Banco Bonito glass from Self et al. (1988). Additional U/Th analytical details and data tables are presented [data repository C](#).

4. Results

4.1 $^{40}\text{Ar}/^{39}\text{Ar}$ dating

Single crystals of sanidine, biotite, and plagioclase were dated from the Battleship Rock ignimbrite. NMVC-07 is a glassy pyroclast, similar in appearance to a breadcrust bomb, in the nonwelded ignimbrite. The youngest population of 61 sanidine crystals yields a weighted mean age of 77.1 ± 1.2 ka (Fig. 3A; all weighted mean errors reported at 2σ). The inverse isochron of this subset population (Fig. 3B), [excluding a single outlier](#), indicates a non-atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ intercept of 337 ± 14 , indicative of excess ^{40}Ar . The inverse isochron age is [74.4 \$\pm\$ 1.3 ka](#), [slightly younger than weighted mean age at \$2\sigma\$](#) . Plagioclase and biotite from NMVC-07 also

yielded a wide range of ages, but with much larger uncertainties for individual analyses (Fig. 3C). Biotite yielded ages ranging from 265 ka to 1 Ma, whereas plagioclase yielded ages ranging from 49 ka to 71 Ma. Sanidine crystals from EC-6 (Fig. 3D), a sample of the welded Battleship Rock, did not yield a single well-defined population.

Sanidine and biotite were dated from the Banco Bonito flow. Only one sample of sanidine from this flow yielded meaningful results (EC-3; Fig. 3E). The 15 youngest sanidine crystals that define a Gaussian distribution yielded a weighted mean age of 68.3 ± 1.5 ka. The inverse isochron of this subset of analyses (not shown) indicates an atmospheric trapped component of 288 ± 8 and an indistinguishable age of 69 ± 2 ka. Biotite from this sample (Fig. 3F) yielded ages ranging from ~350 to 650 ka. A population of 10 crystals defines a prominent peak on the ideogram corresponding to an age of 535 ± 10 ka.

4.2 U/Th dating

Zircon ^{238}U - ^{230}Th ages were obtained from four samples, two from Banco Bonito lava flow and two from the El Cajete-Battleship Rock eruption series (Fig. 4). There is no apparent relationship between U/Th ages and zircon compositions, morphologies, and textures. Dark contrast areas in cathodoluminescence images, interpreted to be U-enriched portions of the grains, were the main targets for the majority of the analytical session in order to maximize precision.

All four samples yielded multiple U/Th age populations (Fig. 4). Three of the four samples contained some zircons that were in secular equilibrium (i.e., > 350 ka). U/Pb dating was not conducted and the ages of these few zircons cannot be determined. Excluding crystals in secular equilibrium, individual zircon ages range from as young as 45-55 ka to 200-250 ka. Although the samples display a range of individual zircon ages, the younger ages are the most

dominant. Some crystal faces were large enough to analyze in two places. In all cases, duplicate analyses of the same crystal face yielded ages that are analytically indistinguishable indicating results are reproducible. For example, the two youngest ages for NMVC-14 (Fig. 4D) are from the same grain and are $44.8 \pm 14.8/-13.8$ ka and $51.1 \pm 17.0/-15.8$ ka.

5. Discussion

5.1 Eruption ages of the East Fork Member units

$^{40}\text{Ar}/^{39}\text{Ar}$ single-crystal laser-fusion dating of sanidine provides the best estimates for eruption ages of the East Fork Member. The preferred eruption age of the Battleship Rock ignimbrite is 74.4 ± 1.3 ka (Fig. 3B). The preferred eruption age of the Banco Bonito lava flow is 68.3 ± 1.5 ka (Fig. 3E). These new ages agree with stratigraphic relationships and field observations. The 6.1 ± 2.8 ka eruption hiatus is consistent with deposition of debris flow material and a period of canyon cutting between the two units. Although $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine ages were not directly determined for the El Cajete pyroclastic beds, stratigraphic constraints indicate that this unit was co-erupted with the 74.4 ka Battleship Rock ignimbrite (Self et al., 1991; Wolff et al., 2011).

U/Th model ages provide additional constraints on the eruption age of the East Fork Member. The youngest zircon population in El Cajete pumice is 70 ± 4 (Fig. 4A), indistinguishable from the 74.4 ± 1.3 ka $^{40}\text{Ar}/^{39}\text{Ar}$ eruption age for the Battleship Rock ignimbrite. Likewise, the youngest zircon population in Banco Bonito NMVC-10 is 68 ± 4 ka (Fig. 4C) also within error of the 68.3 ± 1.5 ka eruption age. U/Th model ages of some individual zircons are younger than the $^{40}\text{Ar}/^{39}\text{Ar}$ eruption ages. For example, the youngest population (n=5) in the Battleship Rock ignimbrite (Fig. 4B) yields an age of 61 ± 5 ka, at least 7.1 ka younger than the eruption age (considering the limits of the 2σ errors). Three U/Th ages of individual

crystals in the youngest population are within error of the eruption age, but two ages are distinguishably younger than the eruption age. A similar scenario is true for the youngest population in Banco Bonito sample NMVC-14 (Fig. 4D).

The discrepancy between the youngest zircon ages and $^{40}\text{Ar}/^{39}\text{Ar}$ eruption age is interpreted to be an artifact of zircon growth and/or resorption in a compositionally mixed and thermally dynamic magma chamber (Wolff and Gardner, 1995). U/Th model ages are calculated using an initial ($^{230}\text{Th}/^{232}\text{Th}$) value, typically determined from analyzing co-erupted glass. Using a single ($^{230}\text{Th}/^{232}\text{Th}$) value requires that disequilibrium between the magma and zircon remains constant during crystal growth. Some zircon surfaces in the East Fork Member are highly irregular, consistent with resorption and/or irregular growth prior to eruption. Furthermore, Wolff and Gardner (1995) identified pervasive disequilibrium textures among phenocrysts and banded pumice in the East Fork Member, concluding that the eruption of these units occurred during mixing and mingling of compositionally different magmas likely related to reheating of a partially crystallized silicic intrusion by mafic underplating. Given the abundant textural and petrologic evidence to support crystal growth in a thermally and compositionally dynamic magma chamber, it is plausible that there was U/Th variation in the host magma, which may affect the U/Th age calculation. For example, a 10-20% decrease to the initial ($^{230}\text{Th}/^{232}\text{Th}$) value causes model ages to increase by 5-20 ka. Crystals with low U values are more sensitive to this initial value. As a result, we prefer the $^{40}\text{Ar}/^{39}\text{Ar}$ ages for eruption ages, whereas U/Th ages, although useful for assessing the eruption age, document the crystallization history of the magmas.

5.2 Crystallization history and inherited components of the East Fork Member

U/Th model ages of zircon provide insight into the crystallization history of the East Fork Member and reveal magmatic pulses not preserved in the exposed volcanic record (Fig. 5). All four samples contain zircon populations that record protracted magmatism. Populations of zircons cluster from 80 to 100 ka and 150 to 160 ka. Mapping has not identified any volcanic events during the 453 ka hiatus between the 527 ka South Mountain Dome (Goff et al., 2011) and the 74 ka Battleship Rock ignimbrite. Thus, the U/Th ages document a previously unknown period of protracted magmatism at the Valles caldera. Furthermore, the spectra of zircon ages for the El Cajete-Battleship Rock unit and the Banco Bonito lava are largely similar (i.e., similar clusters of ages; Fig. 4), suggesting a common magmatic source as previously proposed based on similar mineral assemblages, mineral textures, and geochemical signatures (Spell and Harrison, 1993; Wolff and Gardner, 1995). Because the U/Th zircon ages presented here are only from crystal surfaces and many zircons are in secular equilibrium, the newly identified magmatic events represent only a partial history of young magmatism beneath the southern caldera that **may have** begun prior to 350 ka.

There are several viable origins for the inherited crystal cargo in the East Fork Member. The zircon surfaces display a range of ages rather than a single population implying that the eruption tapped zones in the chamber that varied with respect to the history of zircon saturation. Zircon surfaces with U/Th ages similar to the eruption ages were in zircon-saturated melt near the time of eruption. Zircon with surfaces older than the eruption age likely represent one or more of the following: 1) antecrysts that stopped growing before the eruption, perhaps because they were captured as inclusions in other crystallizing mineral phases, 2) antecrysts that were resorbed prior to the eruption, thereby removing younger rims and exposing older interiors, or 3) xenocrysts from intrusions or nonexposed volcanic rocks that were incorporated into the East

Fork units during eruption. As previously discussed, variation in the U/Th values of the host magma also affect the calculated model ages. However, for most zircon, this correction is less than the calculated 2 σ -error and does not significantly alter the interpretations.

The protracted crystallization history of the East Fork Member magma is similar to other late Quaternary postcaldera systems in the western United States. Both the 640 ka Yellowstone and 770 ka Long Valley caldera systems contain abundant postcaldera rhyolite domes. The Central Plateau Member lavas, the youngest rhyolites at the Yellowstone caldera, erupted between 70 and 160 ka. Zircon U/Th disequilibrium ages from these units range from the eruption ages to as much as 200 ka older (Vasquez and Reid, 2002). Likewise, zircon U/Th ages from the 0.6 and 115 ka postcaldera domes at Long Valley caldera range from the eruption age to > 350 ka. However, the majority of zircons in both of these latter eruptions yield indistinguishable weighted mean ages of ~230 ka (Reid et al., 1997). The similar relationship between eruption ages and U/Th zircon crystallization ages from the youngest eruptions at all three caldera systems suggests that some postcaldera rhyolite eruptions are derived from **long-lived magmatic systems** (i.e., greater than a few 100 ka) with protracted crystallization histories. Temporally distinguishable eruptions that contain similar populations of zircon indicate that postcaldera magmatic systems may be tapped repeatedly for eruptions.

Single-crystal laser-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ dating also indicates significant inherited crystals (Fig. 2), providing additional insight into the origin of the East Fork Member. Some ages suggest that xenocrystic material from older ring-fault domes **and possibly the intrusive equivalents** were incorporated into the eruption. For example, a population of 10 biotite crystals in the Banco Bonito lava flow yields an age of 535 ± 10 ka (Fig. 3F), indistinguishable from the adjacent 527 ka South Mountain and 529 ka La Jara domes (Spell and Harrison, 1993). Abundant sanidine

crystals in the Banco Bonito yield ages between 80 and 135 ka (Fig. 3E), similar to zircon surface age populations (Fig. 4C and D). This overlap between subset populations of U/Th and $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the same unit hints that at least some component of the inherited crystal cargo was derived from nonexposed rocks that were intruded or possibly erupted between the South Mountain and East Fork Member eruption. Partially degassed xenocrysts (Heizler et al., 1999) or excess ^{40}Ar in melt inclusions (Kelley 2002; Esser et al., 1997) may also explain some age scatter. The abundance of xenocrystic material in the East Fork Member explains why previous bulk-step heating experiments did not yield accurate and reproducible eruption ages.

5.3 Implications for volcanic hazards

The $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Th ages of the East Fork Member provide critical information for assessing the volcanic hazards at the Valles caldera. $^{40}\text{Ar}/^{39}\text{Ar}$ ages indicate a 6.1 ± 2.8 ka repose period between the two main eruptions of the East Fork Member. This repose interval is significantly shorter than for some of the older domes. For example, two dated lobes of Cerro Santa Rosa (3 total lobes) yielded ages of 925 ± 4 and 795 ± 15 ka (Spell and Harrison, 1993), or a total duration of dome construction within 130 ± 19 ka. The high-precision ages of the East Fork Member uniquely document a possible eruption frequency should the Valles caldera enter another period of dome activity.

The age of the Banco Bonito lava flow indicates that the Valles caldera has remained dormant for ~68 ka, significantly longer than previously estimated (a dormancy period of as little as 26 ka could be determined based on ^{21}Ne surface ages by Phillips et al. 1997). Although a comprehensive chronology for the ring-fault domes has yet to be determined (i.e., domes consist of multiple flow lobes, yet only one or two lobes have assigned ages), available data suggest that the average eruption frequency is one event every 79 ka (nine well-dated centers with ages

ranging from 1.237 Ma to 527 ka; Fig.1). Certainly, additional dating would further refine this estimate and provide insight into the eruption rate at the Valles caldera. If the East Fork Member marks a new phase of postcaldera volcanism (Wolff and Gardner, 1995) and this new phase of postcaldera volcanism has similar eruption frequencies to the earlier domes, it is tempting to suggest that Valles may soon enter a period of eruption activity. However, without a complete chronology for the postcaldera eruptions at the Valles, this observation is largely speculative.

U/Th ages indicate that magmatism did not completely cease between the eruptions of the South Mountain and East Fork Member of the Valles Rhyolite. Zircon crystallization ages suggest that the present-day low-velocity zone beneath the caldera may not necessary be a young feature related to only the last pulse of volcanism, but may instead represent a longer-lived feature that was punctuated by a brief eruption cycle between 68.3 and 74.4 ka. Furthermore, the U/Th ages of zircon are broadly similar to some U/Th ages for travertine deposits at nearby warm springs (Goff and Shevenell, 1987), suggesting that the protracted assembly and residence of the East Fork Member magma chamber may have been a significant heat source for the Valles caldera hydrothermal system.

6. Summary

High-precision $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Th zircon surface ages establish new temporal constraints for the youngest eruptions and pulses of magmatism at the Valles caldera. The Battleship Rock ignimbrite and El Cajete pyroclastic beds erupted at 74.4 ± 1.3 ka. The Banco Bonito lava flow was emplaced as 68.3 ± 1.5 ka. U/Th ages of zircon indicate a previously unknown period of lengthy magma storage and a protracted crystallization history prior to these eruptions. Results provide supporting evidence to develop a dedicated monitoring network at the Valles caldera.

This study demonstrates the power of combining high-precision, single-crystal $^{40}\text{Ar}/^{39}\text{Ar}$ ages generated with the ARGUS VI mass spectrometer and high-resolution, in situ surface analyses of temporally complex zircon to assess the eruption and magmatic history at Quaternary volcanic fields. This combination of techniques is especially useful for developing chronologies for eruptions that contain an abundance of inherited grains. Additional work combining these two techniques, coupled with detailed geochemistry, has the potential to reveal a more comprehensive eruptive and magmatic history associated with the postcaldera eruptions at the Valles caldera.

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Figure Captions

Figure 1 – A. Simplified geologic map of Valles caldera. White stars indicate sample locations. Ages of rhyolite domes from Spell and Harrison (1993) and Phillips et al. (2007) are also shown. Abbreviations are: CdM – Cerro del Medio, CdA – Cerro del Abrigo, CSR – Cerro Santa Rosa, CSL – Cerro San Luis, CS – Cerro Seco, SAM – San Antonio Mountain, LJ – La Jara, SM – South Mountain, BRI – Battleship Rock ignimbrite, EC – El Cajete crater (vent for El Cajete and Battleship Rock ignimbrite), and BB – Banco Bonito lava flow. Not shown on this map are the postcaldera lavas on the flanks of the resurgent dome. The inset map of New Mexico shows location of the Jemez volcanic field in relation to the Rio Grande rift and Jemez lineament. B. Approximate location of seismically imaged low velocity zones beneath the Valles caldera, from plate 1 of Steck et al., (1998).

Figure 2 – Summary of published ages for the eruptive units of the East Fork Member of the Valles Rhyolite. Ages are reported at 2σ . Inset summary diagram, shown in gray in the top-left corner, depicts only the ages that are <100 ka. Previous dating methods include $^{40}\text{Ar}/^{39}\text{Ar}$ (Spell and Harrison, 1993), zircon fission track (Mijaji, 1985), electron spin resonance (Toyoda et al., 1995; Ogoh et al., 1993), thermoluminescence (Reneau et al., 1996), Carbon-14 (Reneau et al., 1996), optically stimulated luminescence (Lepper and Goff, 2007), and Neon-21 surface dating (Phillips et al., 1997).

Figure 3 - $^{40}\text{Ar}/^{39}\text{Ar}$ age probability plots. Data points are graphically shown with 1σ error bars, whereas weighted mean ages are reported with 2σ errors A: Sanidine in nonwelded Battleship Rock ignimbrite. Analyses in grey were excluded from the weighted mean age calculation. B:

Inverse isochron for the 61 analyses used to determine the weighted mean age in “A”. C: Plagioclase and biotite from nonwelded Battleship Rock ignimbrite. D: Sanidine in the densely welded Battleship Rock ignimbrite. E: Sanidine in the Banco Bonito lava flow. Analyses in grey were excluded from the weighted mean age calculation. F: Biotite in the Banco Bonito lava flow. Age of prominent peak was calculated using a subset of 10 analyses from the total population.

Figure 4 - Age probability plots showing the distribution of U/Th model ages. Data points are graphically shown with 1σ error bars. Age probability curve calculated using symmetrical errors of individual analyses. Maximum and minimum ages, as well as weighted mean ages for “peaks” on the probability curve are reported with 2σ errors.

Figure 5 – Summary geochronology of postcaldera volcanism at the Valles caldera. Ages are from this study, Spell and Harrison (1993), and Phillips et al. (2007). All ages reported with 2σ errors. The probability curve for the East Fork Member crystallization history was calculated using all available U-Th model ages.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5