ABSTRACT

The combination of new $^{40}$Ar/$^{39}$Ar and laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U/Pb zircon ages with published geochemistry of the volcanic and plutonic rocks of the Organ caldera complex (New Mexico) provides a framework for understanding the origin of these silicic magmas and the time scales of caldera magmatism. The Organ caldera complex erupted three ignimbrites: the 36.45 ± 0.08 Ma Cueva Tuff, the 36.23 ± 0.14 Ma Achenback Park Tuff, and the 36.03 ± 0.16 Ma Squaw Mountain Tuff. The ignimbrite sequence is zoned from a crystal-poor, high-SiO$_2$ rhyolite at the base to a crystal-rich, low-SiO$_2$ rhyolite at the top. The ignimbrite sequence is intruded by the zoned Organ Needle pluton, which has previously been interpreted to be the nonerupted silicic cap and less-differentiated residual crystal mush of the caldera-forming magma chamber. The geochronology of the Organ Needle pluton indicates that these silicic magmas were generated via shallow-crustal in situ differentiation. U/Pb zircon and many $^{40}$Ar/$^{39}$Ar biozite ages of the different phases of the Organ Needle pluton are temporally indistinguishable from the Squaw Mountain Tuff eruption age, indicating that this pluton was emplaced and rapidly cooled during or shortly after the youngest caldera eruption. New ages also suggest that Organ caldera magmatism was characterized by protracted emplacement of magmas following caldera collapse. Volcanism continued after the caldera eruptions until at least 35.7 Ma. Three silicic postcaldera plutons were emplaced between 36.0 and 34.3 Ma. Multiple diffusion domain thermal modeling of plutonic K-feldspar suggests reheating events, possibly related to postcaldera magmatism, at 34 Ma, 32–30 Ma, and as young as 26 Ma. Geochronology, geochemistry, and field-based observations of the Organ Needle pluton and caldera-forming ignimbrites support the hypothesis that some plutonic rocks are the nonerupted, geochemically complementary residues of large-volume silicic eruptions.

INTRODUCTION

Determining the processes that generate caldera-related silicic magmas and the origin of compositional zonation patterns of ignimbrites is central to our understanding of caldera-forming eruptions (Smith, 1960; Hildreth, 1981; Lipman, 1984; Bachmann and Bergantz, 2004; Lipman, 2007; Quick et al., 2009). Though the hazards associated with calderas are well known (Francis and Oppenheimer, 2004; Miller and Wark, 2008; Self and Blake, 2008), caldera eruptions are infrequent and have not been directly observed. Because of this, most caldera magmatism models are developed using extinct caldera systems (e.g., Lipman, 2007). Previous studies have shown that ignimbrites display variations in mineral modality, phenocryst contents, and major- and trace-element geochemistry (Eichelberger et al., 2000; Hildreth and Wilson, 2007; Bachmann and Bergantz, 2008). Some large-volume caldera-forming ignimbrites are compositionally zoned, whereas others are compositionally homogeneous (Bacon and Druitt, 1988; Seager and McCurry, 1988; Dunbar et al., 1989; Bachmann et al., 2002; Hildreth, 2004; Lipman, 2007). Despite decades of research, the origin of the $10^2$–$10^3$ km$^3$ of silicic magma erupted during caldera collapse and the processes that occur within caldera-forming magma chambers remain controversial (Glazner et al., 2004; Amm et al., 2006; Eichelberger et al., 2006; Bachmann et al., 2007a; Kennedy and Stix, 2007; Knesel and Duffield, 2007). The compositional zonation patterns observed in ignimbrites are generally interpreted to represent varying degrees of crystal-liquid fractionation of magma in the upper crust (Smith, 1960; Hildreth, 2004; Bachmann and Bergantz, 2008). This model predicts that when the crystal content of a magma chamber is low, convective mixing can efficiently homogenize compositional variations (Jellinek and Kerr, 1999; Bachmann and Bergantz, 2008). However, as a magma chamber cools and crystal percentages increase to 40%–60%, mixing via convection eventually ceases. The quasi-rigid framework of crystals begins to compact and silica-rich melt is extracted from the more-mafic, crystal-rich region of the magma chamber (Bachmann et al., 2002; Miller and Miller, 2002; Bachmann and Bergantz, 2004; Walker et al., 2007). Crystal-liquid fractionation compositionally and mineralogically stratifies the caldera-forming magma chamber. Crystal-poor, silica-rich magma accumulates at the top of the magma chamber, leaving behind crystal-rich, silica-poor magma near the bottom of the chamber. Previous studies have suggested that (1) compositionally zoned ignimbrites represent the eruption of both the silica-rich cap and some volume of silica-poor residual mush, (2) nonzoned rhyolitic ignimbrites represent the eruption of only the silicic cap, and (3) crystal-rich dacites (i.e., monotonous intermediates) represent eruption of the crystal mush before liquid-crystal fractionation occurs (Bacon and Druitt, 1988; Halliday et al., 1991; Bachmann et al., 2002; Bachmann and Bergantz, 2004; Hildreth, 2004; Bachmann and Bergantz, 2008). Accordingly, the nonerupted portions of the magma chamber, which include large volumes of the less-differentiated residual crystal mush and possibly small volumes of the nonerupted silicic cap, are preserved in the plutonic record (Bachmann et al., 2007b; de Silva and Gosnold, 2007; Lipman, 2007).

Although in situ differentiation adequately describes magmatism at many caldera systems,
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recent studies have questioned whether this is the only mechanism that can generate caldera-related silicic magmas (Eichelberger et al., 2000; Coleman et al., 2004; Glazner et al., 2004, 2008; Annen et al., 2006; Knesel and Duffield, 2007; Tappa et al., 2011; Zimmerer and McIntosh, 2012a, 2012b). Models that suggest that voluminous silicic magmas originate via in situ differentiation were largely developed using only the volcanic record (Smith, 1960; Hildreth, 1981; Bacon and Druitt, 1988; Lipman et al., 1996; Bachmann and Bergantz, 2004). However, processes that generate silicic melts are also recorded in plutonic rocks. Many studies of the intrusive record have shown that some compositionally zoned plutons are incrementally emplaced into the upper crust and do not represent the crystal-rich regions of magma chambers where melt was extracted to feed voluminous silicic eruptions (Coleman et al., 2004; Glazner et al., 2004, 2008; Matzel et al., 2006; Michel et al., 2008; Annen, 2009). Studies have also shown that many plutons are emplaced during pre- and/or postcaldera magmatism rather than syncaldera magmatism and, therefore, are not related to the caldera-forming magma chamber. Lipman (1984, 2007; Lipman et al., 1986; Tappa et al., 2011). The lack of evidence preserved in the shallow plutonic record to support upper-crustal in situ differentiation has led researchers to hypothesize that some silicic magmas may originate in mid- to lower-crustal sources by a combination of crustal melting, assimilation, and fractionation (Glazner et al., 2004; Tappa et al., 2011; Zimmerer and McIntosh, 2012a, 2012b). Accordingly, compositional variation within a single ignimbrite is related to assembly of magmas generated from a mid- to lower-crustal source region, coupled with assimilation and melting of country rocks in the upper crust (Eichelberger et al., 2000; Knesel and Duffield, 2007; Tappa et al., 2011). This model for silicic-melt generation predicts that an upper-crustal residual crystal mush, which should be geochemically complementary to the ignimbrite, is not present in the shallow plutonic environment. If crystal-liquid fractionation generates silicic magmas, the complementary residual crystal mush will be located at deeper crustal levels than the upper-crustal, caldera-forming magma chamber.

A more comprehensive approach to developing caldera magmatism models is to determine and examine the connection between the volcanic and plutonic records of a single caldera system. Upper- and lower-crustal silicic melt genesis models predict different relationships for volcanic and shallow plutonic rocks. Therefore, establishing the temporal and chemical relationships of caldera-related volcanic and plutonic rocks provides a framework for understanding caldera-related silicic magmatism and the time scales of caldera-related hazards and magmatic activity.

Faulting, uplift, and erosion along the flanks of the Rio Grande rift have exposed the intracaldera sequence and abundant subvolcanic intrusions at the Organ caldera, south-central New Mexico (Seager, 1981; Seager and McCurry, 1988). Published geochemical studies suggest that the compositionally zoned ignimbrites of the Organ caldera were generated via upper-crustal in situ differentiation (Seager and McCurry, 1988). Additionally, the nonerupted remnants of the caldera-forming magma chamber are preserved as the oldest and largest caldera-related intrusion, the compositionally zoned Organ Needle pluton (Verplanck et al., 1995, 1999). However, the emplacement ages of the exposed intrusions and the eruption ages of the volcanic rocks have yet to be fully investigated.

We conducted 40Ar/39Ar and laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U/Pb zircon dating of the volcanic and plutonic rocks from the Organ caldera complex in order to achieve two primary goals. The first goal was to investigate the time scales of caldera magmatism, from inception to cessation. LA-ICP-MS ages determined the timing of zircon crystallization and represent the best approximation for the timing of pluton emplacement. 40Ar/39Ar ages constrained the durations of pre-, syn-, and postcaldera volcanism. 40Ar/39Ar ages also established the thermal histories of the plutons and helped to refine pluton emplacement histories. Plutonic K-feldspar age spectra were modeled using the multiple diffusion domain (MDD) theory (Lovera et al., 1989, 1991) to establish thermal histories of the intrusive complex and detect reheating events by emplacement of intrusions that are not exposed. The second goal was to determine whether the caldera-forming silicic ignimbrites were generated by upper-crustal in situ differentiation or were generated at deeper crustal levels. This was accomplished by comparing the timing of caldera ignimbrite eruptions to the emplacement history of the Organ Needle pluton, the proposed residual crystal mush of the caldera magma chamber.

**GEOLOGIC BACKGROUND AND PREVIOUS STUDIES**

The Organ caldera complex (Fig. 1) is exposed in the Organ Mountains (Fig. 2), south-central New Mexico, at the eastern margin of the 40,000 km2 Mogollon-Datil volcanic field (Dunham, 1935; Seager and McCurry, 1988; McIntosh et al., 1992). The Mogollon-Datil volcanic field is an erosional remnant of a discontinuous mid-Tertiary volcanic belt that extends from central Colorado to central Mexico (Chapin et al., 2004). Mid-Tertiary silicic caldera volcanism (i.e., the ignimbrite flare-up) of southwestern North America is generally attributed to slab foundering following Laramide flat-slab subduction of the Farallon plate beneath the North American plate, which allowed hot asthenosphere to contact the hydrated North American lithosphere and induce widespread magmatism (Humphreys et al., 2003; Chapin et al., 2004; Lipman, 2007; Chapin, 2012). Following the cessation of caldera magmatism, regional extension eventually led to the formation of the Rio Grande rift (Baldridge et al., 1995; Chapin et al., 2004), Rio Grande rift–related faulting exposed both intracaldera volcanic units and the subcaldera batholith at the Organ caldera complex (Seager, 1981; Seager and McCurry, 1988), as well as at several other mid-Tertiary caldera systems along the flanks of the rift (Lipman et al., 1986; Shannon, 1988; Meyer and Foland, 1991; Lipman, 2007).

The volcanic rocks exposed at the Organ caldera complex consist of incomplete pre- and postcaldera volcanic records and a relatively well exposed intracaldera ignimbrite sequence. Similar to most caldera systems, the catastrophic caldera-collapse eruption was preceded by intermediate-composition volcanism (Seager and McCurry, 1988; Colucci et al., 1991; Lipman, 2007). Pre-caldera volcanic rocks were erupted onto the mid-Tertiary surface, which includes Paleozoic sediments and Precambrian granites and metamorphic rocks. The precaldera volcanic deposits, referred to as the Orejon Andesite (Dunham, 1935), consist of highly altered lavas, lahar breccias, and volumetrically minor pyroclastic deposits. Postcaldera volcanism was characterized by numerous eruptions of rhyolitic and dacitic lavas. Seager (1981) named the postcaldera volcanic rocks the “west-side lavas” because exposures are limited to isolated outcrops located in the western foothills of the Organ Mountains (Fig. 2).

Three caldera-collapse–related ignimbrites are located at the Organ caldera complex. From oldest to youngest, the units are: the Cueva Tuff, the Achenback Park Tuff, and the Squaw Mountain Tuff. The total volume of the ignimbrites is estimated to be between 500 and 1000 km3. Deposits of epilastic rocks (Fig. 3A) are interlayered between each unit, indicating that the ignimbrites were emplaced during temporally distinct eruptions. The ignimbrite sequence thins from 3.3 km in the west (Fig. 3B) to only several hundred meters along the contact with the Organ Needle pluton in the east. The geometry of the intracaldera deposits...
subsidence of the caldera floor likely occurred during trap-door–style collapse. The greatest (1988) to suggest that the Organ caldera formed led Seager (1981) and Seager and McCurry (1988) to suggest that the Organ caldera formed during trap-door–style collapse. The greatest subsidence of the caldera floor likely occurred along the western caldera margin, which is now buried beneath the Rio Grande rift basin. Trap-door–style caldera collapse occurred during the eruption of the Cueva Tuff and each subsequent caldera collapse event probably occurred along existing, structurally weakened, caldera margin faults, producing a nested caldera complex. The intracaldera ignimbrite sequence, as a whole, is zoned from a crystal-poor, high-SiO₂ rhyolite at the base (i.e., Cueva Tuff) to a crystal-rich, low-SiO₂ rhyolite at the top (i.e., Squaw Mountain Tuff) (Fig. 3E). The zonation pattern of the caldera collapse–ignimbrite sequence has been interpreted to represent episodic eruptions from a shallow-crustal, zoned, pre–caldera collapse magma chamber (Seager and McCurry, 1988; Verplanck et al., 1995, 1999). The Organ Needle pluton is compositionally zoned (Fig. 3F) from a monzodiorite (~57% SiO₂) at the base to an equigranular syenite in the interior and inequigranular syenite phases (57%–68% SiO₂) located at the margins of the intrusion. Cupolas of alkali feldspar granite (73%–76% SiO₂) are located at the top of the intrusion (Seager and McCurry, 1988; Verplanck et al.,

The Cueva Tuff is a lithic-rich, compound ignimbrite, consisting of multiple cooling units that are interlayered with minor amounts pyroclastic fall deposits. The composition of the lithics is dominated by rhyolite (e.g., Fig. 3C), but sparse granite, gneiss, and andesite fragments are also common. The Cueva Tuff is generally crystal poor (<1% phenocrysts). However, there are two crystal-rich (10%–20% phenocrysts) intervals in the middle of the unit. The Cueva Tuff has a SiO₂ content of ~77% and is the most silicic of the three caldera collapse ignimbrites. The Achenback Park Tuff is less silicic and displays only slightly more compositional variation than the Cueva Tuff. The SiO₂ content of the Achenback Park Tuff varies from 74% at the top to 75% at the base. The Achenback Park Tuff is also crystal poor, but unlike the Cueva Tuff it contains very few lithic fragments. The last ignimbrite erupted from the Organ caldera complex was the Squaw Mountain Tuff, which is the least silicic and displays the most major- and trace-element variation of the three caldera-related ignimbrites. The SiO₂ content of the tuff ranges from 72% at the base to 68% at the top of the unit. Within the Squaw Mountain Tuff, chemical zonation correlates with an increase in phenocryst content, from 1%–5% at the base to as much as 20% at the top (Seager, 1981; Seager and McCurry, 1988).

Though previous research of the Organ caldera established the volcanic stratigraphy (Dunham, 1935; Seager, 1981), a comprehensive geochronology of the eruptive history did not exist, McIntosh et al. (1992) reported ⁴⁰Ar/³⁹Ar sanidine incremental-heating ages of 36.68 ± 0.13 Ma and 36.22 ± 0.12 Ma for the Cueva Tuff and Squaw Mountain Tuff, respectively (all ages reported in this study are calculated relative to the Fish Canyon Tuff sanidine standard FC-2 = 28.201 Ma; Kuiper et al., 2008). The timing of pre- and postcaldera volcanism, as well as the age of the Achenback Park Tuff, have not been determined.

The Organ Needle pluton, the largest exposed intrusion at the Organ caldera complex, has been interpreted to record the differentiation and crystallization of an upper-crustal magma chamber (Seager and McCurry, 1988; Verplanck et al., 1995, 1999). The Organ Needle pluton crops out along the eastern margin of the caldera complex and probably intruded along caldera-margin ring faults (Seager, 1981). The Organ Needle pluton is compositionally zoned (Fig. 3F) from a monzodiorite (~57% SiO₂) at the base to an equigranular syenite in the interior and inequigranular syenite phases (57%–68% SiO₂) located at the margins of the intrusion. Cupolas of alkali feldspar granite (73%–76% SiO₂) are located at the top of the intrusion (Seager and McCurry, 1988; Verplanck et al.,

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**Figure 1. Simplified geologic map of the Organ caldera complex modified from Seager and McCurry (1988) and Verplanck et al. (1999).** Precambrian rocks consist of granites and foliated metamorphic rocks. Paleozoic rocks include lithologically diverse sedimentary rocks.
Figure 2. Panoramic photo of the Organ Mountains showing some of the plutonic and volcanic rocks related to the Organ caldera. Photo was taken looking to the east. The total field of view is ~25 km. Caldera floor is composed of Paleozoic sedimentary rocks.

The contact between the alkali feldspar granite and the underlying syenite is gradational. Geochemical studies indicate that the interior equigranular syenite has higher εNd and lower 87Sr/86Sr values (~2 and 0.7060, respectively) than the monzodiorite, inequigranular syenite, and alkali feldspar granite (~5 and 0.7085, respectively; Verplanck et al., 1995, 1999). Previously proposed models suggest that the equigranular syenite formed during closed-system fractionation of a mafic source, whereas the inequigranular syenite formed later from a crustal-contaminated mafic source (i.e., the monzodiorite), migrated along the walls of the chamber, and finally differentiated into the alkali feldspar granite near the roof (Seager and McCurry, 1988; Yanicak, 1992; Verplanck et al., 1995, 1999). The geochemical similarities between the Squaw Mountain Tuff and the alkali feldspar granite suggest that the granite may be the nonerupted geochemical equivalent of the tuff (Seager and McCurry, 1988; Verplanck et al., 1995, 1999).

Numerous postcaldera silicic intrusions cross-cut the Organ Needle pluton. The largest postcaldera intrusion is the Sugarloaf Peak quartz monzonite. The Sugarloaf Peak pluton is relatively compositionally homogenous, but contains abundant aplastic dikes at high structural levels and mafic enclave swarms at the deepest structural levels (Fig. 3D). The contact between the Sugarloaf Peak and Organ Needle pluton is sharp, indicating that the latter was cool during emplacement of the Sugarloaf Peak pluton. The Granite of Granite Peak is a cylindrical intrusion that cross-cuts the monzodiorite and equigranular syenite phases of the Organ Needle pluton. Similar to the Sugarloaf Peak pluton, contacts with the Organ Needle pluton are sharp, indicating a large thermal contrast between the two intrusions during emplacement. The smallest postcaldera intrusion is the Baylor Peak rhyolite porphyry, which is exposed in the northern region of the Organ caldera complex (Fig. 2; Seager and McCurry, 1988).

The timing of pluton emplacement at the Organ caldera complex is not well constrained. As previously mentioned, the geochemical relationships between the Squaw Mountain Tuff and Organ Needle pluton suggest that the Organ Needle pluton is temporally similar to the Squaw Mountain Tuff. Rioux et al. (2010) provided a limited data set of Chemical Abraison-Thermal Ionization Mass Spectrometry (CA-TIMS) zircon ages that shed light on the emplacement and crystallization history of the Organ Needle pluton. U/Pb zircon ages of the equigranular and inequigranular syenite phases of the Organ Needle pluton yielded ages between 36.1 and 36.3 Ma (errors not reported), similar to the 36.2 Ma eruption age.
of the Squaw Mountain Tuff (McIntosh et al., 1992). However, Rioux et al. (2010) found that zircon in the northernmost outcrop of the alkali feldspar granite yielded U/Pb ages between 35.1 and 35.2 Ma and therefore was emplaced in a separate magmatic event. Additional cupcakes of alkali feldspar granite crop out in the southern Organ Mountains (Fig. 1) and were investigated in detail by this study. Few ages exist for the silicic postcaldera intrusions that cross-cut the Organ Needle pluton. K/Ar ages of the Sugarloaf Peak pluton and related dikes are 34.4 and 32.1 Ma, providing a minimum emplacement age (Loring and Loring, 1980).

METHODS

Forty-eight volcanic and plutonic rock samples were collected as part of this study. Supplemental File 1 contains the sample names, lithologic unit, and UTM coordinates. Pre-, syn-, and postcaldera volcanic rocks were sampled to obtain a representative suite for the volcanic record. Multiple samples of the various phases of the Organ Needle pluton and two or more samples of each postcaldera pluton were collected. Additionally, one sample of the Precambrian porphyritic granite was collected. From this suite, 32 samples were selected for geochronology analyses. Mineral separates were prepared using standard rock-crushing, acid, magnetic, and mineral-density techniques. Optical picking assured pure separates. Seven zircon separates were dated using the laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U/Pb method. Forty-seven mineral separates (8 sanidine, 17 biotite, 1 plagioclase, 5 hornblende, 4 groundmass concentrates, and 12 plutonic K-feldspar) were dated using the 40Ar/39Ar technique.

LA-ICP-MS U/Pb zircon dating was conducted at the Arizona LaserChron Center (Tucson, Arizona). Zircon mineral separates and the Sri Lanka zircon standard were mounted in 1-inch epoxy disks. Prior to U/Pb dating, the polished pucks were imaged by cathodoluminescence (CL) on a scanning electron microscope. CL images were used to identify xenocrystic cores, mineral and melt inclusions, and magnetic textures. A 193-nm-wavelength excimer laser operating with a spot diameter of 30 μm was used to ablate zircon domains. If CL imaging indicated possible xenocrystic cores, inheritance was assessed by ablating both the rim and core of individual zircons. For each sample, 30–40 spots were analyzed. Isotopic ratios were measured on a NU Plasma MC-ICP mass spectrometer. The precision of 206Pb/238U ages for individual analyses ranged from <2% to >30% (1σ level). The low precision of some analyses is attributed to the electrostatic analyzer on the NU mass spectrometer, which can filter up to 40% of the ion beam (Mark Pecha, 2011, personal commun.). Data were assessed using Agecalc, a Microsoft Excel macro developed by the Arizona LaserChron Center. Because of the large errors associated with some individual analyses, the nominal cutoff of 10% 206Pb/238U error for acceptable data was increased to as much as 30% for some samples to provide a large enough population for statistical calculations. Only the 206Pb/238U ages were used to calculate an age (Gehrels et al., 2008). Zircon crystallization ages were determined using the TuffZirc algorithm (Ludwig and Mundil, 2002) of Isoplot version 3.7 (Ludwig, 2009). The asymmetric TuffZirc errors are useful in describing the source(s) of age dispersion. A large positive uncertainty suggests more complexity related to xenocrystic or antecrystic contamination, whereas a large negative uncertainty suggests more complexity related to Pb loss (Ludwig, 2009). Gehrels et al. (2008) and Johnston et al. (2009) provide comprehensive information about the LA-ICP-MS method. Additional information can be found on the Arizona LaserChron Center Web site (https://sites.google.com/a/laserchron.org/laserchron/home/).

40Ar/39Ar dating was performed at the New Mexico Geochronology Research Laboratory located at the New Mexico Institute of Mining and Technology (Socorro, New Mexico). Mineral separates were irradiated with the interlaboratory FC-2 sanidine standard (28.201 ± 0.046 Ma; Kuiper et al., 2008) in a known geometry. Single crystals of sanidine were fused using a focused CO2 laser. Six crystals from each monitor position in an irradiation tray were analyzed to calculate the neutron flux. Fifteen crystals of each Organ sanidine separate were analyzed to calculate a weighted mean age. Biotite, plagioclase, hornblende, and groundmass-concentrate separates were step-heated using a defocused CO2 laser. Plutonic K-feldspar separates were incrementally heated in a double-vacuum Mo resistance furnace. Heating schedules for K-feldspar separates used the isothermal duplicate heating technique, which is useful for assessing excess 40Ar hosted within fluid inclusions (Harrison et al., 1994). Gas from the heated samples was exposed to SAES getters in an all-metal, fully automated extraction line to remove reactive gases. Cleaned gas was then expanded into a MAP 215-50 mass spectrometer for isotopic-ratio measurements. McIntosh et al. (2003) provides additional information for the typical operating procedures at the New Mexico Geochronology Research Laboratory.

RESULTS

U/Pb Geochronology

U/Pb ages are summarized in Table 1. The corresponding analytical data tables, TuffZirc plots, and representative CL images are located in Supplemental File 2; U/Pb ages ranged from 34.28±0.51 to 36.48±0.89 Ma. Uncertainties (2σ) of the U/Pb TuffZirc ages ranged from 0.6% to 3.7%. Systematic errors during the U/Pb dating session ranged from 1.0% to 1.1%. Zircon ages are geologically consistent with relative ages of the intrusions constrained by cross-cutting relationships. Zircon ages are interpreted to represent the timing of zircon crystallization during pluton emplacement.

Zircon crystallization ages from the Organ Needle pluton ranged from 36.48±0.46 to 34.93±0.25 Ma. U/Pb ages from the structurally highest and lowest parts and the margins of the Organ Needle pluton (samples ORGAN-41, ORGAN-45, and ORGAN-46, respectively) are statistically indistinguishable from each other. The U/Pb age of the equigranular syenite of the Organ Needle pluton (ORGAN-10) yielded an age of 34.93±0.25 Ma. The contact between the alkali feldspar granite and the equigranular syenite, where exposed, is gradational, indicating that the two phases are coeval. The large negative uncertainty of the equigranular syenite may indicate that the slightly younger age is related to Pb loss. Alternatively, ORGAN-10 may be a sample from a previously unknown syenite phase of a postcaldera pluton.

Two postcaldera plutons were dated using the LA-ICP-MS U/Pb zircon dating technique. Zircons from one sample of the Granite of Granite Peak pluton yielded an U/Pb age of 34.25 Ma. Zircons from two samples of the Sugarloaf Peak pluton yielded statistically distinguishable ages of 35.31±0.39 and 34.28±0.25 Ma.

Zircons in Organ caldera–related intrusions lack evidence for significant Precambrian xenocrystic inheritance. Verplanck et al. (1995, 1999) suggested that compositional zoning of the Organ Needle pluton was generated by sideway crystallization and fractionation of a parental magma combined with assimilation and partial...
melting of 1.4–1.7 Ga Precambrian granite. The absence of Precambrian zircon cores suggests that any inherited zircons dissolved following incorporation into the magma chamber (Watson and Harrison, 1983). Only one zircon core in ORGAN-41, the alkali feldspar granite, yielded a statistically different age from the bulk population. The analysis of this core yielded an age of 262 Ma. This analysis may represent a mixing age between a Precambrian zircon core and mid-Tertiary zircon rim. Alternatively, the age of this core may indicate that some Permian sedimentary rocks, which crop out in the southern Organ Mountains, were assimilated into the Organ Needle pluton.

### 40Ar/39Ar Geochronology and Thermochronology

Forty-seven volcanic and plutonic K-bearing mineral separates were dated using the 40Ar/39Ar technique. Table 2 summarizes the 40Ar/39Ar results. Ages were calculated using FC-2 = 28.201 Ma (Kuiper et al., 2008) and decay of 40K = 5.463 × 10^-11 yr^-1 (Min et al., 2000). All 40Ar/39Ar data tables, ideograms, and age spectra are located in Supplemental File 3.

#### Sanidine Single-Crystal Laser Fusion (SCLF)

Samples of the Cueva, Achenback Park, and Squaw Mountain Tuffs, as well as a single postcaldera lava flow, were dated using the sanidine single-crystal laser fusion (SCLF) technique. Sanidine SCLF ages ranged from 35.79 ± 0.09 to 36.46 ± 0.05 Ma. Figure 4 contains the ideograms for the caldera-collapse ignimbrites. Sanidine weighted mean ages are interpreted to accurately represent the timing of eruption. Two or three samples of each caldera-forming ignimbrite were dated. Results indicate that xenocrystic sanidine and phenocrysts of plagioclase were not dated. Some crystals from the Cueva Tuff and Squaw Mountain Tuff had low radiogenic 40Ar yields (i.e., <95% 40Ar*). Many of the low-radiogenic crystals yielded ages that statistically overlapped with ages from high-radiogenic-yield crystals. Exclusions of these low-radiogenic-yield analyses from the age calculation commonly increased the mean square weighted deviate (MSWD) value. Only crystals with extremely low radiogenic yields (i.e., <80% 40Ar*) were excluded from the age calculation.

#### Laser Step Heating

Biotite, plagioclase, and hornblende separates and groundmass concentrates were step heated using a defocused CO2 laser. Six representative age spectra are shown in Figure 5. Ages were calculated using the plateau or the integrated age-calculation methods. A plateau is defined as three or more contiguous steps that contain 50% or more of the 39Ar released from the sample and whose ages are indistinguishable within 2σ limits (Fleck et al., 1977). For samples that did not yield a plateau, the integrated age of all the steps was used only if it was geologically consistent with field relationships.

Seventeen biotite separates (3 volcanic and 14 plutonic) were step heated. The ages of volcanic biotite separates are interpreted as the eruption ages, whereas the ages of plutonic biotites are interpreted to represent cooling to 350–300 °C (Hodges et al., 1994; McDougall and Harrison, 1999). Sixteen separates yielded a plateau segment. Plateau ages ranged from 36.25 ± 0.12 to 33.46 ± 0.19 Ma. Some of the biotite age spectra contained >95% of the 39Ar released, with only minor discordance between the first one or two steps and the plateau segment (e.g., Fig. 5A). However, numerous biotite age spectra are characterized by monotonically increasing ages in the initial 10%–30% of the 39Ar released, which is then followed by the plateau (e.g., Fig. 5B).

The initial age gradient observed in these biotite analyses is interpreted to represent degassing from slightly altered regions of the biotite crystal during the low-power steps.

Only one biotite analysis, ORGAN-45 (see Supplemental File 3 [see footnote 3]), did not yield a plateau. The ages of the steps monotonically increase from ca. 16 to 36 Ma during the step-heating experiment. The K2O value for this biotite is 6.1%, which is slightly lower than the 8%–10% K2O content expected for a pristine biotite (McDougall and Harrison, 1999). The integrated age of this sample, 34.63 ± 0.16 Ma, is interpreted to represent the timing of biotite closure.

Four volcanic groundmass concentrates separates were dated to determine the pre- and postcaldera eruptive history. Only one of the four groundmass concentrate samples yielded geologically reasonable results. Sample ORGAN-11, a dacitic west-side lava, yielded a plateau age of 36.27 ± 0.08 Ma (Fig. 5C). The age spectrum exhibits some discordant steps, which may suggest minor 39Ar recoil (Heizler et al., 1988; Lo and Onstott, 1989). Because some 39Ar was likely recoiled during irradiation, the slightly less precise integrated age, 36.10 ± 0.21 Ma, is the preferred eruption age.

Three groundmass separates from the precaldera Oreocon Andesite yielded disturbed age spectra. Age spectra are characterized by either old steps at the beginning of the spectrum that decrease in age during the 39Ar released and yield integrated ages that are too old to be part of the caldera cycle (e.g., 41–44 Ma), or by initially young steps that increase in age and yield integrated ages that younger than the overlying units. Age-spectra discordance of the groundmass concentrate separates is likely caused by hydrothermal fluid circulation and alteration during the emplacement of the Organ Needle pluton (Seager, 1981).

Five hornblende separates, two from volcanic samples and three from plutonic samples, were dated during this study. Both volcanic horn-
Organ caldera silicic magmatism

**TABLE 2. SUMMARY OF THE **40Ar/39Ar AGES FOR THE ORGAN CALDERA COMPLEX**

<table>
<thead>
<tr>
<th>Caldera stage</th>
<th>Sample</th>
<th>Unit</th>
<th>Mineral*</th>
<th>Age calculation method†</th>
<th>Age§</th>
<th>Internal error#</th>
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<tbody>
<tr>
<td><strong>Precaldera volcanism</strong></td>
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<tr>
<td></td>
<td>ORGAN-18</td>
<td>Cueva Tuff</td>
<td>san</td>
<td>SCLF</td>
<td>36.46 ± 0.05</td>
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<tr>
<td></td>
<td>ORGAN-14</td>
<td>Cueva Tuff</td>
<td>san</td>
<td>SCLF</td>
<td>36.45 ± 0.10</td>
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<tr>
<td></td>
<td>ORGAN-17</td>
<td>Cueva Tuff</td>
<td>san</td>
<td>SCLF</td>
<td>36.43 ± 0.09</td>
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</tr>
<tr>
<td></td>
<td>ORGAN-28</td>
<td>Achenback Park Tuff</td>
<td>san</td>
<td>SCLF</td>
<td>36.28 ± 0.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ORGAN-27</td>
<td>Achenback Park Tuff</td>
<td>san</td>
<td>SCLF</td>
<td>36.17 ± 0.12</td>
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</tr>
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<td>ORGAN-4</td>
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<td>SCLF</td>
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<td>ORGAN-2</td>
<td>Squaw Mountain Tuff</td>
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<td><strong>Caldera-forming ignimbrites</strong></td>
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<td>ORGAN-41</td>
<td>alkali feldspar granite</td>
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<td>plt.</td>
<td>36.25 ± 0.12</td>
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<td>ORGAN-35</td>
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<td>ORGAN-36</td>
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<td>35.98 ± 0.14</td>
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<td>34.28 ± 0.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ORGAN-46</td>
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<td></td>
<td></td>
<td>35.77 ± 0.14</td>
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<tr>
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<td>ORGAN-31</td>
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<td>35.19 ± 0.10</td>
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<td>ORGAN-47</td>
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<td>35.94 ± 0.13</td>
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<td>ORGAN-43</td>
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<td>35.42 ± 0.12</td>
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<td></td>
<td>ORGAN-45</td>
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<td>34.63 ± 0.16</td>
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<td><strong>Syn-caldera intrusion (Organ Needle Pluton)</strong></td>
<td>ORGAN-41</td>
<td>alkali feldspar granite</td>
<td>bt</td>
<td>plt.</td>
<td>36.25 ± 0.12</td>
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<td>ORGAN-35</td>
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<tr>
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<td>ORGAN-10</td>
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<td>34.28 ± 0.17</td>
<td></td>
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<tr>
<td></td>
<td>ORGAN-46</td>
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<td>35.77 ± 0.14</td>
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<td></td>
<td>ORGAN-31</td>
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<td>35.19 ± 0.10</td>
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<td>ORGAN-47</td>
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<td>35.94 ± 0.13</td>
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<tr>
<td></td>
<td>ORGAN-43</td>
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<td></td>
<td>35.42 ± 0.12</td>
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<tr>
<td></td>
<td>ORGAN-45</td>
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<td></td>
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<td>34.63 ± 0.16</td>
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<tr>
<td><strong>Precambrian country rock</strong></td>
<td>ORGAN-42</td>
<td>porphyritic granite</td>
<td>bt</td>
<td>plt.</td>
<td>36.16 ± 0.15</td>
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<tr>
<td><strong>Post caldera volcanism</strong></td>
<td>ORGAN-6</td>
<td>rhyolitic west-side lava</td>
<td>san</td>
<td>SCLF</td>
<td>35.79 ± 0.09</td>
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<td></td>
<td>ORGAN-7</td>
<td>dacitic west-side lava</td>
<td>bt</td>
<td>plt.</td>
<td>35.68 ± 0.09</td>
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<td></td>
<td>ORGAN-8</td>
<td>dacitic west-side lava</td>
<td>bt</td>
<td>plt.</td>
<td>35.77 ± 0.08</td>
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<tr>
<td></td>
<td>ORGAN-11</td>
<td>dacitic west-side lava</td>
<td>gmc</td>
<td>int.</td>
<td>36.10 ± 0.21</td>
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</tr>
<tr>
<td></td>
<td>ORGAN-12</td>
<td>rhyolitic west-side lava</td>
<td>bt</td>
<td>plt.</td>
<td>35.78 ± 0.09</td>
<td></td>
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<tr>
<td><strong>Postcaldera intrusions</strong></td>
<td>ORGAN-37</td>
<td>Granite of granite peak</td>
<td>bt</td>
<td>plt.</td>
<td>35.41 ± 0.13</td>
<td></td>
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<td></td>
<td>ORGAN-24</td>
<td>Sugarloaf Peak pluton</td>
<td>bt</td>
<td>plt.</td>
<td>34.66 ± 0.06</td>
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<td></td>
<td>ORGAN-9</td>
<td></td>
<td></td>
<td></td>
<td>33.60 ± 0.15</td>
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<td></td>
<td>ORGAN-13</td>
<td></td>
<td></td>
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<td>33.48 ± 0.07</td>
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<tr>
<td></td>
<td>ORGAN-25</td>
<td>Sugarloaf enclave</td>
<td>bt</td>
<td>plt.</td>
<td>33.46 ± 0.19</td>
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<td></td>
<td>ORGAN-22</td>
<td>aplitic dike in Sugarloaf</td>
<td>kspar</td>
<td>int.</td>
<td>31.46 ± 0.24</td>
<td></td>
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<tr>
<td></td>
<td>ORGAN-21</td>
<td>Baylor Peak porphyry</td>
<td>kspar</td>
<td>int.</td>
<td>34.13 ± 0.10</td>
<td></td>
</tr>
</tbody>
</table>

*san—sanidine; bt—biotite; kspar—plutonic K-feldspar; hbl—hornblende; plag—plagioclase; gmc—groundmass concentrate.
†SCLF—single-crystal laser fusion (weighted mean); plt.—plateau age; int.—integrated age; a.l.—argon loss via reheating.
§Age calculated relative to age of Fish Canyon Tuff sanidine standard FC-2 equal to 28.201 Ma (Kuiper et al., 2008).
#Error (2σ) includes uncertainty in the flux gradient and irradiation parameters.

blende age spectra, ORGAN-7 and ORGAN-8, contained plateau segments (e.g., Fig. 5D), but are older than the corresponding biotite plateau ages and inconsistent with stratigraphic position. Inaccurate, old ages observed in some **40Ar/39Ar analyses are commonly attributed to excess **40Ar. However, the **40Ar/39Ar intercepts for these two samples do not suggest excess argon. The biotite ages for these two samples are the preferred eruption age.

Three plutonic hornblende separates yielded discordant age spectra (e.g., Fig. 5E). Integrated ages for these three samples do not agree with corresponding U/Pb ages or field relationships. Inverse isochron plots have **40Ar/39Ar intercepts greater than atmosphere (i.e., **40Ar/39Ar = 295.5), but the elevated MSWD values suggest that if excess **40Ar is present it is not homogenously distributed. An accurate age could not be determined for these samples.

A plagioclase separate from sample ORGAN-8, a west-side lava, yielded a plateau age of 36.19 ± 0.21 Ma (Fig. 5F). Similar to the plateau age of the hornblende separate from this sample, the plagioclase plateau age is older than underlying units. The integrated age is 35.17 ± 0.63 Ma, which agrees with field relationships but is imprecise. The corresponding biotite plateau age of this sample is 35.77 ± 0.08 Ma and is the preferred eruption age.

**Plutonic K-Feldspar Analyses and MDD Cooling Histories**

Twelve plutonic K-feldspar separates were dated to determine the low-temperature thermal history of the caldera-related intrusions. Six K-feldspar analyses yielded geologically meaningful results (Fig. 6). These six samples were further investigated using the multiple domain diffusion (MDD) theory, which relates argon retenivity to K-feldspar to a discrete distribution of domain sizes (Lovera et al., 1989, 1991). A detailed description of the MDD modeling technique can be found in Sanders and Heizler (2005). Supporting plots used to model the thermal histories are found within...
Supplemental File 4. Two thermal histories were generated for each of these K-feldspars. Monotonic cooling histories (Figs. 7A–7F) only allow for cooling from an initially high temperature, whereas unconstrained thermal histories (Figs. 7G–7L) allow for multiple reheating events. Some age spectra contain contiguous steps that oscillate with respect to age. This is an artifact of the isothermal duplicate step-heating method. The first isothermal duplicate step releases excess 40Ar from fluid inclusions and the second isothermal duplicate step releases gas from the K-feldspar lattice. MDD thermal histories were generated using model age spectra that did not include the first isothermal duplicate step.

MDD thermal histories provide information on the cooling history of the intrusive suite and indicate protracted postcaldera magmatism. MDD monotonic models indicate variable cooling rates for the intrusions. For example, ORGAN-10 (Fig. 7A) indicates rapid cooling between 36 and 35 Ma, slower cooling between 35 and 33 Ma, and rapid cooling between 33 and 32 Ma. K-feldspar from the alkali feldspar granite and an aplitic dike in the Sugarloaf Peak pluton (Figs. 7C and 7E, respectively) indicate initially rapid cooling followed by prolonged periods of isothermal conditions. Contrastingly, K-feldspar in ORGAN-31, ORGAN-37, and ORGAN-10 indicates rapid cooling between 36 and 35 Ma, slower cooling between 35 and 33 Ma, and rapid cooling between 33 and 32 Ma. K-feldspar from the alkali feldspar granite and an aplitic dike in the Sugarloaf Peak pluton (Figs. 7C and 7E, respectively) indicate initially rapid cooling followed by prolonged periods of isothermal conditions. Contrastingly, K-feldspar in ORGAN-31, ORGAN-37, and ORGAN-10 indicates rapid cooling between 36 and 35 Ma, slower cooling between 35 and 33 Ma, and rapid cooling between 33 and 32 Ma.
heating are commonly attributed to excess 40Ar old steps that correspond to high-temperature Zimmerer and McIntosh, 2012a). Anomalously caldera. Similar results have been observed in or any known magmatic events at the Organ Geosphere, February 2013 163 temperature steps that were older than corre-

samples contained abundant medium- to high-

differentiated residual crystal mush are preserved as the compositionally zoned Organ Needle pluton (Seager and McCurry, 1988; Verplanck et al., 1995, 1999). Following in situ differentiation of a more mafic parental magma, the majority of the silicic cap evacuated the magma chamber during eruption of the Squaw Mountain Tuff. Cupolas of the nonerupted silicic cap and less-differentiated residual crystal mush are preserved as the compositionally zoned Organ Needle pluton (Seager and McCurry, 1988; Verplanck et al., 1995, 1999). New U/Pb and 40Ar/39Ar ages, summarized in Fig. 8, support this proposed genetic model. The 40Ar/39Ar age of the Squaw Mountain Tuff, 36.03 ± 0.16 Ma, and U/Pb zircon and most 40Ar/39Ar biotite ages of the various phases of the Organ Needle pluton are statistically indistinguishable. 40Ar/39Ar and U/Pb ages also show that postcaldera volcanism and plutonism commenced shortly after the eruption of the Squaw Mountain Tuff and cooling of the Organ Needle pluton. Postcaldera pluton emplacement continued until at least 34.3 Ma. Using the MDD modeling technique, argon loss observed in K-feldspar age spectra is interpreted to indicate reheating events at ca. 34, 30–32, and as young as 26 Ma. Reheating events are evidence for intrusions that are either not exposed or have been eroded.

Pre-Organ Caldera Focus

ORGAN-10, Equigranular ONP syenite

ORGAN-31, Equigranular ONP daz. syenite

ORGAN-22, Sugarloaf Peak aplite dike

ORGAN-21, Baylor Peak rhyolite porphyry

ORGAN-37, Granite of Granite Peak

ORGAN-41, ON alkali feldspar granite

Figure 6. Selected age spectra for Organ caldera plutonic K-feldspar. Auxiliary plots include K/Ca and radiogenic yield (% 40Ar*). Modeled age spectra used to generate multiple diffusion domain thermal histories are shown in green. ONP—Organ Needle pluton; MSWD—mean square weighted deviate; Int—integrated age.

MAGMATISM AT THE ORGAN CALDERA COMPLEX

Volcanic and plutonic rocks exposed at the Organ caldera complex provide an opportunity to study the origin of compositionally zoned caldera-related magmas and assess existing geochemical models for the magmatic evolution of this particular caldera system. Published geochemistry suggests that the Organ Needle pluton represents the emplacement and differentiation of a caldera-forming magma chamber (Seager, 1981; Seager and McCurry, 1988), a sequence of variably altered intermediate composition lava flows, breccias, and minor pyroclastic units. Though the Orejon Andesite is the only precaldera volcanic unit preserved in outcrop, abundant rhyolitic lithic fragments (Fig. 3C) in the basal section of the Cueva Tuff suggest that significant rhyolitic magmatism also occurred prior to caldera collapse. Several samples of the Orejon Andesite were collected and dated by the 40Ar/39Ar method, but age spectra are discordant and do not provide robust ages for the timing of pre–Organ caldera volcanism. The Orejon Andesite is stratigraphically located beneath the Cueva Tuff, which indicates that precaldera volcanism ended prior to 36.45 ± 0.08 Ma. Studies of precaldera volcanism at similar caldera systems suggest that volcanism likely occurred for several hundred thousand to several million years before the eruption of the Cueva Tuff (Jellinek and Depaolo, 2003; Hildreth, 2004; du Bray et al., 2004; Lipman, 2007; Zimmerer and McIntosh, 2012a).

The Caldera Collapse Ignimbrites

The Organ caldera complex ignimbrites were erupted during three distinct, trap-door-style caldera collapse events between 36.45 ± 0.08 Ma and 36.03 ± 0.16 Ma (Fig. 4D). The oldest caldera-forming ignimbrite is the Cueva Tuff. Sanidine SCLF analyses of the Cueva Tuff yield a unit weighted mean age of 36.45 ± 0.08 Ma. Because of the limited exposure, very little evidence exists for the associated caldera structure.
The ignimbrite is several hundred meters thick in the southern Organ Mountains and contains abundant micro- and mesobreccias. These characteristics are common features of many intracaldera tuffs (Lipman, 1976; Cole et al., 2005). Following a period of volcanic quiescence, the Achenback Park Tuff erupted at 36.23 ± 0.14 Ma. Similar to the Cueva Tuff, evidence that the Achenback Park Tuff is an intracaldera facies is limited to the exceptional maximum thickness of the unit (~1 km), as well as volumetrically minor microbreccias within the tuff. The final caldera collapse event erupted the Squaw Mountain Tuff at 36.03 ± 0.16 Ma (n = 2 samples). The Squaw Mountain Tuff is ~1.4 km thick at its maximum (Fig. 3B). Though the eruption ages of the Cueva Tuff and the Achenback Park Tuff, as well as of the Achenback Park Tuff and the Squaw Mountain Tuff, are statistically indistinguishable, deposits of epiclastic rocks are interlayered between each of the ignimbrites, indicating periods of volcanic quiescence between the caldera-collapse events (Seager, 1981; Seager and McCurry, 1988). However, these periods of volcanic quiescence indicated by the epiclastic rocks may have been relatively short.

The compositional zonation pattern of the intracaldera ignimbrite sequence led Seager and McCurry (1988) to suggest that the Cueva, Achenback Park, and Squaw Mountain Tuffs represent episodic eruptions from a single compositionally zoned magma chamber. The ignimbrite sequence is zoned from a crystal-poor, high-SiO$_2$ rhyolite at the base to a crystal-rich, low-SiO$_2$ rhyolite at the top. The increase in phenocrysts (~1% to ~20%) and decrease in SiO$_2$ (77–68 wt%) content from the bottom to the top of the ignimbrite sequence correlates with an increase in trace-element contents (e.g., Sr, Ba, La, and Y). Accordingly, the Cueva Tuff represents the most differentiated magma in the source chamber, whereas the Achenback Park Tuff and Squaw Mountain Tuff represent a transitional composition between the most silicic melt (i.e., Cueva Tuff) and the more mafic, less differentiated residual crystal mush (Organ Needle pluton). Seager and McCurry (1988) also noted slight compositional discontinuities between each ignimbrite. The compositional discontinuities suggest that after each eruption the magma chamber was slightly modified by in situ (i.e., fractionation and differentiation) and/or open-system (i.e., assimilation and magma recharge) processes.

The established compositional zonation pattern of the Organ caldera ignimbrites, combined with $^{40}$Ar/$^{39}$Ar SCLF dating of the Organ caldera ignimbrites, indicates that a large-volume magma chamber resided in the upper crust for 420 ± 240 ka, between 36.45 ± 0.08 Ma and 36.03 ± 0.16 Ma. The magma chamber differentiated to generate compositionally diverse magmas and periodically erupted large-volume, caldera-forming ignimbrites. However, there is no reason to believe that the entire magma chamber remained above the solids through-out the syncaldera eruptive history. The Organ caldera-forming magma chamber likely would have waxed and waned with respect to crystallinity and melt content, similar to other silicic systems (Schmitt et al., 2003; Matzel et al., 2006; Buchmann et al., 2007a). However, this idea is highly speculative and therefore is not considered further.

Magma residence times have been determined at numerous caldera systems and provide a
Postcaldera plutons

Sugarloaf Peak Pluton

Granite of Granite Peak

Organ Needle Pluton

monzodiorite - mafic residual crystal mush; some biotite reset by the emplacement of younger postcaldera intrusions

equigranular

inequigranular

alkali feldspar granite (nonerupted silicic cap)

K-feldspars provided evidence for reheating at 32–30 Ma and as young as ~25 Ma

Precambrian biotite thermally reset during emplacement of Organ Needle Pluton

Figure 8. Summary of the Organ caldera complex geochronology. U/Pb and 40Ar/39Ar ages are reported at 2σ and do not include error in the associated decay constant. Bold horizontal lines represent the range of ages observed in K-feldspar age spectra that were modeled using the multiple diffusion domain theory. Colors correspond to map units in Figure 1. GMC—groundmass concentrate; LA-ICP-MS—laser ablation–inductively coupled plasma–mass spectrometry.

framework for comparison to the Organ caldera complex ignimbrite sequence. Some published studies indicate that many caldera-forming magma chambers resided in the upper crust for several hundred thousand years prior to eruption. For example, high-precision CA-TIMS U/Pb dating of zircons in the 5000 km³ dacitic Fish Canyon Tuff, southwestern Colorado, indicate ~600 ka of zircon growth prior to the La Garita caldera eruption (Bachmann et al., 2007b). Likewise, some high-silica rhyolitic ignimbrites yield zircons that are as much as ~300 ka older than the eruption age (Reid et al., 1997; Brown and Fletcher, 1999). In contrast, dating of some other caldera-forming ignimbrites suggest very short magma residence times. Simon et al. (2008) compared U/Pb and U/Th zircon ages to eruption ages for multiple large-volume silicic eruptions from around the world and determined a median residence time of only 70 ka. Dating of a single sample from the earliest erupted material from the compositionally zoned Bishop Tuff, central California, yielded a U/Pb zircon age of 767.1 ± 0.9 ka (Crowley et al., 2007), which is indistinguishable from the 40Ar/39Ar sanidine eruption age (770.4 ± 3.9 ka; Sarna-Wojicki et al., 2000), indicating that the zircons crystallized very shortly before the eruption. However, numerous small-volume precaldera eruptions that are geochemically similar to the Bishop Tuff occurred for ~400 ka prior to the Bishop Tuff eruption, apparently recording assembly of the Bishop Tuff magma chamber during this period (Hildreth, 2004). Some of these results from other caldera systems are consistent with the 40Ar/39Ar dating of the Organ caldera ignimbrites, which suggest a 420 ± 240 ka lifetime for the compositionally evolving magma chamber.

The Organ Needle Pluton

During or shortly after caldera collapse and eruption of the Squaw Mountain Tuff, the Organ Needle pluton intruded into the eastern caldera margin and intracaldera sequence. The compositionally zoned Organ Needle pluton has been previously interpreted to represent both the remnants of the nonerupted silicic cap and the more mafic, less fractionated residual crustal mush of the Organ caldera-forming magma chamber (Seager, 1981; Seager and McCurry, 1988; Verplanck et al., 1995, 1999). U/Pb and 40Ar/39Ar ages, combined with the published geochemistry, indicate that the Organ Needle pluton (1) is coeval with the syn-caldera ignimbrite volcanism, (2) represents the nonerupted remnants of an upper-crustal, compositionally zoned caldera-forming magma chamber, and (3) rapidly cooled following caldera collapse, but several parts of the intrusion were later reheated during protracted, postcaldera magmatism.

U/Pb zircon and some 40Ar/39Ar biotite ages of the Organ Needle pluton are indistinguishable from the eruption ages of the caldera-forming ignimbrites. The alkali feldspar granite is the most silicic and structurally highest phase of the Organ Needle pluton. The U/Pb zircon age of this unit is 36.48±0.46 Ma. 40Ar/39Ar biotite ages of the alkali feldspar granite are 36.25 ± 0.12 and 36.17 ± 0.12 Ma, indicating that this phase cooled rapidly following caldera collapse. Though the U/Pb age of the alkali feldspar granite is statistically indistinguishable from all three caldera-collapse ignimbrites, Seager and McCurry (1988) and Verplanck et al. (1995) determined that this phase is most compositionally similar to the Achenback Park Tuff and lower Squaw Mountain Tuff and therefore may represent a nonerupted intrusive equivalent to these tuffs. Rioux et al. (2010) reported an age of 35.1 Ma for the northernmost outcrop of the alkali feldspar granite (northwest of sample 21 on Fig. 1) and suggested that this phase is not contemporaneous with the Squaw Mountain Tuff eruption. However, our geochronology results suggest that the southern alkali feldspar granite cupolas are indeed cogenetic with the Squaw Mountain Tuff. It appears that there may have been two, temporally distinct pulses of alkali feldspar granite magmatism. The inequigranular syenite, which is exposed as a thin (i.e., ~1–10 m) phase along the eastern contact of the Organ Needle pluton, yielded U/Pb zircon and 40Ar/39Ar biotite ages of 35.53±0.48 Ma and 35.77 ± 0.14 Ma, respectively, indicating that the phase was emplaced during and cooled shortly after the Squaw Mountain Tuff eruption. The U/Pb zircon age of Organ Needle equigranular syenite, 34.93±0.29 Ma, is statistically younger than the 40Ar/39Ar sanidine age of the Squaw Mountain Tuff. The large negative uncertainty of this TuffZirc age may indicate significant Pb loss. Alternatively, this sample was collected from within several hundred meters of the post-
The Precambrian granite is indistinguishable from the U/Pb zircon crystallization ages and some 40Ar/39Ar ages of the Organ Needle plutonic units. Third, most contacts between the various Organ Needle plutonic phases are gradational, suggesting that the phases are cogenetic with one another. Based on geologic and geochronologic data, combined with the published geochemistry (Verplanck et al., 1995, 1999), we believe this provides sufficient evidence to support the prior conclusions that the Organ Needle pluton represents the nonerupted remnants of a zoned caldera-forming magma chamber.

U/Pb zircon and 40Ar/39Ar biotite ages of the Organ Needle pluton establish the emplacement history and provide an opportunity to assess the preexisting geochemical models for the evolution of this intrusive unit. Verplanck et al. (1995, 1999) determined that the top (alkali feldspar granite), side (inexgranular syenite), and bottom (monzodiorite) phases of the Organ Needle pluton have a more crustal radiogenic isotopic signature than the main equigranular syenite phases located within the interior of the intrusion (εNd = −5 and 87Sr/86Sr = 0.7085 versus εNd = −2 and 87Sr/86Sr = 0.7060, respectively). Based on these geochemical differences, Verplanck et al. (1995, 1999) suggested that the alkali feldspar granite, inequigranular syenite, and monzodiorite phases of the Organ Needle pluton evolved separately from the interior equigranular syenite and quartz syenite phases (see fig. 14 of Verplanck et al., 1999, for a more detailed explanation). According to this model, the interior phases were emplaced first and the minor compositional variations within this phase originated from closed-system differentiation. During differentiation of the interior phases, the monzodiorite phase was emplaced at the base of the interior phases. Fractional crystallization of the monzodiorite, coupled with wall-rock assimilation of Precambrian granite, generated the inequigranular syenite. The inequigranular syenite further differentiated during sidewall fractional crystallization, and the alkali feldspar granite accumulated at the top of the intrusion and most was erupted as Squaw Mountain Tuff. The U/Pb and 40Ar/39Ar ages produced as part of this study do not indicate a temporal difference, within analytical uncertainty, between the eruption of the Squaw Mountain Tuff and emplacement and cooling of all of the various phases of the Organ Needle pluton. Though the U/Pb and 40Ar/39Ar ages of the Organ Needle pluton do not negate the genetic model of Verplanck et al. (1995, 1999), the ages do not indicate that the interior equigranular syenite and quartz syenite were emplaced first and that the monzodiorite, inequigranular syenite, and alkali feldspar granite were emplaced and chemically evolved during a separate, later event. It seems possible that the entire Organ Needle pluton was emplaced during a single event and, following emplacement, differentiated via crystal-liquid fractionation to the various compositional phases. The compositional and radiogenic-isotopic variation between the marginal and interior phases of the Organ Needle pluton may reflect small-scale differentiation and the proximity to the degree of assimilation of wall rock. Verplanck et al. (1995) noted that the isotopic differences between the interior and marginal phases of the Organ Needle pluton can be achieved by only 7% bulk assimilation of the Precambrian granitic rocks, which in turn would only yield a ~1% change in SiO2 content. Given the temporal and chemical (whole-rock and isotopic) similarity between the Squaw Mountain Tuff and marginal phases of the Organ Needle pluton, upper-crustal in situ fractionation coupled with assimilation of surrounding country rock appears to have been a significant magmatic process in the genesis of the caldera-forming silicic magmas, regardless of whether or not the interior equigranular syenite phase of the Organ Needle pluton evolved separately.

Postcaldera Magmatism

Records of postcaldera magmatism include several silicic intrusions that cross-cut the Organ Needle pluton and small, isolated outcrops of lava flows located in the western Organ Mountains foothills. 40Ar/39Ar dating of the postcaldera volcanic rocks indicates that volcanism commenced soon after the eruption of the Squaw Mountain Tuff at 36.0 Ma and continued until at least 35.7 Ma. U/Pb zircon dating of the postcaldera plutons indicate pluton emplacement between 35.4 and 34.3 Ma. Postcaldera pluton emplacement caused localized reheating of older intrusions. MDD thermal modeling of K-feldspar from the Organ Needle and postcaldera plutons indicate numerous reheating events at 34 Ma, 32–30 Ma, and as young as 26 Ma, suggesting protracted magmatism. Although argon loss in K-feldspar age spectra can be modeled as slow cooling from magmatic temperatures (i.e., monotonic cooling histories; Figs. 7A–7F), we prefer the interpretation that argon loss is related to reheating events. This is consistent with the shallow depth of emplacement and numerous studies that have documented prolonged magmatism associated with the waning stages of caldera magmatism (e.g., Lipman, 2007). However, we realize our interpretation requires numerous postcaldera intrusions that are not exposed or have been eroded.

Five lithologically diverse west-side postcaldera lava flows were dated to determine the timing of postcaldera volcanic activity. The eruptive...
CONCLUSIONS AND IMPLICATIONS

The spatial, temporal, and chemical relationships of volcanic and plutonic rocks were used to understand the origin of silicic magmas at the Organ caldera complex. We conclude the following:

1) Volcanism at the Organ caldera began as early as 36.45 ± 0.08 Ma during caldera collapse related to the eruption of the Cueva Tuff. Volumentrically minor eruptions of lavas and tuffs preceded the Cueva Tuff, but these units were not successfully dated. The age of the Cueva Tuff also marks the beginning of mid-Tertiary caldera volcanism in the Mogollon-Datil volcanic field.

2) The Organ caldera complex erupted three caldera-forming ignimbrites during a 420 ± 240 k.y. period. The ignimbrite eruptions include the high-silica, rhyolitic, 36.45 ± 0.08 Ma Cueva Tuff, the intermediate-silica, rhyolitic, 36.23 ± 0.14 Ma Achenback Park Tuff, and the zoned, intermediate- to low-silica, rhyolitic, 36.03 ± 0.16 Ma Squaw Mountain Tuff. The zonation pattern of the entire ignimbrite sequence indicates a similar genetic source.

3) The caldera-forming ignimbrites were apparently generated via in situ differentiation within an upper-crustal magma chamber. Following the eruption of the Squaw Mountain Tuff, the compositionally zoned (monzodiorite to alkali feldspar granite) Organ Needle pluton was emplaced into the eastern margin of the Organ caldera. The compositional zonation pattern of the caldera ignimbrites continues into the zoned Organ Needle pluton (Seager and McCurry, 1988; Verplanck et al., 1995, 1999). Most U/Pb zircon and 40Ar/39Ar biotite ages of the Organ Needle pluton are indistinguishable from the caldera-forming ignimbrite ages. The Organ Needle pluton represents the remnants of the nonerupted silicic cap and the less silicic, intermediate to mafic residual crystal mush of a caldera-forming magma chamber. Additionally, we suggest that some intrusions may represent the nonerupted geochemical complementary residue to silicic volcanic rocks.

4) Similar to many caldera systems, protracted magmatism characterized the waning stages of Organ caldera magmatism. Multiple, small-volume, dominantly intermediate-composition lavas were erupted between 36.1 and 35.7 Ma. Three postcaldera plutons intruded the Organ Needle pluton between ca. 36 and 34 Ma. 40Ar/39Ar thermochronology indicates that most plutons rapidly cooled from zircon saturation temperatures to biotite closure temperature. Many plutons were subsequently reheated during protracted, postcaldera magmatism. MDD thermal modeling of plutonic K-feldspar indicates reheating events at 34 Ma, 32–30 Ma, and as young as 26 Ma. Intrusions corresponding to these ages are not exposed or have been eroded. The origins of the youngest reheating events are unknown, but possibilities include the final stages of the Organ caldera cycle, widespread magmatism related to the Mogollon-Datil volcanic field, or prolonged magmatism associated with the Rio Grande rift.

The combination of new U/Pb and 40Ar/39Ar ages with the published geochemistry provides insight into the magmatic history of the Organ caldera complex and, in particular, suggests that these caldera-forming silicic magmas were generated via upper-crustal in situ differentiation. Considering the abundance of high-quality research that supports the genesis of silicic melt in both the upper and lower crust, we are cautious in assuming that magmatism at the Organ caldera describes caldera magmatism elsewhere. Our work is consistent with studies of other caldera systems, which suggest that caldera magmatism is characterized by repeated, prolonged emplacement of compositionally diverse magmas, marked by periodic eruptions of varying volumes. Finally, this work demonstrates the usefulness of investigating both volcanic and plutonic rocks in order to understand magmatic processes.

ACKNOWLEDGMENTS

This work was supported by a National Science Foundation grant (EAR-1050188). The New Mexico Bureau of Geology and Mineral Resources and the New Mexico Geological Society also provided additional funding. Conversations with Peter Lipman, Drew Coleman, Ryan Mills, Kate Wooton, Matt Heizler, Kent Condie, and Andy Campbell improved this research. We would like to thank Mark Pecha, George Gehrels, and the Arizona LaserChron Center staff for their assistance during the LA-ICP-MS analyses. We also want to acknowledge the New Mexico Geochronology Research Laboratory staff for their support during the 40Ar/39Ar analyses. A special thanks to David Winnett of Fort Bliss, who helped us gain access to restricted areas and assisted with sample collection. Finally, we would like to thank Carol Frost, Lang Farmer, Mike Cosca, and an anonymous reviewer for their helpful comments during the review process.

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