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Zircon record of the plutonic-volcanic connection and protracted rhyolite melt evolution

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ABSTRACT

The potential petrogenetic link between a crystal-poor rhyolite (the Rhyolite Canyon Tuff) and its associated subvolcanic intrusion and crystal-rich post-caldera lavas from Turkey Creek, Arizona (USA), is examined using zircon chemical abrasion–thermal ionization mass spectrometry U-Pb geochronology and inductively coupled plasma mass spectrometry trace element analyses. U-Pb ages indicate that zircon growth within the rhyolite and the dacite-monzonite porphyry magmas was coeval over ~300 k.y. prior to the large eruptive event. Trends in zircon trace elements (Hf, Y/Dy, Sm/Yb, Eu/Eu*) through time in the dacitic-monzonitic units and rhyolite reflect melt evolution dominated by crystal fractionation. Importantly, the Y/Dy ratio in zircons in both units remains mostly similar for the first ~150 k.y. of the system's evolution, but the dominant population in the rhyolitic unit diverges from that of the dacite-monzonite porphyry ~150 k.y. before eruption. We interpret this divergence in trace element composition to record the assembly time of the melt-rich cap within its intermediate mush zone in the upper crustal reservoir. These results are consistent with (1) a connection between plutonic and volcanic realms in the upper crust, (2) a protracted time scale for constructing an intermediate mush large enough to hold 500 km^3 of rhyolite, and (3) the prolonged extraction of that melt prior to eruption.

INTRODUCTION

Over the past few decades, constructing a general framework linking plutonic and volcanic realms has been key in trying to understand magmatic processes (see recent reviews by Annen et al. [2015] and Bachmann et al. [2007]). However, fundamental questions regarding their spatiotemporal relationship and the duration over which they evolve or co-evolve remain unanswered. In large, silicic magmatic systems, the origin of high-silica rhyolite by extraction from shallow, batholith-sized intermediate mush magma was presented as one possible mechanism (Bachmann and Bergantz, 2004; Hildreth, 2004). This model requires a complementary intermediate cumulate residue to remain in the mid- to upper-crustal environment and necessarily implies a direct relationship between plutonic and volcanic systems in the shallow crust (Deering and Bachmann, 2010; Gelman et al., 2014; Lee and Morton, 2015). The mechanisms that lead to the accumulation of large volumes of evolved magma in the upper crust have been suggested to occur over a time scale on the order of hundreds of thousands of years (e.g., Schaltegger et al., 2009). However, differentiating between the time scales of reservoir growth and those of rhyolite extraction is problematic, with proposed time scales for the latter varying from hundreds of years (e.g., Pappalardo and Mastrolorenzo, 2012) to many thousands of years (e.g., Pamukcu et al., 2015a; Wotzlaw et al., 2014).

The optimal scenario for studying the relationship between plutonic and volcanic rocks and the time scales of magma evolution is one where remnants of an intrusive body are exposed within the caldera formed by the eruption of a large rhyolitic body. At the Turkey Creek caldera (Arizona, USA), uplift and erosion have exposed the intra-caldera and outflow facies of the Rhyolite Canyon Tuff, as well as a resurgent intermediate intrusion and associated lava flows (Fig. 1). In all units, the ubiquity of zircon provides us with the opportunity to investigate rates of processes using a combination of high-precision geochronology and geochemistry (U-Pb thermal ionization mass spectrometry with trace element analysis [TIMS-TEA]). This paper presents a new data set for these eruptive products in an attempt to determine the (1) duration of magma reservoir growth in the upper crust, (2) relationship between crystal-poor ignimbrite and intermediate resurgent intrusion and lavas, and (3) time scale of melt-rich rhyolite extraction and/or accumulation prior to eruption.

THE TURKEY CREEK CALDERA

The Turkey Creek caldera (~20 km in diameter) of southeastern Arizona (Fig. 1) formed as the result of the catastrophic eruption of

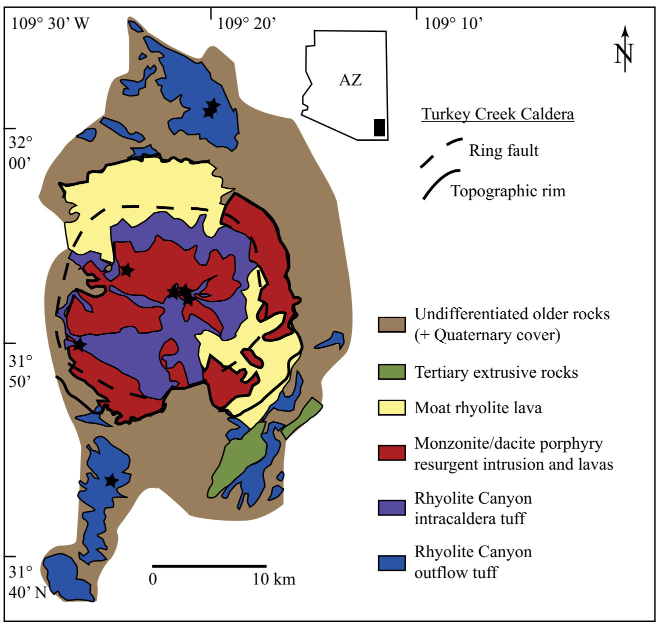

Figure 1. Geologic map of Turkey Creek caldera in Chiricahua Mountains, Arizona (AZ), southwestern USA (modified from du Bray and Pallister, 1991). Black stars indicate sampling localities.

GEOLOGY, April 2016; v. 44; no. 4; p. 267–270 | Data Repository item 2016081 | doi:10.1130/G37539.1 | Published online 24 February 2016

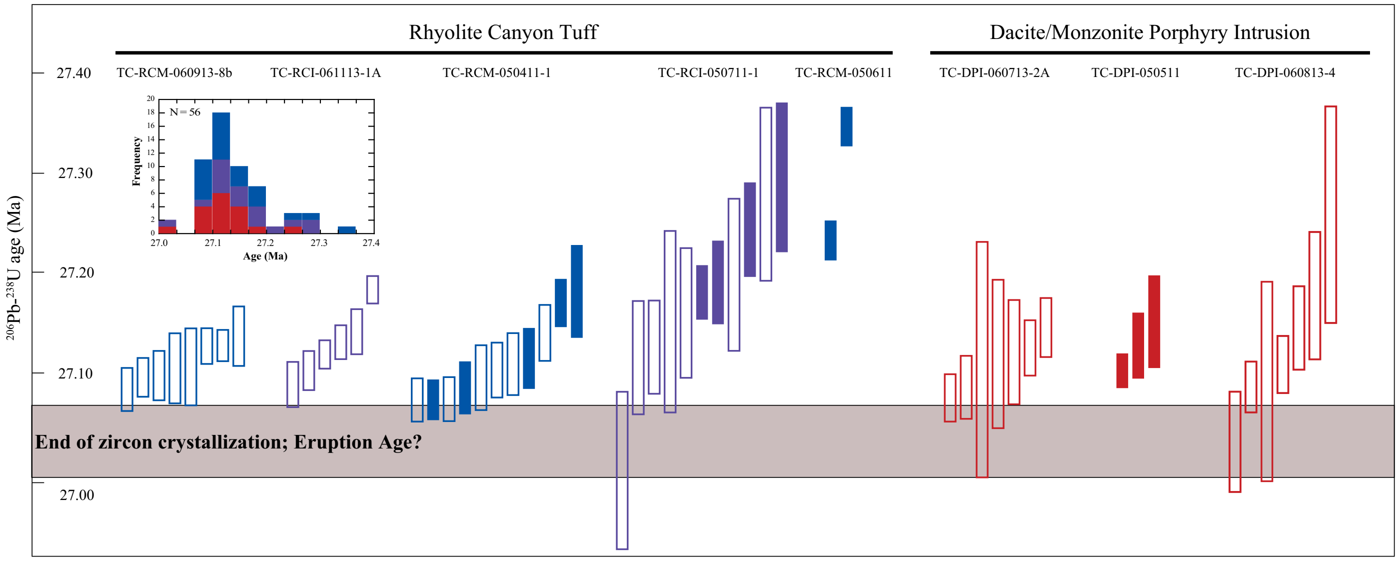

Figure 2. U-Pb geochronology showing $^{206}Pb/^{238}U$ dates for individual zircon from Rhyolite Canyon Tuff (Arizona, USA) eruption and associated dacite-monzonite intrusion of Turkey Creek caldera. Each bar is an individual analysis, and size of vertical bars are ±2s internal uncertainty. Eruptive unit colors are coded as in geologic map in Figure 1. Zircons analyzed at University of Geneva (Switzerland) using ET2535 double-spike are shown with filled bars.

>500 km^3 of high-silica rhyolite (Rhyolite Canyon Tuff). This event has been previously dated to 26.97 ± 0.09 Ma (average Ar/Ar date on sanidine from tuff samples; du Bray and Pallister, 1991). The emplacement of this ignimbrite was followed by a resurgent intrusion of monzonite porphyry. Some of this magma reached the surface as crystal-rich dacite lavas along ring fractures.

The Rhyolite Canyon Tuff outflow is primarily exposed to the north of the caldera and is typically welded and devitrified. The outflow facies deposits can be divided into three separate compound cooling units (upper: Trcu; middle: Trcm; lower: Trcl) separated by air-fall and surge deposits. The outflow facies high-silica rhyolite is crystal-poor to moderate (10–20 vol%), dominated by quartz and sanidine, with minor plagioclase and accessory oxides, augite, apatite, zircon, and titanite. The intra-caldera facies (Trci) contains the same minerals as the outflow, but with up to 30 vol% crystallinity (du Bray and Pallister, 1991).

The hypabyssal monzonite porphyry and the eruptive equivalent dacite porphyry contain a similar mineralogy to the tuff with sanidine and plagioclase (up to several centimeters long). Glomerocrysts are ubiquitous in both monzonite and dacite porphyry including plagioclase, sanidine, quartz, biotite, clinopyroxene, hornblende, and magnetite with accessory oxides, apatite, zircon, and titanite. The groundmass is texturally variable in both the monzonite and the dacite porphyry from microcrystalline and granophyric to glassy, respectively.

A representative sample suite of bulk-rock geochemistry was previously published by du Bray and Pallister (1991), which shows the range of compositions extending from ~64 to 78 wt% SiO_2. The rhyolite and monzonite-dacite porphyry are separated by a compositional gap (~10 wt% SiO_2); only a few samples fall within that gap and show textural and compositional evidence of mixing and/or mingling (du Bray and Pallister, 1991). The trace element characteristics of the magmas suggest wet, oxidized conditions in the source region, consistent with subduction zone magmatism. The pre-eruptive depth of the rhyolite was estimated using the water-saturated eutectic point in the haplogranitic system with the normative (quartz-albite-orthoclase) composition of the melt. This method yields an average equilibration pressure of ~100 MPa indicating a depth of at least 4 km (du Bray and Pallister, 1991), which is similar to storage depths determined for many other high-SiO_2 rhyolites of similar size (e.g., Bégué et al., 2014; Pamukcu et al., 2015b).

METHODS

Zircon ages and trace element geochemistry were obtained by U-Pb chemical abrasion–isotope dilution–thermal ionization mass spectrometry with coupled trace element analysis (U-Pb CA-ID-TIMS-TEA). Individual zircons were annealed, chemically abraded to remove metamict zones, rinsed, and spiked with EARTHTIME (^{202}Pb)-^{205}Pb-^{233}U-^{235}U tracers prior to dissolution and column chemistry. Eluted U and Pb were analyzed by thermal ionization mass spectrometry at Princeton University (New Jersey, USA) and UNIGE (University of Geneva, Switzerland), while eluted trace elements were analyzed by inductively coupled plasma mass spectrometry at Princeton University. All ages are reported with 2σ internal uncertainties calculated using U_Pb Redux (Bowring et al., 2011). Full analytical methods, data tables, and zircon cathodoluminescence images are given in the GSA Data Repository[1].

ESTABLISHING THE PLUTONIC-VOLCANIC CONNECTION

We interpret zircon U-Pb dates to record crystallization from 27.359 ± 0.017 Ma to 27.029 ± 0.050 Ma for both the monzonite and dacite lavas and the Rhyolite Canyon Tuff (Fig. 2; see the Data Repository). The overlap in age distribution among samples implies that these two magmas were crystallizing over the same period of time over ~300 k.y. in the upper crust. This duration is similar to time scales determined in other studies of large silicic magmatic systems (Bachmann et al., 2007; Guillong et al., 2014; Schoene et al., 2012). The monzonite-dacite and rhyolite zircon populations also include much older crystals not related to the magmatic system that formed the Rhyolite Canyon Tuff (ca. 30–75 Ma) that are distinct in composition (e.g., Hf, Y/Dy, Eu/Eu*) and overlap in age with several shallowly exposed local plutons and ignimbrites (see the Data Repository). The presence of these xenocrysts implies that a small amount of assimilation occurred during the evolution of the magmatic system.

While U-Pb dates support zircon co-crystallization in the monzonite-dacite and rhyolitic units in the magma plumbing system, trace element chemistry in the whole rock provides us with an opportunity to further

[1]GSA Data Repository item 2016081, U-Pb CA-ID-TIMS analytical methods, zircon age and trace element geochemistry, and Figure DR1 showing the distinct xenocrystic zircon population, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

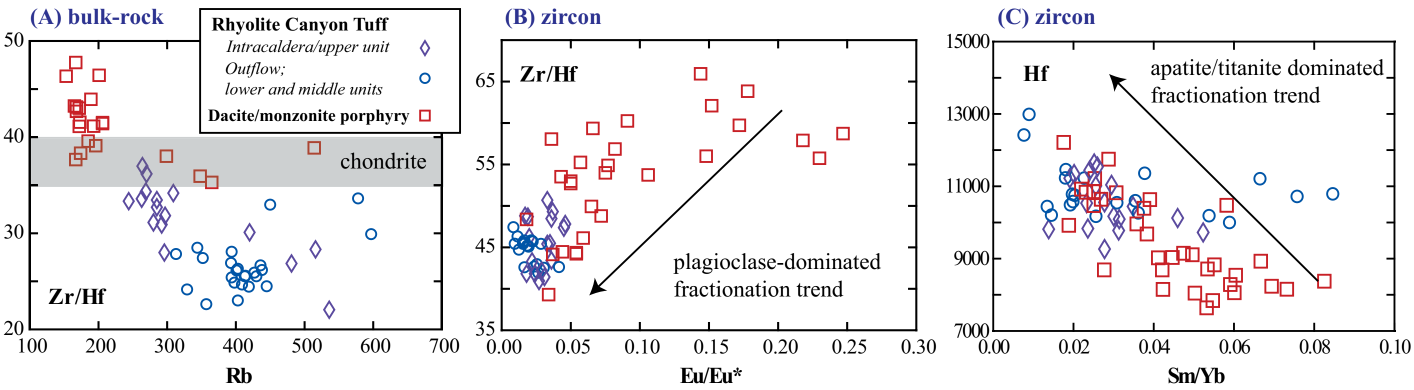

Figure 3. A: Zr/Hf versus Rb showing increase in incompatible element Rb with decreasing Zr/Hf ratio consistent with crystal fractionation. B: Trace element diagram showing negative correlation between Eu/Eu* and Zr/Hf reflecting plagioclase fractionation and overlap between dacite-monzonite and rhyolite units. C: Decreasing Sm/Yb with increasing Hf (proxy for temperature) is likely governed by titanite/apatite fractionation.

evaluate the potential connection between the high-silica rhyolite unit and intermediate resurgent intrusion and lava flows emplaced along the ring fault. Following zircon saturation, Zr/Hf decreases in both melt and zircon such that crystal cumulates are expected to have higher Zr/Hf than the residual melt (Claiborne et al., 2006; Samperton et al., 2015). Deering and Bachmann (2010) showed that the Zr/Hf ratio can thus be used to determine the existence of zircon, and hence crystal, accumulation in silicic magmas in a variety of tectonic settings. The bulk-rock Zr/Hf ratio versus Rb of the Rhyolite Canyon magmas show a decrease from the monzonite and dacite to the rhyolite consistent with the intermediate magmas representing the cumulate residual to the erupted rhyolite (Fig. 3A).

Zircons also reveal compositional trends parallel to those found in the bulk rock, which are consistent with crystal fractionation. In particular, the Eu anomaly (Eu/Eu*) can be used to trace the co-crystallization of feldspars, the most abundant phases in the Turkey Creek system. Eu/Eu* decreases steadily with decreasing Zr/Hf over a continuous compositional range in zircons from the monzonite-dacite to the rhyolite units, indicating the strong influence of feldspar crystallization on zircon chemistry (Fig. 3B). The combination of zircon geochronology and trace element chemistry with bulk-rock trace element patterns provides evidence for the derivation of the rhyolite from the monzonite-dacite magma.

Hafnium has been observed to increase in zircon with decreasing temperature (estimated using Ti-in-zircon) and increasing SiO_2 of the melt (Claiborne et al., 2006). Hafnium, therefore, can be used in conjunction with other trace elements (e.g., rare earth elements [REEs]) that are incorporated into zircon to track the thermal and compositional evolution of the melt from which it crystallized. For example, the Sm/Yb ratio in the Turkey Creek units is negatively correlated with Hf (Fig. 3C). This relationship can be explained by the co-crystallization of titanite and apatite, which preferentially incorporate Sm relative to Yb as the magma cools. Our data also show that Hf in zircons from the rhyolite overlap with that in the monzonite-dacite of similar composition (Fig. 3C), which is consistent with both magmas reaching the same thermal and melt evolution state prior to eruption, albeit with different crystallinities.

The compositional gap between the monzonite-dacite and the rhyolite (Fig. 3) is a common feature of volcanic series worldwide (e.g., Brophy, 1991) and has been explained by extraction of rhyolitic melt from a dacitic mush once crystallinities are high enough to impede the stirring effect of convection (>~50 vol%; Bowen, 1919; Brophy, 1991; Dufek and Bachmann, 2010). If such a model holds, minerals in the monzonite-dacite and rhyolite would not show a clear compositional gap, as they would have crystallized continuously, and would not have been limited to growth at a fixed melt composition (Deering et al., 2011). Our zircon data are consistent with this hypothesis; the compositional series displays trends that overlap (Fig. 3).

The size of the eruption (>500 km^3) suggests that if the eruptible melt was extracted from a mush, a significantly larger partly cumulative monzonitic body must exist beneath the Turkey Creek caldera (>1000 km^3). Partial remobilization of such bodies can occur during large volcanic eruptions (in zoned ignimbrites; e.g., Deering et al., 2011, Bachmann et al., 2014), and the intrusive equivalents have been imaged by geophysical methods (e.g., gravity and seismic studies) in large magmatic provinces around the world (see Lipman and Bachmann [2015] for a review). In particular, the neighboring Southern Rocky Mountain volcanic field bears the mark of a 15–20-km-thick batholith beneath the volcanic apron.

TIME SCALES OF RHYOLITE MELT EXTRACTION

In addition to providing evidence for rhyolite melt extraction from a monzonite-dacite mush, our CA-ID-TIMS-TEA method also has the potential to evaluate the duration of melt extraction. The monzonite-dacite zircon population has a restricted range of Y/Dy ratios of <~15, with a population of older rhyolite zircons that are similar in composition (Fig. 4). Together, this group spans the entire time period of magma evolution between ca. 27.3 and ca. 27.0 Ma (eruption age). However, the dominant rhyolite zircon population has Y/Dy ratios >15 and cluster from ca. 27.15 Ma to ca. 27.05 Ma—a duration of ~150 k.y. when accounting for error in age determinations. Variations in the Y/Dy ratio of zircon are heavily influenced by changes in melt composition due to the preferential incorporation

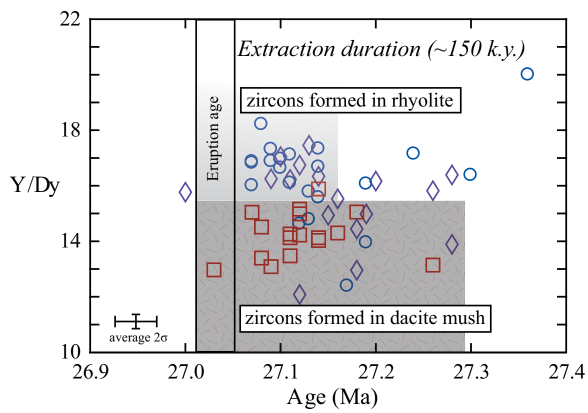

Figure 4. Zircon trace element variation with time determined by U-Pb thermal ionization mass spectrometry with trace element analysis. Dominant population of high-Y/Dy rhyolite zircons formed over ~150 k.y. prior to eruption in more-evolved magma, more heavily influenced by titanite/apatite co-crystallization than dacite-monzonite zircons. Older rhyolite zircons formed in similar conditions as those of dacite-monzonite or are interpreted to be antecrysts scavenged from mostly crystalline portions of the reservoir. Symbols same as in Figure 3.

of middle REEs over Y in titanite (Colombini et al., 2011). We interpret this change in Y/Dy as evidence for additional titanite (+ apatite) fractionation in the rhyolite during and after extraction from the dacite mush. Therefore, the recorded time interval in which the Y/Dy differs provides an estimate for the duration of melt extraction and accumulation.

CONCLUSIONS

The U-Pb CA-ID-TIMS geochronology shows that the evolution of high-silica rhyolite and that of associated dacite-monzonite porphyry of the Turkey Creek system were coeval over ~300 k.y. The TIMS-TEA results further suggest that the rhyolite and dacite-monzonite are related by crystal fractionation. Using trace element ratios in the dated zircons (in particular Y/Dy), we can also resolve changes that occur over relatively short durations and further suggest that the production, and possibly extraction, of the dominant rhyolite melt body from the underlying mush was protracted (up to 100–150 k.y.). These time scales are in agreement with mechanical models suggesting sluggish extraction of highly viscous rhyolitic melt from crystal mush (Bachmann and Bergantz, 2004; Deering et al., 2011). While rapid—centuries to a few millennia—assembly of voluminous melt-rich rhyolite evacuated in large eruptions has been proposed (e.g., Druitt et al., 2012; Pappalardo and Mastrolorenzo, 2012; Wotzlaw et al., 2014), our data suggest that these may record shorter-lived processes such as recharge or remobilization. These processes are not related to the overall duration of assembly of the system, nor to a record of the time scales for large volumes of silicic melt extraction. We do not rule out that melt extraction may occur over relatively short time scales (hundreds to thousands of years) for some systems (particularly smaller ones). However, without direct sampling and dating of the progenitor mush, the interpretation will be severely hindered. The ability to combine the use of zircon age and trace element data from coeval/co-genetic plutonic and volcanic units is, therefore, crucial for deciphering the processes responsible for the generation of the largest volumes of felsic magma to erupt on Earth.

ACKNOWLEDGMENTS

Deering and Beane acknowledge support from National Science Foundation grants EAR-1249821 and EAR-1250259. Thanks to E. du Bray for his help in organizing fieldwork. Andrew Barth, Jonathan Miller, and an anonymous reviewer provided thoughtful and constructive suggestions that greatly improved the manuscript.

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Manuscript received 19 November 2015
Revised manuscript received 3 February 2016
Manuscript accepted 4 February 2016

Printed in USA