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Million-year melt–presence in monotonous intermediate magma for a volcanic–plutonic assemblage in the Central Andes: Contrasting histories of crystal-rich and crystal-poor super-sized silicic magmas

Jason F. Kaiser [a,*], Shanaka de Silva [b], Axel K. Schmitt [c], Rita Economos [d], Mayel Sunagua [e]

[a] *Department of Physical Science, Southern Utah University, 351 West University Blvd, Cedar City, UT 84720, United States*
[b] *College of Earth Ocean and Atmospheric Sciences, Oregon State University, 104 CEOAS Admin Building, Corvallis, OR 97331, United States*
[c] *Institut für Geowissenschaften, Universität Heidelberg, Im Neuenheimer Feld 234-236, 69120 Heidelberg, Germany*
[d] *Roy M. Huffington Department of Earth Sciences, Southern Methodist University, PO Box 750395, Dallas, TX 75275, United States*
[e] *Calle Heroinas No 904, Zona Miraflores, La Paz, Bolivia*

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ABSTRACT

The melt–present lifetime of super-sized monotonous intermediate magmas that feed supereruptions and end life as granodioritic plutons is investigated using zircon chronochemistry. These data add to the ongoing discussion on magma assembly rates and have implications for how continental batholiths are built. Herein, we estimate ~1.1 Ma of continuous melt presence before and after the climactic caldera-forming 2.89±0.01 Ma (2σ error) Pastos Grandes Ignimbrite (PGI) supereruption (~1500 km^3 of magma) in the Andes of southwest Bolivia. Zircon crystallization in PGI pumice and lava from the faulted Southern Postcaldera Dome span ~0.7 Ma prior to the climactic eruption and formation of the eponymous caldera, whereas younger, unfaulted Postcaldera Dome lavas (termed Northern and Middle) and a granodioritic plutonic clast within the products of a Pleistocene eruption indicate a further ~0.4 Ma of post-climactic zircon crystallization. Bulk-rock compositions as well as zircon thermometry and geochemistry indicate the presence of homogeneous dacitic magma before and after the climactic eruption, but a trend to zircon crystallization at higher temperatures and from less evolved melts is seen for post-climactic zircon. We propose a model in which a large volume of crystal-rich dacite magma was maintained above solidus temperatures by periodic andesitic recharge that is chemically invisible in the erupted components. The climactic caldera-forming eruption vented the upper portions of the magma system zircon was saturated. Zircon in postcaldera lavas indicate that residual magma from this system remained locally viable for eruption at least for some time after the caldera-forming event. Subsequently, deeper "remnant" dacite magma previously outside the zone of zircon saturation rose to shallower levels to re-establish hydraulic and isostatic equilibrium where zircon crystallization commenced anew, and drove more resurgent volcanism and uplift. The same magma crystallized as a granodiorite pluton which was sampled as xenoliths in much later volcanic events. Over the ~1.1 Ma zircon crystallization history for the PGI, postcaldera lavas and xenoliths, the melt remained in an ~100–150 °C temperature window as indicated by Ti-in-zircon thermometry. Although chemical trends are consistent with zircon crystallization at variable temperatures, there is no secular cooling, but rather a thermal rejuvenation following the 2.89 Ma PGI eruption. As such these data provide a "low and slow" temporal constraint for models for the pre-eruptive lifetimes of mushy magma in contrast to the "rapid" mobilization of crystal-poor silicic magmas, consistent with a model where the latter are incubated within the former and extracted rapidly prior to eruption. The thermal and chemical monotony of crystal-rich dacites throughout a caldera cycle connotes conditions where near-eutectic melt can be maintained in near-surface magma reservoirs for an extended period of time if the subvolcanic magma reservoir is sufficiently large so that hotter and initially zircon-undersaturated magma can replenish shallow magma vented in a supereruption.

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* Corresponding author.
E-mail address: jasonkaiser@suu.edu (J.F. Kaiser).

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1. Introduction

Large volume crystal-rich, monotonous intermediate ignimbrites, the result of climactic caldera-forming eruptions (Hildreth, 1981; Lipman, 2007), are seen as the eruptive equivalents of granodioritic plutons with the former recording the melt–present history of the latter (e.g. Bachmann et al., 2007). Whether super-sized caldera-forming eruptions with limited compositional variability are the surface expression of cordilleran batholith formation over several millions of years of incremental assembly and piecemeal construction, however, remains contested (e.g., Glazner et al., 2015). Constraints of how long a melt–present state persists in the magmas that feed super-volcanic eruptions underpin our understanding of the "active" lifetimes of plutons, the geothermal and mineral resource potential of these systems, and any associated hazard. A handful of monotonous crystal-rich ignimbrites have been the subject of investigations that reveal, based largely on U–Pb zircon geochronology, >>100 ka pre-eruptive melt–present lifetimes (Brown and Fletcher, 1999; Costa et al., 2008; Wotzlaw et al., 2013; Kern et al., 2016). However, zircon ages for the ignimbrites only pertain to the duration of pre-climactic magma presence, whereas the significant post-climactic history of resurgent volcanism and magmatically-motivated structural uplift (Smith and Bailey, 1968; Marsh, 1984; Kennedy et al., 2012) is rarely accounted for. A more accurate quantification of the melt–present lifetime of large silicic magmatic systems thus requires that the full magmatic cycle, including the pre-climactic and post-climactic magma history culminating in solidification, be investigated. This can be achieved in systems where co-located volcanic and plutonic rocks are found, because where such a record is available, they show striking similarities in geochemistry and petrology that suggest a cogenetic relation (e.g. Lipman, 2007). With the development of techniques that allow coupled chronological and chemical measurements of zircon, we are now in a position to also estimate melt–present lifetimes for volcanic systems where plutons are not exposed, albeit in favorable cases accessible as xenoliths.

Herein, we apply zircon chronochemistry, the combination of U–Pb geochronology with indicators for geochemical evolution (e.g., Zr/Hf, Yb/Gd, Eu/Eu*, U/Th) and model magmatic temperatures for zircon (e.g., through zircon saturation and Ti-in-zircon thermometry), to volcanic rocks and plutonic clasts from the Pastos Grandes caldera in southwest Bolivia. The erupted rocks define a "monotonous intermediate" suite that records the pre- and post-climactic history of a super-sized caldera-related magma system. Here zircon records a quasi-continuous >1 Ma history of thermal, compositional, and textural evolution in a shallow crystal-rich dacitic crustal magma reservoir that is interpreted to have evolved into a regional composite batholith.

2. Geologic background

The Pastos Grandes Caldera Complex (PGCC) in southwestern Bolivia (Fig. 1) is part of the Altiplano–Puna Volcanic Complex (APVC), an ignimbrite plateau active from ∼10 Ma to Recent (<100 ka) (de Silva, 1989; de Silva et al., 2006; Salisbury et al., 2011). The calderas of the APVC overly a ∼500,000 km^3 low-velocity zone, the Altiplano–Puna Magma Body (APMB) that is interpreted as the magmatic feeder zone of a cogenetic batholith (Ward et al., 2014; Burns et al., 2015). The earliest PGCC caldera cycle resulted from the 5.45 ± 0.02 Ma eruption of the 1200 km^3 dense rock equivalent (DRE) Chuhuilla Ignimbrite (Salisbury et al., 2011). A second climactic eruption at 2.89 ± 0.01 Ma resulted in the 1500 km^3 (DRE) Pastos Grandes Ignimbrite (PGI) and produced the eponymous ∼40 × 25 km caldera nested within the larger Chuhuilla caldera (Fig. 1). Following the eruption of the PGI and the formation of the caldera was a series of effusive eruptions resulting in lava domes on the caldera floor. Two types of undated, but structurally distinct post-climactic domes (PCD) are present. The older, Southern PCD is faulted by resurgent uplift of the caldera floor. By contrast, younger post-climactic volcanic activity resulting in the Mid and North PCD are unaffected by resurgence, indicating they erupted after resurgent uplift. The distinct ∼20 km diameter, 1 km-high resurgent dome and its surrounding post-climactic lava flows and domes define the footprint of magmatic and structural resurgence for the Pastos Grandes supereruption. The plutonic part of the Pastos Grandes system is represented by plutonic clasts erupted as ejecta during the much younger (∼85–94 ka) Chascon Runtu-Jarita lava-complex episode (Watts et al., 1999). The few recovered clasts were between 5–10 cm in diameter, and only one of the clasts was used to sample zircons for this study.

PGI pumice clasts are crystal-rich, calc-alkaline dacites between 67 wt% and 70 wt% SiO_2 which contain ∼40% phenocrysts (vesicle free) of plagioclase (maximum diameter 3 mm), quartz, biotite, amphibole, and rare sanidine, set in a vesicular, high-Si rhyolite (76–77% SiO_2) matrix glass. Accessory phases include apatite, titanite, Fe–Ti oxides, and zircon. The post-climactic domes and plutonic clasts have bulk rock compositions closely overlapping those of the PGI (Fig. 2). The post-climactic lavas are similar in mineralogy to the PGI pumice but are denser and coarser (maximum diameter 5 mm for plagioclase and quartz phenocrysts) and with higher phenocryst content (up to 50% based on approximations from petrography). The groundmass of the post-climactic lavas is rich in microlites. The plutonic clasts are granodiorite and have a phaneritic texture with dominant plagioclase, potassium feldspar, biotite, amphibole, and quartz (Fig. 2). Thus, the cogenetic suite of volcanic and plutonic rocks shares a general family resemblance in mineralogy and whole rock chemistry with a trend of increasing textural coarseness (maturity) from pumice to lava to granodiorite (Fig. 2). The chemical similarities extend to the zircon populations as we elaborate below.

3. Methods

3.1. Sample preparation

Zircon crystals were recovered by heavy liquid separation from the 100–250 μm sieved fraction of crushed rock samples. Grains were mounted in epoxy and polished to intersect crystal interiors. Prior to ion probe analyses, each zircon crystal was examined for internal zoning by cathodoluminescence (CL) imaging using a Leo 1430VP scanning electron microscope equipped with an Oxford Mini-CL detector at University of California Los Angeles (UCLA) (Fig. 3). A small subset of representative zircon crystals is shown in the CL images, which were used to target core and rim locations for ion probe analysis with a preference for CL homogenous domains to minimize averaging of multiple growth zones in the zircon crystals.

3.2. Analytical procedures

Ion microprobe analyses were performed using the CAMECA ims 1270 ion microprobe at UCLA. A mass-filtered $^{16}\text{O}^-$ primary beam with an intensity of 15–20 nA was focused to a size of 25–30 μm. For U–Pb analyses, secondary ions were extracted at 10 kV, a mass resolution power $m/\Delta m = 4500$ at 10% of the peak height, and an energy bandpass of 50 eV. Replicate analysis of reference zircon AS3 (Paces and Miller, 1993) yielded a $^{206}\text{Pb}/^{238}\text{U}$ age reproducibility of <3%. U–Pb geochronology ion probe craters were subsequently used for trace element analyses

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