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Petrochronologic perspective on rhyolite volcano unrest at Laguna del Maule, Chile

Nathan L. Andersen[a,*], Brad S. Singer[a], Fidel Costa[b], John Fournelle[a], Jason S. Herrin[b,c], Gareth N. Fabbro[b]

[a] *Department of Geoscience, University of Wisconsin-Madison, Madison, WI, 53706, United States of America*
[b] *Earth Observatory of Singapore, Nanyang Technological University, 639798, Singapore*
[c] *Facility for Analysis Characterization Testing and Simulation, Nanyang Technological University, 639798, Singapore*

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ABSTRACT

Rhyolitic magmas have rarely erupted during historical times, thus we have a poor record of the signals of unrest that precede them. The Laguna del Maule volcanic field (LdM), Chile, is in the midst of a decade-long episode of unrest including surface inflation at more than 200 mm/yr. Geomorphic observations indicate that many similar deformation episodes occurred during the late Pleistocene and Holocene. During this time, approximately 40 km^3 of rhyolite has erupted effusively and explosively from at least 24 vents distributed around a 300 km^2 lake basin. The large volume, protracted eruptive history, and ongoing unrest of LdM offer an unusual opportunity to integrate petrologic reconstructions of recent rhyolite generation with geophysical and geodetic observations associated with an active, growing magma reservoir. New petrochronologic data shows that the most recent rhyolites, erupted during the last 3200 yr, each resided in the shallow crust for only decades following extraction from an underlying reservoir. The rhyolites contain only limited, cryptic evidence for magma replenishment and reheating in the form of Ba concentration spikes in plagioclase, which suggest biotite breakdown in a crystal-rich mush. The absence of evidence for substantial reheating or mixing with intruding magma preceding the rhyolitic eruptions indicates that they must have been triggered by another process. We propose the accumulation of fluids derived from the deeper degassing of mafic melts is capable of pressurizing eruptible magma bodies of low density rhyolite. This process likely continues to this day and is consistent with the best-fit models of the ongoing unrest. The striking absence of visible surface degassing accompanying the unrest at LdM suggests fluids are trapped beneath an impermeable carapace and could catalyze a future explosive eruption.

1. Introduction

Silicic magmatic systems can produce modest-to-large volume ($<$1–10^3 km^3) explosive eruptions and threaten regional population centers, infrastructure, and agriculture (Castro and Dingwell, 2009; Self and Blake, 2008; Sparks et al., 2005). In many settings, silicic magmas are thought to originate from a crystal mush—a crystalline framework containing $<$50% melt—assembled by shallow emplacement of magma over 10^4–10^5 yr (e.g., Hildreth, 2004). Gravity-driven processes such as compaction and hindered settling can extract rhyolitic melt from mush zones (Bachmann and Bergantz, 2004). In addition, the intrusion of hotter, less evolved magma, appears to be a fundamental catalyst of rhyolite generation and eruption by remelting solidified silicic material, mixing with and pressurizing pre-existing magma, and promoting the amalgamation of discrete, heterogeneous magma batches (e.g., Bachmann and Bergantz, 2006; Bindeman and Simakin, 2014; Bergantz et al., 2015, 2017; Huber et al., 2012; Burgisser and Bergantz, 2011; Charlier et al., 2008; Folch and Martí, 1998; Wolff et al., 2015). The time required to mobilize eruptible rhyolite from a long-lived magma reservoir is the subject of active investigations (e.g., Barker et al., 2016; Chamberlain et al., 2014; Druitt et al., 2012; Rubin et al., 2017; Singer et al., 2016; Till et al., 2015). Magma rejuvenation and eruption priming are commonly inferred to occur over months to centuries—timescales that are exceedingly short in geologic terms. However, in the context of volcano monitoring, lag times of months vs. centuries require substantially different approaches to assessing volcanic unrest when attempting to anticipate future eruptions.

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[*] Corresponding author. Current address: University of Oregon, Department of Earth Sciences, Eugene, OR, 97403, United States of America.
E-mail address: nla@uoregon.edu (N.L. Andersen).

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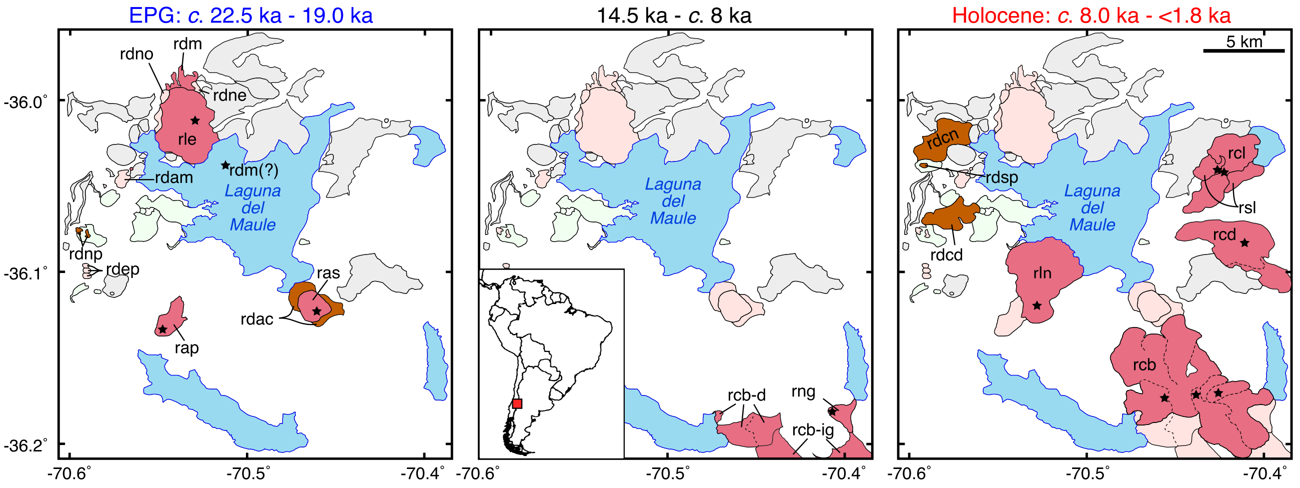

Fig. 1. Simplified geologic maps showing the locations of post-glacial silicic eruptions during the EPG period, the Holocene, and the interim (modified from Andersen et al., 2017; Hildreth et al., 2010). Post-glacial rhyolites, rhyodacites, and andesites are pink, orange, and green respectively. Units erupted prior to the most recent glacial retreat are light gray. Post-glacial silicic units erupted during an earlier period in the center and right panels are pale pink. The black stars mark the rhyolite-producing vents (Hildreth et al., 2010); the location of the vent for the EPG plinian *rdm* eruption within the modern lake is approximate (Fierstein, 2018). The red square in the inset shows the location of LdM in South America. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

In the last 500 yr, only 65 silicic (dacite–rhyolite, trachydacite–trachyte, or phonolite) volcanoes have erupted worldwide, of which only 14 were dominantly rhyolitic, and only 3 (Pinatubo, Puyehue-Cordón Caulle, and St. Helens) were instrumentally monitored (Bignami et al., 2014; Jay et al., 2014; Newhall et al., 2017; Newhall and Punongbayan, 1996; Sherrod et al., 2008; Global Volcanism Program, 2013). This infrequent eruption of rhyolite magma limits our opportunities to integrate petrologic constraints with geophysical observations of volcano unrest. Consequently, forensic petrologic reconstruction of the processes that promoted late Pleistocene through historical eruptions provides a unique context for interpreting geophysical records of unrest (Barker et al., 2016; Jay et al., 2014; Singer et al., 2016; Wilson, 2017).

We present major and trace element compositions and textures of plagioclase and magnetite from rhyolite erupted in the currently restless Laguna del Maule volcanic field (LdM), located in the southern Andes at 36° S (Fig. 1; Hildreth et al., 2010; Singer et al., 2014). We interpret these data within a high resolution eruptive chronology (Andersen et al., 2017) to construct an integrated model of the compositional and physical evolution of the magma reservoir over 10^3–10^4 yr and quantify the tempo of processes preceding the most recent eruptions.

2. Geologic setting

LdM is situated 30 km behind the active volcanic front of the Southern Volcanic Zone (SVZ) of Central Chile. Since the most recent glacial retreat, locally at *c*. 23 to 19 ka based on ^{40}Ar/^{39}Ar dates of unglaciated lava flows (Singer et al., 2000; Andersen et al., 2017), volcanism at LdM has been dominantly silicic and concentrated within the central lake basin (Fig. 1; Andersen et al., 2017; Hildreth et al., 2010). Rhyolite eruptions at LdM were both effusive and explosive, and both eruptive styles yield products that contain less than 10% phenocrysts of plagioclase, biotite, and magnetite ± quartz ± amphibole. The frequency and spatial distribution of the post-glacial rhyolite eruptions at LdM were greatest during two pulses: an early post-glacial (EPG) period, 22.5–19 ka, and the middle to late Holocene (Fig. 1; Andersen et al., 2017). The EPG rhyolite eruptions began with the 20 km^3 plinian Rhyolite of Laguna del Maule, unit *rdm* (Fierstein, 2018), the large volume of which distinguishes it from the subsequent, smaller-volume (<3 km^3) rhyolites. Following an interim period during which rhyolite erupted only from the Barrancas complex in the southeastern lake basin (14.5–*c*. 8 ka), the focus of rhyolite volcanism expanded westward and northward during the Holocene, while also continuing within the Barrancas complex (Fig. 1; Andersen et al., 2017; Fierstein, 2018; Hildreth et al., 2010; Sruoga et al., 2017).

Rhyodacite and andesite eruptions also occurred throughout post-glacial times. However, they comprise a smaller cumulative volume (<5 km^3 total) than the rhyolites and were concentrated in the western LdM basin, away from the locus of rhyolite volcanism (Andersen et al., 2017; Hildreth et al., 2010). The rhyodacite lavas are distinguished from the rhyolites by higher crystallinities (10–20%), ubiquitous amphibole, and common cm-scale chilled mafic inclusions, which are nearly absent from the rhyolites (Andersen et al., 2017; Hildreth et al., 2010).

Geochemical, geochronologic, and geophysical investigations have produced insights into the structure and evolution of the LdM magma reservoir. Amphibole barometry, trace element compositions, and radiogenic isotope ratios indicate the rhyolite erupted at LdM was produced in the shallow crust (Andersen et al., 2017). This shallow magmatism is the uppermost expression of a multi-tiered magma system involving two distinct domains of crustal assimilation. Partial melting occurred both within the stability field of garnet (≥1.2 GPa; Rapp and Watson, 1995) and at lower pressure via garnet-free dehydration melting of amphibole-bearing crust. The depth of this second zone is not well constrained, but it notably does not involve older metamorphic and intrusive basement with highly radiogenic Sr and Pb isotope ratios (Andersen et al., 2017).

The lack of mafic to intermediate eruptions within the locus of rhyolite volcanism is hypothesized to reflect the interception of mafic magma by a voluminous shallow silicic magma reservoir (Hildreth et al., 2010). All rhyolites have similar whole-rock chemistry, but the Holocene rhyolites are subtly enriched in middle rare earth elements (MREE) and Y relative to those erupted during the EPG period. Andersen et al. (2017) propose that this distinction indicates multiple physically discrete batches of crystal-poor rhyolite were extracted from a longer-lived, crystal-rich reservoir through time.

Since 2007, surface uplift at LdM measured by InSAR and continuous GPS has exceeded 200 mm/yr and continues at the time of writing (Feigl et al., 2014; Fournier et al., 2010; Le Mével et al., 2015). The best-fit source of this deformation is an inflating sill at a depth of ∼5 km; a model of coupled time-varying magma injection and reservoir pressurization reproduces 7.3 yr of sur-