The large, restless, rhyolitic magma system at Laguna del Maule, southern Andes: Its dynamics and hazards

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1 Introduction

The Laguna del Maule (LdM) volcanic field, central Chile (**Figure 1**), comprises the highest spatial concentration of young rhyolite in the Southern Andes and is currently in a state of extraordinary unrest (Singer et al., 2014). Since the most recent deglaciation (~25,000 years ago), rhyolite domes and coulées have erupted in a 23 by17 km ring around the central lake basin. Within this ring, the rate of uplift has been at exceptionally high (>19 cm/yr) since some time before 2007, as measured by satellite geodesy and shown in **Figure 2** (Fournier et al., 2010; Feigl et al. 2014; Le Mével et al., in review). Together with their coherent chemical composition, the distribution of the volcanic products and ongoing unrest suggests that the post-glacial rhyolites are the product of a large, shallow silicic magma reservoir that is active and growing. This magmatic system thus has the potential to produce a large, explosive eruption and thus poses a significant volcanic hazard.

The dynamics by which large silicic magma systems grow and eventually erupt are not fully understood. The frequent post-glacial rhyolitic eruptions at LdM provide a spectacular sampling through time of the development of this magma system that allows for the evaluation of spatial and temporal thermochemical changes. Geomorphic features, most prominently a paleoshoreline 200 m above the current lake level, record a history of deformation over as much as 10,000 years. Ongoing geophysical measurements are probing the structure and physical characteristics of the modern magma reservoir. The geologic record of magmatic processes provides a context in which to interpret the ongoing volcanic unrest while the physical characteristic of the modern magma chamber(s) provide constraints for petrologic models of the system evolution since the Pleistocene. This project is an international collaborative effort involving academic and government scientists from Chile, Argentina, the United States, Canada, and Singapore.

In this presentation we will highlight the activities our team during the past four years that have led to the current understanding of magma dynamics at Laguna del Maule. This early progress report is of both scientific and societal interest as it follows the eruptions in 2015 of the composite volcanoes Villarrica and Calbuco, also located in the Southern Andes. Villarrica produced small Strombolian eruptions of basaltic andesite, whereas Calbuco's powerful subplinian eruption was dacitic. We will discuss the less well-known Laguna del Maule rhyolitic system and its hazards in light of these recent eruptions in the Chilean Southern Volcanic Zone.

2 Results

2.1 Geology, petrology & geochronology

^{40}Ar/^{39}Ar dating indicates a decreasing frequency of andesite eruptions during the post-glacial silicic flare-up. This may reflect the accumulation of low-density silicic mush in the upper crust that blocks the ascent of mafic magma. Additionally, the crystal-poor, glassy, rhyolitic eruptions are temporally concentrated in two phases, an initial pulse between the glacial retreat and 19,000 years ago and a second beginning in the early Holocene and continuing until at least 2,200 years ago. The spatial focus of volcanism shifted between these two eruptive phases, with more frequent eruption in the north and west in early post-glacial time and in the south and east during the Holocene, although eruptions occurred throughout the LdM basin during both eruptive periods (**Figure 2**).

Major and trace element compositions of whole rock samples, plagioclase, and Fe-Ti oxides define a narrow compositional range. However, subtle yet consistent chemical differences interpreted in the temporal framework of the ^{40}Ar/^{39}Ar geochronology illuminate spatial and temporal evolution of the LdM magma reservoir. Magnetite compositions identify distinct magma batches for early and later erupted rhyolites that are consistent across a spatial extent of up to 20 km. These compositions indicate the Holocene rhyolites erupted at temperatures as much as 60° C higher than those of the early post-glacial rhyolite. Plagioclase compositions confirm the distinctions observed in the Fe-Ti oxides and show no crystal inheritance from the earlier to later erupted rhyolites indicating either that earlier plagioclase was completely resorbed, or that these magma bodies were temporally distinct and thus did not physically interact with one another.

Zoned plagioclase phenocrysts record a variety of processes related to the intrusion of mafic magma to the upper crust. These events produced both direct mixing between mafic and silicic magmas and partial melting resulting in Mg and Ba enriched domains, respectively. Kinetic modeling of diffusive equilibration of these zones indicates that these crystals could not have been stored at magmatic temperatures for more than a few decades, and potentially shorter periods, comparable to the duration of unrest observed at LdM. Plagioclase-glass equilibrium calculations suggest that the H_2O content of the rhyolitic melts may be as high as 7 weight %.

2.2 Ongoing unrest

Our international team is densely instrumenting and measuring LdM, using several techniques, including continuous and campaign GPS, InSAR geodesy, magnetotellurics (MT), seismology, and gravity. The geodetic and gravity measurements have been ongoing since 2007 and 2013, respectively. Beginning in 2007, InSAR and GPS have measured ongoing inflation at an average rate greater than 19 cm/yr resulting in a maximum cumulative uplift of 1.8 m at the GPS station closest to the center of uplift (Le Mével et al., in review; **Figure 2**). This deformation is centered in the southern end of the lake, near the most recently erupted rhyolite flow.

A Bouguer gravity survey has identified a low density zone in a region that overlaps with the center of inflation possibly reflecting the presence of rhyolitic melt in the upper crust. Moreover, two years of dynamic gravity measurements revealed a mass and density increase during the first year with a smaller increase in the second year reflecting the variable nature of the processes driving the unrest.

The seismic network is still being installed and tomographic work has not begun in earnest, however, the existing network has detected numerous shallow seismic swarms concentrated in the southern LdM basin. A pilot MT inversion using geothermal industry data indicates a zone of low resistivity at 5 km depth below the lake basin. These results suggest that intrusion of magma into a shallow crustal reservoir is driving the surface deformation, and propelling changes in the gravity field.

2.3 Long-term deformation history

The eruption of the Espejos rhyolite flow 19,000 years ago dammed the outlet of LdM producing a paleo-shoreline 200 m above the current lake level (Hildreth et al., 2010). The lake returned rapidly to a lower level during a catastrophic outbreak flood ~9,000 years ago. If crustal deformation has accompanied magmatism throughout the Holocene, the initially level shoreline surface should be raised and deformed. Static GPS measurements show that the paleo-shoreline around the south side of the lake basin is more than 60 m higher than in the north (**Figure 2**). Extrapolating magma intrusion rates calculated based on geodetic observations between 2007 and 2012 (Feigl et al., 2014) suggests that in the absence of faulting, the episodic emplacement of 6-8 km^3 of magma could be responsible for the deformation of the paleo-shoreline during the Holocene.

3 Discussion

3.1 A Note on hazards

During the Quaternary, the northern segment of the Southern Volcanic Zone, between 32^o and 37^o, produced several large volume silicic eruptions emanating from immediately east of the active volcanic front. These include the Diamante ignimbrite and Pudahuel ash from Maipo-Diamante caldera (Sruoga et al., 2012), the Loma Seca Tuff from Calabozos caldera (Hildreth et al., 1984), numerous rhyolitic lavas and ignimbrites comprising the Puelche volcanic field (Hildreth et al., 1999), and two mid-Pleistocene tuffs within the LdM volcanic field (Hildreth et al., 2010)(**Figure 1**). These silicic eruptions produced tens to hundreds of km^3 of ash and many resulted in caldera formation. In this regard, the position of LdM to the east of the mafic-intermediate frontal arc composite volcanoes Tatara-San Pedro and Descabezado Grande-Cerro Azul is not unusual.

However, the eruptive style of LdM is in stark contrast to the historically active composite cones typical of the frontal arc both south and north of 37^o, exemplified by the mafic-intermediate cones of Villarrica and Calbuco. Rather than a single central edifice and vent, LdM comprises at least 24 young silicic vents, each of which has produced explosive and effusive eruptions, distributed across an area of 300 km^2. Notably, tens of km^3 of silicic pyroclastic fall deposits blanket a region that extends up to 30 km east of LdM into Argentina (Fierstein et al., 2013). Moreover, at least two rhyoltic ignimbrites were emplaced in the uppermost Rio Maule valley and south of the LdM basin (**Figure 2**). This explosivity reflects the high water content and viscosity of the rhyolitic magmas erupted at LdM.

There have been no historical eruptions at LdM since the region was colonized by Spanish settlers in the mid-16th century, yet at least 36 silicic eruptions of modest size have occurred during the last 25,000 years, suggesting a recurrence interval of less than 700 years. Familiar analogs to these numerous modest-sized explosive eruptions at LdM include the 2008 eruption of rhyolite at Chaiten volcano, or the 2011 eruption of rhyodacite at Cordon Caulle, each of which caused damage to infrastructure, agriculture, and industry in Chile and Argentina. The preliminary hazard map for LdM prepared for SERNAGEOMIN by Amigo and Bertin (2012) confines the main zone of danger to a largely uninhabited region within 10 km of the shoreline of LdM. However, this assessment reflects the likelihood that future eruptions will be of only modest size.

3.2. Magma system evolution

The shallow magma reservoirs that incubate rhyolite are widely (but not universally) thought to comprise vast crystal-rich 'mush' domains from which crystal-poor melt lenses accumulate and occasionally erupt (e.g., Bachmann & Bergantz, 2008; Hildreth, 2004), leaving behind crystalline "graveyards" in the form of plutons (Gelman et al., 2014). This "mush" model predicts that eruptible, crystal-poor rhyolite will accumulate at the top of a source region of crystal-rich magma. The compositional continuity and increasing prevalence of crystal-poor rhyolitic eruptions at the expense of mafic to intermediate products is consistent with the presence of such a magma reservoir beneath LdM (**Figure 3**).

The subtle geochemical variations among the rhyolites indicate diversity imparted to the eruptible magma batches during their extraction and eruption that appear to be dominated by variations in the interactions of mafic and silicic magmas. Moreover, variations in mineral chemistry indicate that at times since the last glacial retreat there may have been large, integrated lenses of eruptible melt present beneath LdM that fed several eruptions. Such a configuration was likely ephemeral and earlier separated magma did not contribute significant material directly to subsequent eruptions.

The inferred sources of the gravity anomaly and crustal deformation in the southwestern part of the lake are consistent with the location of a growing magma reservoir that could have produced the youngest rhyolite eruptions. Thus, the ongoing unrest may be a continuation of the Holocene magmatism that produced a flare-up of rhyolitic eruptions, contributed to the >60 m uplift of the southern end of the lake basin, and may have emplaced a pluton-sized body of new magma.

During the next four years of our collaborative project, new information on the structure and physical characteristics of the magma reservoir from seismic tomography, ambient noise, and receiver functions, and higher resolution MT data, will be combined with existing data sets to produce dynamic models of shallow magmatism. Integration of these dynamics with petrologic models since the late Pleistocene will illuminate the assembly, storage, and destabilization of large silicic magma systems. Ultimately, our aim is to create models that lead to a better understanding of how these large systems operate, and the hazards they pose.

Acknowledgments

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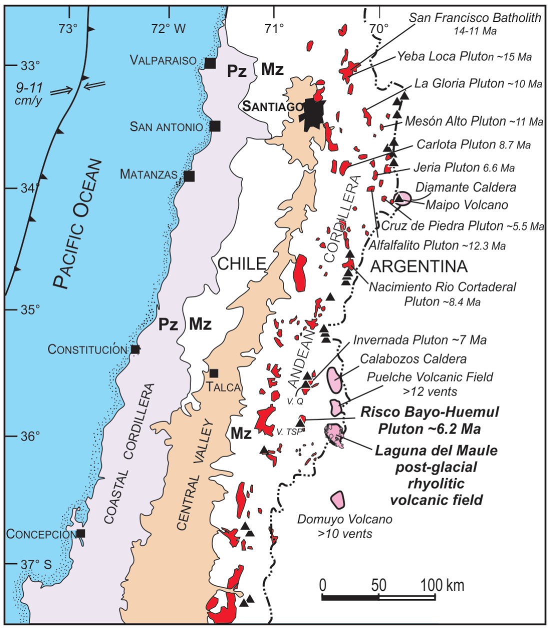

Figure 1. Tectonic and location map. Numerous Oligocene to Miocene plutons are shown in red. Quaternary SVZ frontal arc volcanoes are black triangles. V.Q.=Quizapu Volcano; V. TSP=Tatara-San Pedro Volcano. Continental divide and Cordilleran rangecrest is the border between Chile and Argentina. In pink are calderas or volcanic fields that have produced atypical amounts of silicic eruptive units, including at Laguna del Maule. Adapted from Hildreth & Moorbath (1988) and Hildreth et al. (2010).

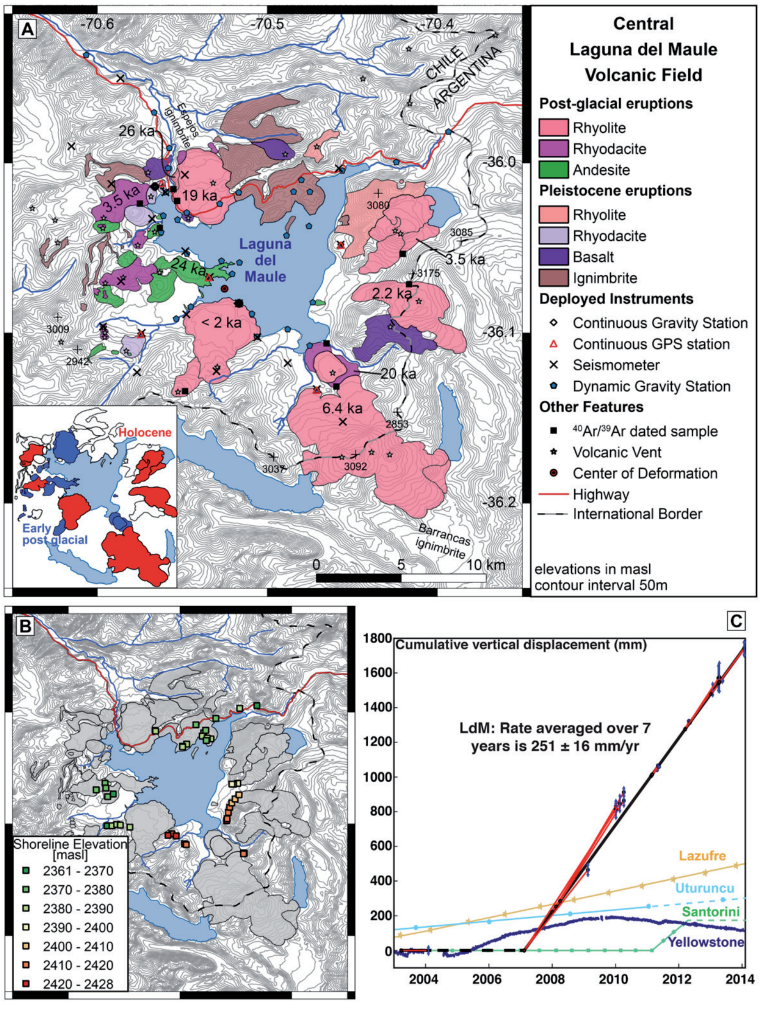

Figure 2. a) Geologic map of central Laguna del Maule with current geophysics stations. Selected $^{40}Ar/^{39}Ar$ age determinations are given in thousands of years (ka). The inset shows the distribution of early post-glacial and Holocene eruptive units. b) Elevations measured by static GPS on the paleoshoreline show that it has been uplifted in the south >60 m relative to the north. c) Time series of vertical uplift calculated from InSAR models using ENVISAT, ALOS, & TerraSAR-X data between 2003 and 2014 (Feigl et al. 2014). Yellowstone cGPS data are shown for comparison at station WLMY Data sources for the other volcanoes are given in Singer et al. (2014).

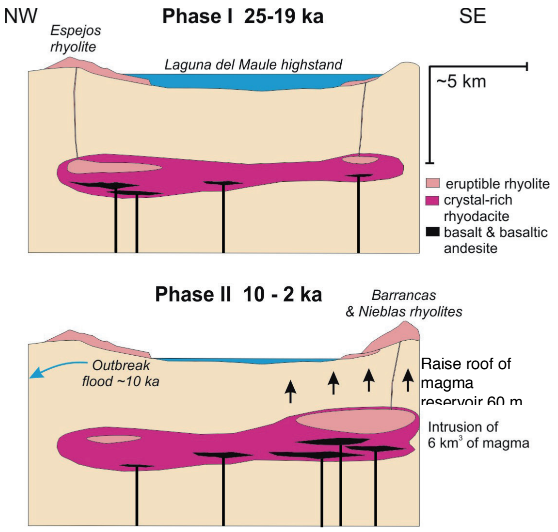

Figure 3. Schematic evolution of the LdM magma system through time. Extraction of rhyolite melt in time and space produced compositional differences revealed in the trace element contents of phenocrysts in the rhyolites. Some of these eruptible lenses of rhyolite may have been integrated beneath the entire lake basin.