Earth and Planetary Science Letters 488 (2018) 168–180

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Imaging the Laguna del Maule Volcanic Field, central Chile using magnetotellurics: Evidence for crustal melt regions laterally-offset from surface vents and lava flows

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ARTICLE INFO

Article history:
Received 26 September 2017
Received in revised form 5 January 2018
Accepted 9 January 2018
Available online 2 March 2018
Editor: P. Shearer

Keywords:
magnetotellurics
volcanism
southern volcanic zone
magma reservoir
hydrothermal reservoir

ABSTRACT

Magnetotelluric (MT) data were collected at the Laguna del Maule volcanic field (LdMVF), located in central Chile (36°S, 70.5°W), which has been experiencing unprecedented upward ground deformation since 2007. These data were used to create the first detailed three-dimensional electrical resistivity model of the LdMVF and surrounding area. The resulting model was spatially complex with several major conductive features imaged at different depths and locations around Laguna del Maule (LdM). A near-surface conductor (C1; 0.5 Ωm) approximately 100 m beneath the lake is interpreted as a conductive smectite clay cap related to a shallow hydrothermal reservoir. At 4 km depth, a strong conductor (C3; 0.3 Ωm) is located beneath the western edge of LdM. The proximity of C3 to the recent Pleistocene-to-Holocene vents in the northwest LdMVF and nearby hot springs suggests that C3 is a hydrous (>5 wt% H_2O), rhyolitic partial melt with melt fraction >35% and a free-water hydrothermal component. C3 dips towards, and is connected to, a deeper conductor (C4; 1 Ωm). C4 is located to the north of LdM at >8 km depth below surface and is interpreted as a long-lived, rhyolitic-to-andesitic magma reservoir with melt fractions less than 35%. It is hypothesized that the deeper magma reservoir (C4) is providing melt and hydrothermal fluids to the shallower magma reservoir (C3). A large conductor directly beneath the LdMVF is not imaged with MT suggesting that any mush volume beneath LdM must be anhydrous (<2 wt% H_2O), low temperature and low melt fraction (<25%) in order to go undetected. The presence of large conductors to the north has important implications for magma dynamics as it suggests that material may have a significant lateral component (>10 km) as it moves from the deep magma reservoir (C4) to create small, ephemeral volumes of eruptible melt (C3). It is hypothesized that there may be a north–south contrast in physical processes affecting the growth of melt-rich zones since major conductors are imaged in the northern LdMVF while no major conductors are detected beneath the southern vents. The analysis and interpretation of features directly beneath the lake is complicated by the surface conductor C1 which attenuates low-frequency signals. The attenuation from C1 does not affect C3 or C4. At 1 km depth directly beneath LdM, a weak conductor (C2; <10 Ωm) is imaged but is not required by the data. Forward modeling tests show that a relatively large (30 km^3), high melt fraction (>50%), silicic reservoir with 5 wt% H_2O at 2 to 5 km depth beneath the inflation center is not supported by the MT data. However, a smaller (10 km^3) eruptible volume could go undetected even with relatively high melt fraction (>50%). The location of large melt regions to the north has important implications for long-term volcanic hazards at LdMVF as well as other volcanoes as it raises the possibility that the vent distribution is not always indicative of the location of deeper source regions of melt.

1. Introduction

Large silicic magma systems have been the subject of intensive study due to their potential to cause very large, explosive eruptions (Self, 2006). However, it is still uncertain what causes these systems to develop and persist in the upper crust and what may

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https://doi.org/10.1016/j.epsl.2018.01.007
0012-821X/

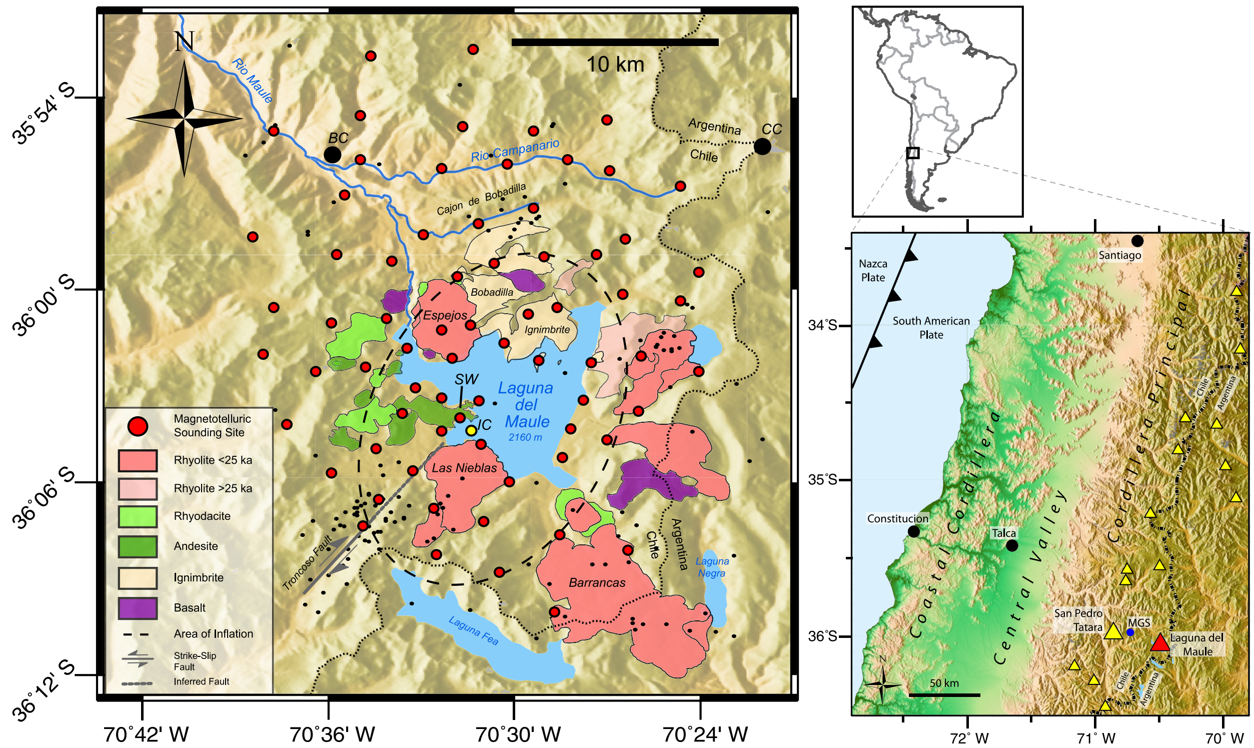

Fig. 1. Map of the study area around the Laguna del Maule Volcanic Field. Red dots are magnetotelluric sounding locations. The thick dashed line indicates the approximate area of observed inflation and the yellow dot (IC) denotes the point of maximum inflation as observed by InSAR (Feigl et al., 2013). Major lava flows are shown as colored polygons; the most recent (<25 ka) rhyolite flows are shown in dark pink (Andersen et al., 2017). Lava flows which are mentioned in the text are labeled on the map as is the southwest peninsula (SW) which is an important landmark. The inferred portion of the Troncoso Fault is shown as a dashed gray line. Small black dots are the locations of earthquakes with magnitude greater than 1 from 2011 to 2017 (Cardona et al., 2018). The thin dashed black line is the Chile–Argentina border. BC = Baños Campanario hydrothermal springs; CC = Cerro Campanario. The smaller regional map shows the location of Laguna del Maule as a red triangle along with San Pedro-Tatara Volcano (large yellow triangle) and Mariposa Geothermal System (MGS; blue circle) to the west. Small yellow triangles indicate other volcanos of the Southern Volcanic Zone. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

cause them to become unstable and erupt (Pritchard and Gregg, 2016). A better understanding of these systems is needed to determine the volcanic hazards they present.

The Laguna del Maule volcanic field (LdMVF; 36°S, 70.5°W) is located on the Andean range crest of the Southern Volcanic Zone in central Chile (Fig. 1). It includes a high concentration of basaltic-to-rhyolitic lava surrounding Laguna del Maule (LdM), an alpine lake at 2165 m above sea level (a.s.l.) near the Chile–Argentina border. A 200 km^2 area of LdMVF has been experiencing rapid upward ground deformation since at least 2007 as indicated by InSAR and ground-based GPS observations (Feigl et al., 2013). Uplift rates have exceeded 25 cm/yr resulting in a net vertical displacement of nearly 2 m (Le Mével et al., 2016). InSAR deformation modeling suggests an inflation source located at a depth of approximately 5 km below lake surface which has been interpreted as the addition of material into the upper crust (Le Mével et al., 2016). Bouguer gravity data also show a large gravity low beneath the lake which has been modeled as a low density body at 2 to 5 km depth (Miller et al., 2017a). Seismicity has been detected around LdM with prominent swarms to the southwest near the Troncoso fault at an average depth of approximately 2 km below sea level (Fig. 1; Cardona et al., 2018).

The distribution of lava flows, previous caldera eruptions, ground deformation, and gravity anomalies suggests that the LdMVF sits above a restless magmatic system which has the potential for large, explosive eruptions. This magmatic system is hypothesized to be a large, laterally-extensive crystal-rich mush zone with the observed inflation caused by mass addition from a deeper crystal-poor basaltic source (Singer et al., 2014; Andersen et al., 2017).

To better understand this system, it is necessary to use geophysical methods to image the subsurface. Various geophysical methods indirectly measure different Earth properties such as density, acoustic velocity or electrical resistivity. Each method is important in giving a different view of the volcanic system depending on the Earth property the method is sensitive to. The electrical resistivity of the Earth is dependent on the presence and chemical composition of hydrothermal fluids and partial melt as well as other factors such as clay minerals, temperature, and pressure (Unsworth and Rondenay, 2013). As such, imaging the electrical resistivity of the subsurface beneath the LdMVF can give insight into the location, size and composition of fluids within this dynamic system.

Magnetotellurics (MT) is a passive electromagnetic geophysical method which is used to image the electrical resistivity of the subsurface by measuring the natural time-varying fluctuations of the Earth's electric and magnetic fields and inverting these data in the frequency domain (Chave and Jones, 2012). MT has been previously applied at other volcanos to identify magma bodies in the shallow crust, investigate deformation sources, and study shallow hydrothermal systems (e.g. Heise et al., 2010; Aizawa et al., 2014; Muñoz, 2014; Comeau et al., 2016). MT is suited to studying the LdMVF because it is able to locate zones of hydrothermal fluid and/or partial melt and place limits on the size and composition of inferred magma bodies.

2. Geological setting

The LdMVF is located approximately 25 km east of the active volcanic arc in a rear-arc extensional setting (Fig. 1; Hildreth et al.,