Earth and Planetary Science Letters ••• (••••) •••–•••

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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3D gravity inversion and thermodynamic modelling reveal properties of shallow silicic magma reservoir beneath Laguna del Maule, Chile

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ARTICLE INFO

Article history:
Received 4 August 2016
Received in revised form 2 November 2016
Accepted 3 November 2016
Available online xxxx
Editor: T.A. Mather

Keywords:
Bouguer gravity
inversion
MELTS
rhyolite
thermodynamics
volatiles

ABSTRACT

Active, large volume, silicic magma systems are potentially the most hazardous form of volcanism on Earth. Knowledge of the location, size, and physical properties of silicic magma reservoirs, is therefore important for providing context in which to accurately interpret monitoring data and make informed hazard assessments. Accordingly, we present the first geophysical image of the Laguna del Maule volcanic field magmatic system, using a novel 3D inversion of gravity data constrained by thermodynamic modelling. The joint analysis of gravity and thermodynamic data allows for a rich interpretation of the magma system, and highlights the importance of considering the full thermodynamic effects on melt density, when interpreting gravity models of active magmatic systems. We image a 30 km^3, low density, volatile rich magma reservoir, at around 2 km depth, containing at least 85% melt, hosted within a broader 115 km^3 body interpreted as wholly or partially crystallised (>70% crystal) cumulate mush. Our model suggests a magmatic system with shallow, crystal poor magma, overlying deeper, crystal rich magma. Even though a large density contrast (-600 kg/m^3) with the surrounding crust exists, the lithostatic load is 50% greater than the magma buoyancy force, suggesting buoyancy alone is insufficient to trigger an eruption. The reservoir is adjacent to the inferred extension of the Troncoso fault and overlies the location of an intruding sill, driving present day deformation. The reservoir is in close proximity to the 2.0 km^3 Nieblas (*rln*) eruption at 2–3 ka, which we calculate tapped approximately 7% of the magma reservoir. However, we suggest that the present day magma system is not large enough to have fed all post-glacial eruptions, and that the location, or size of the system may have migrated or varied over time, with each eruption tapping only a small aliquot of the available magma. The presence of a shallow reservoir of volatile rich, near liquidus magma, in close proximity to regional scale faulting, has important implications for volcano monitoring and hazard mitigation.

1. Introduction

Accumulation of large volumes of silicic magma in the crust is a pre-requisite to Earth's most dangerous style of volcanic eruption (Cashman and Giordano, 2014). Detailed knowledge of the location and physical properties of that magma is therefore important in determining the potential hazard of the magma reservoir, and its likelihood to erupt. Geophysical images of active, high silica magma systems, are usually obtained using InSAR, seismic, or magnetotelluric methods (e.g. Bachmann et al., 2007; Pritchard and Gregg, 2016, and references therein). Surprisingly, gravity images are less common, in spite of the strong density contrast produced by high silica magmas with their surrounding crust (e.g. Masturyono et al., 2001; DeNosaquo et al., 2009; del Potro et al., 2013; Saxby et al., 2016). Many rhyolitic calderas have substantial Bouguer gravity anomalies but these are often caused by caldera infill (Kane et al., 1976; Davy and Caldwell, 1998), rather than the underlying magmatic system.

In this study we present a new, 3D gravity inversion scheme using the open-source Simulation and Parameter Estimation in Geophysics (SimPEG) framework (Cockett et al., 2015) http://www.simpeg.xyz, and importantly, consider thermodynamic effects on the magma system density. Thermodynamic modelling using the

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http://dx.doi.org/10.1016/j.epsl.2016.11.007
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Please cite this article in press as: Miller, C.A., et al. 3D gravity inversion and thermodynamic modelling reveal properties of shallow silicic magma reservoir beneath Laguna del Maule, Chile. Earth Planet. Sci. Lett. (2016), http://dx.doi.org/10.1016/j.epsl.2016.11.007

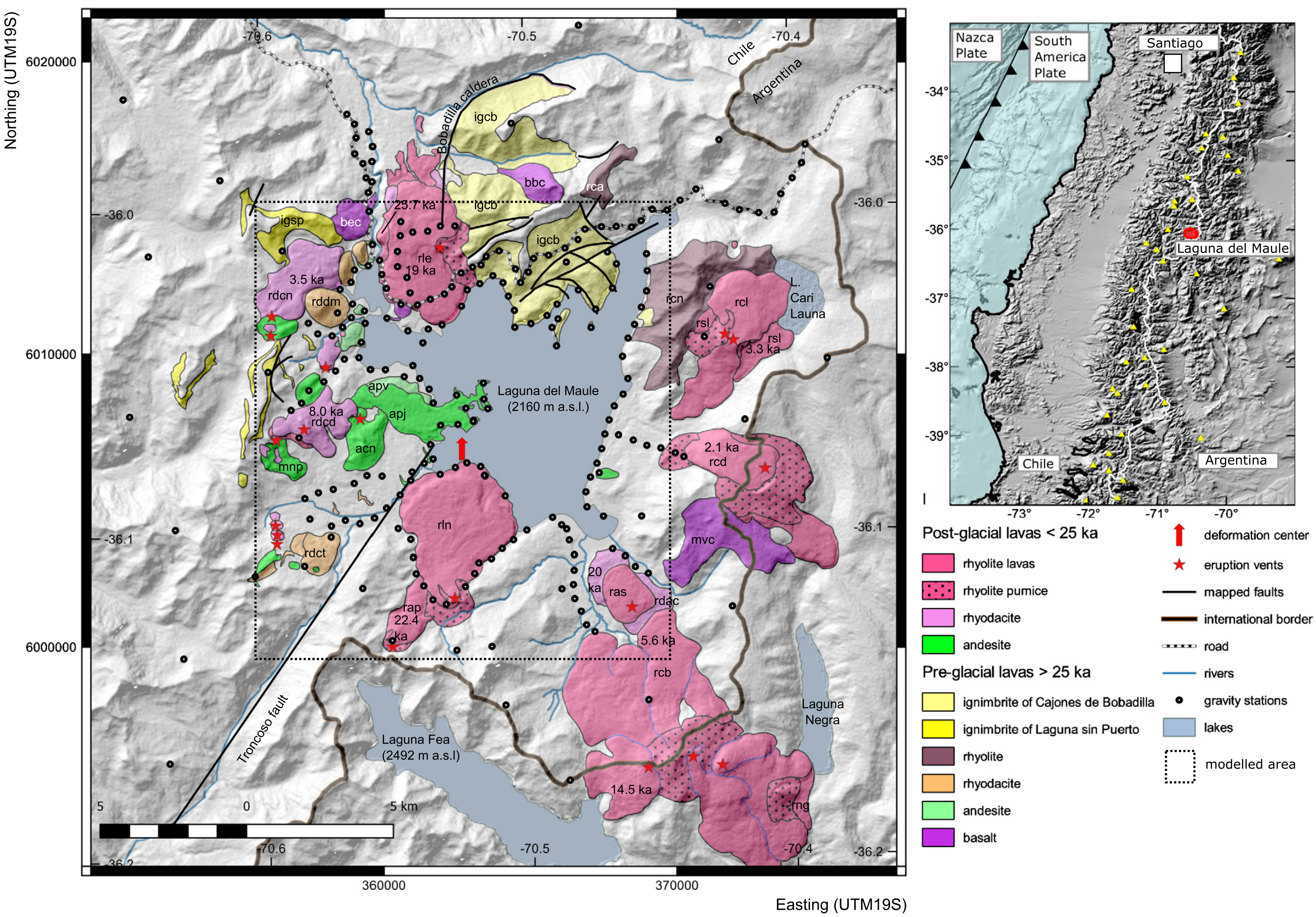

Fig. 1. Simplified geology map of the central basin of the LdMVF (after Hildreth et al., 2010). Gravity station locations are shown as black dots. The red arrow indicates the centre of inflation from Feigl et al. (2014). Ages are from $^{40}Ar/^{39}Ar$ ratios (Andersen et al., 2016) and red stars show post-glacial vents. The dashed black box shows the outline of the modelled area. The smaller location map shows Laguna del Maule volcanic field as a red ellipse, with other Holocene volcanoes as yellow triangles. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

free MELTS code (Gualda and Ghiorso, 2015) considers crystal, melt and volatile phases as well as pressure and temperature conditions when computing magma system densities. Consideration of the volatile phase is important for determining the total magma system density and thus for the correct interpretation of gravity inversion results, as volatiles control many processes which drive or hinder eruptions (Huppert et al., 1982; Sparks and Huppert, 1984; Wallace et al., 1995; Malfait et al., 2014).

Gravity models of volcanoes are not new, however the inversion codes are often poorly documented, proprietary, or expensive, making them difficult to be widely adopted or benchmarked. While there are popular free codes used in volcanology (e.g. Camacho et al., 2011), a growing number of open-source codes are developing in the broader geophysical community (e.g. Uieda et al., 2013; Cockett et al., 2015; Rucker et al., 2015). These codes are transparent, flexible, and maintained by a cohort of users that contribute bug fixes and improvements as desired. SimPEG is open-source and offers significant benefits, including; 1) a mixed L_p norm inversion on both model values, and the gradient of their distribution, to better simulate geologic models with sharp or gradational boundaries according to the user's preference, 2) the option to use a non-zero starting model to incorporate a priori knowledge, 3) the ability to include a reference model in the objective function that may help reconcile models from complimentary disciplines, 4) the option to designate cells as active or inactive in the inversion. The modular framework also allows inversion of other geophysical datasets. SimPEG is Python based, meaning it is free and platform independent, allowing the user to have a seamless work-flow within the Python environment, from data processing to inversion, visualisation and interpretation.

Gravity surveys are well suited for rapid reconnaissance of shallow magmatic systems as the data are quick to acquire, and inversion models are fast to run. Using whole rock geochemistry data for input into MELTS, combined gravity and thermodynamic modelling provide insights into the present state of a magmatic system and the hazard it presents. Importantly, the combined analysis may offer significantly different interpretations than if the gravity data are considered in isolation. We apply this method to image a shallow rhyolite magma reservoir beneath the Laguna del Maule volcanic field (LdMVF) and determine its key physical properties.

The LdMVF is located on the range crest of the southern Andes at 36°S, bordering Chile and Argentina and is geographically characterised by a lake enlarged around 19 ka, following the damming of its outlet by the Espejos rhyolite lava flow (unit *rle*). The LdMVF comprises the largest concentration of high silica rhyolite in the Andes with at least 50 post-glacial eruptions since 25 ka; including four between 3.3 and 2.1 ka (units *rsl, rcd, rln* and western *rcb*) (Andersen et al., 2016). These eruptions were from 24 vents and produced 15 rhyodacite, and 24 rhyolite lava flows and domes (Singer et al., 2014). The position of the eruptive units and post-glacial vents is shown in Fig. 1. Previous large volume silicic eruptions include a dacite ignimbrite at 1.5 Ma (*igsp*), and a rhyo-

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