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Lateral magma propagation during the emplacement of La Gloria Pluton, central Chile

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ABSTRACT

La Gloria Pluton (LGP) in central Chile is a shallow, north-northwest–elongated granitoid body of 18 km length and 4–6 km width, belonging to a regional north-south trend of Miocene plutons, from the San Francisco Batholith and porphyries in the north, to Mesón Alto, and San Gabriel in the south. New U-Pb zircon ages of the LGP indicate that crystallization occurred mostly within an interval between 11.3–10.2 Ma, with a pattern of decreasing ages along the pluton axis from south to north. The progression of zircon ages can be explained either by gradual northwestward migration of the feeder zone that supplied magma to the shallow pluton or, more likely, by shallow lateral magma propagation southeastward from a fixed feeder zone located beneath the northern margin of the pluton. The age progression, together with existing data of subhorizontal mineral and magnetic lineations in the LGP parallel to the pluton axis, indicate lateral propagation of magma during reservoir construction along the hinge of an anticline of the volcanic host sequences. In addition to controlling the position of possible volcanic output, such horizontal migration of silicic magmas in the upper crust significantly increases the surface footprint over which fluids are exsolved and outgas, strongly decreasing the potential for magmatic–hydrothermal ore formation above laterally emplaced laccoliths in the shallow crust.

INTRODUCTION

Magma flow through the crust is typically directed vertically by dikes or diapirs, although lateral emplacement can occur in sills during shallow magma reservoir construction (Gudmundsson, 2011). Examples of such lateral propagation of magma have been recognized in both volcanic (Cole et al., 2010) and plutonic (Johnson et al., 2003; Stevenson et al., 2007) environments. The change from vertical to horizontal propagation can be induced by a number of factors, including (1) a decrease of the effective density contrast between magma and the host rock (Brown and Solar, 1998); (2) changes in the stress regime (e.g., stress barriers, changes on the local stress field, etc.) or in magma overpressure (Rubin, 1995; Watanabe et al., 1999; Gudmundsson, 2006, 2011), and (3) rheological variations of the host rock as a consequence of lithological heterogeneities (Brown and Solar, 1998; Hogan et al., 1998; Kavanagh et al., 2006; Rivalta et al., 2015). Large-scale horizontal diversion of the magma flow in the upper crust can have important consequences for (1) the positions of volcanic edifices (Gudmundsson, 2006; Kiser et al., 2016), and (2) the potential of forming porphyry-epithermal ore deposits (Richards, 2003). In this paper, we combine previous compositional, mineralogical, magnetic, and structural data with new laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) and isotope dilution–thermal ionization mass spectrometry (ID-TIMS) U-Pb zircon ages in the La Gloria Pluton (central Chilean Andes) to document a remarkable case of lateral magma propagation in the upper crust. Such a combination of techniques on a young, well-preserved, and well-exposed pluton allows unprecedented insight into its emplacement and solidification dynamics.

LA GLORIA PLUTON

The La Gloria Pluton (LGP) is a ca. 10–11 Ma (Deckart et al., 2010), shallow, north-northwest–elongated body of 18 km length, 4–6 km width, and at least 2.5 km thickness (based on exposures), belonging to a north-south–trending Miocene plutonic belt in central Chile (Fig. 1). These Miocene plutons intrude into two Tertiary volcanic formations (Abanico

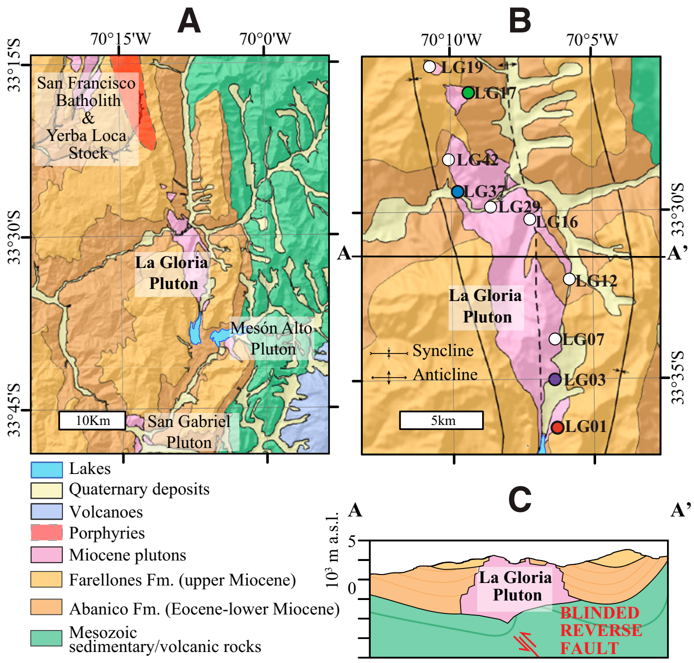

Figure 1. Geological maps showing the Miocene plutons in central Chile. A: Regional map. La Gloria Pluton is part of a north-south belt of felsic intrusive bodies of similar ages. B: Local map with sample (LGxx) locations. C: Schematic profile through the La Gloria Pluton. a.s.l.—above sea level; Fm.—Formation.

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and Farellones Formations; Fig. 1) deposited in continental basins during and after an inferred culmination of crustal extension and thinning (Nyström et al., 2003). The LGP was emplaced in the hinge zone of a north-northwest–trending anticline during the Late Neogene crustal shortening (Armijo et al., 2010; Farías et al., 2010), a consequence of Juan Fernandez Ridge collision at ca. 15 Ma (Yáñez et al., 2002), which may also be linked to regional ore deposit formation (Rosenbaum et al., 2005).

The LGP is slightly compositionally zoned with quartz monzodiorite and subordinate granodiorite in the core, and quartz monzonite and minor granite at the margins (Cornejo and Mahood, 1997). It also shows many leucocratic dikes at its margins, thought to represent melts extracted from the core of the pluton (Mahood and Cornejo, 1992; Aravena et al., 2017). Anisotropy of magnetic susceptibility data of the LGP indicate an oblate magnetic fabric, which has been interpreted as the record of the last increment of strain induced by convective currents inside the cooling and crystallizing magma reservoir (Gutiérrez et al., 2013). Additionally, mineralogical lineation indicates a mostly subhorizontal NNW-SSE direction following the LGP elongation, suggesting that the LGP was emplaced by lateral magma propagation (Payacán et al., 2014). Assuming that most crystallization occurs at the shallow level, we hypothesized that one could evaluate the direction and tempo of this lateral magma reservoir growth by zircon geochronology. To this end, we performed U-Pb dating of zircon crystals extracted from ten samples collected along the whole length of the LGP (Fig. 1B).

U-PB GEOCHRONOLOGY

Analytical Procedures

Zircons separated using routine methods were mounted in epoxy resin, polished, characterized by cathodoluminescence imaging, and analyzed *in situ* for U-Pb by LA-ICP-MS at ETH Zürich (Switzerland). A separate subset of whole zircon crystals from four samples spanning the entire LGP age range was also analyzed by chemical abrasion–ID-TIMS at ETH Zürich, following methods described in detail by Szymanowski et al. (2017). Detailed parameters of LA-ICP-MS analyses following community-derived standards (Horstwood et al., 2016) and all geochronology results can be found in the GSA Data Repository[1].

Results

LA-ICP-MS U-Pb zircon dates of ten samples from across the LGP exhibit a clear younging pattern from the south to the north of the pluton (Fig. 2A). Zircon dates from individual samples have considerable levels of age dispersion (mean square weighted deviation [MSWD] between 1.3 and 6.2; Items DR1–DR3 in the Data Repository) suggesting protracted crystallization histories within individual portions of the pluton. While in most cases no statistically significant differences are observed between adjacent samples in the LA-ICP-MS dating results (Fig. 2A), average sample ages unequivocally follow a pattern of northward younging of the LGP, consistent with previous conclusions based on magmatic and magnetic textures (Gutiérrez et al., 2013; Payacán et al., 2014).

ID-TIMS dates from four LGP samples (Fig. 2B) strongly support the northward younging trend shown by LA-ICP-MS ages. High-precision dating (Item DR4) demonstrates that zircon crystallization occurred during ~1 m.y., mostly within an interval between 11.3 and 10.2 Ma. The final solidification ages approximated by the youngest grain dates range from 11.229 ± 0.015 Ma in the extreme south (sample LG01) to 10.221 ± 0.018 Ma in the north (sample LG17), indicating an along-pluton age progression of ~19 km/m.y. The ranges of individual dates within single samples show that the sampled domains of the pluton remained around the zircon crystallization window (below the zircon saturation temperature of ~740–810 °C; Watson and Harrison, 1983) for ~40–200 k.y.; however, the small number of analyses (n = 5–6) likely makes these time scales underestimates of the true durations. Samples at both the north and the south margin return distinctly shorter apparent zircon crystallization durations of 39 ± 23 k.y. (sample LG01) and 47 ± 23 k.y. (LG17), which is consistent with their emplacement as endmembers in either initially cool (LG01) or already largely cooled surrounding crust (LG17). In contrast, samples from the pluton center have longer apparent zircon crystallization durations of 118 ± 18 k.y. (LG37) and 197 ± 19 k.y. (LG03). In addition, lower bulk-crystal Th/U ratios of zircons from the pluton center (Fig. DR1) suggest greater amounts of crystallization of a mineral assemblage including high-Th/U phases (such as titanite or allanite; Cornejo and Mahood, 1997) consistent with the longer supersolidus lifetime of those magma volumes.

DISCUSSION

Conditions and Emplacement Scenarios for Lateral Magma Propagation

Previous interpretations for the emplacement of the LGP based on mineral and magnetic fabrics (Gutiérrez et al., 2013; Payacán et al., 2014) are consistent with the zircon age-based lateral magma propagation. We suggest that a structure/rheological trap in the host rocks dominantly controlled the depth and style of emplacement; the LGP is found in the hinge of an anticline, over a blind reverse fault in the folded Tertiary formations (Riesner et al., 2018), which led to its elongated shape (Fig. 1). Although both formations are lithologically similar, the older Abanico Formation displays stronger deformation than the overlying Farellones

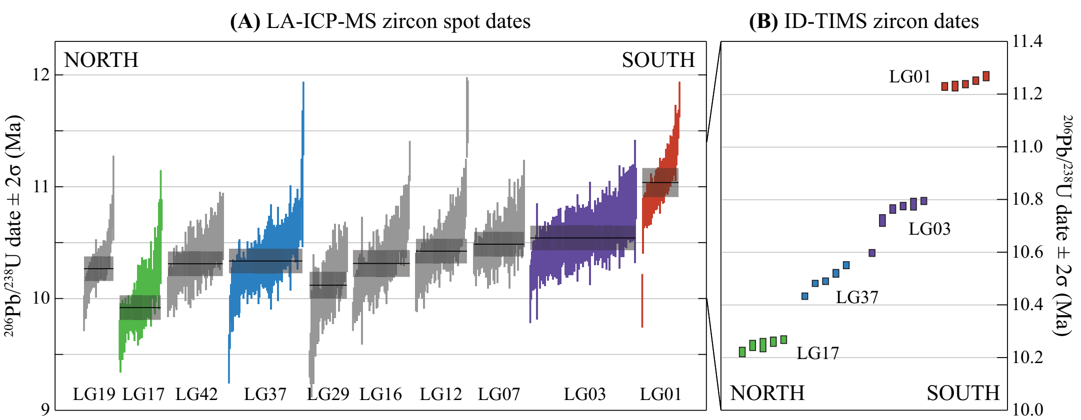

Figure 2. U-Pb zircon geochronology of the La Gloria Pluton, central Chile. A: Rank-ordered laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) zircon spot dates with sample weighted means (2σ uncertainty). LGxx denote sample numbers. B: Isotope dilution–thermal ionization mass spectrometry (ID-TIMS) zircon dates of single crystals. Samples are ordered from north to south; the height of individual bars represents 2σ uncertainty.

[1]GSA Data Repository item 2018398, description of the LA-ICP-MS U-Pb methodology, and Tables DR2 (LA-ICP-MS metadata), DR3 (LA-ICP-MS data); and DR4 (ID-TIMS data), is available online at http://www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org.

Formation (Nyström et al., 2003) that served as the roof of the LGP; the Farellones Formation was less fractured and therefore served as a cap/trap for magma emplacement.

Using mineral and magnetic fabrics, together with within-pluton age distribution, we envision two possible endmember scenarios for LGP emplacement (Fig. 3): (1) the LGP represents a horizontal, laterally emplaced, conduit-like magma reservoir, which was progressively filled from a fixed feeder zone located beneath the northern margin of the pluton; or (2) the LGP was built from a northwestward-migrating feeder zone.

In the first scenario (Fig. 3A), zircon-undersaturated magma would ascend to a shallow level before propagating laterally southward in the hinge of the anticline (formation of a laccolith). The magma is likely to reach both zircon saturation and solidification first at the southern tip of the body, recording the oldest ages. As more magma is emplaced from an upwelling source in the north, the cooling front migrates northward, locking the observed *in situ* zircon age progression within the reservoir. Some zircons may have crystallized early on at the edge of the reservoir in the northern section, and crystal entrainment could have occurred in later pulses, but we expect that this process was limited, as it would have significantly blurred the observed age zonation.

In the second scenario (Fig. 3B), several discrete batches are emplaced from a northward-moving upwelling source. This option requires that all batches of a similar magma are independently emplaced at the same depth to form a single reservoir, whereas the structural conduit is progressively migrating north as the reservoir develops. Migration of the feeder zone must follow a preexisting regional structure; for example, the blind reverse fault related to the anticline system (Fig. 1C).

Given (1) the absence of sharp internal contacts within the pluton, (2) absence of evidence for feeder zones in the field, (3) the well-characterized mineral and magnetic fabrics and narrow range (61–65 wt% SiO_2) of compositions (Cornejo and Mahood, 1997) requiring both lateral propagation and homogenization (Gutiérrez et al., 2013; Payacán et al., 2014), (4) the elongated channel-like geometry of the LGP (rather than discrete lobes), (5) the long crystallization durations of at least 100–200 k.y. in the pluton center, and (6) consistently lower zircon Th/U ratios in samples from the middle of the pluton (Fig. DR1), we conclude that the LGP was most likely emplaced by lateral transport from a source at its northern margin (scenario 1 in Fig. 3). However, we stress that the whole body may not have been emplaced as one pulse, but it rather involved fluctuation of the magma injection rate into the developing laccolith. The long minimum crystallization durations at sample scale in the pluton center require that the shallow magma body was maintained in a partially molten state over time scales longer than the modeled solidification time of individual batches (~10^4 yr; Gutiérrez et al. 2013).

Consequences of Lateral Propagation

The La Gloria Pluton likely represents the upper parts of an extensive magmatic differentiation column with deep roots in the lower to mid-crust. These columns have generally been considered as vertical structures (Bachmann and Huber, 2016; Cashman et al., 2017). However, lateral movements of magmas as they are emplaced in the crust can have important repercussions, both for volcanic processes and for the likelihood of forming economic ore deposits. The low-density magmatic volatile phase exsolving within those crustal columns is typically more concentrated in the apex of such columns, as it outgasses toward the surface (see Sillitoe, 2010; Weis et al., 2012). Any inclined magmatic column or lateral propagation of magma may dilute outgassing of this metal-carrying volatile phase at a given location, reducing the capacity of a magmatic system to form economically important ore bodies despite suitable tectonic and magmatic conditions. Hence, long-lived, vertical advective systems might favor focusing of fluids (Heinrich and Candela, 2014; Chiaradia and Caricchi, 2017) and the construction of large ore deposits above large plutonic complexes. In contrast, shorter-lived shallow silicic magma bodies that are horizontally emplaced in the upper crust, effectively forming large sills or laccoliths, dilute exsolved fluids and may lead to more barren conditions (Fig. 3). We propose here that lateral magma propagation, such as the one documented here for the LGP, may have a profound effect of reducing the ore-forming potential of magmatic-hydrothermal systems irrespective of their initial metal endowment.

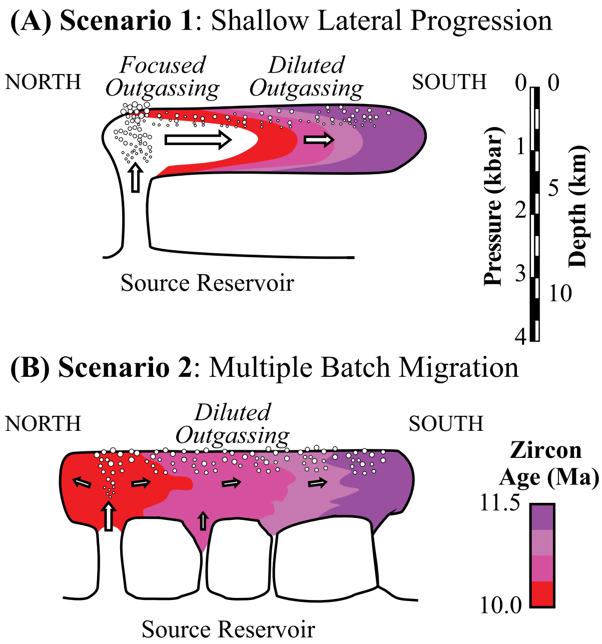

Figure 3. Two possible endmember emplacement scenarios explaining the zircon age progression of La Gloria Pluton, central Chile. A: Scenario 1—*In situ* lateral progression of the cooling front from the boundaries inward into the shallow reservoir. Magma flow from a feeder at the north of the reservoir allows later cooling of its northern end. B: Scenario 2—Multiple batches of magma are emplaced sequentially at the same depth, leaving magma lobes of different ages. Feeders of the different pulses are closed northward, allowing the pulses to be younger at the north of the shallow reservoir.

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