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The role of magma mixing in the evolution of the Early Paleozoic calc-alkaline granitoid suites. Eastern magmatic belt, Puna, NW Argentina

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A B S T R A C T

The outcrops of the Eastern magmatic belt in Puna, NW Argentina, offer an excellent field laboratory to study the interaction processes between magmas of contrasting composition in a plutonic environment. We evaluate the genesis of Cambrian-Ordovician intermediate to acid rocks from the Diablillos Intrusive Complex and the Cerro Bayo area, through detailed geological, petrographic, mineralogical, geochemical, and Nd isotopic analyses in combination with published data. These localities display a great variety of magmatic rocks from diorite/Qz-diorite to two-mica syenogranites with tonalite, granodiorite, monzogranite and Bt-Ttn-leucogranites as mixed products. Major, trace element and whole-rock Nd isotope modeling and petrological data, suggests that magma mixing between hydrous juvenile mantle- and crustal-derived magmas contributed significantly to the geochemical variation of these granites. The estimated proportion of mafic component 0.40–0.67 and 0.14–0.35 in the mixtures may produce the tonalite-granodiorites and monzogranites magmas. The mixing model excludes the predominant influence of fractional crystallization from a mafic magma and local assimilation-fractional-crystallization processes. Isotopic and geochemical comparison between the studied rocks and the magmatic belts in Puna and Tastil batholith suites reveals a marked resemblance. The data suggests that those rocks were probably generated by magma mixing and denotes a regionally and continuous process in a long-lasting (~540-440 Ma) active continental margin. We propose that partial melting of the crust and magma mixing occurred in the lower crust and was possibly triggered by underplated and intraplated hydrous (4.37–5.91 wt% H_2O) mafic magmas. The hybrid magmas were emplaced at shallow depth (~8–9 km, 684–727 °C) and occasionally injected either by synplutonic-to late successive pulses of mafic magmas.

1. Introduction

Petrologists have invoked a range of processes, including fractional crystallization, assimilation, crustal melting, and magma mixing, to explain the compositional diversity among plutonic rocks of the continental crust. The high-K calc-alkaline granites are often considered as “hybrid” in origin, and involving both mantle and crustal-derived components in their petrogenesis (e.g. Barbarin and Didier, 1992). The interactions between both components either occur at deep crust level related to crustal contamination and/or magma mixing with crustal melts, or by magma mingling and local mixing at the emplacement level. Magma mixing has been mentioned to explain the compositional range of high-K calc-alkaline suites, mainly intermediate to acid composition (SiO_2 = 60–75 wt%) that constitute the Western and Eastern magmatic belts in Puna, NW Argentina (e.g. Otamendi et al., 2010). However, this interpretation has been extended from the mixing model of Early Ordovician intermediate to acid plutonism from Valle Fértil-La Huerta (deep-seated crustal section, Otamendi et al., 2009) considering only isotopic and some major elemental composition from Puna magmatic suites. Alternatively, intermediate and acid plutonic rocks from the magmatic belt in Puna, might be the result of crustal recycling processes with minor contribution of juvenile mantle-derived magmas (Becchio et al., 1999; Lucassen et al., 2000; Viramonte et al., 2007) or they could represent fractionated liquids derived from a parental magma of broadly diorite

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composition (e.g. Castro et al., 2014; Bellos et al., 2015). In order to account the high FeO_t-MgO-K_2O, other alternative would the origin by "ferrosilicic magmatism" related to particular petrogenetic models with near-total melting (80–90%) of crustal sources under very high P-T conditions (1000 °C–1200 °C and 1.0–2.0 GPa; Fernández et al., 2008; Castro et al., 2009). Finally, magmatic suite from Puna might results by assimilation of larger amounts of sedimentary, igneous (magmatic enclaves or restite) or local metamorphic country rocks during magma evolution and ascent (e.g. Bahlburg et al., 2016). Thus, considerable uncertainties and controversies remain inconclusive regarding the petrogenesis of the magmatic belts in Puna, particularly on the geochemistry features and volumetrically dominant and spatially extensive intermediate-acid rocks. Coeval mafic and felsic igneous rock associations in the Early Paleozoic Puna magmatic arc and the inference for magma mingling/mixing phenomena is widely reported and documented in the geological literature (e.g. Poma et al., 2004; Coira et al., 2009; Viramonte et al., 2007). However, direct field evidence and detailed study of magma mixing process are scarce (Suzaño et al., 2015). This study addresses on the role of magma mixing process in the origin and evolution of Cambrian-Ordovician intermediate to acid rocks from the Diablillos Intrusive Complex (CID) and the Cerro Bayo area (CBA), southeastern Puna, NW Argentina (Fig. 1). Excellent examples showing the coexistence of magmas of contrasting composition both, in outcrop and mineral scale, give us an opportunity to observe direct evidence for the mixing process. In this paper, we report field, textural, geochemical (elemental and whole-rock isotope Nd), mineral chemistry evidence for magma mixing. For the Nd isotope and mineral chemistry constraints, we focused on Late Cambrian (501 ± 17 Ma, Suzaño et al., 2015) high-K, calc-alkaline suite from the CID. Geochemical (whole-rock major, trace and Sm-Nd data) modeling suggests that mixing is the most likely process explaining the observed compositional variation of the analyzed localities. Also, we applied a mixing test (Fourcade and Allegre, 1981) in order to estimate the proportion of mafic components needed to produce intermediate to acid magmas using a local end-members (hybridized MME and a two-mica syenogranite). The mixing model excludes the predominant influence of fractional crystallization from a mafic magma, as well as local assimilation-fractional-crystallization processes in the genesis of the intermediate-acid magmas. Furthermore, our study, in combination with previously published isotopic compositions and geochemical data reveals marked resemblance between the CID, CBA and those associated with the Eastern magmatic belt in Puna and Tastil batholith (Puna-Eastern Cordillera border, Fig. 1). We interpreted that the mechanisms observed in the CID and CBA related to magma mixing would explain the origin and magmatic evolution of the granites from the Eastern Magmatic belt and Tastil batholith.

2. Geological setting

2.1. Geological framework and tectonic setting

The pre-Andean basement in the central Andes consists mainly of Proterozoic–Paleozoic metamorphic rocks and associated granites. Tectonomorphic provinces of the central Andean include, from west to east (Fig. 1); (1) the Puna, a relatively high plateau (average elevation ~4 km) region of internal drainage, where Cenozoic sedimentary and volcanic rocks bury Neoproterozoic-Early Paleozoic low to-high metamorphic-igneous basement outcrops. (2) The Eastern Cordillera, a topographically high, externally drained Cenozoic thrust belt with predominantly Lower Paleozoic shelf successions, and Neoproterozoic-Lowermost Cambrian low metamorphic grade basement intruded by Cambrian granites (e.g. Tastil batholith, 540-500 Ma, Hongn et al., 2010 and references therein). Hongn et al. (2010) determined that the called "Tilcarean arc (included of the Cachi-Palermo ranges, Fundiciones, Tipayoc Cañañí intrusives and Tastil batholiths (540-500 Ma, e.g. Hauser et al., 2011)" are considered as Famatinian granites and should not be integrated in the Pampean magmatic arc. (3) Finally, the Pampean Ranges, a topographically high, that extends from NW to central Argentina. The Pampean Ranges consist essentially on Neoproterozoic to Lower Paleozoic medium-high metamorphic rocks, intruded by Cambrian-Ordovician granitic plutons.

The evolution of pre-Andean basement during the Upper Proterozoic and Paleozoic is characterized by convergence along the proto-Pacific margin of Gondwana that generated two main orogenic cycles (Aceñolaza and Toselli, 1981): the Pampean (Upper Precambrian–Lower Cambrian) and Famatinian (Upper Cambrian–Lower Silurian). The Pampean and Famatinian metamorphic and magmatic crystallization ages are regionally and spatially overlapped in the western sections of the orogen (see Lucassen et al., 2011, 2000; Pankhurst et al., 2000; Lucassen and Becchio, 2003). Different authors have proposed diverse models to explain the origin of this basement, and those models involve subduction processes with the formation of magmatic arcs, followed by successive collision of peri-Gondwana or exotic terrenes (e.g. Loewy et al., 2004; Escayola et al., 2011; Hauser et al., 2011). Other authors question these collision models due to the lack of evidence and indicators for this process. Instead, it has been suggested, a geodynamic evolution dominated by intracrustal recycling with minor contributions of juvenile materials (Büttner et al., 2005; Becchio et al., 1999; Bock et al., 2000; Lucassen et al., 2000; among others), or by the intrusion of Early Ordovician mafic magmas at a similar rate to that estimated for present-day magmatic arcs (Otamendi et al., 2010). Lucassen et al. (2000) proposed for the Central Andean basement an evolution in a long-standing high-thermal gradient setting, whereby part of the Pampean and Famatinian cycles are not separate events but one non-differentiable event from 600 to 400 Ma.

At the latitude of the Puna (22°–26°S), the common metamorphic basement (Fig. 1) comprises low-to high-grade rocks with sedimentary protoliths (quartz feldspar-rich greywackes and shales) represented by the Puncoviscana Formation and high-grade metamorphic equivalent (Neoproterozoic to Lowermost Cambrian) and very low-to medium-grade Ordovician pelitic-greywacke units interbedded with felsic and basic volcanic rocks. Radiometric absolute dating of medium-to high-grade metamorphic basement with Sm/Nd and U–Pb metamorphic ages yield 515–500 Ma (Becchio et al., 1999; Lucassen et al., 2000; Lucassen and Becchio, 2003). Abundant Cambro-Ordovician granitic plutons (batholiths) and scarce basic dykes intrude this basement.

2.2. Puna magmatic belts

The magmatic belts in Puna (Fig. 1), a thick sequence of dominant acid magmatic rocks (Famatinian Cycle), are represented by two parallel N–S-trending belts; the "Faja Eruptiva de la Puna Occidental" (Palma et al., 1986; referred subsequently as Western belt) and the "Faja Eruptiva de la Puna Oriental" (Méndez, 1972; referred subsequently as Eastern belt). In general, the first one constitutes Ordovician volcanic rocks interbedded with sedimentary sequences and intruded by scarce shallow granites bodies (Pankhurst et al., 1998; Coira et al., 1999; Viramonte et al., 2007). The Western belt represents the northward extension of the Famatinian arc that outcrop along the type localities of the Sistema de Famatina exposed close to the Argentina-Chile-Bolivia borders (e.g. Bahlburg et al., 2016). In the southern most section of the Famatinian arc, deeper levels are exposed with granite–tonalite