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Petrology, geochemistry and thermobarometry of the northern area of the Flamenco pluton, Coastal Range batholith, northern Chile. A thermal approach to the emplacement processes in the Jurassic andean batholiths

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A B S T R A C T

The Flamenco pluton is part of a N–S alignment of Late Triassic to Early Jurassic intrusive belt comprising the westernmost part of the Coastal Range batholith in northern Chile. The Jurassic-Cretaceous voluminous magmatism related to subduction in the western active continental margin of Gondwana is emplaced in the predominantly metasedimentary Paleozoic host-rocks of the Las Tórtolas formation, which in the northern area of the Flamenco pluton present an intense deformation, including the Chañaral mélange.

Geochemically, the Flamenco pluton shows a wide compositional variability (SiO_2 between 48wt % and 67wt %). Gabbros, Qtz-diorites and tonalites, mesocratic and leucocratic granodiorites are classified as calc-alkaline, calcic, magnesian and metaluminous magmatism. Flamenco granitoids define cotectic linear evolution trends, typical of magmatic fractionation processes. Geochemical trends are consistent with magmas evolved from undersaturated and low-pressure melts, even though the absence of transitional contacts between intrusive units precludes in-situ fractionation. Although some granodioritic samples show crossed geochemical trends that point to the compositional field of metasediments, and large euhedral prismatic pinnite-biotite crystals, typical Crd pseudomorph, are observed in contact magmatic facies, geochemical assimilation processes are short range, and the occurrence of host-rocks xenoliths is limited to a few meters from the pluton contact.

A thermal approach to the emplacement process has been constrained through the thermobarometric results and a 2D thermo-numerical model of the contact aureole. Some Qtz-diorites and granodiorites located in the north area of the pluton exhibit granulitic textures as Hbl-Pl-Qtz triple junctions, poikiloblastic Kfs and Qtz recrystallization. The Hbl–Pl pairs have been used for the thermobarometric study of this metamorphic process, resulting granoblastic equilibrium temperatures between 770 and 790 °C, whereas Hbl–Pl pairs in domains that preserve the original igneous textures yield temperatures above 820 °C. This is characteristic of self-granulitization processes during the sequential emplacement of composite batholiths.

In addition, the thermal modeling was used in order to compare the expected and observed thermal contact aureole of the intrusive body. Model P-T conditions have been established between 3 and 4 kbars (extracted from the thermobarometric results), and temperatures between 1159 °C (*liquidus* temperature for a tonalitic composition) and 992 °C (fixed at the rheological threshold of a 50% crystal fraction). The thermal modeling estimates a homogeneous contact aureole, where the established temperatures for the melting reactions in the host-rocks are located at distances between 200 and 650 m from the magma chamber boundary, whereas the temperatures for Crd stabilization extend 1500 m far from the contact in the case of the emplacement at *liquidus* temperatures and 4 kbars. According to field observations, the contact aureole presents a scarce development in the northern area of the Flamenco pluton, with few

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migmatite outcrops and less than 1 Km in thickness for Crd-schists. However, in the southern contact, partially melted rocks are described at distances up to 2 km from the Flamenco pluton boundary.

The processes of self-granulitization and the differences between the observed and calculated (by the thermal modeling of one single pulse) contact aureole suggests a process of incremental emplacement for the Flamenco pluton, by accretion of magmatic pulses from north to south (in its current position), where the thermal maturity reached through the repeated magmatic intrusion generates a more extensive area of high-grade metamorphism.

1. Introduction

The Flamenco pluton is part of the numerous and discontinuous outcrops of Late Paleozoic to Mesozoic igneous rocks emplaced in the Paleozoic metasedimentary basement which, taken together, form the so-called Coastal Range in northern Chile (Brook et al., 1986). Specifically, granitoids that make up the Flamenco intrusive body are framed in the voluminous calc-alkaline arc magmatism of Jurassic-Cretaceous age owing to the Coastal Range batholith. This magmatism was generated along the western Gondwana margin because of the reactivation of subduction in an extensional to transtensional tectonic regime in the Early Jurassic (Mpodozis and Kay, 1990; Dallmeyer et al., 1996; Grocott and Taylor, 2002).

The subduction in convergent margins has been proposed as the most efficient and sustainable mechanism to generate new continental crust since the Late Proterozoic (Kemp and Hawkesworth, 2003; Castro, 2014), supported by the statistical frequency of U–Pb zircon ages obtained from the continental crust (Condie, 1998, 2000). Cortical growth is directly related to the magmatism associated with subduction zones that are active without pronounced breaks, such as on the western margin of South America during the Andean cycle (Von Huene and Scholl, 1991 Plank and Langmuir, 1998). Therefore, subduction is the main engine for calc-alkaline magmatism and the formation of large cordilleran-type batholiths (Wyllie et al., 1976; Wyllie, 1977). Low water content, hybrid geochemical signatures and high compositional homogeneity are essential features for assessing the conditions and the sources of cordilleran magmatism (Castro, 2013; Burgisser and Bergantz, 2011). Several models have been proposed to generate these geochemical characteristics, such as the repeated intrusion of basaltic sills in a fertile lower crust (Annen y Sparks, 2002), the partial melting of crustal andesitic protoliths controlled by peritectic paragenesis ("PAE": peritectic assemblage entraintment) (Clemens et al., 2011, 2012), and the off-crust generation from partial melting of metasediment-MORB mélanges or cold diapirs that are finally relaminated to the continental crust and separated into residues (lower crust mafic granulites) and liquids (cordilleran magmatism) (Castro, 2013, 2014).

Re-thinking the emplacement and formation of large batholiths through geochronological data and detailed field and seismic studies (Glazner et al., 2004; Coleman et al., 2004) has outpaced old ideas about instantaneous balloon-like plutons (Bohrson and Spera, 2001; Huppert and Sparks, 1998). Although the batholith building is nowadays a controversial subject among the petrology community, many authors propose that incremental growth of composite batholiths is accomplished through small discrete magmatic pulses or batches (i. e., Annen, 2011; Michaut and Jaupart, 2011; Menand et al., 2015) over more than 10^5 years according to new and precise geochronological studies (i. e., Miller et al., 2007, 2011; Díaz-Alvarado et al., 2013), as has been confirmed by incorporating the influence of temperature on the crystallinity and thermal conductivity, and the depths of emplacement to the models (Gelman et al., 2013). The positive correlation between the period of amalgamation and the size of the batholith has highlighted that the availability of magmas in the crust depends on the fertility of both mantle and crust and the convergence dynamics between plates in convergent margins (Saint Blanquat et al., 2011). Thus, according to thermo-numerical models, magmatic addition rates in extensional arcs are higher than in continental margins with stable or compressive geodynamic regimes (Vogt et al., 2012). However, calculations for estimating the volumes of magma fluxes ascending to the upper crust are particularly difficult to determine. Although subduction is active during tens of millions of years, volumetrically, most of the magma is emplaced during periods of 10–30 Ma (Paterson et al., 2011).

Processes such as magma differentiation, fractionation, high-grade metamorphism and assimilation of host rocks may occur at the emplacement level, not only in the source area, and they are closely related to the style and emplacement rate of the magma chamber (Annen, 2011). Hence, variations in magma fluxes and the incubation period required to establish high-grade conditions account for the simultaneous presence in magmatic arcs of both magma–magma relations during the main intrusive phases and self-granulitization processes in earlier magmatic pulses (Annen and Sparks, 2002; Castro et al., 2014). The shape and thickness of the thermal aureole associated with a growing igneous body during the amalgamation of magma pulses depends on the emplacement constraints described above in addition to the thermal and mineralogical characteristics of the host rocks (Annen, 2011). Although the volume and the spatial distribution of magmatic increments rather than the shape of individual pulses determines the sequential growth of large batholiths (Paterson et al., 2011), most models propose small tabular bodies with horizontal disposition (i. e., Annen et al., 2006; Annen, 2011; Díaz-Alvarado et al., 2013). Accordingly, the development of the metamorphic aureole depends on the relative location of successive laminar pulses, and an irregular and non-concentric aureole would be formed during over-, under- or intra-accretion (Annen, 2011; Menand et al., 2010). Therefore, the formation of high-grade metamorphic areas in the host-rocks during the batholithic sequential emplacement depends on the temperatures and periodicity of intrusive magma fluxes and the location of crustal rocks in relation to the intrusive sheets; these are mostly related to crustal-scale tectonic structures that can increase and sustain high-grade and hyper-solidus conditions in the host rocks and residual liquids, respectively (Díaz-Alvarado et al., 2012, 2013; Annen, 2011).

The degree of development of the metamorphic aureole and tectonics influence the anisotropy and the disgregation of the host rock, a major control in the magnitude of the interaction processes between the intrusive magma and crustal rocks at the emplacement level. Mechanical mixing and reactive bulk assimilation account for considerable in-situ geochemical variations (i. e., Beard et al., 2005; Saito et al., 2007; Díaz Alvarado et al., 2011).

In this study, we present the first complete geochemical data from Flamenco pluton granitoids. Field relations, petrographic