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Fractionation and incipient self-granulitization during deep-crust emplacement of Lower Ordovician Valle Fértil batholith at the Gondwana active margin of South America

Antonio Castro [a,*], Juan Díaz-Alvarado [b], Carlos Fernández [b]

[a] Unidad de Petrología Experimental, CSIC-Universidad de Huelva, Campus del Carmen, 21071 Huelva, Spain
[b] Departamento de Geodinámica y Paleontología, Universidad de Huelva, 21071 Huelva, Spain

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ABSTRACT

Large granite batholiths were emplaced at the Gondwana active margin during Lower Ordovician in South America. These have contributed to crustal growth by net addition of silicic rocks to the continental crust. New U–Pb SHRIMP zircon age determinations, together with thermobarometric and geochemical data, yield that batholith magma intrusion is the responsible of heating and self-granulitization of early gabbro pulses. Partially molten granulitic gabbros, which appear as either early intruded into the metasedimentary host or as large inclusions within the batholith-forming Qtz-diorites, contain Opx-bearing, trondhjemitic leucosomes surrounding Hbl + Opx + Pl mafic mesosomes forming typical agmatitic structures. Hornblende–Plagioclase equilibria, applied to mineral pairs of granoblastic aggregates in textural equilibrium of metagabbro mesosomes, yield temperatures in the range 850–910 °C for core-to-core pairs and in the range 1000–1075 °C for rim-to rim pairs, at pressures of about 0.7 GPa. SHRIMP zircon age revealed that the whole batholith was emplaced over a narrow time interval of 20 Ma from 465 to 485 Ma, with most ages clustered at about 470 Ma. The age of metagabbros is 473 ± 7 Ma for older zircons and 454 ± 4 for younger zircons. These ages are almost coincident within error with the age of host migmatites (477 ± 5 Ma) and those of batholith intrusion of 476 ± 9 Ma and 475 ± 3 Ma for Qtz-diorites and 475 ± 5 Ma for granites. Zircon overgrowths of these intrusive rocks yield sages clustered around 450 Ma, revealing a protracted thermal history, more complex than previously believed. The geochemical study reveals that Qtz-diorites, tonalites and granodiorites form a continuous trend produced by magmatic fractionation from a parental dioritic magma. A weak adakitic tendency, with Sr/Y > 15 in several samples, implies the presence of Grt in the source or magma chamber at a minimum pressure of 1.0 GPa, higher than the depth of emplacement at 0.7 GPa. The high temperature of magma emplacement, which induced the incipient self-granulitization of early magmatic pulses, together with the cotectic-like fractionation linking coeval Qtz-diorites, tonalites and granodiorites, is compatible with fractionation at the lower crust of a deep-generated, infracrustal, (sublithospheric?) intermediate magma.

1. Introduction

Petrology of lower crustal rocks is characterized by gabbroic to dioritic compositions and granulite facies metamorphic assemblages. These two features are pervasively recognized in lower arc crust sections [e.g. Kohistan: (DeBari and Sleep, 1991; Garrido et al., 2006; Green et al., 2006; Dhuime et al., 2009; Jagoutz and Schmidt, 2012); Talkeetna: (DeBari and Sleep, 1991; Green et al., 2006) and Black Canyon in North America: (Duebendorfer et al., 2001; Jessup et al., 2005)], as well as in lower crust xenoliths transported by basalts to the surface (Al-Mishwat and Nasir, 2004; Huang et al., 2004; Zheng et al., 2006; Lee et al., 2007; Ying et al., 2010; Castro et al., 2011; Liu et al., 2012). The meaning of a lower crust with a quasi-basaltic chemical composition is under debate. The possibility that lower crust represents solid residues left after granite magma segregation that forms upper crust batholiths (Castro et al., 2010, 2011) is compatible with restite-melt compositional relations of andesite systems (Castro et al., 2012) and with the arrival of already fractionated magmatic materials from the underlying mantle as "cold-diapirs", which were previously uprooted as Rayleigh–Taylor instabilities from the subduction channel (Gerya and Yuen, 2003; Gerya et al., 2004; Vogt et al., 2012). Improving the knowledge of batholith magma generation and granulite–granite relations will be of great help to understand processes of new crust generation. Ultimately, all these processes converge in producing remobilization and differentiation of the continental crust through geological time. However, the intricacies of the mechanisms of crustal differentiation from the mantle remain under debate. Whether magma precursors feeding arc magmatism are produced by interaction of subducted materials and

* Corresponding author.
E-mail address: dorado@uhu.es (A. Castro).

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the overlying mantle wedge, or by contrast, they are mantle-derived magmas that undergo modifications by interaction with the continental crust, is a largely debated topic. The former possibility is supported by thermomechanical models of subduction at active margins (Gerya and Meilick, 2011; Vogt et al., 2012).

Although these new models receive important support from phase equilibria experiments and the bulk chemical compositions of subducted mélanges, which are coincident with the average andesite composition of the continental crust (Rudnick and Gao, 2003) and mature intraoceanic arcs (Jagoutz and Schmidt, 2012), they must be tested by field-based studies of large batholith intrusions and related granulite terranes. We show here new data from the Valle Fértil calc-alkaline batholith, developed at the Gondwana active margin during Lower Ordovician times as a part of the Ordovician Famatina arc system that extends for more than 1500 km in Argentina. Some features are peculiar in the studied batholith, which make it of great interest to test crustal making processes (e.g. Otamendi et al., 2009a, 2009b, 2012). Among these peculiar features are (1) the depth of emplacement in the middle to lower crust, (2) the presence of abundant gabbros and diorites associated to tonalite and granodiorite intrusions, (3) and the development of high temperature metamorphic aureoles in the country rocks. We report here field relations, thermo-barometry data and accurate SHRIMP U–Pb zircon geochronology that account for a metamorphism by dehydration melting of early gabbros, which is coeval with the intrusion of the Qtz-diorite–tonalite–granodiorite batholith. We identify a process of incipient self-granulitization that is compatible with the high temperature of emplacement of the whole batholith. The main implication is that generation of new crust is accomplished by the arrival of large batholithic masses to the continental margin, which transport advective heat to the new crust and induce metamorphic reactions in the earlier magmatic rocks of the same magmatic event. Generation of batholiths within the continental crust is seriously questioned according to these data. By contrast, batholith magma generation in mantle-wedge plumes (Castro et al., 2010, 2012; Vogt et al., 2012) is the most suitable scenario to account for the observed chronologic, structural and petrologic data.

2. Geological setting

Two main magmatic events are recognized in the region during Lower Paleozoic: the Pampean (Cambrian) and Famatinian (Ordovician). The generation of calc-alkaline batholiths is a characteristic feature of both events resulting from subduction along the proto-margin of South America (Pankhurst et al., 1998; Lucassen and Franz, 2005; Chew et al., 2007) via subduction of the Iapetus Ocean. The end of this stage (450–420 Ma) is indicated by the development of mylonitic shear zones, which are generated by the oblique collision of the Precordillera Terrane with respect to the Gondwana margin (Baldo et al., 1999).

The Famatinian magmatic belt in western Argentina represents an exhumed section of a Late Cambrian–Middle Ordovician arc formed by subduction beneath the Gondwana margin (Toselli et al., 1996; Pankhurst et al., 1998; De los Hoys et al., 2011). Magmatic rocks are exposed along a distance of more than 1500 km. The deep-seated levels of the arc form a N–S striking belt of batholiths extending for about 600 km. The evolution of the Famatina magmatic arc is linked to the plate tectonic evolution of Gondwana during Lower Paleozoic. A microplate (Cuyania) was docked along the Gondwana margin about 460 Myr ago, when subduction-related magmatism ceased along the Famatinian segment of the Ordovician arc (Astini and Dávila, 2004). The shallowest part of the exposed section corresponds to its eastern boundary, whereas deeper levels of the Ordovician crust are exposed to the west (Otamendi et al., 2008, 2009b). In regard to geochronology, the crystallization age of many plutonic rocks of Valle Fértil and La Huerta mountains indicates clearly that magmatism was active between 490 and 460 Ma (Pontoriero and Castro de Machuca, 1999; Pankhurst et al., 2000). Specifically, U–Pb zircon crystallization ages of magmatic rocks from Valle Fértil area show that this section of the arc was built over a short time interval during the Ordovician, between 485 and 465 Ma (Ducea et al., 2010).

3. Geological and structural outlines of the Valle Fértil batholith

The Valle Fértil batholith (VFB), also called Valle Fértil arc crust section (Otamendi et al., 2009a, 2009b) is a large body of plutonic rocks, dominated by diorites, tonalites and granodiorites, that was emplaced during Lower Ordovician times at the margin of the Gondwana supercontinent in South America. The VFB is part of the Famatina arc magmatic system that extends for more than 1500 km from the southernmost intrusions of Sierras de la Huerta and Valle Fértil in San Juan Province until the northernmost volcanic complexes of Puna Eruptive band in Salta Province in Argentina (Fig. 1). The southern end of the arc shows the deepest rocks, well represented by the VFB studied in this paper.

The VFB forms a NNW–SSE elongated body of about 130 km length and 40 km width bounded by Andean contractive faults developed during Cenozoic to Holocene plate convergence. Intense mylonitization is localized in narrow bands of several meters separating non-deformed blocks where the original structures related to pre-syn- and post-emplacement tectonic are preserved. The magmatic and solid-state structures of the batholith show NW–SE trends, which approximately coincides with the attitude of the large-scale faults. Magmatic foliations, mylonitic shear zones and the most common azimuth of mafic dykes that crosscut the granitoids are N135E to N160E directed, with mostly subvertical dips. This pattern is consistent with the isoclinal folds measured in the batholith. Axial planes and axes of these isoclinal folds follow the trends described above. Batholithic units (Qtz-diorites, tonalites and granodiorites) show mostly transitional contacts with co-magmatic dykes and contain numerous mafic dykes and enclaves (Otamendi et al., 2009a, 2009b).

The batholith was originally mapped by Mirré (1976) stating the basis for further petrological and geochronological studies (e.g. Ducea et al., 2010; Otamendi et al., 2009b; Pankhurst et al., 2000). A relevant structural feature outcoming from the Mirré's map is the alternance of gabbros, tonalites and host migmatites in narrow bands. We have mapped in detail these alternating gabbro–migmatite bands in selected outcrops in order to know the mutual relations and implications. The results of this detailed study are shown in the next section. In general terms, the batholith shows an E–W asymmetrical zoning with mafic rocks (gabbros and diorites) at the west margin and the more felsic rocks (tonalites and granodiorites in the east margin, close to the town of San Agustín (Mirré, 1976; Fig. 1). In the east sector of the batholith, granodiorites and tonalites contain abundant mafic enclaves grouped in elongated swarms; in which gravity-related vertical magma movements were identified as top-to-down intrusions (Castro et al., 2008). These enclave swarms are nearly planar structures, elongated in horizontal section following a general NW–SE orientation, parallel to flow structures defined by planar biotite accumulations (schlieren), which in places are transitional to solid-state shear zones. These relations are compatible with the syn-kinematic emplacement of the VFB into a transcurrent dextral shear system, which has been related with crustal-scale shear zones that produced large-scale crustal displacement parallel to the active margin at the time of magma generation and batholith emplacement (Toselli et al., 1996).

Partially dismembered pelitic migmatites are abundant in the east sector. The presence of these xenoliths is correlated with the presence

Fig. 1. Geological map of Valle Fértil and La Huerta mountains. Insets show (a) the location of the study area in South America, and (b) the distribution of western Gondwana and Laurentia–Cuyania terranes in northwest and central Argentina, modified after Ducea et al. (2010). (c) The sketch map represents a compilation of geological sheets of Mirré (1976) and Furque et al. (2003). Sample locations are shown.