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The off-crust origin of granite batholiths

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A R T I C L E   I N F O

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Granitod batholiths of I-type features (mostly granodiorites and tonalites), and particularly those forming the large plutonic associations of active continental margins and intracontinental collisional belts, represent the most outstanding magmatic episodes occurred in the continental crust. The origin of magmas, however, remains controversial. The application of principles from phase equilibria is crucial to understand the problem of granitoid magma generation. An adequate comparison between rock compositions and experimental liquids has been addressed by using a projected compositional space in the plane F(Fe + Mg)–Anorthite–Orthoclase. Many calc-alkaline granitoid trends can be considered cotectic liquids. Assimilation of country rocks and other not-cotectic processes are identified in the projected diagram. The identification of cotectic patterns in batholith implies high temperatures of magma segregation and fractionation (or partial melting) from an intermediate (andesitic) source. The comparison of batholiths with lower crust granulites, in terms of major-element geochemistry, yields that both represent liquids and solid residues respectively from a common andesitic system. This is compatible with magmas being formed by melting, and eventual reaction with the peridotite mantle, of subducted mélanges that are finally relaminated as magmas to the lower crust. Thus, the off-crust generation of granitoids batholiths constitutes a new paradigm in which important geological implications can be satisfactorily explained. Geochemical features of Cordilleran-type batholiths are totally compatible with this new conception.

> Geology, as the science of Earth history, is prone to controversy. The study of history of any kind depends upon documents and records. For the history of the Earth's crust, these documents are the rocks and their reading and interpretation are often difficult operations.
>
> H.H. Read (1959) "The Granite Controversy"
>
> The method of science is tried and true. It is not perfect; it's just the best we have. And to abandon it with its skeptical protocols is the pathway to a dark age.

Carl Sagan (1997) "The Demon-Haunted World: Science as a Candle in the Dark"

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1. Introduction

Granites are among the most enigmatic rocks of the Earth's continental crust. They have been enigmatic for long time along the history of Geology and still they are in present days. Granite geology, similar to other problems related to the origin and evolution of the Earth, had its proper dark ages, where all kind of conjectures prevailed. Today, with application of advanced methods of modern Earth Sciences, particularly those provided by Mineral Thermodynamics, Geochemistry, Isotope Geology and Geophysics, we have a more accurate view of the granite problem and its implication in the origin of the continents (Taylor and McLennan, 1985; Windley, 1995). Experimental Petrology was the first light into the dark history of the granite controversy. Laboratory experiments are our particular "candle in the dark" that opened the new sight on granite magma generation and accounted for observed field relations and geochemical trends.

Granitic rocks, in contrast with other rock types forming the Earth's continental crust, have been subjects of several controversies along the recent history of Geology. A vigorous debate was leaded in the middle half of the past century by Norman L. Bowen

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and H.H. Read (see Gilluly, 1948). The debate confronted experimental petrology and field geology, crucibles and plutons. The acceptance of more than one granite generation mechanism, and hence more than one granite type ("granites and granites"; Read, 1948, 1957), spread some kind of peace. The experimental determination of fundamental phase relationships in the Ab-Or-Qtz-H_2O system (Tuttle and Bowen, 1958) opened a new window into the granite problem. However, this was a short-lived peace. Only very few granites can be produced at conditions of water saturation and very few have the composition of the granite minimum. The existence of different types of granites is an empirical fact. The S-I granite types (Chappell and White, 1974, 2001) and the anorogenic A-type (Loiselle and Wones, 1979; Bonin, 2007) are broadly recognized around the world. Although the recognition of several granite types is not a solution to the problem, the granite type classification is an important step to approach a global solution. An important advantage of the classification scheme is to set the granite problem at the scale of the whole continental crust as a function of the relative abundance of each granite type. Interestingly, the most enigmatic granites in relation to origin are the most abundant ones, those belonging to the I-type according to the Chappell-White's classification. This short review is focused on these I-type granitoids that not only from the Cordilleran-type batholiths, but also appear forming large post-collisional batholiths in intracontinental orogenic domains. The anatectic S-type granites, formed by partial melting of metasediments, and the anorogenic A-type granites are not included in this discussion. However, transitions between S- and I-types have been reported recently in large batholithic areas of Central Spain (Diaz-Alvarado et al., 2011) and the Famatinian magmatic arc in Argentina (Grosse et al., 2011), as well as between A- and I-types in Mesozoic metamorphic core complexes of large regions of NE Asia (Guo et al., 2012). Whilst S/I transitions are identified as the result of local assimilation of partially molten metasediments at the emplacement level of I-type batholiths, the generation of A/I transitions remains obscure in the same degree of uncertainty than the origin of A-type granites.

But, why these apparently simple rocks, mostly composed of quartz and feldspars, are so enigmatic? First, granites of the Cordilleran-type batholiths are not so simple as believed. Second, a solution to the problem of the origin can be given in the context of the new paradigm of arc magmatism, which is linked to a new conception of the thermal structure of the mantle in supra-subduction zones. I will show in this short review both facets of the problem: on one hand, the relative complexity of Cordilleran-type (i.e., I-type) granitic rocks and, on the other hand, the new genetic mechanisms emerging from thermomechanical models, which are pointing to an off-crust generation of batholiths.

2. Models for granitoid (granodiorite-tonalite) magma generation

In addressing the problem of granitoid (mostly granodiorite and tonalite) magma generation, we find two main handicaps: (1) Petrogenetic models based on experimental phase equilibria (e.g., Naney, 1983; Patiño Douce, 1995; Castro et al., 2010) require thermal conditions ($T > 1000$ °C) that are not prevailing within the continental crust. (2) Hypotheses to get abnormal T gradients in the crust by advective heating from the mantle by basalt underplating (e.g., Annen et al., 2006) do not receive support from geological data related to lower crust composition (Castro et al., 2013b). Consequently, the origin of granite batholiths remains enigmatic, full of controversial and subject to speculative models. An in-depth discussion of the varied models is out of scope of this review, which is focused on geological data supporting an off-crust generation of granite batholiths. However, a short discussion on the most classical "on-crust" models may help to better understanding of the proposed off-crust origin.

Any model for the generation of granite batholiths must account for essential natural observations. Several models have been proposed to account for the generation of granodiorite-tonalite magmas (Fig. 1). However, no one fully satisfies natural observations of batholiths. By contrast, they entail unrealistic and paradoxical implications, which will be discussed below. I will show here that all paradoxes about granite magma generation are solved, or dissolved, if granite sources are initially rooted within the mantle and not within the continental crust. Two large model categories are distinguished depending on the locus of magma generation. These are (1) on-crust models (Fig. 1a–c) and (2) off-crust models (Fig. 1d–f). On-crust models postulate batholith magma generation from lower crust rocks. By contrast, off-crust models propose the generation of parental andesite magmas by processes within the mantle by melting and/or reaction of subducted materials. Among the most relevant on-crust models (Fig. 1) we may mention (1) basaltic underplating and crustal delamination, (2) melting of the lower crust by intrusion of basalts, (3) crustal assimilation by basalt magmas and (4) magma mixing.

2.1. Basaltic underplating. A two-stage process

Basically, this model proposes that granite batholiths are generated in two stages from the mantle. In a first stage, basalts are generated by melting of the peridotite mantle and emplaced by underplating at the lower continental crust. In a second stage, basalts solidified and are partially molten to produce silicic melts that may form batholiths. Large tonalite intrusions from the Cordillera Blanca batholith are explained by this genetic mechanism (Petford and Atherton, 1996). The model was refined (Hawkesworth and Kemp, 2006) and applied as a general mechanism to generate the continental crust. The implication of granite magma generation from partial melting of underplated basalts at the lower crust is the formation of large volumes of ultramafic residues (about 70 wt.% of the intruding basalt), which are missing in the lower continental crust. Two possible solutions can be given to this paradoxical hypothesis. First, the ultramafic residues are missing because they have been sunk into the mantle by process of crustal delamination. Second, granites are not derived from melting, or incomplete crystallization, of underplated basalts at the lower crust. Delamination is an old concept (Bird, 1979) applied by Kay and Kay (1993) to account for a particular magmatism, supposedly unique, of the Puna region of Northern Argentina. A thickened lower crust is a necessary condition to increase the density of a lithosphere that otherwise is buoyant (Kay and Kay, 1993). The delamination hypothesis is supported by seismic evidence in Sierra Nevada, California (Gilbert et al., 2012). We may leave the debate on lithosphere delamination aside and ask a central question: are basalts able to fractionate to granite melts at the lower crust? The question received attention in several studies on mechanisms of new crust generation (e.g., Hawkesworth and Kemp, 2006; Lee et al., 2006, 2007; Castro et al., 2013b). Phase relations are crucial on this point. Olivine is not stable at the pressures of the lower crust and it is necessary to increase the silica of the residual melt without large depletion in Fe and Mg. The stable phase is pyroxene (Px) in a dry basalt system, and pyroxene crystallization slightly modifies the silica content of the residual liquid with respect to the initial basaltic composition (see crystallization modeling with MELTS code in Castro et al. (2013b)). It has been proposed, as a variant of the model, that water-bearing basalt is more favorable to fractionate to silicic (granitic) magmas (Thompson et al., 2002). However, the composition of residual liquids from a wet-basalt is not