The off-crust origin of granite batholiths

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Abstract

Granitoid 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 \(F(\text{Fe}^2+\text{Mg})-\text{Anorthite} - \text{Orthoclase}\). 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.

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...
and H.H. Read (see Gilluly, 1948). The debate confronted experimental petrology and field geology, crucibles and plutos. 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-Qz-H2O 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 granites that are related to the Cordilleran 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 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) granite 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 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 anesite 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 Punta 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
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<td>Melts from the slab react with the peridotite mantle and produce high-Mg andesites (blue). These fractionate within the crust, or in the way upwards through the mantle, to produce silicic-rich melts (batholiths) (red). The model accounts for isotopic features and thermomechanical models. HMA and equivalent plutonic (sanukitoids and appinites) are common in relation to batholiths.</td>
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<td>Water-rich picritic basalts (green) fractionate within the mantle to andesite melts (blue). These are underplated at the lower crust and fractionate again to silicic magmas of batholiths (red). An extra process of crustal assimilation is needed to account for geochemical and isotopic features of batholiths. High water contents not compatible with undersaturated character of batholiths.</td>
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<td>Delamination of lower crust and mantle lithosphere</td>
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Figure 1. Schematic representation of petrogenetic-tectonic models (not at scale) proposed for the generation of batholiths of calc-alkaline, Cordilleran-type affinities (I-type granites). Two large categories are distinguished depending on the locus of magma generation, on-crust (a–c) or off-crust (d–f). On-crust models postulate batholith magma generation by melting of lower crust rocks. These models need of an extra heat source that can be supplied by mantle-derived basalts (a). The required basalt:crust ratio of 2:1 is based on thermal modeling (Annen et al., 2006). Mantle upwelling due to lower crust delamination (b) has also been proposed in active margins (Kay and Kay, 1993) and in intracontinental orogens (e.g., North China; Zhai et al., 2007). The absence of basaltic magmatism and the low fertility of the refractory lower crust, are the two main handicaps of these on-crust models. Off-crust models propose the generation of parental andesite magmas by processes within the mantle by melting and/or reaction of subducted materials. Generation of high-Mg andesites (d) may occur in reaction channels within the mantle (Kelemen, 1995; Kelemen et al., 2003), involving melts and fluids from the subduction zone. The process is supported on recent data from numerical modeling (Vogt et al., 2013) and laboratory experiments (Castro et al., 2013a). Generation of andesites from wet basalt within the mantle may also produce the required silicic compositions that fractionate within the crust to generate batholiths (Alonso Perez et al., 2009). Finally, the generation of batholiths from melting of subducted mélanges (f) has been proposed as the most plausible explanation (see text for further explanations).
matching fundamental geochemical features of granite batholiths. Assimilation of crustal rocks is needed in these models to account for crustal features, such as high K and incompatible elements that characterize granite batholiths. Furthermore, the water content of the silica-rich granite liquid produced by fractionation of a wet basalt with a minimum initial water content of about 3 wt.% H2O, will be at saturation in the residual melt, which is completely unrealistic and far from the low water content that characterize Cordilleran-type granite batholiths. The application of this model to the water-rich granitoids of the Adameel massif (Thompson et al., 2002) seems to be a plausible explanation, but its application to the common water-undersaturated Cordilleran granites is unlike.

2.2. Lower crust melting

Because melting of the peridotite mantle cannot produce granite magma, partial melting of the lower crust is the most immediate explanation for the generation of silicic magmas that are emplaced in the middle and upper crust. It is proposed in these models that granite magmatism is produced at the lower crust by heating from deep asthenospheric mantle that replaces a supposedly delaminated lithosphere. Thus, the need for delamination is also present in these models. Alternatively, heating of the lower crust can be achieved by advective heat transport of mantle-derived basalt to the lower crust (Annen et al., 2006). According to these thermal models, a basalt-to-crust ratio of 2:1 is needed to reach the high temperatures required to get granodiorite and tonalite melts. Furthermore, it is assumed that lower crust is supposed fertile to produce the required granite magma compositions. Nonetheless, the expected high proportions of basaltic rocks are missing in the continental crust, and they never occur in large crustal regions that were pervasively invaded by granite batholiths (e.g. the active margins of the Americas; Pankhurst et al., 1999; Hervé et al., 2007; Lee et al., 2007; Crawford et al., 2009; Castro et al., 2011b) and the Mesozoic large igneous province of NE Asia (Guo et al., 2012). Are they also delaminated and sunk into the mantle? I have documented a case of melting of lower crust assisted by water- and K-rich fluids released from wet basalts intruding into tonalitic TTG gneisses from the Northern Highlands is Scotland (Castro, 2004). The process, however, needs of an already granitic source (TTG complexes) and cannot be applied to the Px-rich, mafic granulites that dominate the relatively more mafic (andesitic) post-Achaean lower continental crust.

2.3. Assimilation and magma mixing

Assimilation of upper crustal rocks by intruding granodiorite-tonalite batholiths is well documented in many granitic areas (Erdmann et al., 2007; Saito et al., 2007; Díaz-Alvarado et al., 2011). The process may be accomplished by means of reactive bulk-assimilation (Beard et al., 2005) without the implication of large energetic budget from the intruding magma. However, geological evidence is not in favor of assimilation as a mechanism to produce the I-type granodioride and tonalite rocks. Assimilation of crustal rocks by basaltic magmas has been tested experimentally as a mechanism able to produce granodiorite melts (Patiño-Douce, 1995; Castro et al., 1999). However, temperatures as high as 1000 ºC are still insufficient to produce tonalite and granodiorite melts matching the composition of batholiths.

Magma mixing and assimilation are normally identified as local phenomena that cannot be applied to account for the generation of granodiorite-tonalite rocks at the scale of batholiths (see discussions in Castro et al., 2010; Clemens and Stevens, 2012). Both processes have in common that they are not selective; they affect the whole compositions of the involved end-members. The implication is that compositional variations in major elements must be accompanied by similar variations in trace elements and isotopes. For instance, in a general diorite-tonalite-granodiorite-granite trend, the terms richer in K (granite) must be the richer in radiogenic 87Sr and poorer in radiogenic 143Nd, in agreement with predictions of the Sr-Nd isotope systematics. By contrast, the general observation is the existence of significant decoupling between major element contents and radiogenic isotopes. An example is the trend displayed in Sr-Nd initial isotope ratios by granitoids of the Patagonian batholith in South America (Pankhurst et al., 1999; Hervé et al., 2007) where granites with identical composition in terms of major elements plot either in the field of mantle-like sources or in the field of evolved crust. Geochemical decoupling is a characteristic feature of Cordilleran granite batholiths. The implication is that rocks represent coticetic liquids from heterogeneous sources, being the composition of liq-uids buffered by the co-existing solid assemblage over a wide range of source compositions (Castro et al., 2010). These observations are essential to constrain potential processes of granite magma generation with two additional implications. First, assimilation and magma mixing can be ruled out as general mechanisms able to produce granodiorite-tonalite magmas. Second, they imply that geochemical variations may be related to coticetic evolution of liq-uids in equilibrium with a changing solid assemblage. Evidences for such a behavior of I-type granite systems are given below.

3. Granodiorite-tonalite systems: magmas or liquids?

Identification of granodiorite-tonalite magmas as either liquids formed by coticetic magmatic systems or magma mushes carrying suspended mafic minerals, is an essential step previous to any discussion about processes of magma generation. Several experimental studies have been addressed to seek for conditions of granodiorite-tonalite liquid generation. Composite systems, containing crustal and mantle sources together are preferred in most experimental studies in order to satisfy the mantle/crust hybrid geochemical sig-natures, in terms of isotopic ratios, of I-type granitoids (Johnston and Wylie, 1988, 1989; Patiño-Douce, 1995; Castro et al., 1999). In gen-eral, the reported experimental melts in these studies are poorer in Fe and Mg compared to natural rocks. It was proposed partial entrainment of peritectic pyroxene (Castro et al., 1999, pag. 274), in a way similar to that proposed lately by Clemens and Stevens (2012), to account for the high Fe and Mg content of most granodiorite and tonalite rocks compared to experimental melts. Restite entrainment is well supported in S-type granitic rocks in which, maficity (expressed as the sum of molar Fe + Mg + Ti; Clemens et al., 2011) is positively correlated with Al saturation index, denoting the entrainment of peritectic minerals such as Grt and/or Cord, which supply jointly Fe + Mg and Al to the system. The application of peritectic restite entrainment to I-type granodiorites and tonalites is not straightforward. Simple mass balance yields that about 20 wt.% of orthopyroxene must be added to experimental granodiorite melts formed at 1000 ºC to increase their maficity to the normal values of I-type granodiorites (Castro et al., 1999). Nevertheless, the generation of these leucogranodiorite melts in equilibrium with pyroxene and plagioclase, either by breakdown of amphibole or by partial crystal-lization of an andesite system, requires temperatures of about 950–1000 ºC. That is, granodiorite melts may increase hypothetically their maficity by incorporating restitic pyroxene from the source, but temperature as high as 1000 ºC is required to get pyroxene in equi-librium with melt at the source. According to experiments, this required high temperature increases with increasing pressure. Addition of water may reduce the liquidus temperature at the same time that Fe and Mg increase their solubility by increasing the water content of the melts. However, a characteristic feature of I-type granitic magmas is strong water undersaturation, as it is...
demonstrated by the crystallization sequence with plagioclase, instead of amphibole, as the liquidus phase. Although some gain of maficity can be accomplished by peritectic restite entrainment, the observed chemical variation trends of batholiths strongly support the cotectic co-variation of Ca, Mg and Fe in tonalite-granodiorite systems. Identification of cotectic trends implies that compositional variations are controlled by the co-existing mineral assemblage, and this is in turn controlled by changes in intensive variables (particularly in $T$) as a result, of cooling and crystallization at the place of emplacement.

### 3.1. Granodiorites and tonalites as cotectic liquids

As granodiorite and tonalite contain a significant proportion of the minimum granite composition, the temperature required for magma generation may range from 650 °C at water saturated conditions to about 850 °C for water-undersaturated systems (at mid-crustal pressures of 600 MPa) inasmuch as the non-minimum components (NMC), namely Ca, Ti, Fe and Mg, are only contained in calcic and mafic minerals and transported as suspensions by the magmas from the source region. However, if these NMC components are dissolved in the melt, the corresponding temperatures can be considerably higher, up to about 1000 °C for water undersaturated conditions (Maaloe and Wyllie, 1975). The implication is that such a high temperature melts are unlikely produced by partial melting of crustal rocks, but they can be produced from andesitic magma systems that, after undergoing potential magmatic differentiation within the lithospheric mantle, can be finally fractionated into liquids and solid residues within the continental crust.

It is apparent from textures and phase equilibrium relationships of water-undersaturated melts (Maaloe and Wyllie, 1975; Naney, 1983) that hydrous mafic intrusions, namely biotite and amphibole, are late phases that precipitate from residual melts at the late stages of magma evolution. The point at which these hydrous ferromagnesian minerals start to precipitate in the magma depends on compositional factors, principally the initial water content, pressure and temperature. Experiments confirm that hydrous ferromagnesian minerals form as peritectic phases associated to the breakdown of pyroxenes in the course of cooling. The implication is that ferromagnesian minerals, either anhydrous or hydrous, are part of the coexisting assemblage over a wide crystallization interval from liquids to solidus in diorite-tonalite-granodiorite systems. Consequently, the composition of melts is controlled by phase equilibria. Consideration of granodiorite-tonalite rocks as either liquids or mechanical mixtures of crystals and low-temperature liquids requires a rigorous comparison of whole rocks and experimental glasses, in terms of major elements, on appropriate diagrams. It is proposed here a projection for calc-alkaline rocks and experimental glasses, in terms of major elements, on appropriate diagrams. It is proposed here a projection for calc-alkaline rocks and experimental glasses, in terms of major elements, on appropriate diagrams. It is proposed here a projection for calc-alkaline melts is controlled by phase equilibria. Consideration of granodiorite-tonalite systems. Whether Amp is early or late in the crystallization process, the cotectic co-variation of Ca, Mg and Fe in tonalite-granodiorite systems is almost parallel to the An-Or join and are related to the presence of Grt in the coexisting assemblage. These systems have in common the high pressure (>1.5 GPa) and low water content (ca. 1 wt.% H$_2$O). The third group is characterized by a gentler slope, compared with the former one, and by a curvilinear shape concave to the F apex. The common features of these systems are water undersaturation (1–2.5 wt.% H$_2$O) and low to moderate pressure (1.0–0.3 GPa). These are also characterized by the common presence of Hbl and Pl ($\pm$Bt, $\pm$Px) along a wide temperature interval along the cotectic lines. The diagram is robust to identify cotectic and non-cotectic relations. For instance, assimilation of country metasediments is easily identifiable by vectors (labeled a in Fig. 2b) departing from the cotectic array. Another non-cotectic pattern is formed by restite unmixing (labeled ru in Fig. 2b) commonly displayed by S-type granites in which incomplete separation of restite and melt produce particular patterns that are easily identified as non-cotectic in the diagram.

Projection of granodiorite samples from different calc-alkaline batholiths strongly suggests that they represent essentially liquids fractionated from a common magmatic source of broadly andesitic (Qtz-dioritic) composition.

### 4. Records of high temperature and high pressure in granitoids

Slow cooling is an intrinsic feature of plutonic rocks. The consequence is resetting of mineral-mineral and mineral-melt equilibria to near-solidus magmatic conditions of the early magmatic stages at the time of segregation from the source or fractionation in a deep-seated magma chamber. However, some relations survive partially as relics from the early magmatic stages, providing with important information on magmatic temperatures and initial water contents of the magma at the time of segregation. Depth is preserved as relations of particular trace elements that are partitioned into mineral phases whose stability field is mostly dependent on pressure. These are the Sr/Y and Ce/Yb ratios, which are strongly controlled by the presence of garnet in the source region. A detailed review on the meaning of the adakitic signature, emphasizing on cautions in handling these geochemical parameters, is given by Moyen (2009). Near-liquidus temperatures may be revealed by the presence of relic minerals that survived peritectic transformations in the course of slow cooling. Crystallization sequence is revealing initial water content in the magma systems.

#### 4.1. Crystallization sequence

Amphibole (Amp) is a common mafic mineral in I-type granodiorites and tonalites. Whether Amp is early or late in the crystallization
Assimilation natural mélanges (0.87 wt.% H₂O for a sediment fraction number 8 is the closest to the rock trend for the high silica rocks. Mineral abbreviations after Kretz (1983).

68 cotectic and not-cotectic (assimilation processes) of granodiorite and monzogranite rocks of the Gredos batholith in Central Spain (Diaz-Alvarado et al., 2011). In this case, cotectic crust contamination with pelitic host rocks. They may contain up to 40 wt.% of contaminant (red dashed curves and numbers beside in red). (d) Projection onto the same diagram of enclaves may represent the parental magmas of this batholith. Heterogenous granites with S/I transitional features (Grosse et al., 2011) of the same batholith are the result of upper 0.3 GPa and 2.5 wt.% water with a basalt-sediment mélange (Castro et al., 2013a). Composition of the starting material is represented by large blue star in the vectors dominated by assimilation of pelitic rocks and restite entrainment. (b) Tentative position of peritectic points and cotectic lines according to assemblages in experiments at Position of cotectic granodiorites from the Velasco batholith (Bellos et al., 2013). Large arrow indicates assimilation in samples departing from the low cotectic, number 7 in (a).

Textural relations are clearly indicating that Amp crystallized from the magma. However, crystallization is rarely early in the magmatic sequence, indicating that the initial water content of the magma was lower than the minimum water required to stabilize Amp. In the course of crystallization of plagioclase and pyroxene, the remaining liquid is becoming richer in water leading to amphibole saturation at any intermediate point of the crystallization sequence between liquidus and solidus. A rough estimation of the initial water content can be made by analyzing the crystallization sequence, which can be compared with predictions of experimental phase relations in T–XH₂O sections (e.g., Maaloe and Wyllie, 1975; Naney, 1983). According to experiments in granodiorite systems, the required water
content to stabilize Amp is of 4 wt.% H$_2$O at $P = 200$ MPa and 2.5 wt.% H$_2$O at $P = 800$ MPa (Naney, 1983). Amphibole crystals show typically anhedral crystalline habits in Cordilleran granodiorites and tonalites. Amphibole is late with respect to plagioclase in the crystallization sequence and it may show euhedral habit only in contact with quartz and/or alkali feldspar. Even in the particular cases, in which Amp is apparently euhedral, it shows molding relations against plagioclase and euhedral habit against quartz (Fig. 3), suggesting that Amp was not the liquidus phase of the system and, thus, that the initial water content of the magma was lower than that required to stabilize Amp. It is difficult to assess the liquid fraction of the magma at the time of Amp crystallization. In the reasonable case of 50 wt.% of plagioclase + pyroxene crystallization, the initial water content is half of the content required for Amp crystallization. This may range from 1.25 wt.% H$_2$O if crystallization proceeds at low pressure ($P = 200$ MPa) to 2 wt.% H$_2$O for deeper crystallization ($P = 800$ MPa), according to the above mentioned experimental requirements (Naney, 1983). These estimations imply high liquidus temperatures of more than 1000 °C for Amp-bearing granodiorite and tonalite liquids. Low temperature granodioritic liquids must have higher water content of around 11 wt.% H$_2$O at $T = 900$ °C and $P = 800$ MPa (Naney, 1983; his Fig. 4), a $T$ value considered as reasonable in anomalously low temperature granodioritic liquids.
Figure 4. (a) Pressure-temperature diagram showing relevant examples of lower crust granulites (xenoliths and lower crust sections). Temperatures of most granulite xenoliths exceed the buffering effect imposed by the amphibole breakdown reaction of amphibolites, expected to occur in case of a hypothetical amphibolitic lower crust. Data sources for granulites are labeled with numbers on the PT field of each xenoliths locality of lower crust region in (a). The same number refers to geochemical data analyses in (b). These are: 1. Pali Aike, Chile (Selverstone and Stern, 1983); 2. Mecaderes, Colombia (Weber et al., 2002); 3. Arabian plate (Al-Mishwat and Nasir, 2004); 4. Nushan, East China (Huang et al., 2004); 5. Junan, North China (Ying et al., 2010); 6. Patan-Dasu complex, Kohistan; 7. Jijal granulites, Kohistan (Yoshino and Okudaira, 2004); 8. Valle Fértil metagabbros, Argentina.
heated lower continental crust domains. This water-rich magma will stabilize Amp at its liquidus, earlier than plagioclase in the sequence. However, so high water contents are unrealistic according to textural relations (Fig. 3), which are characteristic of strongly water-undersaturated magma systems. The scarcity of pegmatites in I-type granites is in agreement with low water content in the magmas.

It is very common the presence of polycrystalline aggregates (clots) of Amp in I-type granodiorites and related enclaves. The detailed study of textural relations of these Amp clots helps to understand the formation of Amp during magma crystallization (Castro and Stephens, 1992). The presence of these clots is telling us that Amp was in equilibrium with the melt at least at the time of magma segregation. Whatever the origin of these clots as early phenocrysts or peritectic restites from the source (Stephens, 2001), they imply that temperature was high enough to stabilize Amp in a water-bearing magma system. According to experiments (Patiño-Douce, 1995; Castro et al., 1999), this temperature may be around 1000 °C in anesite magmas.

4.2. Metagabbro inclusions

Other indication for high temperature is given by metagabbro inclusions within tonalites and Qtz-diorties of the Valle Fértil batholith in Argentina (Castro et al., 2012). The high temperature assemblages of these inclusions is not reset to low temperature during cooling because they are amagmatites with an effective separation of liquid (trondhjemitic) and solid (Opx) residues. Orthopyroxene is present in association to hornblende breakdown. Orthopyroxene is partially transformed to paragassic hornblende formed in equilibrium with plagioclase during cooling. Thermometry results in metagabbros are obtained from those Hbl–Pl pairs, yielding values of T = 1000 ± 40 °C. New data of U–Pb SHRIMP zircon age determinations, together with thermobarometric and geochemical data (Castro et al., 2012), yield that batholith magma intrusion is the responsible for heating and self-granulitization of early gabbro pulses. Metagabbros are not common inclusions in batholiths. They are more common in deeply-emplaced plutons, where they provide a valuable information about magma early temperatures.

5. The granite-granulite coupled association

In an independent way, it is possible to address the origin of granite batholiths by addressing experimentally the reverse problem. That is, to determine the nature and composition of the source by identification of near-liquidus saturation phases. Reverse problem studies are very scarce in tonalite-granodiorite systems (Naney, 1983). In partially crystallized anesite systems, a granodiorite liquid is in equilibrium with assemblages dominated by orthopyroxene and plagioclase at temperatures of about 1000–1100 °C for initial water contents in the magma of about 1.0 wt.% H2O (Patiño-Douce, 1995; Castro et al., 1999, 2010). Interestingly, many granulite xenoliths from the lower crust record peak temperatures close to, or even higher than 1000 °C (Fig. 4a) and fairly reproduce the Px-Pl (±Grt, ±Spl) solid assemblages predicted by experiments with anesite systems mentioned above.

Textures indicating decompression at 1.0 GPa and 1000 °C (Opx → Olivine reaction textures; see Castro et al. (2011a), in favor of a system that was magmatic in origin and was fractionated and recrystallized during cooling and decompression as a solid rock to produce the observed metamorphic-like textures. The possibility that these granulite rocks are the source of granite magmas is very unlikely. First, they are characterized by refractory assemblages and, in case they are partially molten, the needed T may exceed 1100 °C for very low melt fractions. Second, these melts will not be granodioritic, but anesitic. That lower crust granulites were in equilibrium with a granodiorite melt is strongly supported by experimental phase equilibria studies. The possible link between batholiths and lower crust granulites have been explored recently (Castro et al., 2013a) with implications on mechanisms of new crust generation in arcs without involvement of crustal delamination. The most outstanding geochronological relations between granulites and batholiths are summarized in this section.

It is a common observation that granite batholiths define linear arrays in geochemical variation diagrams, which resemble cotectic-like trends (Fig. 2). By contrast, diorite and Qtz-diorite rock compositions (SiO2 < 60 wt.%) and lower crust granulites (xenoliths and the Kohistan gabbros) are scattered and do not defined linear arrays (Fig. 4b). There is a compositional gap at SiO2 = 54–58 wt.% separating linear and scattered regions in silica variation diagrams of batholiths (Fig. 4b). Granite samples plotting along a common cotectic trend are not always coeval, with differences in age of about 20 Ma (170–150 Ma) in the case of the North Patagonia batholith (Castro et al., 2011b). These non-coeval samples cannot be fractionated from a common magma at the place of emplacement. More likely, they represent cotectic magma pulses extracted at different temperatures from a common partially crystallized magma at depth. Looking at the MgO-SiO2 diagram of Fig. 4b, it is apparent that parental magma composition to the Patagonia batholith is at the silica gap with values of 56–60 wt.% SiO2. The same reasoning can be applied to granites and lower crust gabbros of the Kohistan (Pakistan) arc section (Fig. 4b). Lower crust granulite xenoliths, which are scattered on the low-silica side of the diagrams, left of the silica gap, can be interpreted in the same way, as residues left after granite (batholiths) magma segregation. The scattered distributions of lower crust granulites report a large compositional heterogeneity for the lower crust, which sharply contrast with the more homogeneous upper crust, dominated by large homogeneous granodiorite-granite batholiths.

The wide compositional region of lower crust xenoliths plotted in the MgO-SiO2 diagram (Fig. 4b), overlaps the composition of gabbroic rocks that form the ca. 30 km thick lower crust at the Kohistan arc section (Garrido et al., 2006; Dhuime et al., 2009). All these mafic xenoliths and the Kohistan gabbros have in common an abnormal composition compared to common magmas: in spite of having silica contents close to basalts (ca. 50 wt.%), they have values of MgO < 7.0 wt.% and Mg# < 0.6, which are too low for basaltic magmas equilibrated with the peridotite mantle. Although a specific explanation has been proposed for these low Mg# values...
Interestingly, temperatures of more than 900 °C represent the corresponding solid residues is implied a parental magma that can be close to an andesite. The same order (ca. 1000 °C) lower crust xenoliths (Fig. 4a). These high temperatures are coincident with those of melting experiments needed to generate andesite) are generated by melting of subducted materials in silicic and aluminous arc magmatism (Castro et al., 2010). If lower crust granulites are the product of thermally induced metamorphism by mantle upwelling and lithosphere extension, mantle melts (basalts) must be produced pervasively from the ascending hot mantle and intruded into the crust at the time of lower crust metamorphism. However, they are absent. Advective heat transport by mantle-derived basalts to the lower crust has been postulated as a possible cause of lower crust metamorphism and melting (Annen et al., 2006). However, according to these thermal models, a basalt-to-crust ratio of 2:1 is needed to reach the high temperatures recorded by granulites. Nevertheless, these expected high proportions of basaltic rocks are missing in the continental crust, and they never occur in relation with batholith magma generation. Several interesting questions emerge from these observations. Where is the heat source for lower crust granulite metamorphism? Are lower crust granulite true metamorphic rocks? Or simply are they magmatic residues left after granite magma segregation? Is there a protolith at the lower crust undergoing metamorphism and partial melting? The hypothesis of magmatic residues seems to be the most plausible. The high temperature recorded by mineral equilibria is that of granite magma at the time of segregation. Relations with batholiths (upper crust) are obvious from both major and trace elements.

6. Plume assisted relamination: the off-crust origin of batholiths

Plume-assisted relamination is a new concept in subduction-related magmatism emerging from varied and independent approaches, namely thermomechanical numerical experiments (Gerya and Yuen, 2003; Gerya et al., 2004; Gerya and Mellick, 2011; Vogt et al., 2013), experimental phase equilibria of batholith magma generation (Castro et al., 2010, 2013a) and mass balance calculations (Hacker et al., 2011). Essentially, the new concept proposes that magmas of intermediate composition (diorite, andesite) are generated by melting of subducted materials in silicic composite plumes (oceanic crust and sediments), which are finally relaminated to below the lower crust, where they split by melt segregation into liquids, which are emplaced at the middle and upper crust (batholiths), and solid residues that remain at the lower crust (mafic granulites). The relaminated andesite magmas may reach the lower continental crust at high temperatures of about 1000–1100 °C, containing a crystal fraction of about 50% according to predictions by phase equilibria experiments. Temperatures of the same order (ca. 1000 °C) are recorded by lower crust granulite xenoliths around the world (Fig. 4a). Furthermore, the characteristic low-water content of calc-alkaline batholiths, with initial water contents of about 1–2 wt.% H2O is compatible with high temperatures of about 1000 °C at the time of magma segregation from the composite underplated plumes.

The important role of subducted materials (sediments and altered oceanic crust) in arc magmatism has been pointed out by means of geochemical studies of arc lavas (Plank and Langmuir, 1998; Plank, 2005; Hacker et al., 2011). A detailed geochemical study of batholithic rocks with adakitic affinities in Tibet (Gandese batholith; Gao et al., 2007), yield to the conclusion that subducted sediments, and not crustal assimilation, were responsible for crustal signatures. The rocks of the Gandese batholith in Tibet are truly calc-alkaline granodiorites and tonalites in which, a prominent adakitic signature is identified by high Sr/Y and La/Yb ratios. The long-lived granodiorite-tonalite magmatism represented by the large Cordilleran batholiths of the Americas is pointing in the same off-crust origin for magmas. For instance, the Mesozoic Canadian Coast batholith, extending for more than 1200 km along the coast of British Columbia (Canada), shows an almost continuous and uniform plutonic activity for about 105 Ma (Crawford et al., 2005); the Coast batholith in northern Chile (Parada et al., 1999) shows an almost continuous plutonic activity for about 200 Ma since Carboniferous to Tertiary; the South Patagonian batholith (Pankhurst et al., 1999) is formed by amalgamation of 25 plutons with uniform granodiorite to tonalite composition, which are emplaced along 105 Ma; and, finally, the South Patagonian batholith is characterized by an intense plutonic activity of granodiorite to tonalite composition lasting for 150 Ma along Mesozoic and Tertiary. These data strongly suggest that a crustal source, located within the continental crust, is very unlike, either as crustal contaminant or as direct source of magmas. Subduction is the only mechanism able to renew continuously the source of magmas without changing the composition of batholiths.

In the new paradigm of mantle-wedge diapirs, emerging from the above-mentioned thermomechanical numerical modeling, batholiths are the natural consequence of protracted introduction of fertile subducted materials into hot zones of the sublithospheric mantle. Potential magmatic implications have been checked by laboratory experiments aimed to assess melt fractions and compositions and to compare these with natural rocks (Castro et al., 2010, 2013a). Also the geochemical implications in terms of radiogenic isotopes Sr and Nd have been modeled (Vogt et al., 2013). In summary, thermal and compositional requirements are totally satisfied by the plume-assisted relamination model (Vogt et al., 2012; Castro et al., 2013b). A detailed analysis of chemical variation trends in batholiths, and their comparison with experimental phase equilibria, yield that an andesite magmatic precursor is favored to account for the generation of both granite batholiths and lower crust granulites. Consequently, the study of lower crustal rocks, represented by xenoliths transported by basalts and exumed sections in continent-continent or arc-continent collision zones (e.g., the Kohistan arc section; Garrido et al., 2006, 2007; Dhuime et al., 2009), is essential to understand the origin of batholiths.

Fig. 5 shows a cartoon based on numerical thermomechanical models (Gerya and Mellick, 2011; Vogt et al., 2012, 2013) summarizing the essentials of the proposed mechanism of plume-assisted crustal relamination (Castro et al., 2013b). Details of structures generated in numerical models supporting this general scheme (Vogt et al., 2013) reveal the complexity of processes with varied magmatic implications. Two main types of diapiric structures are formed in the models, depending on the magnitude of melt weakening effects on the overlying lithosphere (Gerya and Mellick, 2011; Vogt et al., 2013). These are: (1) Underplating diapirs (Fig. 5a),
which spread below the lithosphere for several million years if melt percolation has little effect on lithosphere strength and (2) translithospheric diapirs (Fig. 5b), which are formed when lithosphere is weakened by melt propagation, allowing silicic diapir to move upwards. These translithospheric diapirs ascend rapidly through the lithosphere mantle and are finally emplaced at crustal levels resulting in the formation of magma chambers and batholiths (blue plutons in Fig. 5c). The lower parts of the diapirc structure (“diapir
The tail”) remain attached to the slab, forming a weak zone, where intense reaction between subducted materials and the surrounding peridotite mantle is expected to occur. These translithospheric diapirs can be seen as reaction channels, which were previously inferred to account for the chemistry of arc lavas, and particularly the generation of high-Mg andesites (Kelemen, 1995; Kelemen et al., 2003). These inferences were tested experimentally with satisfactory results (Castro et al., 2013b). By contrast, underplated diapirs are growing for long periods of time (up to 20 Ma) below the lithosphere (Fig. 5a). Melt extraction from the diapir may weaken the lithosphere and provoke the ascent and emplacement at the lower crust, contributing largely to remelting and crustal growing (Fig. 5b). During the ascent and emplacement within the lower crust, granitic melt may segregate to form silicic (tonalite-granodiorite) batholiths at the upper crust (red plutons in Fig. 5c), leaving behind solid residues that form lower crust mafic granulites, which are mostly composed of pyroxene and plagioclase. Depending on pressure and temperature during magma segregation of these composed diapirs, garnet may be a stable phase in the solid residue, which may confer to the melt particular adakitic signatures (high Sr/Y and Ce/Yb ratios) that are reported in particular cases of calc-alkaline intrusions. Because garnet is not the liquidus phase in water-bearing adakite systems below 2.3 GPa (Ringwood, 1982), adakite liquids can be devoid of this adakitic signature, which is not transferred to the respective fractionated liquids. Finally, we have to mention that mantle peridotite surrounding both translithospheric channels and sublithospheric diapirs, can be affected by fluids released from the water-rich silicic systems leading to mantle metasomatism and generation of paragastic amphibole within the mantle. This metasomatized mantle region is ready to generate new magma types of shoshonitic and monzonitic affinities by decompression melting. These potassic magmas are typically associated to late stages of lithosphere convergence related to extension and mantle upwelling.

7. Concluding remarks

Fundamental paradoxes emerging from the application of on-crust models for the generation of granite batholiths can be solved by application of off-crust models. These receive support from thermomechanical numerical modeling and laboratory experiments. The off-crust generation of granite batholiths constitutes a new paradigm in which important geological implications of granite magmatism can be satisfactorily explained. Geochemical variations with time in Cordilleran batholiths are in good agreement with this new conception.

That granites are hybrid rocks is a fact widely documented by isotopic ratios. However, the ways by which these hybrid signatures are acquired have remained controversial. That they are acquired within the continental crust by modifications imposed to mantle-derived magmas is not supported by natural data. Phase equilibria relations allow us to explore the possibility that batholith rock series represent liquids derived from crystallization or partial melting of a hybrid, homogeneous system. Major-element compositional trends follow coticetic trends, whose composition is largely dependent on intensive variables. The comparison between experiments and batholith chemical trends produces an empirical thermodynamic framework useful to understand in a first approach the origin and evolution of magmas forming granite batholiths.

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