Generation of new continental crust by sublithospheric silicic-magma relamination in arcs: A test of Taylor's andesite model

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ABSTRACT

The paradox of the Earth's continental crust is that although this reservoir is generally regarded as having differentiated from the mantle, it has an andesitic bulk composition that contrasts with the intrinsic basaltic composition of mantle-derived melts. Classical models for new crust generation from the mantle in two-stage processes fail to account for two fundamental facts: the absence of ultramafic residues in the lower crust and the hot temperature of batholith magma generation. Other models based on the arrival of already-fractionated silicic magmas to the crust have not received the necessary attention. Addition of new crust by relamination from below of subducted materials has been formulated as a process complementary to delamination of mafic residues. Here we show important support to relamination from below the lithosphere as an important mechanism for new crust generation in magmatic arcs of active continental margins and mature intraoceanic arcs. The new support is based on three independent lines: (1) thermo-mechanical modeling of subduction zones, (2) experimental phase relations and melt compositions of subducted materials and (3) geochemical relations between mafic granulites (lower crust) and batholiths (upper crust). The mineral assemblage and bulk geochemistry of lower crust rocks are compared with solid residues left after granite melt segregation. The implication is that an andesite magma precursor is responsible for the generation of new continental crust at active continental margins and mature oceanic arcs. According to our numerical and laboratory experiments, melting and eventual reaction with the mantle of subducted oceanic crust and sediments produce the andesite magmas. These ascend in the form of mantle wedge diapirs and are finally attached (relaminated) to the continental crust, where they crystallize partially and produce the separation of the solid fraction to form mafic granulites (lower crust) and granitic (*sl*) liquids to form the batholiths (upper crust).

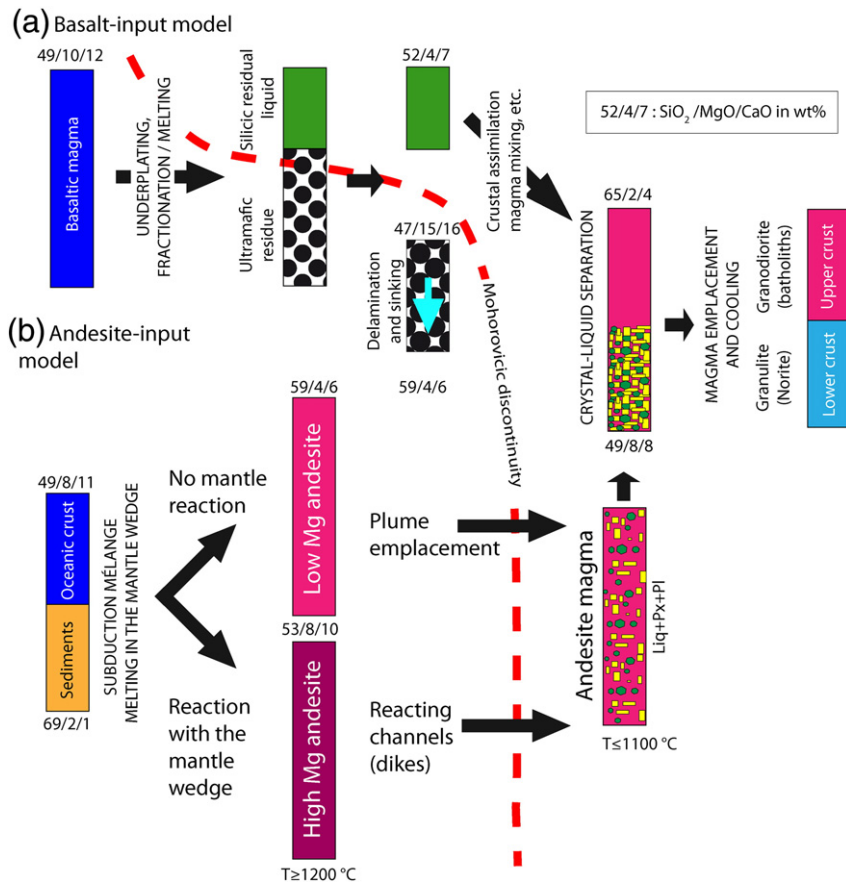© 2012 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.

1. Introduction

The Earth's continents are mostly composed of igneous and meta-igneous rocks that on average yield an andesite composition with $SiO_2 = 60.6$ wt.% and $MgO = 4.7$ wt.%. (Taylor and McLennan, 1985; Rudnick and Gao, 2003). New estimates (Hacker et al., 2011), based on physical properties of rocks and geophysical data, yield more felsic compositions with $SiO_2 = 65.2$ wt.% and $MgO = 2.5$ wt.%. Although these figures are only tentative approaches, they are by far out of range of basaltic compositions ($SiO_2 = 50$ wt.%; $MgO = 8$ wt.%) and, thus, they represent a system that is not in equilibrium with the underlying peridotite mantle (Rudnick, 1995). Because the continental crust as a whole is ultimately derived from the underlying mantle (Hofmann, 1988), the differences in composition between mantle-derived basaltic melts and the average andesite composition of continents are an intriguing paradox in Earth Sciences. Hypotheses to account for this paradoxical fact can be grouped in two categories (Fig. 1). One is represented by the *andesite model* formulated by S. R. Taylor in the sixties (Taylor, 1967). According to the *andesite model* (or Taylor's model) new crust is formed in relation to subduction in arcs, the places of andesite magma generation (Taylor, 1967; Weaver and Tarney, 1982; Kelemen, 1995), at least from the establishment of normal subduction regime at Late Archaean times (Cawood et al., 2006). The other group of hypotheses (basalt-input model) postulates that magma composition fluxing the continental crust is basaltic and, thus, formed by melting of the peridotite mantle. The basalt-input model intrinsically entails the elimination from the continents of an unseen ultramafic residue by sinking into the underlying mantle (Arndt and Goldstein, 1989; Kay and Kay, 1993; Rudnick, 1995). Although the andesite model is more realistic according to observations, as andesite rocks fit the whole composition of the continents, the origin of andesite magmas in arcs, as either primary melts or fractionates from basalts, is controversial and consequently weakens the basis of the andesite model.

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Fig. 1. Panel showing the main differences between the two models for the generation of the continental crust. The basalt input model (a) needs of two important additional processes to achieve the final composition represented by the bulk continental crust: 1: sinking of an ultramafic residue, not existing in the lower continental crust. 2: the addition of crustal components via processes of assimilation and/or magma mixing to account for the crustal isotopic features of the continental rocks. The andesite-input model (b) does not assume any intermediate process. It departs initially from an already hybrid source composed by a mixture of oceanic crust and sediments. The net flux throughout the Mohorovicic discontinuity is andesitic in this model. System compositions are depicted by wt.% of SiO_2, MgO and CaO. Note that subducted mixtures composed of equal parts of sediments and oceanic crust are close in composition (59/4/6) to an andesite liquid (52/4/7) produced by fractionation of 58 wt.% of pyroxene-rich residue (47/15/16) from a basalt. Other components as K and incompatible elements are assumed to be acquired within the continental crust in the basalt-input model. Both processes, delamination/sinking of the ultramafic residue and assimilation/mixing with crustal materials, are needed in the basalt-input model to account for the final bulk composition of the continental crust. Compositions and liquid-to-crystal proportions have been calculated with MELTS code (Ghiorso and Sack, 1995; Asimow and Ghiorso, 1998) for the basalt input model, starting with a typical island arc calc-alkaline basalt with $SiO_2 = 49.4$ wt.%, FeO = 10.2 wt.%, MgO = 10.4 and CaO = 12.2. This basaltic magma produces an andesite liquid with $SiO_2 = 52.4$ wt.% and MgO = 4.2 wt.% after removal of 58 wt.% of a clinopyroxene-rich residue at T = 1250 °C (pressure = 800 MPa; dry conditions and fO_2 buffered at QFM + 2). The large amount of pyroxenites, compared to the volume of the total continental crust in a ratio of 6:4, is not present in the continental lithosphere mantle. Similar results are obtained by assuming 2.0 wt.% water in the parental basalt. The compositions of components in the mixed source, their liquid and residues were obtained from melting experiments (Castro et al., 2010) at 1100 °C and 1.5 GPa.

The new paradigm for magma generation in arcs leads to reconsider the initial formulation of Taylor's andesite model for the origin of the continental crust. It has been proposed recently that relamination of subducted materials (Hacker et al., 2011) can account for the addition of silicic rocks or magmas to the continents. However, the intricacies and mechanisms of relamination require special attention to processes able to convert subducted rocks in magmas and to transport these partially molten rocks through the lithospheric mantle. Both thermomechanical and phase equilibria experiments are necessary to constrain the dynamics of silicic magma relamination.

According to the new paradigm, new crust can be formed in arc settings by a mechanism of relamination of subducted materials assisted by the action of partially molten silicic diapirs rooted at the subduction channel (Gerya and Yuen, 2003; Gerya et al., 2004; Castro and Gerya, 2008; Castro et al., 2010; Gerya and Meilick, 2011). Such a scenario can explain the andesitic bulk composition of the continents and alleviate the long-standing mass balance difficulties that arise if the magmatic continental precursor was more mafic (basaltic), as is generally thought. Minor basaltic magmas can also be formed in this scenario by fluid-assisted melting of the peridotite

mantle (Grove et al., 2002) in agreement with thermo-mechanical models of stable subduction (Vogt et al., 2012). This paper is focused on the silicic magmas (andesites), formed in compressional arcs with silicic diapir development (Vogt et al., 2012), because these fit the composition of the average continental crust.

In addition of new numerical models, we complement previous experimental studies of subducted basalt + sediment mixtures (Castro et al., 2010) with new experiments assuming complete reaction with the peridotite mantle. We also report new data from lower crust xenoliths, whose composition and mineral assemblages fairly compare with experimental residues left after granitic melt segregation from and andesite magma precursor. In sum, we confirm Taylor's *andesite model* (Taylor, 1967; Kelemen, 1995) of new crust generation starting with an andesitic, not basaltic, precursor. An additional inference for this test is that in contrast to intra-oceanic subduction models (Nikolaeva et al., 2008), models of active margins (Vogt et al., 2012) suggest that average melt composition produced in this setting can significantly deviate from basaltic due to the addition of melting products of subducted crustal rocks. Although a comprehensive review of the alternative basalt-input model is out of the scope of

this paper, which is focused to test Taylor's andesite model, an outline of the most debated topic in relation to the generation of the rocks forming the continental crust is given in the next section with the aim of offering a reference framework on the problem of continental crust generation.

2. Taylor's andesite model: An overview on the origin of upper and lower continental crusts

Besides the intriguing andesite average composition, an outstanding feature of the Earth's continental crust is the dichotomy between an upper layer of broadly granodioritic composition ($SiO_2 = 68$ wt.%; $MgO = 2$ wt.%), which is rich in incompatible elements, and a mafic lower layer ($SiO_2 = 52$ wt.%; $MgO = 6$ wt.%), which is variably depleted in incompatible elements (Rudnick and Gao, 2003). The possibility that both layers are linked by processes of magma fractionation is explored here by considering batholiths (upper crust) as melts extracted from a parental magma leaving behind a solid residue that can be compared to the rocks of the lower continental crust. The possibility that the parental magma linking both upper and lower crusts is an andesite, with a composition close to that of the bulk continental crust, opens new insights to the study of crustal making processes and a renewal of old ideas. The andesite model has to account for two fundamental observational facts; one is the production of an andesite magma precursor; the other is the separation of liquids and residues to produce the upper and lower continental layers. Because andesite magmas are formed in arc settings, the problem of new crust generation is closely related to the origin of andesite magmas. However, the proportion of andesite to basalt in arcs is a debated topic with the consequence that a bulk andesite composition for arcs has been questioned. This was one of the most important handicaps to accept the andesite model in the past. This point is analyzed below.

The andesite model was a paradigm and inspired experimental studies aimed to produce andesite primary magmas in relation to subduction (Green and Ringwood, 1966, 1968; Green, 1980, 1982). However, the model was almost abandoned for three main reasons. One is that field studies apparently revealed that primitive basalts were the dominant primary magma derived from beneath the Moho at oceanic arcs and continental active margins (Arculus, 1994; Davidson and Arculus, 2006). A second reason is based on the difficulty of getting silica-rich, andesite melts from the mantle peridotite, even if affected by water-rich fluids (Gaetani and Grove, 1998). The third reason is that temperatures are too low at the subduction channel to melt the eclogitized subducted oceanic crust (Peacock, 1993), as initially proposed (Green and Ringwood, 1968). However, the increasing knowledge about (1) the complex thermal and mechanical structure of subduction systems (Gerya and Yuen, 2003; Gerya et al., 2004; Gorczyk et al., 2007; Gerya and Meilick, 2011), and (2) the composition and deep structure of magmatic arcs (Kelemen et al., 2003a, 2003b; Davidson and Arculus, 2006; Garrido et al., 2006; Green et al., 2006; Lee et al., 2007; Takahashi et al., 2007; Dhuime et al., 2009; Straub and Zellmer, 2012) reveals a new scenario for arc magmatism that allows us a better understanding of the processes involved in magma generation.

2.1. The andesite composition of arcs

Although volcanic rocks of basaltic composition are extruded at intraoceanic and continental arcs, geophysical and geological studies reveal a large proportion of plutonic rocks of tonalite ($SiO_2 > 63$ wt.%) composition in continental margins. The average composition of arcs is close to andesite rather than to basalt, even if basalts are common. A good example is the Izu–Bonin–Mariana arc, where a continental crust-like, tonalitic middle arc crust, with P wave velocities in the range 6.0–6.5 km s^{-1}, has been identified (Suyehiro et al., 1996; Takahashi et al., 2007). The average compositions of exposed arc

sections (e.g. Kohistan; Garrido et al., 2006; Dhuime et al., 2009; Jagoutz and Schmidt, 2012) also are andesitic ($SiO_2 > 53$ wt.%). These sections are characterized by the scarcity of ultramafic residues compared with the large volumes of diorite and norites at the lower parts, with granite batholiths and silicic volcanics (dacites and rhyolites) dominating the upper half of the exposed sections.

Large Cordilleran batholiths formed at active continental margins (e.g., the Andes and Western North America), clearly reveal that subduction is an important mechanism for new crust generation (Wyllie, 1977). However, the way crust is generated in these active margins remains unknown. The idea that magmatic rocks are more felsic in continental domains compared with intraoceanic arcs just because the crust is thicker and magmas have more probability to fractionate by *filtering* (Hildreth and Moorbath, 1988; Annen and Sparks, 2002) is not sustained by geological observations of exposed lower crust sections, where ultramafic cumulates are scarce or absent.
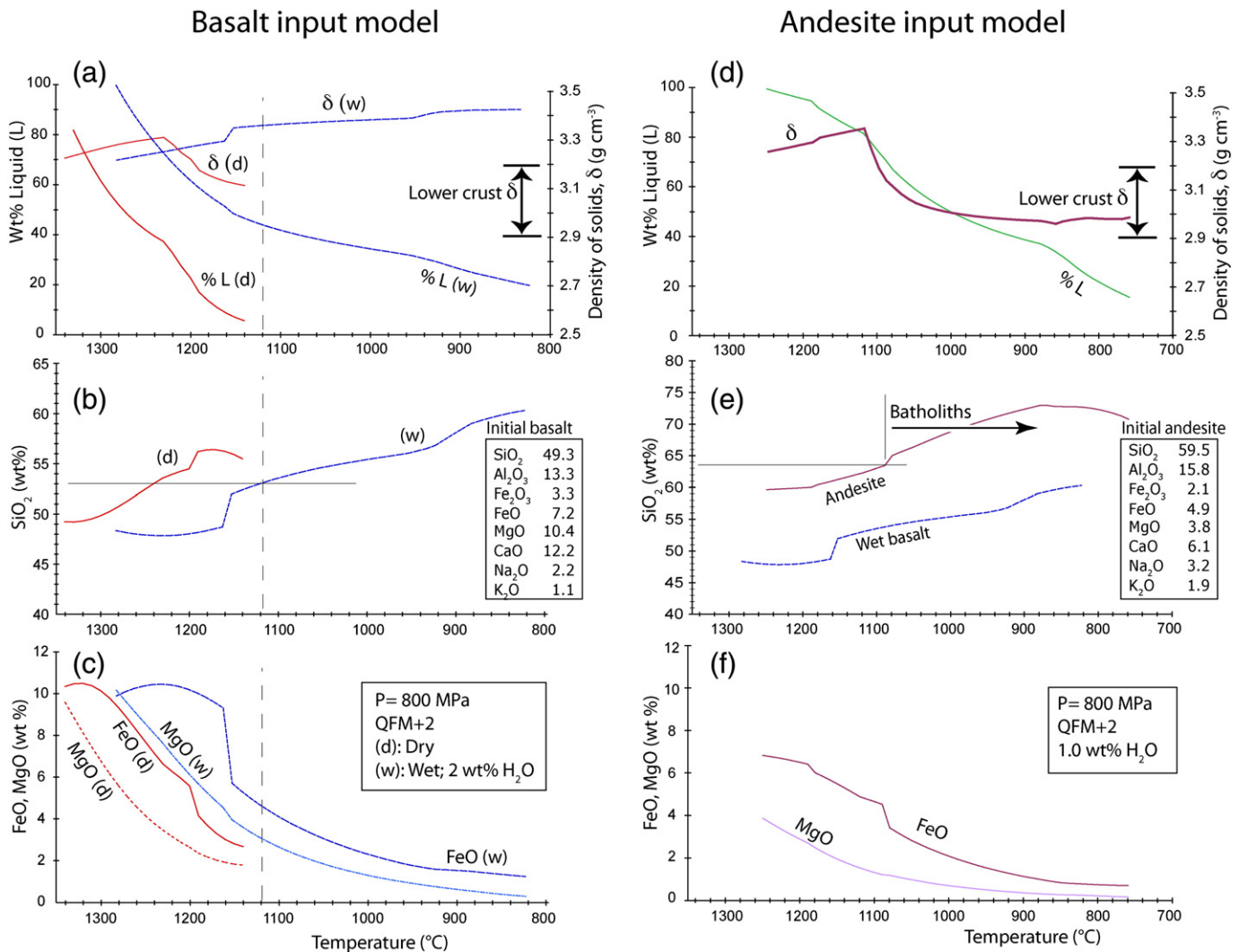
Delamination of ultramafic residues is a required condition in the basalt-input model (Fig. 1; Kay and Kay, 1993; Hawkesworth and Kemp, 2006). However, delamination of mafic residues requires the presence of garnet to yield favorable density contrasts with the underlain mantle, as well as hot thermal regimes at the Moho interface to allow rheological instability and diapiric foundering (Jull and Kelemen, 2001). Although these requirements can be fitted in arc settings (Jull and Kelemen, 2001; Kelemen et al., 2003a, 2003b), there will be a density-stable, garnet-free mafic part remaining in the crust, which is not compatible with the average crust composition (DeBari and Sleep, 1991; Green et al., 2006).

2.2. Phase equilibria constraints

Another important requirement of the basalt-input model is high water contents of the intruding basaltic magmas needed to depress the plagioclase stability field and to produce mafic residues (Kay and Kay, 1993). However, these assumptions are not compatible with phase equilibria at high pressure and not with the strongly water-undersaturated nature of calc-alkaline batholiths, presumably resulting as the last fractionates from the wet basalt magmas that produced the hypothetically delaminated residues. Phase equilibria at middle to lower crustal pressures (> 0.6 GPa) dictate that pyroxene, instead of olivine, is the dominant stable phase in basaltic systems. Because the silica content of pyroxenes is similar (may be higher) to the parental basalt, large amount of residues of more than 50 wt.% must be removed to allow the formation of a silica-rich andesitic ($SiO_2 > 52$ wt.%) residual liquid. Essential phase relations and densities of residues are illustrated in Fig. 2 by means of thermodynamic modeling with MELTS code (Ghiorso and Sack, 1995; Asimow and Ghiorso, 1998). According to MELTS modeling of equilibrium crystallization, a wet tholeiitic basalt (2 wt.% initial water) may produce a 40 wt.% liquid with an andesite composition ($SiO_2 \approx 53$ wt.%, $FeO \approx 5$ wt.% and $MgO \approx 3$ wt.%) at $T = 1120$ °C. The solid residue is ultramafic and has an average density $\delta > 3.3$ g cm^{-3}. The early formation of plagioclase in the dry basalt at 1220 °C leads to a decrease in density of the solid residue. In the wet system, density is almost constant for a wide temperature interval. Fractionation to granite batholiths ($SiO_2 > 63$ wt.%) will produce small melt fractions (<20 wt.% liquid) which will have 5 times the initial water content (ca. 10 wt.% water), implying saturation at the low pressure of batholith emplacement (100–300 MPa). This result sharply contrasts with the most characteristic feature of calc-alkaline batholiths: they are strongly water undersaturated as demonstrated by the scarcity of pegmatites.

2.3. Isotopic ratios and arc magma genesis

It is a fact that arc magmas are characterized by a mixture of fresh and old recycled components on the basis of Sr–Nd isotope systematics (McCulloch and Wasserburg, 1978; Allègre and Ben Othman, 1980; De

Fig. 2. Testing petrologic relations of the basalt input model against the andesite input model for continental crust generation. Plots show modeled crystallization of a tholeiitic arc basalt with 0 and 2 wt.% initial water and a high silica andesite (HSA) with 1 wt.% water, at 800 GPa and QFM + 2 oxidizing conditions, using MELTS code (Ghiorso and Sack, 1995; Asimow and Ghiorso, 1998). The composition of the initial basalt and andesite is shown in the respective insets. Wet basalts may produce a 40 wt.% liquid with an andesite composition ($SiO_2 \approx 53$ wt.%, $FeO \approx 5$ wt.% and $MgO \approx 3$ wt.%) at T = 1120 °C. The solid residue may have an averaged density $\delta > 3.3$ g cm^{-3}. The composition of the residue is ultramafic at this T = 1120 °C. The early formation of plagioclase in the dry basalt at 1220 °C leads to a decrease in density of the solid residue. In the wet system, density is almost constant for a wide temperature interval. The averaged density of the residue left after crystallization of the andesite system at 1000 °C is close to the upper range of lower crust densities [lower crust density range after Christensen and Mooney (1995), for Vp = 6.7 to 7.1 km s^{-1}]. At 1100 °C the HSA system produces 70 wt.% liquid of tonalite to granodiorite composition ($SiO_2 > 63$ wt.%; $FeO \approx 4$ wt.%; $MgO \approx 1$ wt.%). These are the favorable conditions for Cordilleran batholith generation in agreement with phase equilibria experiments by Castro et al. (2010). Variable melt segregation temperatures within the range 950–1100 °C will produce the required melt compositions for batholiths (upper crust) and a noritic (Pyroxene + plagioclase) residue with average density (ca. 3.1 g cm^{-3}) within the range of Vp predictions.

Paolo, 1981; Allègre and Rousseau, 1984), which is confirmed by Hf and oxygen isotopic studies in zircons (Hawkesworth and Kemp, 2006). The same pattern is characteristic of the whole continental crust and sedimentary rocks, strongly supporting a continuous growing of the continents with time (Dhuime et al., 2011, 2012). However, the way recycled components are added to new crust is controversial. The idea of crustal-sourced processes involving a parental basalt that undergoes fractionation and assimilation in the continental crust (Hildreth and Moorbath, 1988) became popular. However, the new geochronological, isotopic and experimental data from batholiths and volcanic successions at active margins are favoring the influx of already contaminated materials crossing the Mohorovicic discontinuity (Stern, 1991). By consequence, geochemical and isotopic characteristics of erupted andesites at modern arc volcanoes seem to be better explained by melting of a hybrid source rather than crustal contamination. The existing controversy on isotopic data interpretations tells us that isotopic ratios by themselves cannot discern between competing hypotheses. However, several geological observations are crucial to assess the role of competing

processes. For instance, we call here the attention on the longevity of batholith magmatism in continental arcs and on the decoupling between major element chemistry and isotopic ratios of the volcanic and plutonic rocks in arcs. The two are analyzed here in detail with special regard to American Cordilleran batholiths.

We strongly argue later in this paper that lower crust is a granulitic residue and not a fertile source of magmas. Nevertheless, in the hypothetical and remote case that lower crust is the source of batholiths, it is a volume-limited reservoir that will be exhausted with time by successive melt extractions. By contrast, the source of magmas in continental arcs seems to be inexhaustible for time periods of more than 50 Ma. Subduction is the most plausible explanation to this inexhaustible source instead of a crustal-localized source or crustal contaminant. Although the peak of magmatic activity took place during the Cretaceous, the age of the batholiths spans for long periods of time of 40 and 31 Ma in Sierra Nevada and Peninsular Ranges batholiths respectively (Lee et al., 2007), 200 Ma in the Chilean Coastal batholith (Parada et al., 1999), 130 Ma in the North Patagonian

batholith (Pankhurst et al., 1999) and 150 Ma in the South Patagonian batholith (Hervé et al., 2007). During these large time intervals the major element compositions of granitoids remain unchanged. However, there is a marked compositional evolution with time in terms of Sr and Nd isotopic ratios, denoting an increase in mantle contribution with time. For instance, drastic changes from $\varepsilon_{Nd} = -4$ to $+6$ are characteristic of plutons of the South American batholiths (Pankhurst et al., 1999 and references herein) evolving to positive values from Carboniferous to Tertiary. This time–composition evolution seems incompatible with assimilation of sub-arc continental rocks as the cause of silicic magmatism. It also conflicts with derivation from a volumetrically limited source within the continental crust. For the case of assimilation, a parallel evolution to compositions richer in silica and alkalis is expected. For the case of intra-crustal origin (basalt-fluxed melting and assimilation models), a localized source within the continental crust will evolve to more refractory compositions due to the continuous extraction of melts during tens of million years.

Because magma mixing and assimilation are not selective processes, they will affect equally major and trace elements and isotopic ratios. That is, the isotopically more evolved will be the more felsic. However, decoupling between major element geochemistry and isotopic ratios is the general rule: granites sharing a common major element composition plot in both mantle-like and crustal-like regions in terms of Sr and Nd initial isotopic ratios (see compilation in Castro et al., 2010). To understand how a hybrid source supplying with mantle and crustal components and leading to melting and arc magma generation, it is necessary to analyze the dynamics and thermal regime of subduction zones. This is addressed here by means of thermo-mechanical numerical experiments.

3. Thermo-mechanical numerical modeling of continental active margins

We show here new numerical thermo-mechanical models that yield several petrologic scenarios in which hybridization between mantle and subducted materials takes place above subduction zones. One of these scenarios is provided by the formation of ascending partially molten materials from the subduction interface (Gerya et al., 2004), which may be preserved from reaction with the mantle, giving rise to low-Mg, high-silica andesite (HSA) magmas ($SiO_2 > 55$ wt.%). These correspond to most erupted andesites in arc volcanoes and to the common quartz-diorite rocks associated to granite batholiths. Another petrologic scenario resulting in our models is the formation of reaction channels in which basalt + sediment subducted mixtures, and silicic melts derived from them, go into reaction with the peridotitic mantle, giving rise to high-Mg# andesites (HMA; Mg# = molar $MgO/MgO + FeO > 0.6$, with FeO representing total Fe) (Kelemen, 1995). Magmas from these two scenarios may fractionate to more silicic compositions giving rise to upper crust batholiths (melts) and lower crust mafic granulites (residues) that constitute new continental additions by a mechanism of *relamination* (Hacker et al., 2011).

The 2D thermo-mechanical model simulates the process of forced subduction of an oceanic plate beneath a continental plate and is similar to the one explored by Gerya and Meilick (2011). Crustal growth during silicic diapir emplacement is analyzed on a 4000 km × 200 km lithospheric/upper mantle section during a 40 Ma time span. The oceanic plate (2500 km) is pushed toward a fixed continental plate (1500 km) with a constant velocity of 5 cm/year. The rectangular grid with 2041 × 201 nodes is non-uniform, containing a high resolution area (1 × 1 km) in the center of model domain. In the remaining part of the domain the resolution is lower (5 × 1 km). The oceanic crust is composed of 2 km of hydrothermally altered basalt, underlain by 5 km of gabbroic rocks. The continental crust is felsic and has a total thickness of 30 km, composed of 15 km upper crust and 15 km lower crust. Both the asthenosphere and the upper mantle are composed of anhydrous peridotite and are defined by the temperature profile.

All mechanical boundary conditions are free slip only the lower boundary being permeable in vertical direction (Gorczyk et al., 2007). The top surface of the lithosphere is treated as an internal free surface by using a top layer (of 8–12.5 km thickness) with low viscosity (10^{18} Pa s) and low density (1 kg/m^3 for air, 1000 kg/m^3 for sea water).
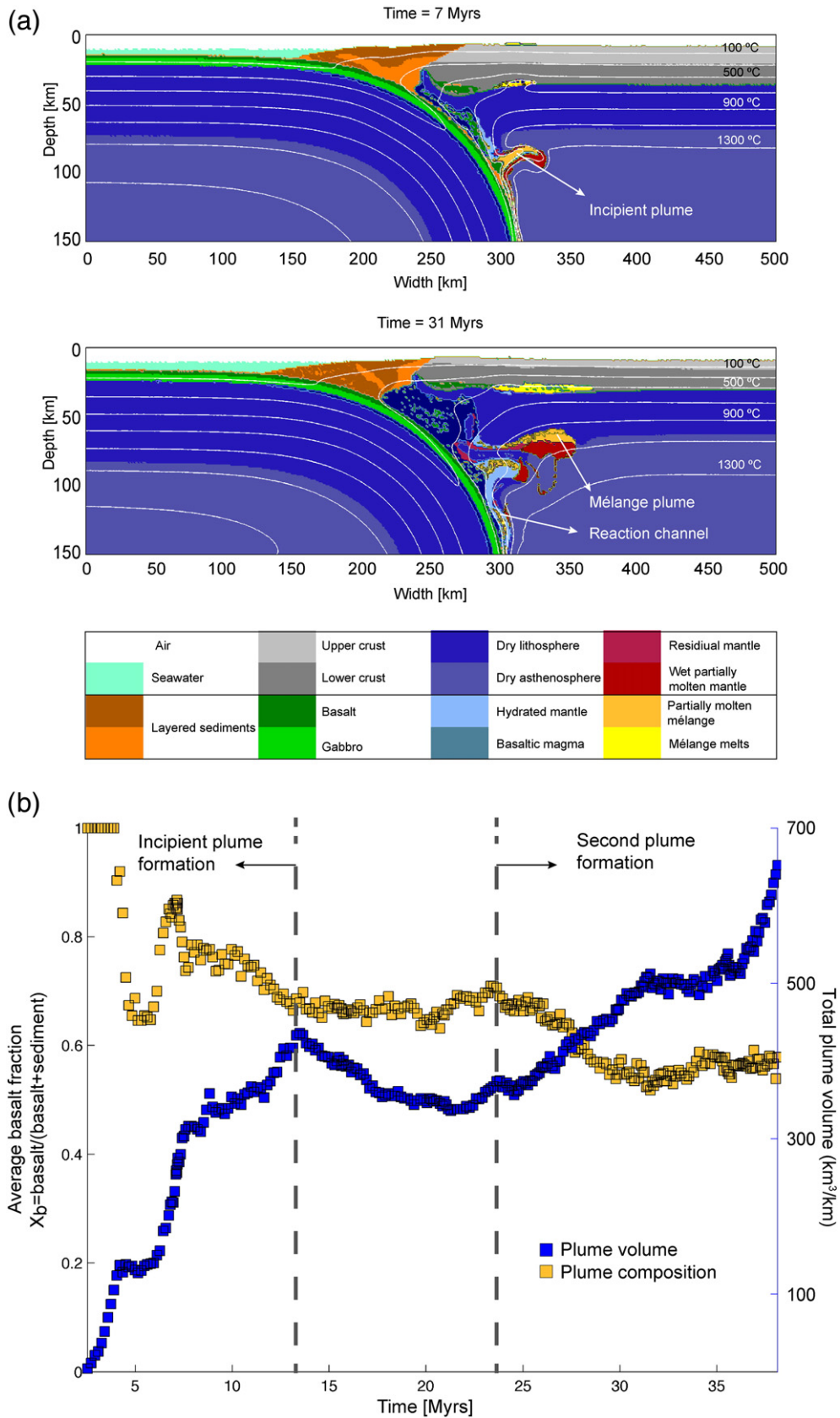
The model is based on the i2vis code (Gerya and Yuen, 2003), combining conservative finite differences and a non-diffusive marker in cell technique to simulate multiphase flow. The governing conservation equations of mass, momentum and energy and the constitutive relationships between stress and strain-rate are solved on an irregularly spaced staggered grid in Eulerian configuration.

We have analyzed the dynamics of crustal growth at active continental margins using a two dimensional (2D) thermo-mechanical numerical model of an oceanic-continental subduction zone. This model includes dehydration of subducted crust, aqueous fluid transport, partial melting, melt extraction and melt emplacement in the form of both extrusive volcanics and intrusive plutons. Model design and boundary conditions are shown in the Experimental test of mantle reaction channels section. A description of observed processes is given below (Fig. 3).

In the course of subduction water is released from the subduction channel due to compaction or as result of dehydration reactions. Subsequently progressive mantle hydration forms a serpentinized zone at shallow slab interfaces (<130 km) and induces partial melting of slab (sediments and basalts) and mantle components (hydrated peridotite) at greater depth (>80 km). A sandwich of partially molten sediments and basalts, hydrated mantle and flux-melting products is formed atop the slab prior to diapir development (0–8 Ma). Partially molten sediments and basalts intermix at the slab interface forming an oceanic crust + sediment mixture [X_b = basalt / (basalt + sediment) = 0.78–0.66, (Fig. 1b)]. The continuous supply of sediments into the subduction channel increases the sediment fraction in the mixture (Xb = ~0.65) and enables the formation of a buoyant hybrid diapir (Fig. 1). Lately, after 17 Ma, the diapir detaches from the slab and it underplates atop the lithosphere. Meanwhile, new material accumulates at the slab interface (23 Ma), forming a second diapir (Fig. 3) and increasing the total volume of partially molten material. This period, starting at about 23 Ma, is characterized by periodic fluctuations of the basalt / (basalt + sediment) ratio in the subducted mixture within discrete intervals of X_b = 0.71–0.52. Melting experiments of subducted mixtures at sublithospheric depths have revealed that values of X_b = 0.75 to 0.25 are favorable for the production of cotectic silicic magmas of granodiorite to tonalite composition (Castro and Gerya, 2008; Castro et al., 2010).

Finally, the diapir underplates the lithosphere as a buoyant hybrid, partially molten system. At the same time, partially molten materials coming from the subduction channel at depth are feeding the diapir after mixing with the surrounding peridotite mantle. These diapir-feeding tails are in fact hybridization channels in which complete reaction between subducted mixtures and mantle takes place. Melts extracted from any of the partially molten systems (basalt + sediment subducted mixtures and hydrated mantle) emplace at crustal levels in the form of extrusive volcanics and intrusive plutons. The latter forming sill-like intrusions in the lower crust, where they may fractionate to produce granulite residues and silicic melts.

It is concluded from these numerical experiments that two main petrologic scenarios involving hybridization are produced in the course of subduction. These are hybrid diapirs and reaction channels. Diapirs can be seen as non-reactive andesite magma reservoirs, where material inside the diapir can retain their original features during travel through the mantle wedge in the way up to form new continental crust. Low-Mg/high-silica (HSA) andesite magmas are formed by this mechanism. Reaction channels in the mantle wedge

Fig. 3. Results of numerical experiments showing the formation of a hybrid diapir. a: Localization and partial melting of sediments and basalts along the slab enables diapir formation. New incoming material is added at the diapir tail, where complete reaction between subducted rock mixtures and the mantle occurs. b: Average basalt fraction [X_b = basalt/ (basalt + sediment)] of the diapir in relation to diapir growth. After diapir formation values vary between X_b = 0.71–0.52.

form the second important hybridization scenario. This allows silicic material from the subduction zone (i.e., the whole subducted mixtures or partial melts from them) to react with the peridotite mantle and hybridize. High-Mg, low-silica (HMA) andesite melts are expectedly formed at these reaction channels. Our models predict discrete channels that remain in a fixed position for million years. New magma is channeled upwards using a common place with the implication that reaction may be less and less efficient with time due to the formation of reacting aureoles composed of pyroxene and pargasitic amphibole in agreement with experimental simulations with peridotite and silicic melts (Sekine and Wyllie, 1982; Carroll and Wyllie, 1989; Rapp et al., 1999; Prouteau, et al., 2001; Castro and Gerya, 2008). Phase equilibria, melt compositions and fertility of basalt-sediment mixed diapirs were experimentally tested in a previous study (Castro et al., 2010). Below we show an experimental test of the reaction channels involving chemical interactions of subducting mixtures and the mantle.

4. Experimental test of mantle reaction channels

Spontaneous formation of reaction channels, together with silicic diapirs, is a systematic feature emerging from the above-mentioned thermal–mechanical modeling of subduction at active margins. These numerical results satisfy inferences from high-Mg# andesite (HMA) chemistry (Kelemen et al., 2003b) with important implications for the origin of the continental crust. Reaction has been inferred by study of mafic xenoliths (Liu et al., 2005) and olivine composition in andesites (Straub et al., 2011). Although melts are preferred instead of fluids to account for large incompatible element enrichments (Kelemen et al., 2003b), the nature and composition of the silicic component, fluids, melts or partially molten rocks, remain unclear. Experiments have shown that slab-derived silicic melts are the most likely metasomatic agents in subduction zones (Prouteau et al., 2001). In contrast with previous hypotheses requiring a hot (young) lithosphere to promote extensive melting of subducted materials, reaction channels of our thermomechanical models are independent of the age and thermal state of the subducting plate because channels occur within the hot, overlying mantle wedge. Consequently, modeled reaction channels provide fundamental information on intensive variables and compositions of hybrid magmas in the mantle. These are tested experimentally here assuming complete reaction of subducted oceanic crust and sediments with the peridotite mantle.

Compositions of starting materials are given in Table 1. To simulate reaction channels we use composite capsules that were filled with a homogenous mixture of peridotite and subducted basalt-sediment mixture, the latter composed of amphibolite and greywacke sediments. Details on the composition of starting materials are given in Appendix A (Supplementary data).

Arguments for choosing a greywacke composition have been given in a previous paper (Castro et al., 2010). This composition may differ from typical pelagic sediments occurring in intraoceanic arc trenches. However, we do not consider intraoceanic setting in this paper. We refer to the role of active margin magmatism, with particular emphasis on cordilleran-type batholiths (mature arcs can be similar to active continental margins). The most abundant sedimentary rocks at active margins are greywackes. Also greywackes are the most abundant sedimentary rocks in the geological record (Taylor and McLennan, 1985). The rock we use is representative of the several km thick Neoproterozoic and Lower Paleozoic sequences of South America and Europe. These are very close in composition to post-Archaean greywackes according to Taylor and McLennan (1985) estimates. In particular, the composition used in our experiments is close to the quartz-intermediate greywackes of the Franciscan Formation (Taylor and McLennan, 1985). We consider this composition as representative of terrigenous sediments coming from denudation of

Table 1
Composition of starting materials used in the melange–mantle reaction experiments.

	MORB amphibolite	Greywacke gneiss	Spinel lherzolite
SiO_2	49.14	69.1	45.8
TiO_2	1.61	0.52	0.14
Al_2O_3	16	15.23	3.92
Cr_2O_3			
Fe_2O_3	10.94	4.19	9.07
MgO	7.17	1.51	36.7
MnO	0.22	0.04	0.14
CaO	10.7	1.28	2.88
Na_2O	3.29	3.06	0.38
K_2O	0.09	3.81	0.06
LOI	0.44	1.3	
Total	99.79	100.22	100.88

continental areas. Greywackes are the most likely sediments accumulated in trenches at active margins and dragged by subduction to the mantle under appropriate tectonic settings.

Conditions of reaction experiments were set at temperatures ranging from 1050 to 1300 °C and pressures of 1.0 to 1.5 GPa. Water content also was varied from strongly undersaturated ($H_2O<1$ wt.%) conditions, with only the water released by hydrous minerals of the mixture components, to water-rich ($H_2O=10$ wt.%) conditions in an experiment at the lowest T = 1050 °C. Compositions of melts (quenched glass) and mineral phases are given in Table 2. Representative back-scattered electron images of runs RC1 and RC4 (Table 2) are shown in Fig. 4a,b. Details on experimental procedures, analytical techniques and detailed descriptions of experimental runs are given in the Appendix (Data Repository).

In summary, water-added runs produced high melt fractions (>25 wt.%) at temperatures as low as 1050 °C at 1.0 GPa. Similar melt fractions are obtained from fluid-absent experiments at conditions of 1200 and 1300 °C. Results indicate that water released from dehydration of mica and amphibole from the basalt–sediment mixture is enough to produce significant melt fractions at temperatures of the upper mantle close to the reaction channels above the subducting slab. Melts formed in water-absent experiments have water contents of about 1 wt.%, calculated by mass balance from the water content of the starting materials and assuming no water loss during experimental runs. They fit the composition of high-Mg# andesites (Fig. 4c). The wide variation in melt compositions from reaction channels and non-reaction mixed diapirs follows the compositional trends of classical volcanic arc associations (Fig. 4c).

5. Discussion: Application to natural examples of batholiths and lower crust xenoliths

It is noticeable that melts produced in our reaction experiments are andesitic ($SiO_2>53$ wt.%) with an Mg# (molar MgO/MgO/FeO) of around 0.6 for MgO contents in the range 5.9–7.6 wt.%. These are typical values of high Mg# andesites (HMA), rocks that are considered relevant in the generation of the continental crust (Kelemen, 1995). Similar experimental results were obtained in previous studies about mantle-crust hybridization simulations (Carroll and Wyllie, 1989; Johnston and Wyllie, 1989; Rapp et al., 1999), strongly supporting the role of mantle hybridization in the generation of andesitic melts. A subducted basalt–sediment mixture as crustal contaminant within the mantle is considered in this study for the first time. Comparisons with melts from isolated mixed diapirs (Castro et al., 2010) reveal the net effect of reaction and re-equilibration with the peridotite mantle. Further fractionation of the mantle-hybridized HMA melts will produce high-Mg silicic (dacitic) magmas (Fig. 4c), which otherwise cannot be produced by isolated basalt–sediment mixtures in diapirs. The interest of these results is twofold. First, the proportion of basalt to sediment + basalt ($X_b = 0.5$) in the reaction experiments is taken

Table 2
Experimental conditions, melt (glass) and mineral compositions obtained in the reaction experiments.

RUN	Starting material	Pressure (GPa)	T (°C)	wt.% water	Duration (h)	Phase	Vol.%	SiO$_2$[a]	TiO$_2$	Al$_2$O$_3$	FeOt	MgO	MnO	CaO	Na$_2$O	K$_2$O	P$_2$O$_5$	Total[b]	100-total	Mg#[c]
RC1	KLB1:gneiss: amphibolite (8:1:1)	1	1050	10	42	Glass	28	57.1	0.9	20.5	4.9	6.2	0.1	8.4	0.8	0.9	0.1	100.0	12.25	0.69
						Ol	50	40.7	0.0	0.0	10.2	49.2	0.1	0.1	0.0	0.0	0.0	100.8		0.90
						Cpx	15	52.2	0.3	2.8	3.4	18.2	0.1	20.5	0.3	0.0	0.0	98.9		0.91
						Opx	5	54.6	0.0	4.6	6.5	32.5	0.0	1.0	0.0	0.0	0.0	99.7		0.90
						Amp	<2	Not analyzed[d]												
RC3	KLB1:gneiss: amphibolite (8:1:1)	1	1200	<1	28	Glass	19	53.3	0.9	17.0	7.1	7.6	0.1	10.7	1.9	1.3	0.1	100.0	4.12	0.65
						Opx	29	52.8	0.1	5.4	6.3	32.6	0.1	1.0	0.1	0.0	0.0	98.9		0.90
						Ol	47	39.9		0.1	8.9	50.7	0.1	0.2			0.0	100.0		0.91
						Cpx	<1													
RC4	KLB1:gneiss: amphibolite (8:1:1)	1.5	1200	<1	44	Glass	22	55.0	1.1	20.8	6.6	5.9	0.1	6.9	1.8	1.6	0.2	100.0	8.31	0.61
						Opx	37	47.4	0.2	3.2	8.4	39.5	0.1	1.0	0.0	0.0	0.0	100.4		0.89
						Cpx	13	51.1	0.4	7.3	3.4	15.8	0.1	18.9	1.4	0.0	0.0	99.5		0.89
						Ol	28	40.4			11.0	47.8						99.1		0.89
RC5	KLB1:gneiss: amphibolite (8:1:1)	1.5	1300	<1	19	Glass	29	55.8	0.9	17.1	7.8	6.0	0.1	9.6	1.5	1.1	0.1	100.0	7.50	0.58
						Ol	45	41.1	0.0	0.1	7.4	52.0	0.1	0.2	0.0	0.0	0.0	101.1		0.93
						Opx	18	54.2	0.2	5.3	6.5	31.3	0.1	1.7	0.1	0.0	0.0	100.8		0.90
						Cpx	7	49.4	0.9	10.4	8.2	17.0	0.3	13.3				100.0		0.79

[a] Analyses are averaged values of several point analyses (3 to 5 points in most cases). Standard deviations are less than 10% relative on average.
[b] Glass analyses are normalized to an anhydrous base. The original difference with 100 is shown.
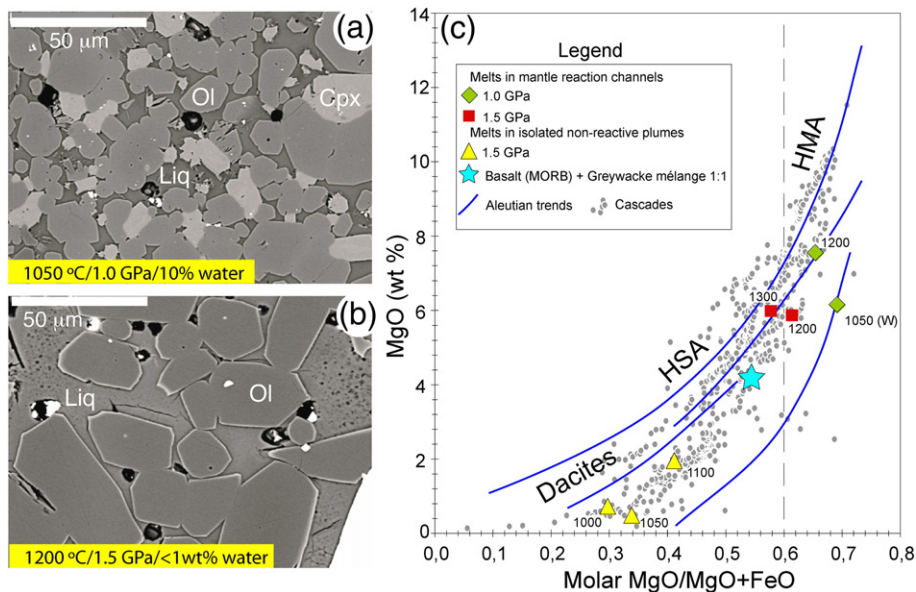[c] Mg# = molar MgO/MgO + FeO; FeO is total Fe as FeO.
[d] Very tiny crystals of less than 2 μm are not analyzed.

according to the non-prescribed thermo-mechanical models of sub-duction at active continental margins (Vogt et al., 2012). This ratio is about 0.65 in the model shown in Fig. 3. A decrease in the fraction of sediments will have net effects on the potassium content of the resulting andesite melt, because more than 90% of K is supplied by the sediment component. Other chemical components are less affected by changing the fraction of sediments in the mixture, as these are buffered by coexisting mineral phases (Px, Hbl, Ol, Spl) with the implication that the composition of the andesite magma is strongly dependent on temperature. The other point of interest is that olivine was in excess in all runs, ensuring that reaction with the mantle is not dependent on time or the scale of the process. These results explain the most outstanding geochemical features of HMA, namely (1) the high Mg# (>0.6) denoting equilibrium with the peridotite, (2) the high contents

in incompatible elements, which are mostly supplied by the sediment fraction of the subducted contaminant mixture, and (3) the hybrid isotopic features referred to above.

In summary, our experiments demonstrate that HMA may be generated from hybridized regions of the mantle that are fluxed by subducted mixtures composed of oceanic basalts and sediments. In the case of non-reactive mixed diapirs, primary high-silica andesite (HSA) magmas may segregate and underplate the lower crust contributing to the generation of silica-rich, low-Mg granulites and silicic melts that may form batholiths and dacitic volcanism. Granitic magmas derived from each hybrid source, namely reaction channels and non-reaction mixed diapirs, will have very similar composition as this is imposed by cotectic relations. A direct implication of the cotectic behavior of melts is that little compositional differences in

Fig. 4. Backscattered images (a and b) of basalt–sediment–peridotite reaction experiments showing equilibrium textural relations between forsterite-rich olivine (Fo$_{90}$) and an-desite liquid with compositions close to high-Mg# andesite (HMA). a: run RC1, starting material: spinel lherzolite + greywacke + amphibolite (8:1:1), 1050 °C/1.0 GPa/10 wt.% added H$_2$O. b: run RC4, starting material: spinel lherzolite + greywacke + amphibolite (8:1:1), 1200 °C/1.5 GPa/no-added H$_2$O. Mineral abbreviations are: Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Liq, liquid. The MgO vs Mg# diagram (c) shows the projection of experimental melts from reaction channels and non-reaction diapirs compared with classical magmatic trends from Cascades in California and Aleutians (data from Georoc database: http://georoc.mpch-mainz.gwdg.de/georoc/). Numbers beside data points denote temperature in °C and (W) denotes experiments with 10 wt.% added water. The approximate fields of HMA, HSA and dacites are labeled.
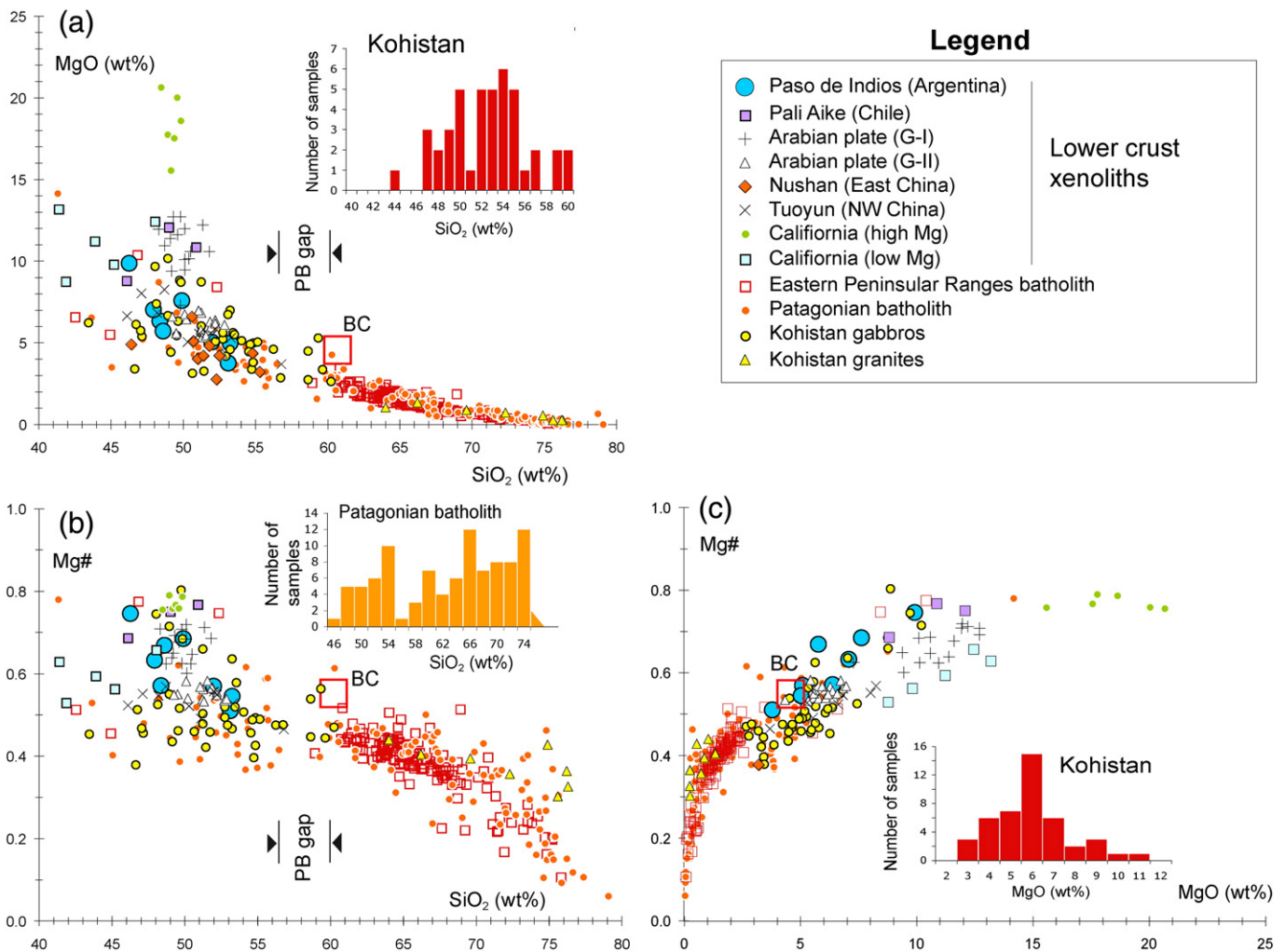
the parental magmas will be amplified and transferred to the composition of the solid residues left after melt segregation. If these solid residues remain at the lower crust as mafic granulites, they will be more heterogeneous in comparison with the more homogeneous cotectic melts represented by upper crust batholiths. These expected compositional relationships are tested with natural examples. This is fundamental to achieve a robust model about the generation of new crust in arcs.

5.1. Differentiation of upper and lower continental crust layers

The continental crust is structured in two main layers with contrasted compositions. A granodioritic upper crust is well-represented by cordilleran-type batholiths, whilst lower crust is represented both by (1) granulite xenoliths dragged by basalts to the surface and (2) exposed lower arc crust sections (e.g., Kohistan; Garrido et al., 2006; Dhuime et al., 2009). When plotting together cordilleran batholiths and lower crust rocks in mayor-element variation diagrams (Fig. 5) several interesting observations can be made in supporting a genetic link between both crustal layers.

5.1.1. Batholiths as cotectic systems

Granite batholiths define linear arrays, which resemble cotectic-like relations. Diorite and Qtz-diorite rock compositions ($SiO_2 < 60$ wt.%) and lower crust granulites (xenoliths and the Kohistan gabbros) are scattered and do not define linear arrays. There is a compositional gap at $SiO_2 = 54$–58 wt.% separating linear and scattered regions in silica variation diagrams. Precise U–Pb radiometric ages form zircons of Cordilleran granites from the North Patagonian batholith (Castro et al., 2011b) yield ages ranging 20 Ma (170–150 Ma) for samples plotting on the same cotectic array. Obviously, these non-coeval samples cannot be fractionated from a common magma at the place of emplacement. More likely, they represent magma pulses extracted at different temperatures, representing distinct melt fractions, from a common partially crystallized magma at depth. The composition of the parental magma is critical because this can be the primary magma fluxing from below the crust–mantle Mohorovicic discontinuity. It is concluded that parental magma composition to the Patagonian batholith (Castro et al., 2011a, 2011b) is at the silica gap (Fig. 5) with values of 56–60 wt.% SiO_2. Diorite and Qtz-diorite rocks from this batholith, plotting to the left of the gap ($SiO_2 < 56$ wt.%), are rich in hornblende and magnetite and represent

Fig. 5. Major compositional relations between lower crust granulites and cordilleran batholiths of North Patagonia (Castro et al., 2011b) and Eastern Peninsular Ranges (Lee et al., 2007) compared with experimental residues and melts (Castro et al., 2010) respectively. The composition of the bulk crust (Rudnick and Gao, 2003) (BC) and the arc sections of Kohistan (Garrido et al., 2006) are shown for reference. The Paso de Indios xenoliths (blue circles) plot within the field of gabbroic rocks from the Kohistan paleo-arc section. Average bulk crust is andesitic and lies close to the compositional gap displayed by granitoids of the Patagonian batholith (labeled PG gap) at about 54–58 wt.% SiO_2. Dioritic Patagonian rocks to the left of the gap with $SiO_2 < 56$ wt.% are low pressure cumulates (Castro et al., 2011a). Histograms show the high-silica and low MgO contents of most rocks from Kohistan paleoarc section. As these are residual rocks, the parental magma must lie at higher silica content and lower MgO, compared to its residue, possibly close to the Patagonian batholith gap.

low pressure cumulates. Lower crust granulites, 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 less heterogeneous upper crust, dominated by large homogeneous granodiorite–granite batholiths. These relations can be explained in terms of phase equilibria as the expected relations between cotectic melts and their corresponding mafic residues. The establishment of a thermodynamic relation between upper and lower crusts will lead to the identification of the magmatic precursor involved in the generation of the whole continental crust.

5.1.2. Lower crust granulites as residues

Heterogeneity is a general feature of the lower continental crust. Thus, comparisons between particular xenoliths and the averaged bulk lower crust (Taylor and McLennan, 1985; Rudnick and Gao, 2003) must be taken as approximations within boundaries of the scattered compositions of both lower crust xenoliths and lower crust estimates. It is remarkable that xenoliths from Paso de Indios locality in Patagonia (Castro et al., 2011a), which share in common age, Sr–Nd isotopic relations, trace element features and thermobarometric relations, display a large heterogeneity in terms of major element compositions, occupying a great part of the total heterogeneity area of lower crustal rocks (Fig. 5). The wide compositional region of lower crust xenoliths 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 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. These values are much lower than cumulates or residues left after, either incomplete crystallization or partial melting of a basaltic source. The possibility that lower crust mafic granulites represent underplated basaltic magma can be ruled out. Moreover, trace element relations strongly represent residues left after segregation of a melt. Because any process of fractionation and melt extraction will produce residues richer in MgO and poorer in SiO_2 compared to the parental magma, the composition of the residual lower crust implies a parental magma that can be close to an andesite.

Lower crust xenoliths from Paso de Indios locality in South America (Castro et al., 2011a) are extremely depleted in incompatible elements (Rb=2–15 ppm; Y=1–7 ppm; Zr=3–40; Th=0.1–1 ppm; U=0.1–0.5 ppm; ΣREE=10–50 ppm; see Table 3), which are typically partitioned into melts. Incompatible element depletion is taken as a characteristic feature of model lower crust compositions (Weaver and Tarney, 1982). These xenoliths also show a pronounced positive Eu anomaly on chondrite-normalized REE diagrams in agreement with the high plagioclase proportion (>60 vol.%) that characterizes these mafic granulite xenoliths. Also interesting to note is the high temperature of more than 900 °C recorded by lower crust xenoliths (about 1000 °C for the Patagonia xenoliths; Castro et al., 2011a). These high temperatures are coincident with those determined by melting experiments to generate tonalitic and granodiorite batholiths from partially molten basalt–sediment mixtures (Castro et al., 2010). A close association between lower crust mafic xenoliths and calc-alkaline plutons was found in the North America active margin in California (Lee et al., 2007) with important implications on crustal-making processes. Geochemical and geochronological studies on zircons from granulite xenoliths reveal that granulite generation is coeval to processes of magmatic underplating (Zhang et al., 2012) in Asia at various episodes along the Phanerozoic. This is in agreement with our model predictions about the generation of lower and upper crusts as part of a single magmatic episode.

Table 3
Geochemical compositions of continental crust, experimental liquids and residues, lower crust xenoliths and batholiths.

	1	2	3	4	5	6	7	8
	GRX	BLC	RES	Gr-Pat	BUC	LIQ	MPM	MEL
SiO_2	49.89	53.40	50.74	67.05	66.60	69.30	58.28	59.12
TiO_2	0.40	0.82	1.26	0.45	0.64	0.83	0.65	1.07
Al_2O_3	21.30	16.90	14.97	15.53	15.40	16.40	17.22	15.62
FeOt	6.71	8.57	11.80	3.77	5.04	2.72	6.19	6.81
MgO	6.33	7.24	7.85	1.57	2.48	1.05	4.01	4.34
MnO	0.10	0.11	0.22	0.09	0.10	0.04	0.10	0.13
CaO	10.47	9.59	9.28	4.12	3.59	2.76	7.47	5.99
Na_2O	2.50	2.65	3.77	3.07	3.27	2.66	2.91	3.18
K_2O	0.86	0.61	0.00	2.43	2.80	3.96	1.89	1.95
P_2O_5	0.25	0.10	0.11	0.13	0.15	0.28	0.22	0.16
Loi	0.88			1.09			1.05	0.87
Total	99.69	99.99	100	99.29	100	100	100.00	99.22
Mg#	0.62	0.60	0.54	0.43	0.47	0.41	0.54	0.53
ppm								
Li	7.3	13.0	19.0	24.0		12.4		
Be	0.4	1.4	1.5	2.1		1.2		
Sc	16.7	31.0	13.4	14.0		18.2	21.2	
V	135	196	85	97		151	140	
Cr	218.5	215.0	179.3	92.0		126.0	167.8	
Co	27.4	38.0	9.9	17.3		20.3	38.3	
Ni	62.8	88.0	11.9	47.0		29.0	48.6	
Cu	30	26.0	13.6	28.0		68.3	30.6	
Zn	44.0	78.0	51.7	67.0		48.1	51.8	
Ga	17.1	13.0	17.8	17.5		18.4		
Rb	8.0	11.0	73.5	82.0		44.4	93.9	
Sr	1006	348	339	320		472	170	
Y	3.9	16.0	17.3	21.0		11.8	28.3	
Zr	14.3	68.0	15.3	193.0		28.4	131.8	
Nb	2.2	5.0	6.1	12.0		6.9	14.7	
Cs	0.1	0.3	3.0	4.9		1.6		
Ba	221	259	548	628		395	380	
La	4.3	8.0	22.8	31.0		16.1	19.0	
Ce	8.3	20.0	44.6	63.0		34.8	42.0	
Pr	0.9	2.4	5.3	7.1		3.8	5.3	
Nd	3.8	11.0	20.0	27.0		14.2	20.3	
Sm	0.9	2.8	4.0	4.7		2.9	5.1	
Eu	0.6	1.1	0.9	1.0		0.9	1.1	
Gd	0.8	3.1	3.3	4.0		2.5	5.1	
Tb	0.1	0.5	0.6	0.7		0.4	0.9	
Dy	0.8	3.1	3.0	3.9		2.2	5.1	
Ho	0.2	0.7	0.7	0.8		0.5	1.0	
Er	0.4	1.9	1.8	2.3		1.2	2.8	
Tm	0.1	0.2	0.3	0.3		0.2	0.4	
Yb	0.4	1.5	1.8	2.0		1.2	2.4	
Lu	0.1	0.3	0.3	0.3		0.2	0.3	
Sum	53.3	56.6	109	148		81.3	111	
REE								
Hf	0.5	1.9	0.8	5.3		1.0		
Ta	0.3	0.6	0.6	0.9		0.8		
W	39.3	0.6		1.9				
Pb	4.7	4.0	11.5	17.0		8.1		
Th	0.3	1.2	9.5	10.5		5.2		
U	0.3	0.2	2.1	2.7		1.3		

GRX	Average granulite xenoliths of Paso de Indios (Patagonia)
BLC	Bulk composition of the lower continental crust (Rudnick and Gao, 2003)
RES	Average residues at 1.5 GPa from experiments with the MEL composition (Castro et al., 2011a)
Gr-Pat	Average granodiorites and tonalites from the North Patagonian batholith (Castro et al., 2011b)
BUC	Bulk composition of the upper continental crust (Rudnick and Gao, 2003)
LIQ	Average liquid compositions in experiments with MEL at 1.5 GPa (Castro et al., 2010)
MPM	Model primary magmas with 50% granulite residue and 50% granodiorite melt
MEL	Basalt–sediment melange used in melting (Castro et al., 2010) and melange–mantle reaction.

5.2. Composition of a common parental magma for lower and upper crusts

Once the residual nature of lower crust xenoliths, and their relations with the fractionated liquids – represented by upper crust batholiths –

have been sufficiently proven, the composition of the parental magma for both, granulites and batholiths, can be easily determined by mass balance using mineral-melt phase equilibria. Lower crust xenoliths show strong similarities with mineral assemblages formed in melting experiments of subducted basalt–sediment mixtures (Castro et al., 2010) at 1.5 GPa and 1000–1100 °C (Fig. 6). According to these experimental results, the mass melt fraction (f) extracted from the parental magma or solid source may range from 0.5 to 0.8 at 1.5 GPa and 1000 to 1100 °C respectively. Values of f = 0.5 and greater are needed to get melts of granodiorite to tonalite compositions departing from basalt–pelite composite systems at 1000 °C (Patiño-Douce, 1995). These figures, predicted by phase equilibria experiments, represent finite cumulative results. Most likely, melt extraction is accomplished in steps. Geological and petrological evidences tell us that batholiths are built-up by sequential amalgamation of magma pulses (Glazner et al., 2004; Castro et al., 2011a), and not by at-once liquid segregation and emplacement. Each magma pulse may represent batches of melt extracted from the source at different times. Because first extraction from the source or magma chamber will modify the bulk composition, the further batches of melt will be in equilibrium with a more refractory system, introducing slight differences in the composition of melts that may depart from the ideal equilibrium assumed in our comparisons between experiments and nature. These differences can be neglected for major elements if melts follow a cotectic behavior in multisaturation systems (Castro et al., 2010). A detailed knowledge of time–composition relations in batholiths is required. The available data are insufficient to produce a robust comparison between experiments and nature. The figures we give here are only first order approach that must be contrasted and improved in the future.
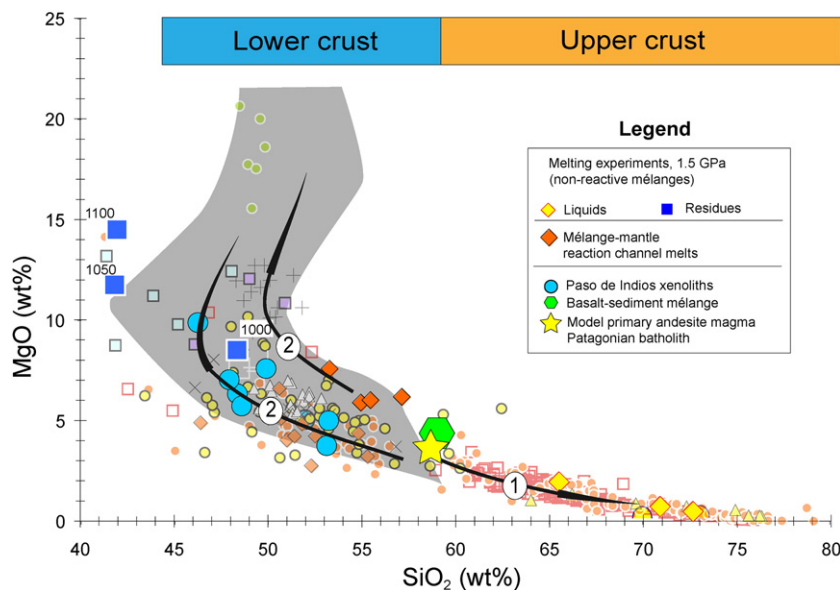
Assuming a minimum cumulative melt fraction f = 0.5, we may estimate by mass balance the composition of the primary magma. This composition may vary within discrete intervals of wt.% SiO_2 (54–59), wt.% MgO (6–4) and wt.% CaO (8–6) depending on the fraction of basalts in the mixture (X_b) from $X_b = 0.75$ to $X_b = 0.5$. It has been proven that liquids within this interval are buffered by the coexisting

assemblage (Castro et al., 2010). The immediate consequence of buffered liquids is that little differences in the composition of the parental magma are transferred to the solid residues giving rise to the characteristic scattered distribution of residues in chemical variation diagrams, which is mimicked by lower crust granulites and the Kohistan gabbros (Fig. 6). In the case of the Patagonian xenoliths and most of the Kohistan gabbros, the high silica contents impose high silica compositions to the corresponding andesite magma precursors. By contrast, the lower silica contents and higher MgO from other lower crust xenolith localities (e.g. California, Arabian plate and South Chile, Fig. 6) indicate a more mafic and less silicic composition for the parental magma. The latter may approach the composition of HMA formed along suprasubduction reaction channels.

It can be inferred that low-MgO, high-silica andesites (HSA) are the most appropriate to fractionate at the lower crust as suggested by the most abundant low-MgO residues compared to the more mafic compositions (Fig. 6). High-Mg andesites (HMA) are possibly less viscous and tend to reach the upper crust and fractionate at shallow magma chambers.

6. Concluding remarks

We conclude that andesite magmatic precursors reach the continental crust in active continental margins directly from partially molten subducted materials. Reaction with the mantle may play a relatively important role in producing high-Mg# andesites in arcs. An andesitic magmatic precursor not only solves the paradoxes around the bulk composition of the continents, but also accounts for the layered structure of the continental crust with granite batholiths at the upper crust and mafic granulites at the lower crust. In agreement with phase equilibria, the large heterogeneity of the lower crust compared with the more constant composition of upper crust is in fact determined by cotectic nature of melts (upper crust) and the residual origin (cumulates) of the lower crust.

Fig. 6. Relevant compositional relations in terms of MgO–SiO_2 major oxides between silicic batholiths (upper crust) and mafic granulites (lower crust). The shaded area represents the zone of residues calculated with MELTS code at 1.0 GPa using several starting materials within the range of reactive mixtures (high-Mg# andesites, HMA) and non-reactive mixed diapers (high-silica andesites, HSA). The model primary magma estimated by mass balance between the average composition of batholiths and lower crust xenoliths from Patagonia is shown. This is very close to the mixed materials formed by oceanic crust and greywackes in equal proportions (1:1). While large compositional variations are found in residues by changing only few units in the silica content of the parental magma, little changes are observed in the melts, corroborating the cotectic behavior of silicic plutons and volcanics. These differences between liquids and residues are predicted by thermodynamic modeling (MELTS code) and experiments and they fairly match the compositional relation found between homogenous batholiths and heterogeneous lower crust. Large arrows trace the trajectories of liquids (1) and residues (2). Most granulite rocks cluster in areas of low melt fractions, normally less than 50 wt.% liquid. High Mg granulites (e.g. from California) may represent low fractionation with less than 20 wt.% solid. Symbols for rock compositions as in Fig. 3.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2012.07.004.

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