Gondwana Research 23 (2013) 1554–1566

Contents lists available at SciVerse ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

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

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ARTICLE INFO

Article history:
Received 1 May 2012
Received in revised form 8 July 2012
Accepted 19 July 2012
Available online 28 July 2012

Handling Editor: M. Santosh

Keywords:
Continental crust
Batholith
Granulite
Silicic diapir
Tectonics
Andesite model

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).

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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http://dx.doi.org/10.1016/j.gr.2012.07.004

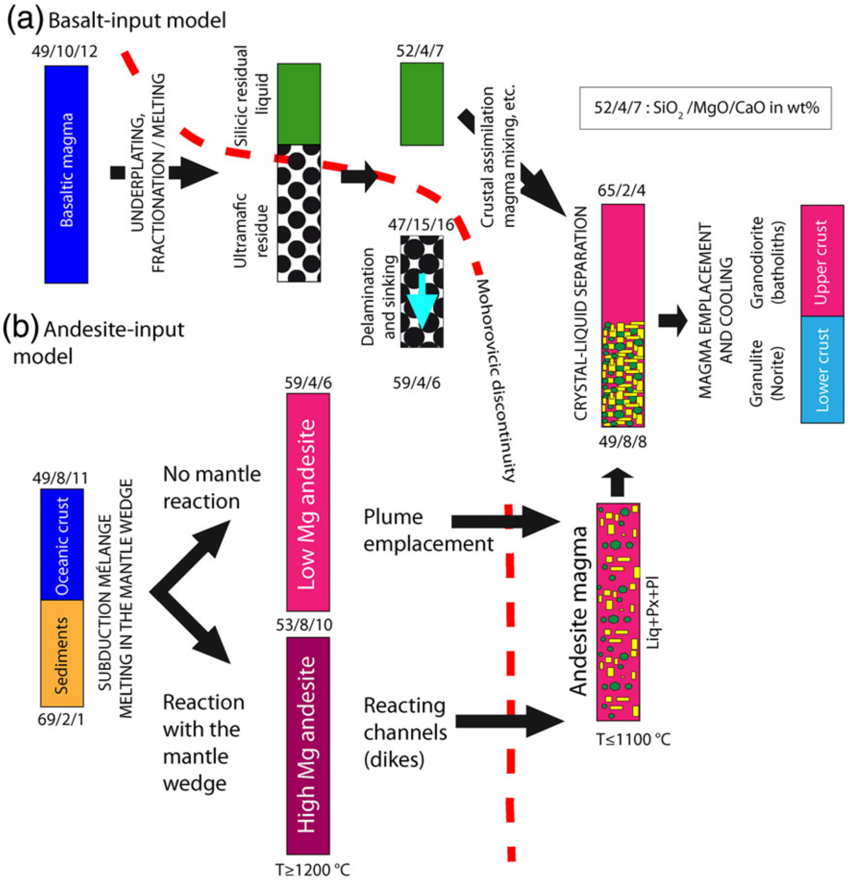

Fig. 1. Panel showing the main differences between the two models for the generation of the continental crust. The basalt input model (a) needs of two important additional processes to achieve the final composition represented by the bulk continental crust: 1: sinking of an ultramafic residue, not existing 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