Origin of high Mg# andesite and the continental crust

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The continental crust has an andesitic composition with high Mg/(Mg+Fe) and Ni contents which may be too high to have formed by differentiation of basaltic magmas. Instead, mantle-derived, high Mg# andesites (HMA) may form a substantial component of the crust [where HMA have SiO_2 > 55 wt %, and wt% MgO/(MgO+FeO*) > 0.33]. HMA may be produced by partial melting of previously depleted, subsequently metasomatized mantle peridotite. However, they are more likely produced by reaction between ascending melts and mantle peridotite. HMA are less common than basalt among lavas in modern island arcs, but may have been more common in the past, may be produced in specific environments (such as 'ridge subduction'), may be more common among plutonic rocks in the lower and middle crust than among lavas at the surface, and may be selectively preserved during later erosion and subduction processes.

New distribution coefficients and trace element modelling [Kelemen *et al.*, 1993, 1]

Depletion of Nb relative to K and La is characteristic of lavas in subduction-related magmatic arcs, as distinct from mid-ocean ridge basalts. Nb depletion is also characteristic of the continental crust. This and other geochemical similarities between the continental crust and HMA found in arcs suggests that the continental crust may have formed by accretion of andesites. Previous studies have shown that the major element characteristics of HMA may be produced by melt/rock reaction in the upper mantle. In this paper, new data on partitioning of K, Nb, La, and Ce between garnet, orthopyroxene and clinopyroxene in mantle xenoliths, and on partitioning of Nb and La between orthopyroxene and liquid, show that garnet and orthopyroxene have Nb crystal/liquid distribution coefficients which are much larger than those of K and La. Similar fractionations of Nb from K and La are expected in spinel and olivine. For this reason, reactions between migrating melt and large masses of mantle peridotite can produce substantial depletion of Nb in derivative liquids. Modeling shows that reaction between ascending, mantle-derived melts and mantle peridotite is a viable mechanism to produce the trace element characteristics of HMA and the continental crust.

Alternatively, small degree melts of metabasalt and/or metasediment in the subducting slab may leave rutile in their residue, and will thus have large Nb depletions relative to K and La [2]. Slab melts are too rich in light rare earth elements and other incompatible elements, and too poor in compatible elements, to be parental to arc magmas. However, ascending slab melts may be modified by reaction with the mantle. Our new data permit modeling of the trace element effects of reaction between small degree melts of the slab and mantle peridotite. Modeling shows that this type of reaction is also a viable mechanism for producing the trace element characteristics of HMA and the continental crust. These findings, in combination with previous results, suggest that melt/rock reaction in the upper mantle has been an important process in forming the continental crust and mantle lithosphere.

Review of experimental and theoretical work on the genesis of andesite [Kelemen, 1994, 3]

The integrated composition of the continental crust must correspond to the net material flux through the Moho during crustal formation. In a simple model, the crust is produced by magmas passing through the Moho beneath subduction-related arcs [4]. More complex models involve rift magmatism, , within plate magmatism, and recycling due to selective subduction or delamination of basaltic components from the existing crust. However, the arc model is a good starting point, since estimates of the continental crust composition [e.g. 5, 6] are strikingly similar to HMA in arcs.

Modelling and experiments on reaction between mantle peridotite and picritic, basaltic or 'tonalitic' magmas [e.g. 7, 8] produced HMA with major element compositions of HMA and the continental crust. By contrast, HMA have not been produced by partial melting of basalt or mantle peridotite, or by crystal fractionation from basalt. Among 483 experimental liquids produced in peridotite and basaltic bulk compositions, under conditions of high and low pressure, with and without H_2O, at high and low f_{O_2}, none are HMAs, with one exception [9] to be discussed further in the paper. Thus, crustal anatexis and/or crystal fractionation probably have not been essential in forming the continental crust. Also, high pressure 'slab melts' of hydrous metabasalt do not have appropriate compositions for the continental crust. Combination of basaltic and granitic compositions, by magma mixing, assimilation, and/or mechanical mixing, may produce HMA, but for the continental crust this requires the unlikely explanation that crustal mixing processes are essential in creating the crust. In summary, hypotheses for the origin of andesitic crust by differentiation of an earlier, basaltic crust may not be tenable.

Selective chemical erosion and subduction of 'basaltic' components from the crust is an important alternative to igneous fractionation. However, the Archean continental crust is also estimated to have had an HMA composition, very similar to the present-day crustal composition [e.g. 5,6]. If these estimates are correct, two billion years of weathering, erosion and subduction have not substantially changed the Mg# or SiO_2 content of the crust, and thus these processes may not have been essential in producing an HMA crustal composition.

In conclusion, the continental crust may have formed primarily by accretion of HMA in arcs. HMA may be formed by direct anatexis of metasomatized, previously depleted mantle peridotite. However, hydrous fluid metasomatism above subducting slabs probably does not transport sufficiently large amounts of essential ingredients to explain the total magmatic flux in arcs. Instead, HMA may be more commonly produced by melt/rock reaction between depleted upper mantle and initial liquids formed by mantle and/or slab anatexis.

HMA are subordinate to basalts among 'primary' lavas in contemporary island arcs. However, HMA are abundant in a compilation of 795 analyses of Archean igneous and meta-igneous rocks, and 234 analyses of Cenozoic, island arc-related plutonic rocks. The following hypotheses are offered to explain these distributions of HMA: 1. HMA were formed more commonly in the Archean than at present [e.g. 10]. 2. HMA are initially more viscous than basalt, and become more so during mid-crustal dehydration, so are rarely erupted. 3. Andesitic crust, when it forms, may be less susceptible to later subduction than denser, basaltic crust. 4. Special tectonic circumstances, such as subduction of young, hot oceanic crust, may be required to produce voluminous HMA [e.g. 11]. In the latter case, production of continental crust may be a periodic phenomenon, and may have been more common in the Archean when geotherms were steeper and/or subduction rates were greater.

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