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Crystallization of a basal magma ocean recorded by Helium and Neon

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A B S T R A C T

Interpretation of the noble gas isotopic signature in hotspots is still controversial. It suggests that relatively primitive material remains untapped in the deepest mantle, even while mantle convection and sub-surface melting efficiently erase primordial heterogeneities. A recent model suggests that significant differentiation and fractionation affects the deepest mantle following the formation of a dense basal magma ocean (BMO) right after core segregation (Labrosse et al., 2007). Here we explore the consequences of the crystallization of a BMO for the noble gas evolution of the mantle. The crystals extracted from a BMO upon cooling generate dense chemical piles at the base of the mantle. We show that if the solid–melt partition coefficients of He and Ne are >0.01 at high pressure and temperature, He and Ne isotopic ratios in pile cumulates can be pristine like. Hence, the entrainment of modest amounts of BMO cumulate in mantle plumes ($<10\%$) potentially explains the primitive-like He and Ne signatures in hotspots. Because pile material can be depleted in refractory elements while simultaneously enriched in noble gasses, our model forms a viable hypothesis to explain the complex relationship between He and refractory isotopic systems in Earth's interior.

1. Introduction

The isotopic signatures of oceanic island basalts (OIBs) are a cornerstone for building models of the evolution of Earth's mantle through time (Hofmann, 1997 for a classic review). Lithophile isotopic systems are particularly useful, since most of them document fractionation and segregation upon melting, and hence crust–mantle differentiation. In the 1980s, Sr, Nd and Pb isotopes were used to show that the mantle sources of many oceanic islands contain recycled crustal components (e.g. Allègre et al., 1987; Dupré and Allègre, 1983; Hart, 1988; Storey et al., 1988). Improvements in geochemical analytical methods allowed higher precision studies on isotopic systems such as Re/Os or Lu/Hf. These new data confirmed the presence of recycled crustal components from deep oceanic crust to pelagic sediments in the source of most hotspot basalts, with Hawaii and Iceland being the most popular targets (Blichert-Toft et al., 1999; Hauri and Hart, 1993).

Helium and Neon both have U and Th parentage: ^{4}He and ^{21}Ne are radiogenic and nucleogenic isotopes, respectively, produced within the radioactive chains of ^{235,238}U and ^{232}Th. Other isotopes are stable and almost non-radiogenic/nucleogenic (e.g. primordial): ^{3}He and ^{20,22}Ne. Variability in ^{4}He/^{3}He and ^{21}Ne/^{22}Ne is caused by ancient degassing and extraction/recycling of U and Th. Low ^{4}He/^{3}He and ^{21}Ne/^{22}Ne isotopic ratios have been measured in many OIBs (Honda et al., 1991; Moreira et al., 1995; Moreira et al., 2001; Moreira et al., 2004; Poreda and Farley, 1992; Trieloff et al., 2000; Yokochi and Marty, 2004). These signatures have not been observed in crustal rocks, perhaps owing to release of noble gasses into the atmosphere upon formation of the crust.

Models are then needed to reconcile the simultaneous occurrence of primitive-like isotopic ratios of noble gasses and ubiquitous recycling of crustal components in mantle plumes. The proposed alternative was that the source of these OIBs (a) sample a deep pristine and little degassed reservoir (Allègre et al., 1987) or (b) contain old recycled lithospheric mantle depleted in radioactive elements (Coltice and Ricard, 1999). In the pristine model, the primitive mantle has to be intrinsically denser to be preserved from convective mixing. However, there is no evidence for any significant major element difference between primitive and depleted mantle that would lead to such a density difference. Moreover, the refractory isotope ratios of primitive-like OIBs are almost similar to those of the depleted bulk mantle, which is the source of mid oceanic ridge basalts. An argument against the recycling model was proposed by Kurz et al. (2009) based on Neon isotopes in Galapagos samples. In order to explain observed non-nucleogenic ^{21}Ne/^{22}Ne ratios by a residual component, a depletion age of 4.4 Ga is implied, which is difficult to justify. Thus both the pristine reservoir and crustal recycling models

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have shortcomings, prohibiting the development of any consensus regarding the origin of noble gas signatures in OIBs.

Recently a new class of models has emerged, in which early differentiation generated a fractionated enriched reservoir, for instance subducted early crust, that would have sequestered a significant fraction of incompatible element in the deepest mantle (Boyet and Carlson, 2006; Tolstikhin and Hofmann, 2005). The peculiar noble gas signature of some OIBs would be explained by sampling of the early reservoir by mantle plumes (Jackson et al., 2010). Within this family of models, Labrosse et al. (2007) proposed that early differentiation took place in the deep mantle with the formation of a basal magma ocean (BMO). The presence of dense material above the core–mantle boundary in the present-day Earth has been inferred in ultralow seismic velocity zones (ULVZ) at the core–mantle boundary, which may be close to the solidus or partially molten (Rost et al., 2005; Williams and Garnero, 1996). Because the core has been cooling for more than 3.2 Ga as evidenced by the persistence of a geomagnetic field (Labrosse, 2003; Tarduno et al., 2007), these ULVZ patches lying above the core should naturally be remnants of a larger magma body formed early in Earth's history (Labrosse et al., 2007). It has been proposed that the entrainment of the material crystallized from the cooling BMO could explain the signature of primitive-like noble gasses in mantle plumes. Contrarily to Boyet and Carlson (2006) and Tolstikhin and Hofmann (2005), it is not the entrainment of the enriched reservoir that would occur, but that of the cumulates (i.e., the crystals extracted as the melt crystallizes). Here we explore this scenario further, and predict the required Helium and Neon partitioning upon deep melting/crystallization to simultaneously explain depleted lithophile characteristics along with primitive-like noble gas signatures in OIB.

2. Influence of a basal magma ocean on mantle heterogeneity

The slow cooling of the BMO induces its progressive fractional crystallization. Because of the large Grüneisen parameter of the magma (Mosenfelder et al., 2007; Mosenfelder et al., 2009), the isentropic temperature gradient in the melt may be larger than the gradient of the liquidus due to a small molar volume difference between melt and solid at high pressure (Fig. 1). Under these circumstances, crystals would form at the top of the melt layer. The phase diagram of the deep mantle is poorly known but since the starting composition of the BMO is very similar to that of the mantle (Labrosse et al., 2007) the liquidus phase is very likely to be (Mg, Fe) SiO_3 perovskite (Fiquet et al., 2010). Hence, crystals are Mg rich and consequently less dense than the melt. This results in a fractional crystallization evolution, with solid cumulates rising upward to the top of the BMO and subsequently becoming accessible to entrainment in convection currents in the solid mantle (see Fig. 2A). As crystallization advances, the residual melt becomes richer and richer in iron, and so do the crystals that subsequently form. Eventually, cumulates become dense enough to be gravitationally stable against immediate entrainment by mantle convection and accumulate as thermo-chemical piles above the BMO as proposed in Fig. 2B. To resist entrainment, the intrinsic density of the crystal must exceed about 2.5% in the deepest mantle (Davaille, 1999). This scenario is consistent with the presence of broad low shear wave anomalies extending several hundred kilometers above the core–mantle boundary, which represent a ubiquitous and robust feature in seismic tomographic models (Bolton and Masters, 2001; Hernlund and Houser, 2008; Karason and van der Hilst, 2001; McNamara and Zhong, 2005; Megnin and Romanowicz, 2000).

The deep and dense piles which form by accumulation of dense cumulates above the BMO are the only possible vector to transfer the chemical signal of the BMO to the surface because the liquid is itself relatively dense and is expected to have a very low viscosity (Karki and Stixrude, 2010). The crystals from the BMO can be entrained viscously by deep mantle plumes that start from the edges of piles which are the hottest regions of piles and location of BMO melt remnants (McNamara et al., 2010). Depending on the partitioning behavior of noble gasses at high pressure and temperature, piles can have a high concentration of noble gasses. Indeed, the crystals form out of the BMO, protected from subsurface degassing which has stripped most of the volatiles from the convecting mantle (Allègre et al., 1987).

3. Dynamical model of rare gas evolution

Our goal is to compute the rare gas evolution in the piles formed out of the BMO. The model is developed on the basis of previous work proposing a model of BMO evolution (Labrosse et al., 2007). The considered reservoirs are: the bulk mantle which is the whole

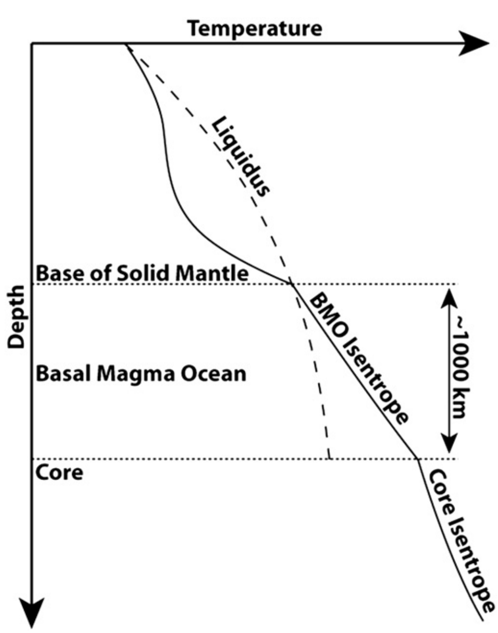

Fig. 1. Schematic temperature profile in the mantle, basal magma ocean and the core of the Earth. The liquidus is represented to discuss the nature and fate of crystals formed through the cooling of the basal magma ocean.

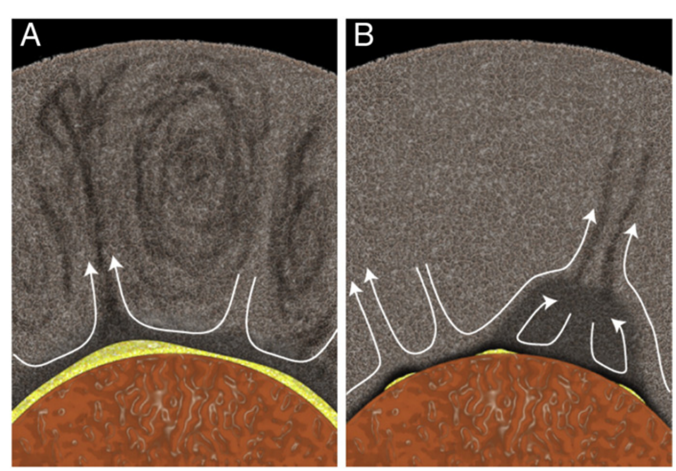

Fig. 2. Schematic dynamical evolution of the deep mantle. While the BMO crystallizes following mantle cooling, the crystals become richer in Fe. In a first stage (A) the crystals can be easily entrained and mixed back in the bulk mantle. In a later stage (B), the crystals are dense enough to form stable piles resisting convective entrainment. Today only plumes anchored on piles can modestly sample them.