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# The evolution of He Isotopes in the convecting mantle and the preservation of high $^3He/^4He$ ratios

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**Abstract**

A key requirement for any model of mantle evolution is accounting for the high $^3He/^4He$ ratios of many ocean island basalts compared to those of mid-ocean ridge basalts. The early, popular paradigm of primitive, undegassed mantle stored in a convectively isolated lower mantle is incompatible with geophysical constraints that imply whole mantle convection. Thus it has been suggested more recently that domains with high $^3He/U$ ratios have been created continuously from the bulk mantle throughout Earth history. Such models require that the $^3He/^4He$ ratio of the convecting mantle was at least as high as the highest values seen in OIB at the time the OIB source was generated. These domains must also be created with sufficient He to impart distinctive He isotopic signatures to ocean island basalts. However, the He isotope evolution of the mantle has not been consistently quantified to determine if such scenarios are plausible.

Here a simple model of the He evolution of the whole mantle is examined. Using a wide range of possible histories of continental extraction and He degassing, the bulk convecting mantle was found to have had $^3He/^4He$ ratios as high as those seen in the Iceland hotspot only prior to 3 Ga. Such high $^3He/^4He$ ratios can only be preserved if located in domains that are not modified by convective mixing or diffusive homogenisation since that time. Further, there are difficulties in producing, with commonly invoked magmatic processes, domains with sufficiently high $^3He/U$ ratios and enough $^3He$ to be able to impart this signature to ocean island basalts. The results are consistent with models that store such He signatures in the core or a deep layer in the mantle, but are hard to reconcile with models that continuously generate high $^3He/^4He$ domains within the mantle.


*Keywords:* mantle evolution; noble gases; He isotopes; ocean island basalts

## 1. Introduction

Noble gases provide important constraints on mantle structure. The long popularity of a layered mantle convection model, with a degassed and depleted upper mantle supplying mid-ocean ridge basalts (MORB) underlain by an unprocessed lower mantle supplying distinctive chemical characteristics to ocean island basalts (OIB), was partly due to its success in accounting for noble gas geochemistry (Kurz et al., 1982; Allègre et al., 1983; Kaneoka, 1983). However, incompatible trace element compositions of OIB are clearly non-primitive (see Hofmann, 1997). Moreover, geophysical data indicate that plates are subducted to depths > 660 km (e.g. Grand, 1987), illustrating that a pattern of whole mantle convection occurs and the lower mantle has not been chemically isolated throughout Earth history. The OIB data then require material from either a reservoir that is isolated at much greater depths (see Kellogg et al., 1999; van Keken et al., 2002; Tolstikhin and Hofmann, 2005), or from heterogeneities contained within the convecting mantle that are generated from subducted components or melting (e.g. Graham et al., 1990; Helffrich and Wood, 2001).

With whole mantle convection, the most prominent noble gas feature that must be explained is the distribution of He isotope compositions. In contrast to MORB, which have

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$^3He/^4He$ ratios that fall within a relatively narrow range of ~6 to $9R_A$ (where $R_A$ is the atmospheric ratio of $1.4\times10^{-6}$), a number of OIB have much higher values, extending up to ~$50R_A$ (see Graham, 2002 for review). Thus some OIB require sources with higher integrated $^3He/U$ ratios than the MORB source. The challenge has become identifying where such sources are stored in the mantle.

Several mechanisms have been suggested for generating high $^3He/^4He$ ratios in material isolated from within the convecting mantle. Most simply, domains isolated from a continuously degassing mantle will retain higher $^3He/U$ ratios and so evolve with higher $^3He/^4He$ (Class and Goldstein, 2005). Alternatively, since U can be slightly more incompatible than He under some melting conditions (Parman et al., 2005; Heber et al., 2007), melting of the mantle might leave depleted domains with high $^3He/U$ (Graham et al., 1990; Anderson, 1998; Helffrich and Wood, 2001). It has also been suggested that a volatile phase segregated near the surface can carry He, unaccompanied by U, into previously depleted oceanic lithosphere (Anderson, 1998; Foulger and Pearson, 2001). While such high $^3He/U$ domains would be progressively stirred into the surrounding mantle and so destroyed (see van Keken et al., 2002), others would be continuously created, so that their storage over a significant part of Earth history may not be necessary.

However, the possible role of such domains clearly must be evaluated quantitatively in the context of overall mantle evolution. There are two essential factors that must be considered. First, the mantle material from which it is formed must have sufficiently high $^3He/^4He$ ratio. The $^3He/^4He$ ratios of the general mantle reservoir progressively decrease due to $^4He$ production (Fig. 1). If a portion of mantle was isolated at some time in the past, its $^3He/^4He$ cannot exceed the value of the evolving mantle at that time. Such domains must therefore be formed before the $^3He/^4He$ ratio of the evolving mantle has dropped below that of OIB. Second, these domains must maintain enough He to impart their high $^3He/^4He$ signature to an OIB, even where other components are involved.

Little previous work has been done on the evolution of the convecting mantle to determine if conditions allow the generation of high $^3He/^4He$ domains over most of Earth history. Seta et al. (2001) calculated the evolution of $^3He/^4He$ in mantle reservoirs, although this was for an open system layered mantle model. Class and Goldstein (2005) provide an evolution curve for the bulk mantle, although as discussed below it does not take into account a number of known constraints. The present study examines a whole mantle convection model in which OIB sources are continuously created by magmatic processes. Two tests are applied to the model. The first is how recently the convecting mantle, as sampled by MORB, could have had $^3He/^4He$ ratios as high as those now seen in OIB, since this establishes how long such domains must be preserved within the convecting model. The benchmark used is $50R_A$, the highest value found in volcanic rocks from the proto-Iceland mantle plume (Stuart et al., 2003). The second test is whether domain $^3He/U$ ratios are sufficiently high to maintain high $^3He/^4He$ ratios and are accompanied by sufficient $^3He$ to supply OIB.

## 2. Modelling the convecting mantle

A model of the He isotope evolution of the convecting mantle requires 1) a time-dependent $^4He$ production function, determined by the concentrations of U and Th that are progressively depleted by extraction into the continental crust; and 2) a time-dependent He degassing function that is linked to the $^3He$ concentration and monotonically decreases with declining mantle He concentration and mantle cooling. The boundary conditions are the initial $^3He$ concentration and $^3He/^4He$ ratio of the Earth, the present upper mantle $^3He$ concentration and $^3He/^4He$ ratio, and the present mantle He flux to the atmosphere (Table 1).

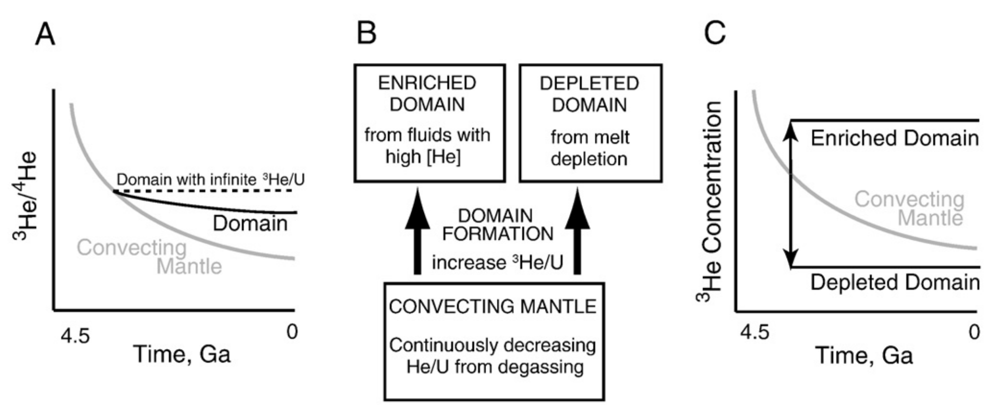


Fig. 1. Generating high $^3He/^4He$ domains from the bulk mantle. (A) The $^3He/^4He$ ratio of the convecting mantle decreased with time from a high, early solar system ratio to that measured in MORB. Models for creating mantle domains from this reservoir with higher present ratios as seen in OIB envision extracting He from the convecting mantle into domains with higher $^3He/U$ ratios where higher $^3He/^4He$ ratios will be preserved, and which may have a maximum value (dashed line) equal to that of the convecting mantle at the time of its formation. (B) Distinctive domains may be continuously generated from the convecting mantle by two possible mechanisms. During the removal of melts near the surface, if U is more incompatible than He, then the source will be a depleted residue domain with a higher $^3He/U$ ratio, though lower He concentration, than the surrounding mantle. Alternatively, if a volatile-rich fluid separates near the surface, it can enrich a previously depleted region of the convecting mantle or lithosphere with He. (C) The $^3He$ concentration of the convecting mantle will continue to decrease due to degassing at ridges and subduction zones, while that in the domains may remain constant after the strong depletion during domain formation.