Dynamical models of mantle $^3He/^4He$ evolution

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Geochemical reservoirs in the mantle

Observed $^3He/^4He$ from mantle sources provides a very simple yet powerful constraint on the mantle system, and demonstrates that terrestrial degassing of primitive volatiles from the mantle is still occurring. An equally important geochemical observation is that ~50% of the radiogenic ^{40}Ar produced in the Earth since accretion is now in the atmosphere. There is one very uniform $^3He/^4He$ source, supplying mid ocean ridge basalts (MORB). Ocean islands basalts (OIB) however, require at least one other source, capable of supplying $^3He/^4He$ both higher and lower than the MORB source. The differences observed in $^3He/^4He$ between MORB and OIB require the existence of at least two different reservoirs within the mantle, preserved over long periods of the planet's history. This has been used to justify geochemical models invoking a layered structure of the mantle system.

Nevertheless, the formation and survival of distinct geochemical reservoirs required by simple layered models also need to be consistent with dynamical models. The principle test for the validity of any model must be the ability of that model to reproduce the first order geochemical observables of; 1) a uniform $^3He/^4He$ source capable of supplying MORB; 2) a source capable of supplying high $^3He/^4He$ analogous to the plume source; and 3) a dynamical system which is capable of degassing ~50% of the radiogenic ^{40}Ar produced internally within the mantle.

Modelling approach

In previous work (Van Keken and Ballentine, 1998) we have used cylindrical models of mantle convection that incorporate helium isotope evolution and degassing to test both geophysical and geochemical parameters which may account for the creation and preservation of the observed mantle heterogeneity. In particular, we investigated the role of a high viscosity lower mantle in the volatile evolution. Although the higher viscosity retards mixing, models that were sufficient Earthlike in terms of present-day heat flow and plate velocities showed efficient large scale mixing over the life time of the Earth. None of the models examined could provide a dynamical explanation for the coexistence of two distinct reservoirs or for the long term survival of primitive mantle.

We have now developed a number of increasingly more realistic models of mantle convection that satisfy present day heat loss and plate velocities to study the effects of convective mixing, radiogenic ingrowth and degassing on the mantle $^3He/^4He$ evolution. We have included the influence of strongly temperature- and pressure-dependent rheology and that of phase transitions on the mixing efficiency of the mantle. Our models are based on the solution of the dynamical equations governing mantle convection in a cylindrical geometry using the extended Boussinesq approximation. In addition to prescribed rheology, rate of internal heating and geometry, the dynamics are governed by the Rayleigh number Ra and the dissipation number Di. For a finite dissipation number, the effects of compressible heating, viscous dissipation and latent heat exchange at the phase changes are taken into account.

We have adjusted the parameters governing rheology and internal heating such that all four models have the following characteristics in common: i) the surface heat flow on average is equal to the present day surface heat flow of the Earth; ii) the lower mantle is heated internally at a rate of approximately three times the present day chondritic value. This on average represents about 70% of the surface heat flow; iii) the surface velocity is between 2 and 4 cm/yr; iv) the average lower mantle viscosity is 30 to 50 times higher than that of the upper mantle. v) each model has three arbitrarily assigned degassing zones. These constraints allow us to focus on the effects that the (p,T) dependent rheology and phase changes cause in a sufficiently Earth-like model, and avoids possibly erroneous conclusions that may be drawn by comparing models with an intrinsic decrease in convective vigor.

Results

The four models shown below (Fig. 1) are of increasing rheological and thermodynamical

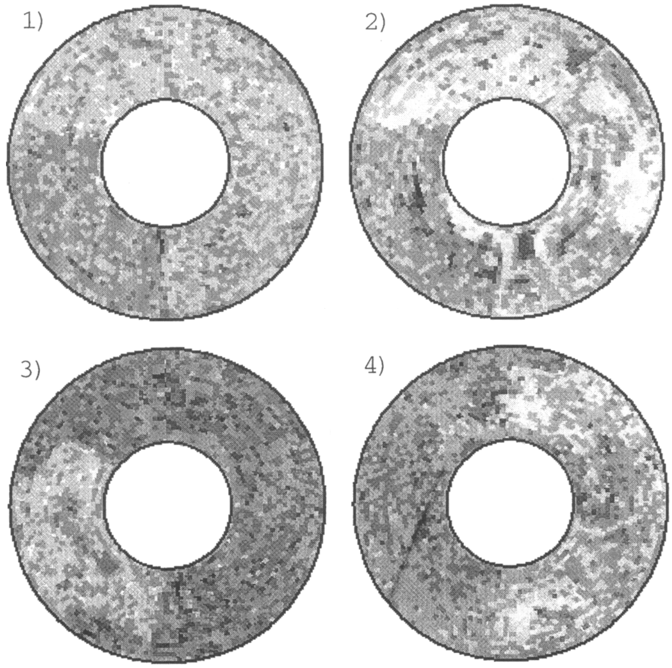

FIG. 1. Showing mantle $^3He/^4He$ variation as a function of greyscale (White = 36 Ra, Black = 0.02 Ra) for four different dynamical models run for 4 Ga (See Text).

complexity: 1) no phase changes; stepwise increase in viscosity (after Van Keken and Ballentine, 1998); 2) no phase changes but with strongly temperature- and pressure-dependent viscosity (Van Keken *et al.*, 1994); 3) 400+670 km phase changes with density changes controlled by PREM and Clapeyron slopes which are in turn based on high pressure and seismological observations (e.g. Tackley *et al.*, 1993). 4) same as 3, but now with 3x higher density increase at the phase transitions. Of these models, we consider the viscosity and phase change parameters in 3 to be the most 'Earth-like'. The fourth is included to show the effect of extreme values which may be expected to induce strong layering of the mantle.

Summary

Although it is evident that the additional effects decrease the efficiency of mantle mixing and enhance the persistence of chemically different areas, none of these models, including the one with the exaggerated effects of the phase changes, provide large scale isolated reservoirs. Geophysical models of mantle convection have not yet been reconciled with even the simplest of geochemical observables. Future directions include considering the effects of long wavelength heterogeneity induced by the simulation of oceanic and continental plates, the influence of previously neglected dynamical mechanisms such as compressibility, non-Newtonian viscosity, depth dependent thermal diffusivity and expansivity, and internal heat production locally proportional to heat producing element concentrations. If a combination of the above is still unable to reproduce the first order noble gas observables, it may be prudent to consider sources of ^3He external to the mantle system.

References

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