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Heat and Helium: A Numerical Investigation of Mantle Heterogeneity Lengthscale

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In recent years we have seen a major shift in our appreciation of the role of the mantle in the Earth's convective heat loss. Tomographic and geodynamical evidence for whole mantle involvement has prompted a re-evaluation of our conceptual ideas of chemical layering in the Earth. Yet, whole-mantle models are generally not reconciled with some major geochemical observations that are interpreted as being the result of a deep isolated large scale reservoir containing the majority of the Earth's radiogenic elements.

Evaluation of the uranium concentration in the bulk silicate Earth (BSE) following a chondritic reference model yields about 20 ppb which is substantially higher than that inferred for the MORB source (5 ppb). After correcting for the U estimated to be in the continental crust, it follows that a major contribution to the Earth's U budget must be stored either in the deep mantle or the core. Heat budget considerations add weight to this argument. Crustal heat sources account only for 6-8 TW of the present-day budget of 44 TW. If the entire mantle would be composed of MORB source material, it would produce only about 5 TW. With an average BSE composition, the mantle would contribute 19 TW (assuming Th/U=4, K/U=12,000). The remainder of the surface heat flow can then be contributed to a moderate amount of secular cooling of the mantle (5-8 TW for 50-75 K/Byr) and about 10 TW from the cooling of the core.

Heat and ^{4}He are produced at a constant ratio during the decay of U and Th. Correcting for the heat produced by K and that due to secular cooling, it might be expected that the heat flux (due to U+Th) and the ^{4}He flux from the mantle be at this ratio. The He/Heat observed ratio is ~10 times smaller than predicted. This has been used as one of the principal pieces of evidence sited in support for the classic chemically layered mantle model, in which a deep boundary layer allows heat to escape but retains the radiogenic ^{4}He (O'Nions & Oxburgh, 1983). How can this be reconciled with the tomographic evidence for whole mantle flow?

It is important to note that the extraction of heat and ^{4}He at the surface of the Earth occur by different processes with strongly different temporal and spatial scales. Helium is mainly extracted during eruption and hydrothermal activity at the mid-ocean ridges. Heat is more gradually released by conductive cooling of the entire oceanic lithosphere. As a consequence, the present day extraction rates may be representative of a state that is far from equilibrium with the average, steady state assumption. To investigate the variance in Heat/He of a non-steady state system, we have evaluated He and heat extraction calculated in a number of previously published time-dependent models of whole mantle convection (Van Keken and Ballentine, 1999). We observe that the heat loss and in particular the ^{4}He release are strongly time-dependent, but that the time variation in flux amplitude can be completely out of phase. This is enhanced in a model where we imposed a relatively strong effect of the phase boundaries, which led to occasional 'avalanche' style exchanges between upper and lower mantle. We show in this case the peak to peak change in ^{4}He/heat is a factor of 5. This exercise illustrates that the ^{4}He/heat is strongly time-dependent with very different time constants for heat and ^{4}He respectively. The extrapolation of the current ^{4}He/heat ratio to a steady-state value should be undertaken with caution. Nevertheless, the fluctuation in this ratio isn't sufficient to account for the observed difference of a factor of 10.

Our preliminary conclusion is that although the magnitude of it may be lessened, the non steady state differential extraction of heat and He alone cannot account for the heat/He paradox. Of particular note is the small length scale (few hundreds of kilometers) of isotopic heterogeneity ($^{3}He/^{4}He$) produced in our numerical models of whole mantle convection. Although it is tempting to suggest that long lived small scale heterogeneity could contribute some of the isotopic variation observed, this scale of heterogeneity cannot reproduce observed Heat/Helium. This observation supports the conceptual models requiring a large scale major boundary layer in the Earth below 670 km.

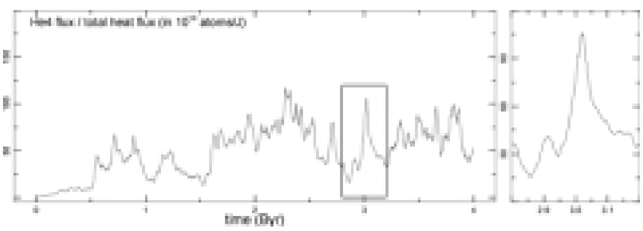

Figure 1: The ratio of helium and heat can be highly variable as is shown in this diagram, evaluated for a previously published model of mantle convection.

O'Nions RK & Oxburgh ER, *Nature*, **306**, 429-431, (1983).
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