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Energetics of mantle convection and the fate of fossil heat

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[1] Reconstructing the thermal history of the Earth, consistent with the low concentration of heat-producing elements in convecting mantle as well as with modest secular cooling required by geological records, has been a major challenge in geophysics and geochemistry. By developing the self-consistent energetics of plate-tectonic mantle convection, we show that the low Urey ratio of convecting mantle can yield a geologically reasonable solution in the thermal evolution model of the Earth. The effect of dehydration on mantle rheology during plate formation with mantle melting results in more sluggish plate tectonics (i.e., lower heat flow) for hotter mantle. This inverse relationship between mantle temperature and surface heat flux leads to the efficient storage of fossil heat, preventing the drastic secular cooling of the Earth. *INDEX TERMS:* 3040 Marine Geology and Geophysics: Plate tectonics (8150, 8155, 8157, 8158); 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8125 Tectonophysics: Evolution of the Earth; 8130 Tectonophysics: Heat generation and transport; 8162 Tectonophysics: Rheology—mantle. **Citation:** Korenaga, J., Energetics of mantle convection and the fate of fossil heat, *Geophys. Res. Lett.*, *30*(8), 1437, doi:10.1029/2003GL016982, 2003.

1. Introduction

[2] The problem of the so-called missing heat source in the Earth's mantle has been central to our understanding of the style of mantle convection. The present-day terrestrial heat flux is ~44 TW [*Stein*, 1995]. About 80% of this global heat flux (i.e., ~36 TW) comes from mantle convection, whereas the rest of ~8 TW originates in continental crust. This convective heat flux must be supported by internal heating due to radiogenic elements and the secular cooling of the Earth itself. A long-standing problem is that the convecting mantle, the melting of which produces mid-ocean ridge basalts (MORB) and thus oceanic crust, is known to be highly depleted in heat-producing elements (^{238}U, ^{235}U, ^{232}Th, and ^{40}K) [*Jochum et al.*, 1983]; the MORB source mantle (i.e., geochemically observable mantle beneath mid-ocean ridges) is estimated to have at most ~8 ppb U, ~32 ppb Th, and ~100 ppm K, whose total heat production is only ~6 TW if the entire mantle is comprised of the MORB source mantle. If we define the present-day Urey ratio, γ_0, as the ratio of internal heat production with respect to the total convective heat flux, the MORB source mantle has the Urey ratio less than 0.16. On the basis of whole-mantle parameterized convection models [e.g., *Schubert et al.*, 1980; *Davies*, 1980; *Christensen*, 1985], this low Urey ratio has long been considered to be unacceptable because it requires a considerable degree of secular cooling resulting in an extremely hot mantle in the Archean (>2.5 Ga), which is inconsistent with the petrogenesis of Archean komatiites [*Richter*, 1985; *Parman et al.*, 2001]. Instead of presuming a rapidly cooling Earth, therefore, it is common to assume the existence of a hidden mantle reservoir, enriched in radiogenic elements and somehow sequestered from global mantle circulation, to explain the present-day global heat budget. The actual topology of such a hidden reservoir is unknown. A convectively-isolated deep layer is a popular hypothesis [*Kellogg et al.*, 1999], though it also requires for such a layer to be seismically invisible [*Vidale et al.*, 2001]. An alternative reconciliation is to assume numerous blobs of enriched mantle spread in the entire mantle [*Becker et al.*, 1999; *Helfrich and Wood*, 2001], though it is unclear how such blobs can be 'hidden' from sampling at mid-ocean ridges. In either case, this missing heat source argument, free from any assumption on the bulk composition of the Earth's mantle, has been important theoretical justification for thermochemical mantle convection [*Kellogg et al.*, 1999; *Tackley*, 2000]. The purpose of this paper is, on the basis of recent advance in variable-viscosity convection, to revisit a heat-flow scaling law for mantle convection, which has been playing the fundamental role in this paradox.

2. A New Heat-Flow Scaling Law

[3] To understand the first-order influence of time-varying internal heat source (owning to radiogenic decay) on the thermal history of the Earth, the proper use of a parameterized convection model is essential, though it is far from being a trivial task. The degree of secular cooling predicted by a parameterized convection model, for a given Urey ratio, strongly depends on a heat-flow scaling law adopted for mantle convection, which is generally expressed as

$$Nu \propto Ra^{\beta}. \quad (1)$$

Here *Nu* is the Nusselt number, which is a nondimensionalized heat flux, and *Ra* is the Rayleigh number, which measures the convective potential of the mantle. The Rayleigh number is inversely proportional to mantle viscosity, which is in turn sensitive to mantle temperature. Thus, the above scaling law basically determines the sensitivity of surface heat flux to internal mantle temperature. The exponent β controls this sensitivity, and it has been controversial what value of this exponent is appropriate for

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the convection of the Earth's mantle. The study of isoviscous convection shows that β is approximately 0.3 [*Turcotte and Oxburgh*, 1967], though *Christensen* [1985] later pointed out that β should be less than 0.1 if the temperature-dependency of mantle rheology is taken into account. *Gurnis* [1989] then demonstrated that Christensen's value is applicable only for stagnant-lid convection, and that β ∼ 0.3 is appropriate for plate tectonic convection (note that later studies show that β ∼ 0.3 even for stagnant-lid convection if steady-state is achieved [*Davaille and Jaupart*, 1993; *Solomatov*, 1995]). Most recently, *Conrad and Hager* [1999] suggested that β ∼ 0 because plate tectonic convection is likely to be regulated by subduction-zone dissipation and is not very sensitive to internal mantle temperature. Tectonic plates are strong due to temperature-dependent viscosity. A need to bend plates at subduction zones, therefore, becomes an important bottleneck in plate tectonics.

[4] Although the significance of subduction-zone dissipation is hard to dismiss, this zero exponent results from the assumption of a constant plate thickness over a wide range of mantle temperature, which does not seem realistic because the maximum thickness of plate is most likely limited by its own convective instability [*Parsons and McKenzie*, 1978; *Solomatov and Moresi*, 2000]. With higher mantle temperature (i.e., less viscous mantle), sublithospheric convection can take place more easily, so plate thickness is expected to be thinner. Based on a recently developed scaling law derived for the onset of convection with temperature-dependent viscosity [*Korenaga and Jordan*, 2002], we calculate the variation of plate thickness as a function of mantle temperature (Figure 1a). We use the following Arrhenius-type viscosity,

$$\eta(T) = A \exp(E/RT), \qquad (2)$$

where A is a constant factor and R is the universal gas constant. The activation energy, E, is set to 300 kJ mol^{-1} and A is chosen to have the reference viscosity of 10^{19} Pa s at the potential temperature of 1350°C [*Karato and Wu*, 1993]. A corresponding heat-flow scaling law is calculated by combining the scaling law for the plate tectonic convection [*Conrad and Hager*, 1999, eq. 5] and this variation of plate thickness. The curvature radius of plate bending is set to 200 km [*Bevis*, 1986], and effective lithospheric viscosity is assumed to be 10^{23} Pa s. Our result indicates β ∼ 0.3 (Figure 1b). We thus recover the classical estimate. This calculation is fairly robust, not strongly depending on the particular choice of parameters. Lowering lithospheric viscosity to 10^{22} Pa s (i.e., reducing subduction-zone dissipation), for example, introduces only a systematic increase in *Nu* and does not affect the exponent β. We note two different kinds of (lithospheric) viscosity here. Temperature-dependent viscosity of equation (2) is used to determine plate thickness, whereas (much lower) average lithospheric viscosity (10^{23} or 10^{22} Pa s) is used to calculate subduction-zone dissipation. This approach is justified because in a region like subduction zones where deformation is significant, thermal stiffening is most likely overcome by multiple competing deformation mechanisms, considerably reducing effective lithospheric viscosity.

[5] Mantle rheology is, however, not only temperature-dependent. The most important complication with regard to the dynamics of sublithospheric convection is intrinsic depth-dependent viscosity introduced by mantle melting beneath mid-ocean ridges [*Karato*, 1986; *Hirth and Kohlstedt*, 1996]. Dehydration during mantle melting makes residual mantle stiffer by about two orders of magnitude, considerably increasing the convective stability of plate. Hotter mantle starts to melt deeper, resulting in a thicker, compositionally more viscous plate. Thus, increasing mantle temperature has two competing effects on maximum plate thickness. Using a more general scaling law for temperature- and depth-dependent viscosity [*Korenaga and Jordan*, 2002], we can include these two effects in

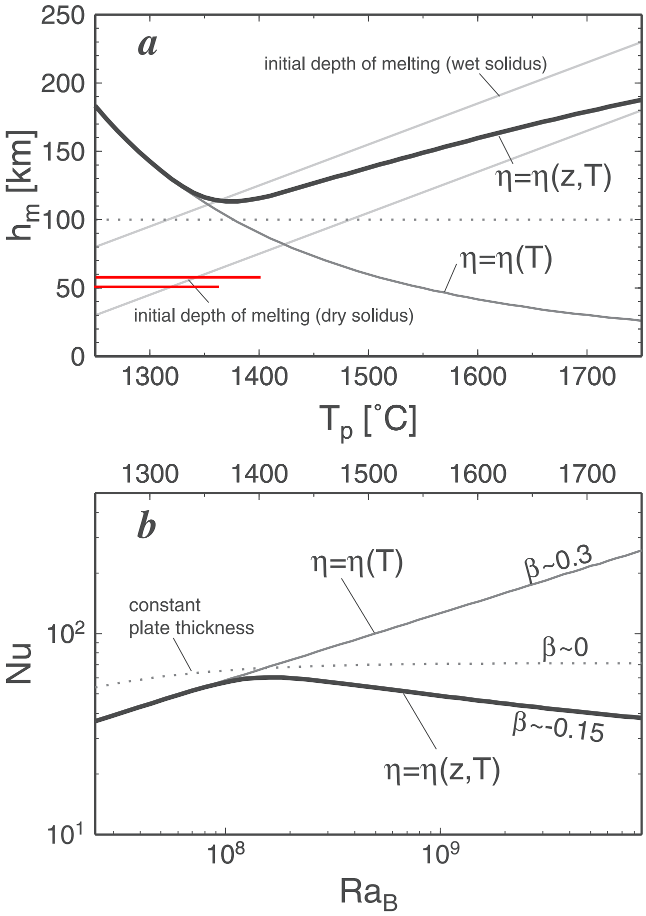

Figure 1. (a) Plate thickness variation as a function of mantle potential temperature (which is the hypothetical temperature of mantle adiabatically brought to the surface without melting). The critical Rayleigh number is set as 2000. Cases of temperature-dependent viscosity (thick gray curve) and temperature- and depth-dependent viscosity (thick solid curve) are shown. The solidii of dry and wet peridotites are shown by thin gray curves. The constant thickness of 100 km is also shown as dotted. (b) *Ra-Nu* relationships for whole-mantle convection: constant plate thickness (dotted), temperature-dependent viscosity (gray), and temperature- and depth-dependent viscosity (solid). The bottom Rayleigh number, Ra_B, is calculated based on the lower mantle viscosity, which is assumed to have a 30-fold higher viscosity than the upper mantle [*Hager*, 1991]. The absolute value of Ra_B is, however, not important for parameterized convection models. Corresponding temperature range is shown in the upper horizontal axis.

estimating the variation of maximum plate thickness as a function of mantle temperature (Figure 1a). As in *Hirth and Kohlstedt* [1996], the melting of partially wet mantle is assumed to start ~50 km below the melting of dry mantle, for which we use the solidus of dry peridotite [*Takahashi and Kushiro*, 1983]. Depth-dependence of reference viscosity induced by mantle melting is then modeled after *Phipps Morgan* [1997]: ~30-fold viscosity increase during the wet-to-dry transition, followed by ~5-fold increase per every another 10% of melting. After crossing the dry solidus, melting is assumed to take place continuously at the rate of 10%/GPa. Our prediction of plate thickness variation for this temperature- and depth-dependent viscosity is shown in Figure 1a. When mantle potential temperature becomes higher than ~1400°C, the effect of dehydration starts to dominate the dynamics of sublithospheric convection, and plate thickness roughly follows the depth of the wet-to-dry transition. With this variation in plate thickness, a heat flow scaling law exhibits negative sensitivity to mantle temperature as $\beta \sim -0.15$ (Figure 1b).

[6] Throughout the calculation of these scaling laws, plate tectonics is *assumed* to be always operating, which is probably appropriate for back-tracking the thermal history of the Earth from the present time to the late Archean. With this assumption, the compositional buoyancy of lithosphere (i.e., thicker crust and more depleted subcrustal lithosphere for hotter mantle) is insignificant for the global energetics of mantle convection, because of the basalt-to-eclogite transition at relatively shallow depths (<60 km) [*Ringwood and Green*, 1964] with respect to the dimension of subducting slabs. Though the importance of compositional buoyancy for shutting down plate tectonics has been suggested [e.g., *Davies*, 1992; *Sleep*, 2000], it remains speculative because the very origin of plate tectonics itself is still highly controversial [e.g., *Bercovici et al.*, 2000].

3. Thermal Evolution With Negative Feedback

[7] The permissible range of the Urey ratio varies widely with the assumed value of β in the calculation of Earth's thermal history. The theoretical formulation here follows exactly that of *Christensen* [1985]. The convective heat flux is assumed to be 36 TW. The heat capacity of the whole Earth is set as 7×10^{27} J K^{-1}, and the effect of core cooling is taken into account as a part of whole-Earth secular cooling. The activation energy of temperature-dependent viscosity is 300 kJ mol^{-1}. U:Th:K is assumed to be 1:4:1.27 $\times$ 10^4. The present-day mantle is assumed to have a potential temperature of 1350°C. Figure 2 shows three different thermal evolution models with the present-day Urey ratio of 0.15. To explain the present heat flux with $\beta = 0.3$, such low Urey ratio requires intense secular cooling, which leads to a 'thermal catastrophe' about one billion years ago. To reconstruct a plausible thermal history (i.e., a modestly hot Archean Earth) with this conventional β value, it is known [*Christensen*, 1985] that the Urey ratio must be greater than 0.7. With decreasing β, however, this constraint on the Urey ratio becomes much more relaxed, and the negative β, in particular, allows one to recover a reasonable thermal history with the secular cooling of only ~80 K/Gyr (Figure 2). These calculations indicate that the common notion of secular cooling has strongly been guided by the assumption of positive β. A hotter mantle has long been considered to have higher surface heat flux, but this apparently innocuous assumption may not be valid for the convection of the Earth's mantle, whose chemical differentiation processes can strongly interact with its dynamics. We emphasize that the inverse relation between mantle temperature (not the Rayleigh number) and heat flux is fundamentally important for parameterized convection models. It is physically plausible to expect that the relation between some sort of 'effective Rayleigh number' [e.g., *Parmentier et al.*, 1976] and heat flux may still be characterized by a positive exponent.

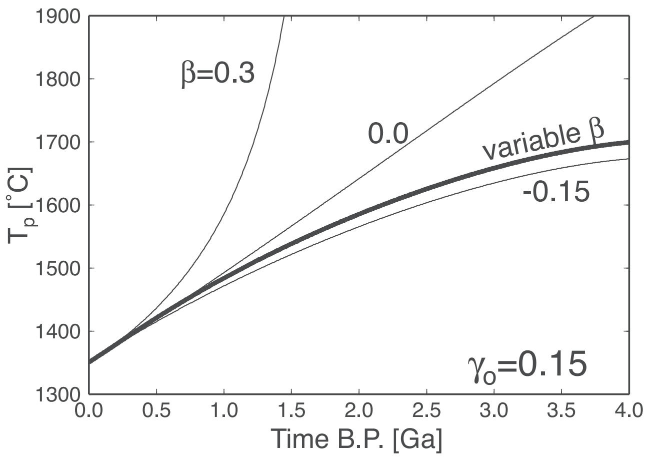

Figure 2. The first-order thermal history of the Earth for the last four billion years in terms of mantle potential temperature, based on parameterized convection models. The present-day Urey ratio is 0.15 for all cases. Each curve is labeled with the assumed value of β. The mean age of accumulated internal heat is ~1.5 Ga for the case of $\beta = -0.15$ (compare with ~2.5 Ga corresponding to the extreme case in which all fossil internal heating is accumulated). Thick solid curve corresponds to the case of variable β (Figure 1b, thick solid curve).

[8] The modeled thermal history presented in Figure 2 assumes the operation of plate tectonics for the last four billion years. Though we cannot tell when plate tectonics could cease to function, we can make a rough guess what might have happened if plate tectonics did not exist for, say, earlier than 3 Ga. Because $\beta \sim 0.3$ for stagnant-lid convection, the mode of thermal evolution switches to thermal catastrophe, which can bring quickly the Earth into a magma-ocean state in the Hadean. Thus, if plate tectonics started to operate sometime after the formation of the Earth, there may have been a drastic change in the cooling rate of the Earth.

[9] This success of reconstructing a reasonable thermal history with a low Urey ratio (Figure 2) implies that the bulk majority of the Earth's mantle may well be represented by the MORB source mantle. We are not claiming that the entire mantle is composed of the MORB source mantle. Isotope and trace-element geochemistry of ocean island basalts clearly require the existence of other geochemical reservoirs in the mantle [*Zindler and Hart*, 1986; *Hofmann*, 1997], but the volumetric contribution of such reservoirs can be small. The low Urey ratio of the convecting mantle

may violate the chondritic assumption for the bulk composition of the Earth, though such violation is not totally unexpected [*Drake and Righter*, 2002].

[10] The missing heat source problem has been a robust argument for layered convection. This argument is also intimately coupled with a long-standing paradox in the noble gas budget of the Earth [*Allègre et al.*, 1996; *O'Nions and Oxburgh*, 1983]; we do not observe enough noble gas in the atmosphere (produced by the radiogenic decay of heat-producing elements) to be consistent with a commonly assumed high Urey ratio (e.g., ~0.5). Thus, the depleted whole mantle suggested here may also resolve this noble gas paradox. To sum, we have shown that it is possible to reconstruct a reasonable thermal history of the Earth with a low Urey ratio, on the basis of the self-consistent energetics of multi-scale mantle convection. An invisible, immiscible, undegassing mantle reservoir enriched in heat-producing elements may be nonexistent as well.

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