

Evidence for layered mantle convection: implications for lower mantle plumes

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Experimental and theoretical studies of convecting systems generally yield plumes of some sort. For the Earth, of particular interest is whether deep plumes reach the surface. A critical limit on the egress of lower mantle plumes is whether mantle convection is whole or layered. Numerical models are under-constrained: the system is multi-phase, with extreme pressure and temperature differences, an uncertain chemistry, and the behaviors of the relevant physical properties are incompletely known. Given this complexity, controversy exists concerning whole or layered mantle convection. The points numbered below set forth key results from existing literature, mainly from the perspective of mineral physics, and provide new information from relatively unexplored avenues, all of which indicate that mantle convection is layered.

(1) Available rock samples have invariably originated at shallow depths. Inclusions in diamonds have the deepest source, near 670 km¹. A plausible interpretation is that the circulation of the lower and upper mantles are separate, whereby significant amounts of material from the lower mantle should not pass through the transition zone (TZ).

(2) The steep velocity profiles found in the TZ cannot be explained by adiabatic gradients for the phases possibly stable in this region, but can be modeled as a gradual transformation of pyroxenes to majoritic garnets as depth increases². Their comparison to laboratory measurements of shear and bulk moduli of majoritic garnets suggests enrichment of Ca in the lower mantle, and thus chemical layering. Alternatively, the observed velocity profiles are compatible with a sub-adiabatic gradient, which could arise from heat flow from the lower mantle being impeded by the low thermal conductivity of majoritic garnet³. For this to happen, the proportion of garnet in the TZ must be larger than that provided by a pyrolitic upper mantle composition, again pointing to chemical layering. A sub-adiabatic gradient in the transition zone could lead to catastrophic overturns of this layer with the upper mantle. Mantle avalanche has recently been inferred from length of day perturbation in the Cretaceous⁴.

(3) Grain size (d) differences seem to exist between the upper and lower mantles. Rock samples from the upper mantle have variable d with megacrysts as large as 1 cm. Mantle viscosity has been used to estimate d as 0.3 cm near 670 km⁵, whereas grain growth modeling⁶ suggests d is roughly 0.01 to 0.1 cm for the lower mantle. Whole-scale mixing would not produce such differences. More importantly, two of the physical properties which exert key controls on mantle convection, viscosity⁷ and diffusive radiative thermal conductivity⁸, strongly depend on grain-size. The latter dependence results from the emission spectrum of a mineral grain and physical scattering depending on d , and the results support small grain size in the lower mantle. Importantly, heat transfer in the lower mantle is largely radiative, whereas in the upper mantle, phonon transfer dominates. Because the sign of dk/dT determines stability,⁹ the differences in mode of heat transport suggest layered convection.

(4) Dynamical models limit the secular cooling delay to 1-2 Ga, given favorable conditions for heat retention that include a low conductivity layer, low radiative transfer, and high initial heating.¹⁰ A 1 Ga delay requires that radioactive decay contributes at least 80% of the total power. The heat generation of K, U, and Th now and at 1 Ga constrains the bulk silicate earth (BSE) composition, irrespective of uncertainties in surface heat flux and on the secular delay¹¹. Our BSE composition differs from known compositions of the upper mantle suite¹², again indicating chemical differences between the upper and lower mantles.

(5) To understand the effect of layering heat producing elements, we model the Earth as an onion with thick shells. The heat flow through any given shell equals that of its internally generated heat, plus the heat produced in all deeper shells. Therefore, the most efficient means for the Earth to expel heat is if the radioactive elements are located in the shallow shells. The continental crust is the known, extreme example. Both chemical differentiation and the dynamics of heat flow lead to stratification of U, Th, and K within the mantle. The amount of radiogenic heating inside the mantle is also overstated, as this hinges on the current estimate of total power as 44 TW. However, this value was deduced assuming that the thermal conductivity be unrealistically constant.¹¹ Several independent approaches to analyzing surface flux provide a global power of 31 TW.¹¹

(6) A two-layer model of the convection pattern inside the Earth can be inferred from the surface expressions, i.e., the long-lived hot spots¹³ and the subducting plates. Most of the surface complexity comes from upper mantle and TZ phenomena. In a three-dimensional visualization, convection in the lower mantle consists of two hemispherical cells, with zones of up-welling centered on and underlying Hawaii and South Africa (see figure). Thus, these antipodal hot spots do not originate from plumes, but instead are edge effects for the simplest possible configuration for 3-D convective flow in the spherical cell representing the lower mantle.

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