Plume magmatism and mantle convection: Revising the standard model

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Despite its elegant simplicity and its agreement with important first-order observations of the Earth's surface, the mantle plume hypothesis has become a target of focused criticism and the source of considerable debate (Anderson, 2001; Foulger, 2002; Hamilton, 2002). Its lack of acceptance can be attributed in part to the inability of plume adherents to articulate the role of plumes in an integrated mantle convection scheme that satisfies available geophysical, geochemical, and petrologic observations. In fact, there is little consensus among earth scientists today regarding the pattern of mantle convection. While the combined efforts of geophysicists and geochemists have greatly advanced our understanding of the structure of the Earth, vigorous debate still surrounds the central issue of where and how the mantle moves. Plate tectonic theory has enjoyed enormous success in explaining the origin and evolution of the Earth's crust, yet the theory that describes motion on the Earth's surface offers few insights regarding motion beneath it. Even the most basic questions still lack a satisfying answer: does convection in the mantle consist of large cells that continuously transport material across the upper mantle/lower mantle boundary at ~670 km depth, or do the upper and lower mantles evolve as separate chemical reservoirs? Indeed, the nature of convection in the Earth's interior remains one of the most important unsolved problems toward understanding the structure and evolution of our planet.

The mantle plume hypothesis is attractive because it can account for the profound compositional heterogeneities (in stable and radiogenic isotopes as well as major and trace elements) observed between and among ridge-related and intraplate magmas in the oceanic setting (Hoffman and White, 1982; Weaver, 1991; Hart et al., 1992). The plume theory was supported by scaled tank experiments that elucidate the nature of rising buoyant material (Whitehead and Luther, 1975; Olson and Singer, 1985; Griffiths and Campbell, 1991). These experiments, in turn, have led to the prediction and subsequent identification of flood basalts as the expression of melting of plume starting heads (Richards et al., 1989). However, the simple concept of a continuous plume conduit supplying material to a point source over an extended interval of time cannot successfully be applied to many (if not most) localities of intraplate magmatism. Furthermore, tomographic studies have failed to image definitively a low velocity conduit at hypothesized hotspot localities. Perhaps most significantly, a simple compelling model that satisfies the observations of each of the subdisciplines focusing on mantle convection has not yet been presented. Thus, the plume hypothesis has fallen out of favor among a growing contingent of earth scientists (see www.mantleplumes.org).

At the heart of our inability to assemble a complete picture of mantle convection is our lack of quantitative data of the critical parameters (viscosity and density) that control flow in the mantle. The mantle is cooled from above (driven by conduction in the uppermost mantle and hydrothermal circulation in the crust) and heated from below (powered by latent heat of crystallization in the core) as well as from within (powered by radioactive decay throughout the mantle). Because of the strong dependence of density and viscosity on pressure, temperature, and composition, we have few constraints to guide our development of whole mantle convection models. In the absence of a quantitative description of the variables that control the dynamic behavior of the Earth, we are forced to rely upon the models that best fit the available first-order observations.

Geophysicists and geochemists are generally divided in their view of mantle evolution, despite the rich record of observational constraints derived from a wide variety of techniques. Geophysicists have determined that some down-going slabs penetrate the 670 km discontinuity, and thus generally hold to the view that convection in the mantle is single-celled and involves circulation that spans the entire silicate interior. In contrast, geochemists cite isotopic evidence indicating that long-lived mantle reservoirs have remained isolated from one another throughout much of Earth history and argue that the upper mantle and lower mantle convect independently with little exchange of matter between them. Are there two chemically distinct mantles, or does Earth's interior consist of just one poorly stirred reservoir? Recent measurement of the time scales required for chemical diffusion at the great pressures within the mantle bolster the geophysicist's argument that giant, mantle-wide convection cells exist, but that large, chemically-distinct regions can remain incompletely mixed within a ‘plum-pudding like’ mantle. Geochemists counter this position by noting the consistent extraction of (presumably) *shallow* material with uniform composition at spreading ridges and by contrasting this with the composition of material extracted at intraplate point-sources of magmatism, (presumably) from *deeply*-derived, upwelling plumes.

Here, I posit an integrated model for mantle circulation that reconciles the seemingly opposing viewpoints of geophysicists and geochemists. This model incorporates a recent analysis of hotspot volcanism (the ‘plumelet’ model, Ihinger, 1995) and offers a new approach to understanding circulation in the upper mantle. The plumelet model, in conjunction with established geophysical and geochemical constraints, suggests that convection in the mantle consists of three circulation ‘cells’ that are not entirely independent of one another. In brief, the integrated circulation model considers four spatially and chemically distinct reservoirs: the continental crust, the upper mantle, the lower mantle, and the region between the outer core and the lower mantle known as the D" boundary layer. Upper mantle convection is driven by the sinking of cold slabs in subduction zones; the return flow to spreading ridges is accommodated by material flow within a diffuse *shallow* zone extending laterally for thousands of kilometers beneath the lithosphere (Figure 1). The diffuse zone of return flow begins tens of kilometers below the rigid lithosphere, and extends to depths marked by the boundary with the lower mantle (at ~670 km), although most of the flow is accommodated in the upper ~100 kilometers of the zone (Figure 2). Material is removed from the upper mantle reservoir when: (1) partial melts rise above subduction zones to form the continental crust; and (2) portions of the down-going limbs (the subducted slabs) of some upper mantle cells sink to the deep D" layer. The continual process of continental crust formation has served to deplete the upper mantle of incompatible elements throughout Earth evolution and give it a distinctive ‘depleted’ character. Note that in this model, the oceanic crust is considered part of the ‘upper mantle’ reservoir, and that chemical fractionation associated with the formation of mid-ocean ridge basalts (MORB) does not serve to "deplete" the reservoir. Some subducted slabs do not penetrate into the lower mantle and are cycled directly back into the upper mantle circulation. Other slabs are lost from the upper mantle and descend through the lower mantle to the poorly-stirred D" layer, where they reside for hundreds of millions of years before returning to the upper mantle in the form of upwelling plumes (thus contributing, at least temporarily, to the depletion of the upper mantle; Figure 3). In contrast, the lower mantle reservoir evolves primarily as an independent, closed system. Material in this reservoir does not undergo chemical processing and has retained a chemical character similar to that of the primordial, undegassed early mantle. Some material exchange both into and out of the lower mantle reservoir has occurred throughout Earth history via thermal entrainment due to the cycling of the hot and cold limbs of the upper-mantle/D" convection system passing through it. This integrated model of mantle convection, composed of: (1) one 'cell' confined to the upper mantle; (2) one 'cell' that exchanges material between the upper mantle and the D" layer; and (3) one 'cell' confined to the unprocessed lower mantle, is consistent with and reconciles existing first-order geophysical and geochemical observations.

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