Dynamics of mantle plumes and their implications for the heat budget and composition of the mantle

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Seismic and geochemical observations indicate a compositionally heterogeneous mantle in the lower mantle, suggesting a layered mantle. The volume and composition of each layer, however, remain poorly constrained. This study seeks to constrain the layered mantle model from observed plume excess temperature, plume heat flux, and upper mantle temperature. Mantle plumes are caused by thermal boundary layer instabilities. The thermal boundary layer from which the plumes are derived could be at either the core-mantle boundary for whole mantle convection or a density interface for layered mantle convection. Mantle plumes are responsible for releasing the heat from the core for whole mantle convection or the bottom layer of the mantle for layered mantle.

3-D spherical models of whole-mantle and layered mantle convection are computed for different Rayleigh number, internal heat generation, buoyancy number, and bottom layer thickness for layered mantle models. The model results show that these plume observations are controlled by internal heating rate in the layer overlying the thermal boundary layer from which mantle plumes are originated. To reproduce the observations, internal heating rate needs ~65% for whole-mantle convection, but for layered mantle models, the internal heating rate for the top layer is ~60% for averaged bottom layer thicknesses <~1100 km. The heat flux at the core-mantle boundary (CMB) is constrained to be ~12.6 TW for whole-mantle convection. For layered mantle, an upper bound on the CMB heat flux is ~14.4 TW. For mantle secular cooling rate of ~80 K/Ga, the current study suggests that the top layer of a layered mantle is relatively thick (>2520 km) and has radiogenic heat generation rate $>2.82\text{x}10^{-12}$ W/kg that is >3 times of that for the depleted mantle source for MORB (DMM). For the top layer to have the radiogenic heat generation of the DMM, mantle secular cooling rate needs to exceed 145 K/Ga. The current study also shows that plume temperature in the upper mantle is about half of the CMB temperature for whole-mantle convection or ~0.6 of temperature at compositional boundary for a layered mantle, independent of internal heating rate and Rayleigh number. Finally, the model calculations confirm that mantle plumes accounts for the majority (~80%) of CMB heat flux in whole-mantle convection models. However, plume heat flux decreases significantly by as much as a factor of three, as plumes ascend through the mantle to the upper mantle.