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The effect of heterogeneous conductivity on the long-term thermo-chemical evolution of the lower mantle: implications for primordial reservoirs

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The long-term evolution of the mantle is simulated using 2D spherical annulus geometry to examine the effect of heterogeneous conductivity on the stability of primordial thermo-chemical reservoirs. Conductivity of the mantle is often emulated in numerical models using purely depth-dependent profiles (e.g., taking on values between 3 and 9 W/m-K). This approach is meant to synthesize the mean conductivities of mantle materials at their respective conditions in-situ. However, because conductivity depends also on temperature and composition, their role in the conductivity of the mantle is masked. This issue is significant because dynamically evolving temperature and composition introduce lateral variations in conductivity, especially in the deep-mantle. Minimum and maximum variations in conductivity are due to the temperatures of plumes and slabs, respectively, and depth-dependence directly controls the amplitude of the conductivity (and its variations) across the mantle depth. Our simulations allow assessing the consequences of these variations on mantle dynamics, in combination with the reduction of thermo-chemical pile conductivity with iron composition, which has so far not been well examined.

First, we examine the effect of depth (D)-dependence employing a linear profile and vary the bottom-to-top conductivity ratio. We find that increased conductivity ratio acts to reduce pile temperature. Greater conductivity in the lower mantle helps to efficiently extract heat from piles (at rates sufficient to overcome or suppress temperature increases due to enrichment in HPEs). This reduction in thermal buoyancy stabilizes the piles and may play a major role in organizing thermo-chemical reservoirs into two distinct piles.

Next, the combined effects of temperature (T) and composition (C) are examined. A positive feedback occurs when the reduced conductivity of piles inhibits its cooling and the resulting increase in temperature further reduces its conductivity. Consequently, the augmented thermal buoyancy destabilizes piles (i.e., greater topography or enhanced erosion). Furthermore, the combined T and C-dependences can greatly underestimate typical mantle conductivities if D-dependence is also underestimated. By increasing the amplitude of D-dependence, the destabilizing effects of T and C-dependence can be suppressed.

Finally, mineral physics data is employed to emulate a more realistic depth-dependent profile for the upper and lower mantle. Depth-dependence is no longer a linear profile and values range from 3 to 27.5 W/m-K. Buoyancy ratio and the enrichment in heat-producing elements in piles are examined for this conductivity model to determine potential evolution scenarios of primordial thermo-chemical piles. We find that this model produces stable piles for periods exceeding the age of the Earth. When B is reduced from 0.23 to 0.15, piles are destabilized earlier (by approx 1 Gyr) for cases with lesser depth-dependence. HPE enrichment in piles increases their temperature over time (and further reduces their conductivity). For HPE enrichment 10 times the mantle heat production, two distinct piles are formed with moderate topography. For greater enrichment, the piles become unstable and material becomes entrained by thin plume conduits.