Soft Core-Mantle Boundary: A Mechanism for Chemical Interactions Between the Core and Mantle

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A recent study measuring global isotopic compositions in ocean island basalts (OIBs) combined with geochemical mixing models suggested that to explain the negative correlations between $\mu^{182}W$ values with $^3He/^4He$ values, there should be at least three mantle reservoirs present, two of which are primordial and preserved in the deep mantle. One of the primordial mantle reservoirs is hypothesized to contain material at the core-mantle boundary (CMB) that is chemically and isotopically equilibrated with the core, such that it records core-like isotopic signatures. Although there have been discussions on the possibility of core metal being entrained in mantle material, there is a lack of evidence of correlated enrichment in siderophile elements in OIBs. This raises doubts as to whether the unique isotopic signatures are a manifestation of interactions between the core and lowermost mantle. We propose a mechanism involving metal intrusion to explain how it is possible for mantle rock to obtain core-like isotopic signatures without the presence of metal itself: In the vicinity of mantle downwellings, deviatoric stresses at the CMB deform the boundary to produce a dynamic topography that depresses into the liquid core. At the high pressure-temperature conditions, the metal intrudes between the solid grains and “wets” the grain boundaries. Combining with the excess fluid pressure head induced in topographic lows, this drives intrusion of metal into the basal mantle rock. The intrusion of metal rheologically weakens the metal-rock mixture, promoting lateral gravitational spreading which draws additional material downwards. This enhances the circulation into the mixed layer and “softens” the lower boundary condition for mantle convection. During lateral spreading, liquid metal is squeezed out of pore spaces due to viscous compaction and falls back into the core. This can allow dense, reacted rocks to accumulate away from downwelling flows that contain isotopic signatures from the core without any trace of siderophile elements. As a first order approximation, we assume that the infiltration of metal into submerged rock occurs on timescales much shorter than the residence time of mantle rocks at the CMB, and the subsequent compaction of the mixture and expulsion of metal occurs on similarly short timescales. Next, we assume that the intruded layer is sufficiently thin such that the thin-layer approximation for a viscous fluid can be applied. To obtain a rough idea of the dynamics involving the rock-metal mixture, we incorporate the thin-layer approximation at regions with negative dynamic topography in a numerically simulated 2D Cartesian mantle convection model. This model assumes that the mantle is an isoviscous, incompressible, Boussinesq fluid. The addition of the thin layer at the CMB generates a boundary-driven flow which superimposes on the buoyancy-driven one in the mantle. Initial results show that the viscosity contrast between the submerged layer and reference mantle has a significant effect on which flows dominate: for the thin layer at sufficiently low viscosities, the boundary-driven flows dominate the dynamics and impede the movement of downwellings. This is accompanied by the increase in temperature of the mantle from the bottom-up as the secondary flow field spreads warm material from the CMB towards the top, thereby reducing the heat flux through the CMB. In addition, we observe that as Rayleigh number increases, the average amplitude of the dynamic topography and gain (the ratio between the flux of material into the layer due to the boundary-driven flow to that of the buoyancy-driven one) decreases.

Keywords: Core-mantle boundary, Core-mantle interaction, Dynamic topography, Isotopic signatures