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Numerical Modeling of Deep Mantle Flow: Thermochemical Convection and Entrainment

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One of the most robust results from tomographic studies is the existence of two antipodally located Large Low Shear Velocity Provinces (LLSVPs) at the base of the mantle, which appear to be chemically denser than the ambient mantle. Results from reconstruction studies (Torsvik et al., 2006) infer that the LLSVPs are stable, long-lived, and are sampled by deep mantle plumes that rise predominantly from their margins. The origin of the dense material is debated, but generally falls within three categories: (i) a primitive layer that formed during magma ocean crystallization, (ii) accumulation of a dense eclogitic component from the recycled oceanic crust, and (iii) outer core material leaking into the lower mantle.

A dense layer underlying a less dense ambient mantle is gravitationally stable. However, the flow due to thermal density variations, i.e. hot rising plumes and cold downwelling slabs, may deform the layer into piles with higher topography. Further deformation may lead to entrainment of the dense layer, its mixing with the ambient material, and even complete homogenisation with the rest of the mantle. The amount of the anomalous LLSVP-material that gets entrained into the rising plumes poses a constraint on the survival time of the LLSVPs, as well as on the plume buoyancy, on the lithospheric uplift associated with plume interaction and geochemical signature of the erupted lavas observed at the Earth's surface. Recent estimates for the plume responsible for the formation of the Siberian Flood Basalts give about 15% of entrained dense recycled oceanic crust, which made the hot mantle plume almost neutrally buoyant (Sobolev et al., 2011).

In this numerical study we investigate the mechanics of entrainment of a dense basal layer by convective mantle flow. We observe that the types of flow that promote entrainment of the dense layer are (i) upwelling of the dense layer when it gets heated enough to overcome its stabilizing chemical density anomaly, (ii) upwelling of the ambient material in the vicinity of the dense material (mechanism of selective withdrawal (Lister, 1989)), and (iii) cold downwellings sliding along the bottom boundary, and forcing the dense material upwards. The objective of this study is to compare the efficiency of entrainment by each of these mechanisms, and its dependence on the density and viscosity anomaly of the dense material with respect to the ambient mantle.

To perform this study, we have developed a two-dimensional FEM code to model thermal convection in a hollow cylinder domain with presence of chemical heterogeneities, and using a realistic viscosity profile. We present the results of the simulations that demonstrate the entrainment mechanisms described above. In addition, we perfom numerical experiments in a Cartesian box domain, where the bottom right boundary of the box is deformed to resemble the geometry of an LLSVP edge. In some of the experiments, the bottom left part of the boundary is moving towards the right boundary, simulating a slab sliding along the core-mantle boundary towards an LLSVP. These experiments allow a detailed study of the process of entrainment, and its role in the thermochemical evolution of the Earth.