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Stabilization of thermochemical piles by compositional viscosity contrasts

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The large low shear velocity provinces (LLSVPs) observed in the lowermost mantle are widely accepted as chemically distinct, but their origin and long-term evolution remain poorly understood. Their survival time and shape have been attributed to their excess density, while viscosity heterogeneity associated with the LLSVPs is thought to have a lesser effect. However, recent studies indicate chemical exchange reactions between the lowermost mantle and the core, which is oversaturated in silica and undersaturated in oxygen due to conditions present during its formation. As a consequence, we expect fluxes of SiO_2 from the core to the mantle and FeO from the mantle to the core, which should increase the bridgmanite/ferropericlase ratio and thus the viscosity of the lowermost mantle material. Since the reaction between mantle and core is most efficient for a global layer of very iron-rich material above the core-mantle boundary (CMB), we expect primordial LLSVP material to have higher viscosity than the surrounding mantle, despite the high temperature of the thermochemical piles. We test the influence of high compositional viscosity of the LLSVPs using 2-D numerical models in an annular geometry. These models show that a compositionally-induced viscosity increase of about one order of magnitude is already sufficient to significantly reduce entrainment of dense LLSVP material into the mantle, enhancing LLSVP stability. By examining a wide range of model parameters, we identify trade-offs between LLSVP excess density and viscosity contrasts induced by both temperature and composition for long-term (>4.5 Gyrs) survival of dense material in coherent piles beneath active mantle convection. In particular, the excess density and/or the thermal viscosity contrast required to keep piles stable on the CMB decreases with increasing compositional viscosity contrast. Moreover, our results indicate that the conditions needed to keep piles stable are lower than the requirements to form them, which indicates long-term survival of piles once they have formed. We conclude that bridgmanite-enrichment of lowermost primordial mantle was a critical event in Earth's history because it produced viscosity heterogeneity in the lower mantle that facilitated the formation and long-term stability of the LLSVP regions that we observe today.