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Deep mantle primitive reservoirs as a partial source of Ocean Island Basalt

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Ocean Island Basalts (OIB) have specific signatures in rare gases (large scattering in ^{4}He/^{3}He ratio) and trace elements (high ^{143}Nd/^{144}Nd) suggesting that they originate from several reservoirs, one of which should be primitive ($i.e.$, undegassed). The lowest observed value of ^{4}He/^{3}He in OIB imposes a constraint on the entrainment of primitive material by plumes. Geochemical mass balance calculations indicate that the mass fraction of primitive material in plumes should not exceed 10%. It was long assumed that the undegassed reservoir is the lower mantle, but the discovery of slabs penetrating in the deep mantle invalidated this hypothesis. This contradiction can be solved by assuming that the primitive reservoir is not the entire lower mantle, but consists of pools of chemically differentiated material located in the lowermost mantle, similar to those observed by seismology. Experimental and numerical models of thermo-chemical convection with an initial basal layer of dense material have shown that pools of primitive material can be maintained for periods of time comparable to the age of the Earth, and that plumes may rise from the top of these reservoirs up to the surface. Important ingredients to maintain stable reservoirs may include (1) a moderate chemical density contrast between primitive and regular material, to avoid chemical stratification; (2) a strong thermal viscosity contrast, which creates and maintains large pools of dense material at the bottom of the system; and (3) an endothermic phase transition at 660-km depth, to prevent dense material from massively flowing into the upper mantle.

Here, we quantitatively assess the hypothesis that OIB partially sample reservoirs of primitive material located in the deep mantle. We run a series of numerical experiments of thermo-chemical convection, in which we varied the chemical density contrast between the primitive and regular materials (measured by the buoyancy ratio B), and the Clapeyron slope at 660 km (Γ_{660}). For each experiment, we have then quantified the entrainment of primitive material by plumes rising from the top of the primitive reservoirs ($i.e.$, the relative fraction of primitive material in these plumes), and compared this entrainment to available constraints from geochemistry. We observe that the thermo-chemical structure and the entrainment strongly depend on B, and to a lesser extent, on Γ_{660}. If $B \leq 0.16$, thermo-chemical piles are swept out, and in the long term the power spectra of the resulting density anomalies do not explain those from probabilistic tomography. For these models, the entrainment is larger than 11% whatever the value of Γ_{660} we considered, and up to 21%. By contrast, if $B \geq 0.22$, reservoirs of primitive material remain stable and induce density distributions that explain probabilistic tomography well. Within error bars, the entrainment is always lower 7%. For intermediate values of B, we again observe the formation of pools of primitive material, but whether these pools are maintained for a long period of time depends on the value of Γ_{660}. If this value is negative enough ($e.g.$, -1.5 MPa/K for B = 0.20), reservoirs can be maintained, and the entrainment of primitive material remains lower than 10%.

Because they fit probabilistic tomography better and yield the most relevant values of B (between 0.20 and 0.22) and Γ_{660} (between -3.0 and -2.0 MPa/K) for the Earth's mantle, stable pools are more likely structures than eroding piles. Our calculations indicate that for stable pools, entrainment of primitive material never exceeds 9%. Therefore, our results qualitatively and quantitatively support the hypothesis that OIB partially sample a reservoir of primitive material located in the lower mantle.