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The interplay between recycled and primordial heterogeneities: predicting Earth mantle dynamics via numerical modeling

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Numerical modeling is a useful tool to integrate geochemical and geophysical observations in a physics-based dynamic framework and to help resolve outstanding questions regarding our planet's interior evolution. For instance, the isotope taxonomy of igneous rocks carries the footprint of both recycled and primordial geochemical reservoirs, but the geometry, distribution, and interaction in the mantle between these two types of heterogeneity remains under debate. Two end-member models have been described: a 'marble cake' scenario, in which convection stirs recycled oceanic lithosphere into thin streaks of basalt and harzburgite throughout the mantle; and a 'plum pudding' scenario, where coherent blobs of $MgSiO_3$-rich, primordial material resist convective entrainment due to their intrinsic strength. While previous geodynamic studies have successfully reproduced these regimes of mantle convection in numerical models, only few of them have investigated how the viscosity and density of recycled and primordial materials affect their interaction in the mantle.

Here, we apply the finite-volume code StagYY to model thermochemical convection of the mantle in a 2D spherical-annulus geometry. We investigate how material properties influence the style of mantle convection and heterogeneity preservation by varying the following parameters: the intrinsic strength (viscosity) of the primordial material; the intrinsic strength and density of basalt; the activation energy and reference viscosity of the lower mantle.

Preliminary models predict a range of mantle mixing styles. A 'marble cake'-like regime occurs for low-viscosity primordial material, with thermochemical piles near the core-mantle boundary and streaks of recycled oceanic lithosphere throughout the mantle. Conversely, for stronger primordial material, plum-pudding primordial blobs survive alongside these marble-cake features. Most notably, the rheology and density anomaly of basalt affect the appearance of both types of heterogeneity, controlling the size and geometry of thermochemical piles and the extent of primordial material preservation. For example, segregation of basaltic from harzburgitic materials is less efficient in cases with intrinsically strong basalt, leading to smaller piles in the lowermost mantle. As our models demonstrate, primordial and recycled heterogeneities mutually affect their preservation in the mantle, with implications for geochemical signatures of mantle-sourced igneous rocks through geologic time.