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The Heterogeneous Earth Mantle: Numerical Models of Mantle Convection and their Synthetic Seismic Signature

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Our understanding of the compositional structure of Earth's mantle is still incomplete. Heterogeneity in the lower mantle, documented by both geochemical and geophysical observations, has not yet been explained within a definitive geodynamic framework. Moreover, the origin, geometry and interaction of such heterogeneities remain controversial. In the “marble cake” mantle hypothesis, slabs of basaltic Recycled Oceanic Crust (ROC) are subducted and deformed but never fully homogenized in the convecting mantle. Conversely, $MgSiO_3$-rich primordial material may resist convective entrainment due to its intrinsic strength, leading to a “plum pudding” mantle. While previous geodynamic studies have successfully reproduced these regimes of mantle convection in numerical models, the effects of the physical properties of ROC on mantle dynamics have not yet been fully explored. Furthermore, predictions from numerical models need to be tested against geophysical observations. However, current imaging techniques may be unable to discriminate between these two end members, due to limited resolution in the lower mantle.

Here, we model mantle convection in a 2D spherical-annulus geometry with the finite-volume code StagYY. We investigate the style of heterogeneity preservation as a function of the intrinsic density and strength (viscosity) of basalt at lower-mantle conditions. Additionally, we use the thermodynamic code Perple_X and the spectral-element code AxiSEM to compute, respectively, seismic velocities and synthetic seismograms from the predictions of our models.

Our results fall between two end-member regimes of mantle convection: low-density basalt leads to a well-mixed, "marble cake"-like mantle, while dense basalt aids the preservation of primordial blobs at mid-mantle depths as in a "plum pudding". Intrinsically viscous basalt also promotes the preservation of primordial material. These trends are well explained by lower convective vigour of the mantle as intrinsically dense (and viscous) piles of basalt shield the core. In order to test these results, we translate the predicted compositional, temperature and pressure fields to seismic velocities for two opposite end-member cases. These two synthetic velocity maps are first analysed and compared in terms of their respective radial correlation matrices and spherical harmonic spectra. Then, we use AxiSEM to simulate wave propagation through the two velocity models. Finally, we discriminate between the two end-members by comparing statistical

properties of the corresponding ensembles of synthetic seismograms. Our results highlight how the interplay between primordial and recycled heterogeneities shape the evolution of the thermal and compositional structure of the lower mantle. Furthermore, they provide a framework for relating the style of heterogeneity preservation in the Earth's lower mantle with specific features of the seismic waveforms.