



The formation, preservation and seismic signatures of chemical heterogeneities in the lower mantle

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Despite stirring by vigorous convection over billions of years, the Earth's lower mantle appears to be chemically heterogeneous on various length scales. Constraining this heterogeneity is key for assessing Earth's bulk composition and thermochemical evolution, but remains a scientific challenge that requires cross-disciplinary efforts. On scales below ~1 km, the concept of a "marble cake" mantle has gained wide acceptance, emphasising that recycled oceanic lithosphere, deformed into streaks of depleted and enriched compositions, makes up much of the mantle. On larger scales (10s-100s of km), compositional heterogeneity may be preserved by delayed mixing of this marble cake with either intrinsically-dense or intrinsically-strong materials. Intrinsically dense materials may accumulate as piles at the core-mantle boundary, while intrinsically viscous domains (e.g., enhanced in the strong mineral bridgmanite) may survive as "blobs" in the mid-mantle for large timescales, such as plums in the mantle "plum pudding"^{1,2}. While many studies have explored the formation and preservation of either intrinsically-dense (recycled) or intrinsically-strong (primordial) heterogeneity, only few if any have quantified mantle dynamics in the presence of different types of heterogeneity with distinct physical properties.

To address this objective, we use state-of-the-art 2D numerical models of global-scale mantle convection in a spherical-annulus geometry. We explore the effects of the *(i)* physical properties of primordial material (density, viscosity), *(ii)* temperature/pressure dependency of viscosity, *(iii)* lithospheric yielding strength, and *(iv)* Rayleigh number on mantle dynamics and mixing. Models predict that primordial heterogeneity is preserved in the lower mantle over >4.5 Gyr as discrete blobs for high intrinsic viscosity contrast (>30x) and otherwise for a wide range of parameters. In turn, recycled oceanic crust is preserved in the lower mantle as "marble cake" streaks or piles, particularly in models with a relatively cold and stiff mantle. Importantly, these recycled crustal heterogeneities can co-exist with primordial blobs, with piles often tending to accumulate beneath the primordial domains. This suggests that the modern mantle may be in a hybrid state between the "marble cake" and "plum pudding" styles.

Finally, we put our model predictions in context with recent discoveries from seismology. We calculate synthetic seismic velocities from predicted temperatures and compositions, and

compare these synthetics to tomography models, taking into account the limited resolution of seismic tomography. Convection models including preserved bridgmanite-enriched domains along with recycled piles have the potential of reconciling recent seismic observations of lower-mantle heterogeneity³ with the geochemical record from ocean-island basalts^{4,5}, and are therefore relevant for assessing Earth's bulk composition and long-term evolution.

¹ Ballmer et al. (2017), *Nat. Geosci.*, 10.1038/ngeo2898

² Gülcher et al. (in review), *EPSL: Variable dynamic styles of primordial heterogeneity preservation in Earth's lower mantle*

³ Waszek et al. (2018), *Nat. Comm.*, 10.1038/s41467-017-02709-4

⁴ Hofmann (1997), *Nature*, 10.1038/385219a0;

⁵ Mundl et al. (2017), *Science*, 10.1126/science.aal4179