GEODYNAMICS

Surviving mantle convection

Hints from seismic tomography and geochemistry indicate that Earth's mantle is heterogeneous at large scale. Numerical simulations of mantle convection show that, if it started enriched in silicates, the lower mantle may remain unmixed today.

Frédéric Deschamps

The bulk composition of Earth's mantle is not well known. Based on basaltic magmas derived from mantle rocks, Ringwood suggested[1] in the 1960s that the upper mantle rocks are made of about 45 wt% silicate oxide, 40 wt% magnesium oxide, and 8 wt% iron oxide — a composition that has been termed pyrolitic. By extension, it has been assumed that the lower mantle, from a depth of 660 km down to the core–mantle boundary at 2,890 km, is also pyrolitic, implying that its dominant minerals, bridgmanite and ferropericlase are present in proportions of about 80 wt% and 20 wt%, respectively. Since then, geophysical[2] and geochemical[3] observations have, however, revealed the presence of large-scale heterogeneities and hidden, non-pyrolitic, reservoirs in the lower mantle. Various geodynamic models of mantle convection allow persistent reservoirs of chemically distinct material for long periods of time[4]. Writing in *Nature Geoscience*, Ballmer *et al.*[5] present geodynamic simulations that explore a different scenario: they start from a lower mantle with a higher-than-pyrolitic fraction of bridgmanite, and find that under these initial conditions large coherent reservoirs of primordial material persist in the lower mantle to the present.

So far, two main pieces of evidence pointed towards distinct reservoirs in the deep mantle: (1) geochemical analyses of basaltic rocks from hotspot volcanism locations such as Hawai'i, that sample the deepest mantle, imply the existence of primordial material in the deep mantle[3]; (2) seismological observations show large provinces with relatively lower seismic shear-wave velocity at the bottom of the mantle that are likely to be chemically distinct from surrounding mantle material[2,6]. Another hint may be provided by the observation that some pieces of the oceanic crust that subduct from the Earth's surface do not sink deep into the mantle but stack up[7] at depths of around 800–1,200 km. These pieces of crust could be prevented from sinking further by a change in viscosity[8],

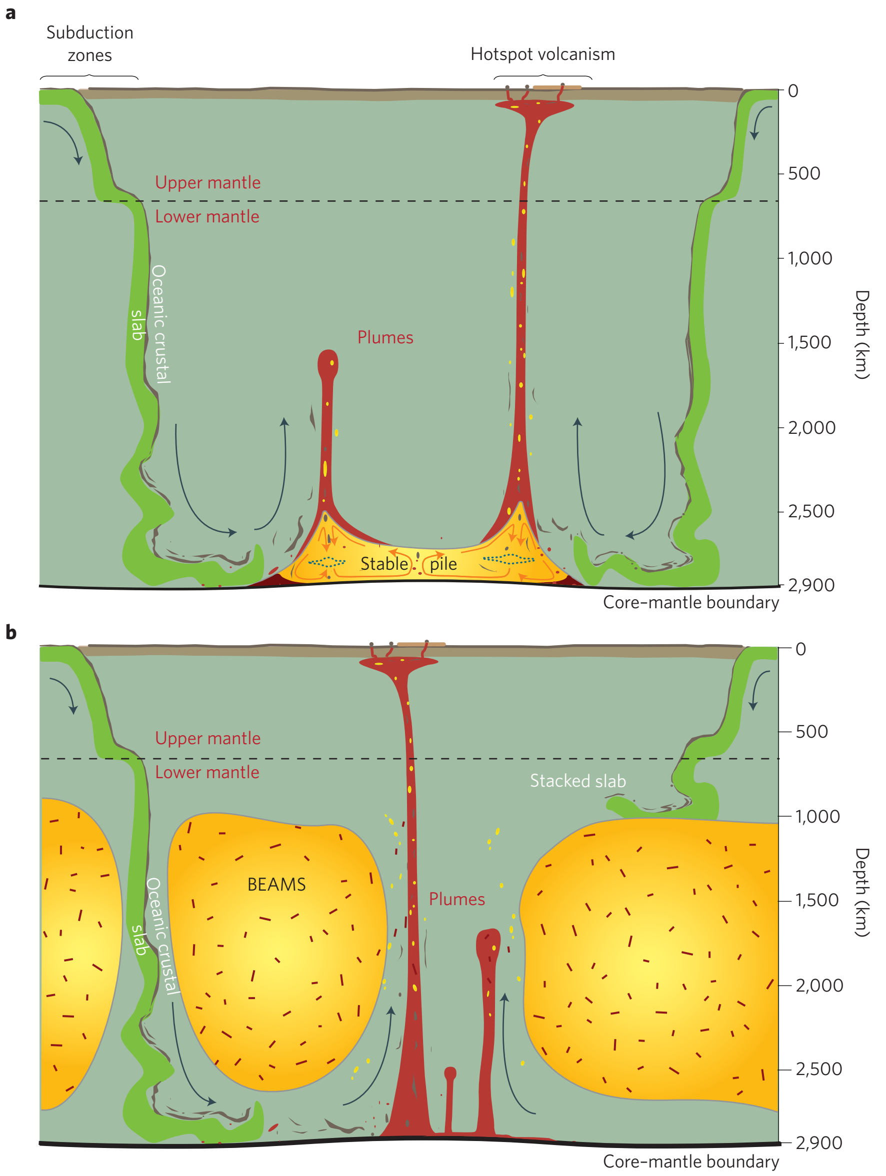

Figure 1 | Two thermochemical models of lower mantle structure. **a**, The thermochemical piles theory (here, in its 'stable pile' version), in which an initial layer of dense, primitive material evolves into pile(s) of material during Earth's history. **b**, According to the BEAMS hypothesis introduced by Ballmer and colleagues[5], the lower mantle was initially enriched in bridgmanite and was consequently more viscous than pyrolitic rocks by a factor of 20 or more. As a result, a large fraction of this bridgmanite-enriched mantle, the BEAMS, persisted until now, leaving a contemporary unmixed mantle. Adapted from ref. 2, Macmillan Publishers Ltd.

perhaps because of a divergence from a pyrolitic composition.

But preservation of such primordial reservoirs throughout Earth's history in a mantle animated by convection is not easy to explain. One much-investigated hypothesis, the thermochemical piles theory (Fig. 1a), suggests that a layer of primordial material was trapped in the lowermost mantle early in the evolution of the planet, and henceforth participated in convection only to a very limited extent. Importantly, the basal primordial reservoirs hypothesis can explain the geochemical[9] and seismological[10] observations, as well as the location of past and present hotspots[11].

Ballmer and colleagues[5] note that specific types of meteorites that are thought of as analogues for primordial mantle contain a relatively higher proportion of silicates compared to other elements, and propose an alternative scenario. They infer that the primordial mantle could have plausibly had a higher fraction of the bridgmanite than the pyrolitic composition (and hence less ferropericlase). Because bridgmanite is more viscous than ferropericlase by up to three orders of magnitude[12], and slightly denser, the more viscous primordial material assumed by Ballmer and colleagues is expected to lead to very different mantle dynamics and evolution, compared to a pyrolitic lower mantle (Fig. 1b). To explore the implications of their assumption, the team ran numerical simulations of convecting mantle in a two-dimensional Cartesian geometry with a chemically distinct and more viscous initial lower mantle, and found that a substantial fraction of the lower mantle can remain unmixed to the present day. Simulated upwelling mantle plumes and subducting crust circulate around large regions of preserved material, which Ballmer and colleagues term bridgmanite-enriched ancient mantle stuctures, or BEAMS.

The most important parameter in determining the fraction of unmixed mantle is the ratio of viscosity between the bridgmanite-enriched material and the pyrolitic upper mantle. Because the viscosities of bridgmanite and ferropericlase differ by two to three orders of magnitude, estimating this value is complicated; the viscosity of aggregate material depends on the partitioning of strain between weak and strong grains, and small variations in composition can trigger significant changes in viscosity. Ballmer and colleagues explored a range of primordial mantle compositions with feasible viscosity relative to pyrolitic mantle. Interestingly, even relatively small viscosity ratios between pyrolitic mantle and the bridgmanite-enriched material of around 1:20 can allow persistent reservoirs to form. The conceptual BEAMS model also fits several geochemical and geophysical observations. It provides reservoirs that host primordial material from which the hotspots and the basaltic rocks they create at the surface are partially sourced; these simulated mantle structures offer a simple explanation for those subducting slabs of oceanic crust that seem to get stuck at around 1,000 km — they are unable to sink further into the high-viscosity material. These BEAMS also stabilize mantle flow, ensuring the long-term geographical fixation of upwelling mantle plumes. Finally, the BEAMS model is consistent with the radial seismic reference model of Earth, and with the mid-mantle shear-wave velocity anomalies.

Some limitations remain. The current two-dimensional model cannot fully describe the spatial heterogeneity of seismic velocity measurements in the lowermost mantle (2,500 km and deeper). Three-dimensional simulations would be necessary to test the BEAMS hypothesis against the tomographic models of mantle thermal and chemical structure. Ballmer and colleagues suggest observational tests for the presence of these BEAMS: flow and compositional changes at their top interface may trigger seismic anisotropy and reflections of seismic waves, which should be detectable in global or regional seismic studies.

Ballmer and colleagues[5] propose a scenario of silicate-enriched lower mantle structures that explain a diverse range of geochemical, seismological and geophysical observations. Their simulations suggest that these relatively more viscous mantle provinces could be preserved from the earliest part of Earth's history, and thus offer a different perspective on the evolution of the whole planet. ☐

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BIOGEOCHEMISTRY

Deep ocean iron balance

Dissolved iron is mysteriously pervasive in deep ocean hydrothermal plumes. An analysis of gas, metals and particles from a 4,000 km plume transect suggests that dissolved iron is maintained by rapid and reversible exchanges with sinking particles.

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Iron, which limits primary production in many parts of the ocean[1], rarely persists in dissolved forms. Although dissolved iron ought not to sink through the seawater in which it is dissolved, it forms and binds to particles that sink readily through the water column. However, writing in *Nature Geoscience*, Fitzsimmons *et al.*[2] report dissolved iron that persists and sinks steadily next to particulate iron in a hydrothermal plume that stretches halfway across the Pacific Ocean, suggesting that a dynamic balance between the dissolved and particulate forms