Dynamics and composition of mantle plumes:
Insights from connecting geodynamic models to seismic observations

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The Earth's biggest magmatic events are thought to originate from massive melting when mantle plumes reach the base of the lithosphere. These hot, buoyant upwellings can recycle chemical heterogeneities from the deep lower mantle and carry them toward the surface, providing a window to the composition of the lowermost mantle. Here, we investigate plume dynamics from the core-mantle boundary to the surface using a combination of geodynamic models and seismic observations. This makes it possible to constrain the composition of mantle plumes and to better understand the the exact nature of this link between surface and deep Earth.

Seismic observations indicate that the lowermost mantle is strongly heterogeneous. Body waves reveal a variety of ultra-low velocity zones (ULVZs), which extend not more than 100 km above the core-mantle boundary and have been suggested to be evidence of partial melting at the base of mantle plumes. We explore the hypothesis that present-day deep mantle melting creates ULVZs and introduces compositional heterogeneity in the mantle. However, we find that for a wide range of plausible melt densities, permeabilities and viscosities, lower mantle melt is too dense to be stirred into convective flow. Partial melt alone does not explain the observed ULVZ morphologies and solid-state compositional variation is required to explain the anomalies.

Mantle plumes that best fit observations of low premagmatic surface uplift and geochemical data contain up to 15–20% of recycled oceanic crust in the form of dense eclogite, which drastically decreases their buoyancy and makes it depth dependent. They have columnar tails with a diameter of more than 500 km that remain stable in the mantle for tens or hundreds of millions of years. Consequently, they should be easier to resolve with seismic methods than classical narrow plume tails. Large enough thermochemical plumes can rise through the whole mantle despite their reduced buoyancy as long as the fraction of eclogite does not exceed 15%.

On the other hand, the detection of the X-discontinuity beneath some hotspots, interpreted as the coesite-stishovite transition, requires the presence of high percentages (at least 40%) of eclogite-rich plume material. We propose this contradiction can be resolved by taking into account the segregation of chemical heterogeneities within the plume. Our models show how large fractions of basaltic material exceeding 40% can accumulate within plumes in the upper mantle, explaining the seismologic detection of the X-discontinuity, and providing insights into how recycled material is carried towards the surface.

Our findings provide an important step towards constraining the nature of the heterogeneities within mantle plumes and their influence on the thermal, compositional and dynamic evolution of the Earth.

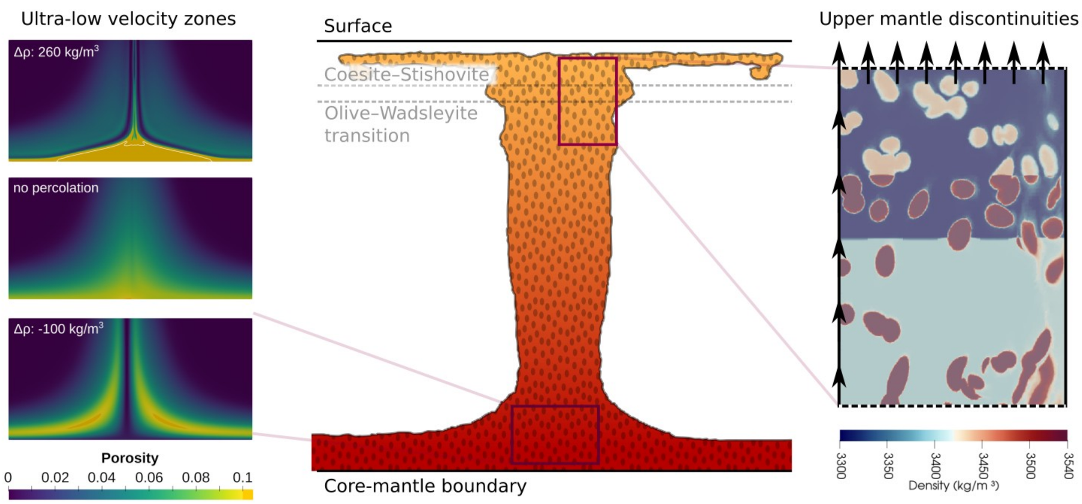

Figure 1: Geodynamic models of plume dynamics across scales from the core-mantle boundary to the surface. Modified from Dannberg & Sobolev, 2015 (https://doi.org/10.1038/ncomms7960) and Dannberg el al., 2021 (https://doi.org/10.1093/gji/ggab242).