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Geodynamic modelling of low-buoyancy thermo-chemical plumes

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The Earth's biggest magmatic events that form Large Igneous Provinces are believed to originate from massive melting when hot mantle plumes rising from the lowermost mantle reach the base of the lithosphere. Classical models of thermal mantle plumes predict a flattening of the plume head to a disk-like structure, a kilometer-scale surface uplift just before the initiation of LIPs and thin plume tails. However, there are seismic observations and paleo-topography data that are difficult to explain with this classical approach.
Here, using numerical models, we show that the issue can be resolved if major mantle plumes are thermo-chemical rather than purely thermal. It has been suggested a long time ago that subducted oceanic crust could be recycled by mantle plumes; and based on geochemical data, they may contain up to 15-20% of this recycled material in the form of dense eclogite, which drastically decreases their buoyancy and makes it depth-dependent.

We perform numerical experiments in a 3D spherical shell geometry to investigate the dynamics of the plume ascent, the interaction between plume- and plate-driven flow and the dynamics of melting in a plume head. For this purpose, we use the finite-element code ASPECT, which allows for complex temperature-, pressure- and composition-dependent material properties. Moreover, our models incorporate phase transitions (including melting) with the accompanying rheological and density changes, Clapeyron slopes and latent heat effects for both peridotite and eclogite, mantle compressibility and a strong temperature- and depth-dependent viscosity.

We demonstrate that despite their low buoyancy, such plumes can rise through the whole mantle causing only negligible surface uplift. Conditions for this ascent are high plume volume and moderate lower mantle subadiabaticity. While high plume buoyancy results in plumes directly advancing to the base of the lithosphere, plumes with slightly lower buoyancy pond in a depth of 300-400 km and form pools or a second layer of hot material. These structures are caused by phase transitions occurring in different depths in peridotite and eclogite; and they become asymmetric and finger-like channels begin to form when the plume gets entrained by a quickly moving overlying plate. We also show that the bulky tails of large and hot low-buoyancy plumes are stable for several tens of millions of years and that their shapes fit seismic tomography data much better than the narrow tails of thermal plumes.