Geophysical Research Abstracts
Vol. 16, EGU2014-11370, 2014
EGU General Assembly 2014

Geodynamic modeling of eclogite-bearing mantle plumes: Ascent dynamics, plume-plate-interaction and surface manifestations

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According to widely accepted models, plumes ascend from the deep mantle and cause massive melting when they reach the base of the lithosphere. Classical geodynamic models consider plumes as purely thermal and thus predict a flattening of the plume head to a disk-like structure and thin plume tails. However, geochemical data indicate that plumes have a different composition than the average mantle material and it has been suggested a long time ago that subducted oceanic crust could be recycled by mantle plumes. In addition, seismic imaging reveals thicker plume tails as well as a more complex plume structure in the upper mantle, including broad low-velocity anomalies up to 400 km depth and elongated low-velocity fingers fed by plumes.

While recent numerical models have considered a different chemistry to explain complex plume shapes or zoning within plumes, they either are restricted to only a part of the plume evolution or use simplified material models. However, due to the high density of recycled oceanic crust, thermo-chemical plumes are expected to have much smaller buoyancy than thermal plumes. Therefore it is especially important to incorporate realistic material properties, as they can influence the plume dynamics crucially and determine if a plume reaches the lithosphere or remains in deeper parts of the mantle.

We perform numerical experiments in a 3D spherical shell geometry to study the dynamics of the plume ascent, the interaction between plume- and plate-driven flow and the dynamics of melting in a plume head. For that 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 the peridotite and eclogite phase, mantle compressibility and a highly temperature- and depth-dependent viscosity.

We study under which conditions thermo-chemical plumes ascend through the whole mantle and what structures they form in the upper mantle. Modeling shows that plumes with a buoyancy higher than some critical value directly advance to the base of the lithosphere, while 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 become asymmetric and finger-like channels begin to form when the plume gets entrained by a quickly moving overlying plate. Our models also suggest that thermo-chemical plumes ascend in the mantle much slower compared to thermal plumes and have thicker plume tails. The conversion of plume excess temperatures to anomalies in seismic velocity shows that thermo-chemical low-buoyancy plumes can explain a variety of features observed by seismic tomography much better than purely thermal plumes.