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The thermo-chemical structure of the deep mantle: observations and models

Frédéric Deschamps (1), Jeannot Trampert (2), Paul J. Tackley (1), and Joe Resovsky (3)

(1) Institute of Geophysics, ETH Zurich, Zurich, Switzerland (deschamps@erdw.ethz.ch), (2) Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands, (3) Roosevelt Academy, Middleburg, The Netherlands

Our description of the Earth's mantle structure has considerably changed during the past decade. The hypothesis that large chemical heterogeneities (whose nature and origin is still to be determined) gained increasing support, in particular from normal mode seismology observations (including probabilistic tomography). The key point in these studies is that the mapped density anomalies and shear-wave velocity anomalies are not correlated, which is inconsistent with a purely thermal origin of the observed seismic velocity anomalies. Interestingly, other studies, using other observations and arguments (e.g., the seismic ratio between the relative anomalies of compressional and shear wave velocities) arrive to similar conclusions. The classical interpretation that the large low shear-wave velocity provinces seen in the deep mantle (LLVSZ) are hot and buoyant must be revisited. Instead, LLVSZ are likely the result of superposed thermal and chemical heterogeneities. Using a careful equation of state modeling, it is possible to estimate the distributions of temperature and composition (e.g., the volume fractions of perovskite and iron oxide) from the distributions of seismic velocities and density. This operation also requires an appropriate treatment of the various sources of uncertainties in the thermo-elastic parameters of the Earth's mantle minerals through Monte-Carlo searches. Sensitivities of seismic velocity and density to temperature and composition indicate that in the deep mantle shear-wave velocity is sensitive to both the temperature and the volume fraction of iron. Furthermore, density is mainly sensitive to variations in the volume fraction of iron oxide, and bulk velocity anomalies are a good proxy for variations in the volume fraction of perovskite. Additional data and observations independent from seismological are needed to further break the trade-off between temperature and composition. A promising constraint is electrical conductivity. Unlike thermo-elastic data and density, electrical conductivity increases with increasing temperature. Using available mineral physics data, the thermo-chemical structure predicted by probabilistic tomography results in an equatorial belt of high electrical conductivity in the deep mantle.

The thermo-chemical structure and dynamics of the mantle are intimately linked, and a successful model of mantle convection must explain seismological observations. A key question is therefore to build models of mantle dynamics that can maintain large pools of dense material at the bottom of a convective layer for a long period of time. So far, two independent sources of chemical heterogeneities have been investigated by models of thermo-chemical convection: the interaction of primitive reservoir(s) of dense material with mantle convection, and the production and recycling of MORBs. Models with an initial basal layer of dense material indicate that strong thermal viscosity contrasts are able to create and maintain large pools of dense material at the bottom of the system, and that an endothermic phase transition at 660-km depth prevents the dense material to massively flow into the upper part of the system. Models that include MORBs recycling indicate that the formation and survival of pools of dense material at the bottom of the mantle is sensitive to the buoyancy ratio of MORBs, and to the properties of the post-perovskite phase transition. Individually, primitive reservoirs and MORBs do not fully explain the available seismological observations. It is likely that the chemical contribution to the observed seismic velocity and density anomalies originate from two or more sources.