Investigating the Earth's upper mantle structure: Numerical and laboratory experiments on mantle flow and entrainment processes

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The physical and compositional structure of the Earth's mantle is still a controversial issue. This is apparent in the ongoing debate whether whole-mantle convection or a separate evolution of upper and lower mantle are consistent with seismic observations and geochemical data from mid-ocean ridges and hotspots. Based on current evidence for a relative low density and low viscosity layer ($\eta \sim 10^{18-19}\ Pa\ s$) sandwiched between the overlying strong oceanic lithosphere ($\eta \sim 10^{25}\ Pa\ s$) and underlying more viscous mantle material ($\eta \sim 10^{21}\ Pa\ s$), Phipps Morgan et al. (1995) and Phipps Morgan and Morgan (1999) considered the idea of a weak and buoyant asthenosphere layer that is fed by upwelling mantle plumes. In this scenario the asthenosphere layer is hotter than 'normal' underlying mantle, thus less dense and less viscous.

Based on this scenario we investigate mantle flow in response to forced plate motion and possible entrainment processes at subduction zones. We use a two-dimensional numerical model that solves for viscous flow in the Boussinesq-approximation (FE-solver) and for temperature (Smolarkiewicz FD-solver). Flow and entrainment of a 200 km thick asthenosphere layer are tracked by a tracer particle advection scheme. Speed of the oceanic plate, asthenosphere viscosity, and age of the subducting slab are varied (19 to 95 km/Ma, 10^{18} to 10^{20} $Pa\ s$, 20 to 160 Ma, respectively), while the angle of subduction (45°) and the initial viscosity of the deeper mantle (10^{21} $Pa\ s$) are held constant. Both sides of the subducting plate are modeled in separate numerical experiments, processes related to melting, slab-dehydration, or phase transitions are not implemented in the numerical model.

We find the lower (hot) side of the slab to entrain a 10-30 km-thick downdragged layer of asthenosphere, whose thickness depends upon the subduction rate and the asthenosphere viscosity and density. The upper (cold) side entrains as much by thermal 'freezing' onto the slab's top as by mechanical downdragging. Underneath the oceanic plate a relative pressure high at the subduction zone tilts the asthenosphere bottom and drives a return flow within the deeper asthenosphere towards the mid-ocean ridge. This flow pattern has been observed in all calculations, even in those having low viscosity contrasts (factor of 10) between asthenosphere and underlying mantle. Furthermore the low viscous asthenosphere acts as a lubrication layer that completely decouples plate motion from deeper mantle flow, at least down to the 410 km- or 670 km-discontinuity where asthenosphere viscosity may increase. In the mantle wedge a recirculation forms whose shape, extension, and circulation speed depend on the asthenosphere viscosity and the slab's speed and age.

In order to verify the numerical code we conducted laboratory experiments for the oceanic side of the slab. In each experiment, a corn-syrup + water mixture was placed on top of a denser and more viscous pure corn-syrup layer. Plate motion was simulated by a sheet of mylar moving along a fixed lithosphere-slab geometry (angle of subduction 45°). Illuminated glass beads were used to track the motion of the 'asthenosphere' and to quantify the amount of entrainment. The laboratory experiments evolve very similar to the numerical counterpart showing a tilted asthenosphere bottom, a return flow in the deeper asthenosphere, and entrainment at the slab's bottom. Numerical calculations using the measured densities and viscosities of the laboratory fluids and the dimensions of the experimental setup reproduce the lab observations in all aspects.

A boundary layer theory was developed to estimate the maximum entrainment at the base of the subducting slab. This simple theory neglects conductive heat loss into the slab. It is found to be in good agreement with the numerical results for moderate to large asthenosphere viscosities (which are numerically best resolved) and moderate to high plate speeds, due to the growing relative importance of conductive heat loss with decreasing subduction speed.

Laboratory and numerical experiments as well as the analytical boundary layer solution imply that slab entrainment is relatively inefficient at removing a buoyant and low viscosity asthenosphere layer. The entrained downward flux is roughly 20-40% of the flux within the slab itself which is composed of former asthenosphere that has been accreted to the oceanic lithosphere during its aging. Thus, most asthenosphere returns to the deeper mantle by accretion into and subduction of lithospheric plates, not being directly downdragged by subducting slabs. In our numerical experiments we found entrainment rates to be in accord with the maximum rates predicted by the analytical model only if the numerical grid-spacing is less than about 4-8 km. If the grid-spacing is larger, the numerical experiments tend to improperly entrain too much asthenosphere.

Current work focusses on the implications of the "plume-fed asthenosphere"-Earth model for mid-ocean ridge melting processes, emphasizing plume-ridge interaction. First steps cover the incorporation of melting related geochemical processes into a mantle convection model. Tracking the partition of trace element and isotope ratios between melts and residues within a convection mantle will help to constrain potential mantle compositions. In addition feedback mechanisms between the melting behavior (in response to geochemical composition) and viscous flow of the mantle may affect both geodynamic processes significantly.

References:

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