Delamination of Sub-Crustal Lithosphere

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Introduction: Lithospheric delamination from the base of continents is common beneath tectonically active areas. This is especially obvious beneath the western U.S., where tomographic images (Fig. 1) have relatively high resolution. While the style of delamination is debated in most instances, it is accepted that downwelling is driven by the negative buoyancy of the delaminating lithosphere (e.g., Bird, 1979; Meissner and Mooney, 1998), and that the strength resisting sinking is low enough to allow sinking to occur faster than thermal conduction diffuses the thermal anomaly responsible for the observed seismic structure and negative buoyancy.

Computational Methods: We solve the mass, momentum, and energy equations assuming infinite Prandtl number and using the Boussinesq approximation for buoyancy forces using the incompressible Navier-Stokes equations for fluid motion, and couple it to temperature using the energy conservation equation:

$$\rho \left[ \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right] - \nabla \cdot \sigma + g \rho \alpha (T - T_0) + \nabla P = 0$$

where $\mathbf{u}$ is the velocity, $t$ is the time, and $\rho$ is the material-dependent density with $\rho_0$ being a reference density, and $\alpha$ is the effective coefficient of thermal expansion for the material, and $T$ is the temperature with $T_0$ being a reference temperature. $\eta$ is the effective viscosity given by an Arrhenius viscosity law:

$$\eta = \eta_0 \exp\left(\frac{E + PV}{nRT}\right)$$

where $\eta_0$ is a reference viscosity, $E_\text{mol}$ is the activation energy, and $V$ is the activation volume.

Brittle and plastic failure is implemented using an internal angle of friction (i.e., Mohr – Coulomb failure criterion) for brittle failure and a temperature, viscosity, and material-dependent yield stress.

$$\sigma_{\text{yield}} = C \sin \phi$$

Results: Shown below are results using an open-source Matlab-based finite difference code by Teras Gerya (2010) — Figures 3 and 4, that we are working on implementing using Comsol. Preliminary results showing high shear stresses at zone of weakness where subduction initiation takes place.

Conclusions: Using the Matlab-based finite difference (FD) code by Gerya (2010) as a numerical benchmark, we are implementing a similar simulation using Comsol. An important challenge has been mimicking the “marker-in-cell” technique within a FD framework that the example above uses for advection of different rock materials (e.g., basaltic upper crust, gabbroic lower crust, mantle lithosphere, mantle asthenosphere). In addition, the Matlab-based implementation of plastic yield and brittle fracture coupled to fluid flow has not been implemented yet in our Comsol model. These challenges have made for a long development time than anticipated and this is a work in progress. We plan to continue this work to improve our Comsol model to resolve some of these challenges.

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References:
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