Geophysical Research Abstracts
Vol. 20, EGU2018-5007-1, 2018
EGU General Assembly 2018
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Rheological and petrological controls on slab stagnation and penetration in the shallow lower mantle

Hana Cizkova (1), Craig Bina (2), and Arie van den Berg (3)

(1) Charles University in Prague, Faculty of Mathematics & Physics, Dept. of Geophysics, Praha 8, Czech Republic (hana.cizkova@mff.cuni.cz), (2) Northwestern University, Dept. of Earth and Planetary Sciences, Evanston, IL, U.S.A., (3) Utrecht University, Dept. of Earth Sciences, Utrecht, The Netherlands

Solid-state creep facilitates buoyancy driven material flow in the Earth mantle and mantle viscosity is indispensable for predicting Earth's mechanical behavior at scales ranging from deep mantle material flow to local stress accumulation in earthquakes zones. Viscosity can be estimated from high-pressure experiments or numerical models of creep laws, viscosity-depth profiles can be alternatively obtained also by inverting the geophysical observables arising from Earth's response to surface and internal loading and by the analysis of sinking speed of subducted lithosphere. All these methods however result in a range of viscosity models. Geodynamical modeling thus provides an additional tool that may help to test whether these rheological models predict realistic mantle circulation. Here we use recent tomographic results that report subducted slabs stagnating in the shallow lower mantle as an 'observable' and perform a modelling study that may help to constrain the character of the rheological transition between the upper and lower mantle.

The boundary between the upper and lower mantle associated with an endothermic phase transition constitutes a barrier that in most cases prevents the direct penetration of subducted slabs and subducted material in many subduction zones seems to be trapped at the bottom of the transition zone, just above the 660-km phase boundary. Recent tomographic models however also report subducted material that penetrates to the shallow lower mantle, and there it is observed to flatten at about 1000-km depth. Multiple lines of evidence, including recent experiments, indicate that viscosity may gradually increase in the uppermost $\sim$300 km of the lower mantle, rather than simply changing abruptly at the upper-lower mantle boundary. We test the effects of smoothing the viscosity increase over 300 km and shifting it to a depth of 1000 km or even deeper. Slab stagnation at the bottom of the transition zone is found to be closely related to trench migration – retreating slabs tend to flatten above the 660-km interface, while non-retreating slabs penetrate to the lower mantle. Trench retreat is mainly controlled by crustal viscosity - weak crust favours rollback and stagnation while stiff decoupling crust reduces rollback and allows for slab penetration to the lower mantle. The nature of the viscosity interface between the upper and lower mantle plays only a secondary role. However, in the case of intermediate crustal viscosity, slab dynamics are close to a threshold between penetrative mode and stagnating mode. In this case, the character of the viscosity transition between the upper and lower mantle selects for slab penetration or stagnation. Horizontally lying slab segments are trapped in the transition zone if the sharp viscosity increase occurs at 660 km, but shifting the viscosity increase to 1000 km depth results in temporary stagnation below the upper-lower mantle boundary.

One of key factors that affect trench-retreat rate and consequently slab deformation in free subduction models turns out to be the strength of the crustal shear zone that decouples the subducting and overriding plate. We therefore discuss its rheological parameterisation in more detail and show several applications to natural subduction systems.