Deformation of Subduction Lithosphere in the Upper Mantle

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Observations of the geometry of slabs provide strong constraints on the dynamic evolution of subducted lithosphere in the upper mantle. Slabs generally have shallow dip in the upper mantle (30–45°), steepening sharply at 200–350 km depth, and the dip of the deeper portion of the slab (just above the 670 km discontinuity) may shallow with time (Jarrard, 1986). Analytic models of corner flow and kinematic models with rigid slabs predict that slab geometry should depend strongly on convergence rate and age of the subducting lithosphere, due to the strong low pressure region that develops in the mantle wedge, which acts to pull the slab upwards (Stevenson & Turner, 1977; Tovish et. al., 1978). The evolution of slabs likely depends on both a local balance of forces due to the buoyancy of the slab and slab-induced flow, as well as trench roll-back and large-scale mantle flow. However, both numerical and laboratory dynamic models of subduction with a moderate viscosity increase across the slab often develop steeply dipping slabs unless trench roll-back or other large-scale flow is included (e.g, King, 2001). In this study, we examine how slab shape depends on the local balance of forces, in the absence of trench roll-back and mantle-scale flow, in order to determine how rheology affects the evolution slabs.

We present 2D simulations of subduction using a visco-plastic rheology constrained by laboratory experiments for olivine with temperature-, pressure- and stress-dependent viscosity (Hirth & Kohlstedt, 2003; Goetze & Evans, 1979). Internal deformation of the slab can strongly influence the force balance on the slab, leading to time-dependent evolution of slab geometry with feed-backs on the mantle flow surrounding the slab. The interaction of the subducting plate with the non-Newtonian upper mantle leads to the generation of isolated low viscosity regions in the wedge and a halo of low viscosity surrounding the slab. The low viscosity regions diminish internal deformation and thickening of the slab. The model results demonstrate that stiff slabs (high yield stress) and a non-Newtonian viscosity produce shallow dipping slabs at shallow depths (<200 km). Slab dip increases rapidly through a hinge-like deformation of the slab, which occurs when stresses due to the buoyancy of the deeper slab exceed the yield stress. In addition, interaction of a stiff slab with an increase in viscosity and change in rheology (Newtonian) at a depth of 670 km stabilizes the evolution the slab and produces a slow shallowing of the deep slab. This shallowing of the deep slab can propagate up-dip and cause the shallow protion of the slab to flatten under the overriding plate. Subduction rate also affects the early evolution of the slab, but lithosphere age has only a minor influence. These models demonstrate that while roll-back and large-scale mantle flow certainly influence the shape of slabs, if slabs are strong, the local balance of forces may exert strong controls on the evolution of slabs through time.

References:

Goetze, C., and B. Evans, Stress and Temperature in the Bending Lithosphere as Constrained by Experimental Rock Mechanics, Geophys. J. of the R. Astro. Soc., v. 59, 463–478, 1979

Hirth, G. and D. Kohlstedt, Rheology of the Upper Mantle and the Mantle Wedge: A View from the Experimentalists, in Inside the Subduction Factory, ed., J. Eiler, American Geophysical Union, 2003

Jarrard, R. D., Relations Among Subduction Parameters, Rev. of Geophys., v. 24, 217–284, 1986

Stevenson, D. J., and J. S. Turner, Angle of Subduction, Nature, v. 270, 334–336, 1977

Tovish, A., G. Schubert and B. P. Luyendyk, Mantle Flow Pressure and the Angle of Subduction: non-Newtonian Corner Flows, J. of Geophys. Res., v. 83, 5892–5898, 1978