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Dynamic control of the downgoing lithosphere on subduction kinematics

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Cold, rigid lithosphere sinking into hot and relatively fluid mantle exerts an important control on plate tectonics and mantle convection. Subduction kinematics - velocity, dip and trench roll-back – are affected by the mantle, through viscous resistance to subduction and the hydrodynamics of slab- and otherwise-induced flow, and the lithosphere, through its negative buoyancy and its resistance to deformation. Previous efforts disagree on the relative importance of lithospheric dynamics and the role of the mantle.

In this study, we analyze the behavior of a sinking visco-elastic lithosphere (with various Newtonian viscosity distributions) in a passive mantle (implemented through a mantle drag boundary condition), with a free surface and without an overriding plate. This model set-up allows a more realistic representation of the lithosphere than most others, while excluding some of the complexities resulting from a more dynamic mantle, which many previous studies analyzed.

We find that plate-mantle interaction though drag dissipates the bulk of the system's energy, while the contribution of lithospheric bending and stretching to energy dissipation lies between 3-5% (in fast slabs) and 10-30% (in slow subduction). Yet, the rheology of the plate significantly affects the rate and angle at which plates enter the mantle, while mantle viscosity and buoyancy of the plate determine the slab's sinking velocity. Stiff plates (thick/high viscosity) enter the mantle at almost twice the speeds and 15-25° shallower dips than slabs with an order of magnitude lower average viscosity. The freely subducting plates in our models achieve subduction mainly by trench rollback. With a very weak asthenospheric drag, the contribution of rollback to subduction rates can be reduced to about 75%. A higher active convergence rate would require external forcing (lithospheric or mantle). The effect of lithospheric rheology on subduction kinematics is two-fold. Whereas the resistance to bending (proportional to viscosity times thickness cubed) defines the dip and subduction/roll back velocity, this resistance may be reduced significantly by slab stretching in slow and/or weak plates, resulting in an apparent control of the resistance to stretching (viscosity times thickness).