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On the dynamics of subducting slabs in the presence of a free surface.

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Subduction zone dynamics has been extensively studied with laboratory models in which a dense, high viscosity slab sinks into a less dense and less viscous mantle. The resulting slab shapes appear realistic compared to, e.g., the shapes that are imaged by seismic tomography, and subduction models have therefore been compared with various observables such as trench motion, subduction angle and subduction speed. If a similar setup (viscous slab in viscous mantle) is modeled in an Eulerian numerical code, however, a very different behavior is observed: Instead of bending and subducting, the slab ‘drips off’ in a Rayleigh-Taylor like instability. Since this result does not appear very natural, many workers have introduced a Byerlee-type, plastic yielding rheology in the slab, or added a low-viscosity ‘crust’ on top of the subducting slab. If the parameters (in particular the effective friction angle) are tuned accordingly results appear indeed similar to laboratory models. A direct comparison of such models with laboratory experiments, however, remains incomplete since the rheology and/or geometry is different. In addition, no scaling law exists that predicts slab velocity (or slab behavior) as a function of slab thickness, slab/mantle viscosity ratio and slab/mantle density difference. Existing scaling laws, such as the approach of Conrad and Hager [1999, JGR], rely on knowing the radius of curvature of subducting slabs, which is a parameter that is typically known only after an experiment has been performed. Before applying results to nature, where complicating factors such as depth-dependent nonlinear viscosities may play a role, it is important to have a more thorough (and quantitative) understanding of the fluid dynamics of a single, freelysubducting viscous slab in a viscous mantle. Ideally, such understanding should come from rigorously comparing numerical experiments with analytical and numerical models.

As a first step in this direction, Schmeling et al. [PEPI, 2008] performed a benchmark study that addressed the effects of the upper boundary condition on slab dynamics. The results show that models in which the upper boundary condition is a true free surface, or in which a ‘sticky-air’ layer is employed, are indeed capable of reproducing laboratory experiments, as long as sufficiently fine numerical resolutions are employed.

Here, we build on this work and perform a much more extensive analysis on the effect of numerical settings (resolution, time step), initial geometry (slab tip length and angle), and rheology on subduction dynamics. For this purpose, we use the most efficient code from the benchmark study, a 2D adaptive FEM code (MILAMIN) capable of modeling both slab and mantle in a single computational domain in the presence of a free surface.

Results confirm earlier findings that slab dynamics is to a large extent controlled by the effective viscosity contrast between slab and mantle. Two main deformation modes exist as a function of viscosity contrast: the ‘drip’ or ‘Rayleigh-Taylor’ mode occurs for viscosity contrasts smaller than about 100, and is dominated by slab-stretching and non-constant horizontal plate velocities (which are significantly larger towards the trench). The ‘plate’ mode, on the other hand, occurs for viscosity contrasts larger than about 500 and is characterized by slabs that do not change their initial length during subduction. Horizontal plate velocities are homogeneous along the slab and bending occurs in the trench area, with a bending radius that depends on viscosity contrast and slab thickness.

In the plate mode, the initial slab tip length and angle have a significant effect on the initial subduction rate. After the slab tip reaches a depth of several hundreds of km, however, subduction rates are largely independent on the initial geometry. A visual analysis indicates that this is the stage when slab bending at the trench is well established.

If an increase in viscosity at 670 km depth is taken into account, the numerical models reproduce a range of observed slab dynamics in laboratory experiments, including forward trench motion, slab folding at the 660 and stagnant slabs. In particular, the results of Enns et al. [GJI, 2005] are confirmed for purely viscous behavior. Moreover, since our numerical simulations do not incorporate surface tension and are only mildly sensitive to

the mantle-air density difference, this suggests that the effects of surface tension in laboratory experiments are unlikely to be of first-order importance.

We are currently in the process of deriving scaling laws from the numerical simulations and are comparing the numerical models with simplified semi-analytical models.