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One-sided subduction in self-consistent models of global mantle convection: the importance of a free surface and a weak crustal layer

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Previous global dynamical models using a visco-plastic rheology are able to reproduce some aspects of plate tectonics and mantle convection (Moresi et al., 1998; van Heck and Tackley, 2008). However, these models still fail to reproduce some first-order features of plate tectonics, as for example Earth-like one-sided subduction. Instead they show a convergence and downwelling of the plates that is two-sided and more or less symmetric. One important assumption of such models is the definition of the top boundary: it is defined as a free-slip surface, where the uppermost part of the model is free to move horizontally (i.e. along the boundary) but not vertically (i.e. across the boundary). This assumption thus inhibits the development of topography. In contrast, subduction zones display some of the largest variations in surface topography on Earth.

Schmeling et al. (2008) showed that it is necessary to include a proper free surface in numerical models in order to reproduce laboratory results. According to their benchmark study, mimicking a free surface by a low viscosity, zero density layer on top of the crust is an adequate approach. For this reason, we have implemented such a "sticky-air layer" in our global numerical model.

We here study the effect of a free surface on the mode of subduction from Cartesian 2-D to spherical 3-D global, fully dynamic mantle convection models with self-consistent plate tectonics. For this we use the finite volume multi-grid code StagYY (Tackley, 2008) with strongly temperature and pressure-dependent viscosity, ductile and/or brittle plastic yielding, and non-diffusive tracers tracking compositional variations (the 'air' layer in this case).

We observe that indeed, a free surface leads to single-sided subduction, whereas identical models with a free-slip upper boundary develop double-sided subduction. A free surface is thus an essential ingredient to obtain realistic subduction behaviour in numerical models, probably because it allows the slab to bend in a natural manner.

Although the models appear one-sided from the temperature or viscosity fields, there is strong mechanical coupling between the slab and the mantle wedge that makes them mechanically double-sided. Regional models of subduction (Gerya et al, 2008) indicate that one requirement for stable one-sided subduction is a low strength interface between the plates achieved by the presence of metamorphic fluids in the subduction channel. Such a lubrication layer consisting of weak hydrated sediments accommodates stable one-sided subduction by strain localisation.

In conclusion, a free surface is the key ingredient to obtain thermally one-sided subduction, while additionally including a weak crust is essential to obtain subduction that is both mechanically and thermally one-sided.

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