Constraining viscosity in transition zone and shallow lower mantle from numerical models of subduction

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Introduction

It is accepted that over a long timescale, mantle behaves like a viscous fluid, while lithosphere can be seen as a brittle layer. However, a viscosity profile throughout the whole mantle is far from being accurate. Different models were proposed to find the best-fit viscosity distribution based on the imposition of different sets of constraints (e.g. geoid, Haskell, tomography model) (Steinberger and Calderwood, 2006). There are some common factors in all the possible profiles: 1) there seems to be a sharp viscosity increment between transition zone (TZ) and lower mantle (LM) and 2) a slow increase in viscosity with depth in the first hundreds of km of LM.

Many authors (e.g. Mitrovica and Forte, 2004) agree that the asthenosphere should be the layer with lowest viscosity. However, others claim that the TZ maybe weaker than upper mantle (UM) and LM due to the presence of water stored in wadsleyite or ringwoodite.

The positive Clapeyron slope associated with the olivine-spinel phase transition at \(\sim 410\) km favours that the cold slab can go through it, accelerating the subduction process. The opposite situation seems to occur on the spinel-perovskite phase transition at \(\sim 660\) km, where the Clapeyron slope is negative and inhibits or slows the subduction (Tackley et al., 1993). Whether the slab is able to sink beyond this boundary depends, not only on the value of the Clapeyron slope, but also on other factors like absolute velocities of the plates, viscosity of the underlying mantle (TZ and LM) and discontinuities in its distribution, among others.

Numerical method and set-up

We used a coupled elasto-visco-plastic thermomechanical numerical model based on code SLIM-3D (Popov and Sobolev, 2008) to run all experiments. The model has true free surface and elastic deformation is included. Realistic rheology was applied to the subducting and overriding plates as well as the upper mantle. In this part of the model, viscosity is stress and temperature dependent. Three different types of creep (diffusion, dislocation and Peierls) are included, following the approach of Kameyama et al. (1999). In particular, Peierls creep plays a key role to reduce stress in the deep cold slab.

Volumetric deformations are followed by corrections in the calculation of density by means of the Murnaghan approach. Density is increased by 6% at the olivine-spinel phase transition (Christensen, 1995) and 8% at the spinel-perovskite (Dziewonski and Anderson, 1981).

All phase transition boundaries (gabbro-eclogite, coesite-stishovite, olivine-spinel and spinel-perovskite) in this implementation are totally dynamic. Clapeyron slope for olivine-spinel transition is considered to be +2.0 MPa/K and -2.5 MPa/K for the spinel-perovskite.

Subduction channel was considered as a well lubricated interface with low viscosity and friction coefficient, which favours the development of subduction.

The structure of the overriding plate was also handled as was done by Sobolev and Babeyko (2005). It consists of a layer of continental crust (30 km), a layer of continental gabbro (10 km) and lithospheric mantle up to a depth of 100 km. A strong shield was defined under the foreland, with a depth of 110 to 140 km on its eastern-most part.

Subducting slab is composed of \(~7\) km of oceanic gabbro and \(~73\) km of oceanic lithospheric mantle. It is considered to have a thermal age of 40 My, but according to Christensen (1996), slab age does not play a key role when determining the style of subduction. Trench motion is allowed and in none of our experiments was imposed neither kinematically nor by another means.

No overriding is prescribed in most of our experiments in order to isolate the influence produced by the tested values. However, some experiments where repeated with overriding velocity to estimate the influence on results.
Figure 1: Different styles of subduction detected in the experiments. Colours indicate temperature and dark lines the limit between different materials. a) Penetrating slab; b) Penetrating slab with some buckling; c) Piling up and slow sinking after flat slab with late penetration under subduction zone; e) Flat slab. (After Quinteros et al. (2010))

The viscosity profile of TZ and LM was represented in a simplified way by means of two parameters: viscosity in TZ and viscosity step at the spinel-perovskite phase transition.

Slab is pushed with a constant high velocity at the beginning of simulation at its left edge for 2 My to develop the subduction zone and obtain a coherent thermal state. After that moment evolution is driven by gravity.

Left side of the domain is totally opened as only hydrostatic pressure boundary conditions were defined. This gives the slab the freedom to move on any direction and with any velocity. This assures that subduction will evolve in a self-consistent way. The top side of the domain is a free surface with zero stress. On the bottom and right side free slip conditions are applied.

Results

Examples of the different styles of subduction that were classified on the experiments are shown in Fig. 1, from direct penetration (Fig. 1.a) to slabs that lay over the 660 km boundary (Fig. 1.e).

Taking 1.a as a reference case, one can see in 1.b that the increment of viscosity in TZ reduces subduction velocity ~2-3 times (see Fig. 2) and how a small part of the subducted slab is reaccommodated by slightly buckling.

A very similar situation (not shown) is obtained if the viscosity step between TZ and LM is increased. Even if this is not enough to stop the subduction, it is actually retarded in LM. However, as the subduction velocity is mainly dependent on the slab-pull generated along the upper mantle, the difference is solved by folding of the slab. If the jump is further increased (1.c) it is more difficult for the head of the slab to sink and this causes folding and
piling up of the slab, which slowly reactivates the sinking process.

In the last case (1.d) TZ and LM are more viscous and thus offer more resistance to slab penetration. Subduction velocity diminishes to 1-3 cm/yr during almost the whole simulation (~50 My). At 15-16 My slab starts folding and velocity increases slightly. Slab flattens even before being close to LM, what delays the contact until 23 My. As subduction continues, many Mys later a pile is formed and slowly sinks.

In all the experiments, subduction accelerates when slab enters TZ. The main cause is the positive Clapeyron slope related to the olivine-spinel phase transition, which further increases the density contrast caused by the low temperature. Velocity is reduced when the head of the slab gets closer to the 660 km boundary and after that it becomes stable for the next Mys (see Fig. 2).

A summary of the cases without overriding, classified by viscosity in TZ and the jump between TZ and LM, can be seen in Table 1.

Additional experiments to test the influence of other variables show that substantial reduction of Clapeyron slope at 660 km has almost no influence on the results. We also ran experiments with an oceanic crust of 10 and

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**Table 1:** Summary of the models without overriding. P = straight penetration of slab; RP = retarded penetration; B = buckling; PIL = slab folding and piling up; SP = pile sinking into the lower mantle; FS = flat slab, penetration triggered near the subduction zone and flat segment dragged into lower mantle; F = flat slab without penetration.
12 km and the subduction styles were not changed, while velocity patterns suffered only minor changes. Inclusion of overriding velocity influenced on the subduction style (more stagnant slabs) but not on the velocity pattern.

From our results we can conclude that the most reasonable range of viscosity values for the TZ would be $(3 \times 10^{20} - 10^{21})$ Pa s. A value of $3 \times 10^{21}$ is too high to allow a subducting slab to penetrate into the LM with a reasonable velocity if a viscosity step is present. The same situation arises if the viscosity step is greater than 10, in which case most of the times a piling up of material next to the LM or flat slabs can be seen, but no direct penetration. It should also be noted that, for higher jumps, viscosity in LM would be too large under certain combinations. A substantial reduction of the Clapeyron slope at the 660 km boundary did not help to enhance subduction and showed only a small influence over the evolution of the slab.

On the other hand, when viscosity in TZ is significantly lower than $3 \times 10^{20}$ Pa s slab accelerates to more than 30 cm/yr while (or before) penetrating the TZ, a phenomenon that is rarely seen in nature. If viscosity step is not present, exaggerated or very high velocity values are also obtained for the most reasonable viscosity. The best results were obtained with a step around 5. Even if overriding velocity can change the style of subduction toward more flattened slab, it cannot much reduce the exaggerated velocities obtained with the low values of both variables.

With a viscosity of $3 \times 10^{20}$ Pa s in TZ, a step between 5 and 10 gives the best velocity patterns, considering that this is a case of fast subduction. If viscosity is $10^{21}$ Pa s, the step between TZ and LM should be smaller than 5 in order to get reasonable subduction velocities. These viscosity values are in total agreement with those suggested by Billen (2008).

References


