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Assessing the role of slab rheology in coupled plate-mantle convection models

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ABSTRACT

Reconstructing the 3D structure of the Earth's mantle has been a challenge for geodynamicists for about 40 yr. Although numerical models and computational capabilities have substantially progressed, parameterizations used for modeling convection forced by plate motions are far from being Earth-like. Among the set of parameters, rheology is fundamental because it defines in a non-linear way the dynamics of slabs and plumes, and the organization of lithosphere deformation. In this study, we evaluate the role of the temperature dependence of viscosity (variations up to 6 orders of magnitude) and the importance of pseudo-plasticity on reconstructing slab evolution in 3D spherical models of convection driven by plate history models. Pseudo-plasticity, which produces plate-like behavior in convection models, allows a consistent coupling between imposed plate motions and global convection, which is not possible with temperature-dependent viscosity alone. Using test case models, we show that increasing temperature dependence of viscosity enhances vertical and lateral coherence of slabs, but leads to unrealistic slab morphologies for large viscosity contrasts. Introducing pseudo-plasticity partially solves this issue, producing thin laterally and vertically more continuous slabs, and flat subduction where trench retreat is fast. We evaluate the differences between convection reconstructions employing different viscosity laws to be very large, and similar to the differences between two models with the same rheology but using two different plate histories or initial conditions.

1. Introduction

Reconstruction of the 3D structure of the Earth's mantle was an inaccessible challenge until the end of the 1990s, when a leap forward in the quality of seismic data and computational power gave rise to tomographic models in which slabs could be detected in the lower mantle (Grand, 1994; van der Hilst et al., 1997). During the same period, Bunge (1998) and Gurnis (1998) pioneered convection reconstructions from 3D convection models forced at the surface by the velocities of plate tectonic models. Thermal and seismic imaging at this time were found to be consistent, mostly imaging the large scale temperature anomalies caused by the slow sinking of slabs throughout the mantle. Today the deepest mantle remains the region of conflicting interpretations in terms of teleseismic signals and mantle tomography versus convection calculations (McNamara and Zhong, 2005; Davies et al., 2012; Bower et al., 2013).

Computing mantle convection through time requires (a) suitable initial conditions, (b) realistic material properties, and (c) accurate reconstructed surface velocities. Initial conditions are fundamentally unknown and initial errors grow quickly (Bello et al., 2014). Therefore several strategies to define a starting temperature field have been used, the most consistent being variational data assimilation (Bunge et al., 2003; Ismail-Zadeh et al., 2004; Liu et al., 2008). Realistic material properties are difficult to implement, because of numerical difficulties or uncertainties on their values, a fundamental one being rheology. Reconstructed surface velocities are produced by plate kinematic models, which inevitably lose accuracy as deeper time is concerned (Seton et al., 2012).

Among these three issues, the impact of kinematic models is the most studied. Kinematic models have been incrementally improved using geological and geophysical observations, paired with mantle convection reconstructions and seismic tomography. Comparisons between dynamic topography computed from the convec-

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tion model and stratigraphic observations have been interpreted to locate sinking slabs (Gurnis, 1998; Flament et al., 2014). Similarities between tomographic models and convection models are a basis for proposing particular scenarios of slab sinking in the mantle (for instance Bunge and Grand, 2000), or in aiding improvements of the reference frame for plate reconstructions (Shephard et al., 2013).

While it is often stated as a fundamental issue to investigate (Bunge and Grand, 2000), the impact of rheology on slab reconstructions has been neglected. Hence, this manuscript focuses on the impact of the choice of rheology on reconstructing sinking slabs in the mantle. Modeling the viscosity variations in models for convection reconstruction is crucial because it drives slab shape and plume dynamics (Zhong et al., 2000). For instance, rheological parameters used in former studies are not consistent with the velocities imposed at the surface. In studies with no or a small temperature dependence of the viscosity, the surface should be deformable and toroidal motion negligible, whereas in studies with a larger temperature dependence of the viscosity, convection should be in the stagnant lid regime (Solomatov, 1995). In recent years, 3D spherical models of convection with plate-like behavior have been developed (van Heck and Tackley, 2008; Rolf and Tackley, 2011), producing convection models more consistent with Earth's surface tectonics (Coltice et al., 2012, 2013). These models are in principle closer to Earth's dynamic regime, with stiff mobile plates and narrow shear zones where deformation is localized.

We here evaluate the reconstructions produced by sophisticated test case models of 3D spherical convection employing a variety of rheological parameters. We show that models with plate-like behavior are the only models that can (a) be consistently scaled to exhibit a reasonable similarity to plate reconstructions and (b) produce flat subduction in regions of fast trench retreat. Differences between two models with different rheological parameters are large for the position and morphology of slabs, and similar in magnitude to those produced by alternative initial conditions or plate kinematics uncertainties.

2. Modeling convection reconstructions

Building a convection reconstruction model takes 3 steps: starting from a specific initial condition, imposing surface velocities from a plate reconstruction model, and solving the equations of convection. In this study, the numerical solution of convection motions is obtained using the 3D spherical convection code StagYY (Tackley, 2008). StagYY solves the conservation equations for mass, momentum and energy on a staggered Yin–Yang grid (Kageyama and Sato, 2004), and allows for large lateral viscosity variations. The specific rationale for using StagYY is that we aim to resolve up to 10^6 viscosity changes, which is 2 to 3 orders of magnitude higher than in previous convection studies (Zhong et al., 2000; Zhang et al., 2010; Bower et al., 2013, for instance). We are then able to produce convection models with stiff slabs.

2.1. Convection model

We work here with dimensionless equations, and we make several approximations. First, convection is assumed to be incompressible under the Boussinesq approximation. We understand that compressibility can be an important factor, especially in the deepest mantle, but we here focus on the impact of rheology. Because of this choice, we do not take into account variable material properties (expansion coefficient, thermal diffusivity, heat production), except for the viscosity.

Table 1
Non-dimensional convection parameters used in this study.

Symbols	Definition	Value[a]
Ra	Rayleigh number	10^6
L	Mantle thickness	1
d_0	Depth of viscosity jump	0.276
B	Factor of viscosity increase	30
d_{step}	Half thickness of viscosity jump	0.02
ΔT	Temperature drop across the mantle	1
Ts	Surface temperature	0
H	Internal heating rate	32
E	Activation energy	9–30
σ_Y	Surface yield stress	1.5×10^4
$\dot{\sigma_Y}$	Yield stress gradient with total pressure	0.025

[a] Non-dimensional.

The Rayleigh number *Ra* in our calculations is given by:

$$\mathrm{Ra} = \frac{\rho g \alpha \Delta T L^3}{\kappa \eta_0}, \tag{1}$$

where ρ is density, g is gravitational acceleration, α is thermal expansivity, ΔT is the temperature drop across the whole depth, L is mantle thickness, κ is thermal diffusivity and η_0 is the reference viscosity obtained at non-dimensional temperature $T = 1$ at the base of the mantle. In our models, Ra is 10^6, which is about 10–50 times lower than what is expected for the Earth. This choice is governed by the computational power required to solve for convection with large viscosity variations. The average resolution is 45 km in the 3 directions for all the models. As a consequence, we are not able to exactly reproduce Earth's structures since lower *Ra* convection produces thicker convective structures (thermal boundary layers, slabs and plumes). However, the goal here is not to predict Earth-like structures but rather to evaluate how choosing a rheological parameterization impacts the quality of reconstructions. Hence, the only parameters we vary in this study are the activation energy and the stress dependence of the viscosity. A complete summary of the parameters used in this study is in Table 1, and typical temperature and viscosity profiles are shown in Fig. 1.

The viscosity η in our models depends on temperature and depth as

$$\eta_T(T, z) = \eta_z(z) \exp\left(A + \frac{E}{T}\right), \tag{2}$$

where T is the temperature, z is the depth, A is a constant that ensures the viscosity is $\eta_z(z)$ when T is 1, and E is the non-dimensional activation energy. The depth-dependence of viscosity is taken into account such that

$$\eta_z(z) = a \exp\left(\ln(B)\left[1 - \frac{1}{2}\left(1 - \tanh\left(\frac{d_0 - z}{d_{\text{step}}}\right)\right)\right]\right), \tag{3}$$

where B stands for the factor of viscosity jump at depth d_0 over a thickness $2d_{\text{step}}$, and a is a prefactor that ensures that the reference viscosity is η_0 for temperature $T = 1$ at the base of the mantle. Geoid (Hager, 1984; Ricard et al., 1993) and post-glacial rebound studies (Mitrovica, 1996) suggest the viscosity jumps by a factor of 30 to 100 in the deep mantle. The cause of this jumps and its exact location are not known yet, but the 660 km seismic discontinuity is a relevant candidate. We choose here to impose a 30-fold viscosity increase between 790 and 890 km, because our thermal boundary layer is thicker than on Earth (about 350 km, see Fig. 1). Indeed, choosing a jump at 660 km would make the asthenospheric upper mantle smaller than the thermal boundary layer.

The viscosity can also vary with stress in our calculations through a pseudo-plastic rheology, in a way that plate-like behavior can be modeled (see Moresi and Solomatov, 1998; Trompert and Hansen, 1998; Tackley, 2000). The yield stress σ_Y increases