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Subduction induced mantle flow: Length-scales and orientation of the toroidal cell

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ABSTRACT

Subduction-induced mantle circulation plays an important role in the dynamics of convergent margins. Different components of the flow, i.e. toroidal and poloidal, provide relevant driving forces for back-arc basin formation, overriding plate deformation, curvature of subduction zones and volcanic activity. Here, we investigate on the emergence and controls on the toroidal component of the subduction–induced mantle flow by means of numerical modeling. To characterize the toroidal cell's three-dimensional flow, size and length-scales and its disposing factors, we test separately a series of lithospheric and mantle parameters, such as the density difference and viscosity ratio between the slab and the mantle, the width of the slab, as opposed to the size, the stratification and the rheology of the mantle. Out of the tested parameters, the numerical results show that the strength of the flow depends on the mantle viscosity and the magnitude of the slab pull force, that is slab-mantle density difference and the mantle thickness, however the characteristic length, axis and the shape of the toroidal cell are almost independent of the slab's properties and mainly depend on the thickness of the convecting mantle.

1. Introduction

Subduction of the negatively buoyant lithospheric plates provides the main driving mechanism of plate tectonics as well as the geodynamic evolution of our planet (e.g. Forsyth and Uyeda, 1975). While slabs actively drive plate convergence and orogeny at the surface, at depth subduction triggers mantle circulation which controls the transport of melt and volatiles in the wedge, the deformation of the upper plate, the geometry and the dynamics of the slab (Forsyth and Uyeda, 1975; Jacoby, 1973; Sleep and Toksöz, 1971; Uyeda and Kanamori, 1979). Because subduction and mantle flow are coupled on Earth, slab's control on mantle circulation have remained still poorly understood, such as, whether the subducting lithosphere or the mantle properties determine the flow strength and partitioning is still unaddressed.

Geochemical data and seismic anisotropy provide indirect information on the mantle flow above and behind subduction zones. Geochemical tracing has been locally used to map the extent of mantle flow, as the compositional gradient of isotopes and trace elements mirror the decompression and the following extraction of small degree melts produced by mantle circulation (e.g., Turner and Hawkesworth, 1998). Seismic anisotropy is a key methodology to shed light on the fabric of mantle circulation since anisotropy is a direct consequence of deformational processes (e.g., Barn et al., 1977; Long and Becker, 2010; Skemer and Hansen, 2016). When mantle rocks are deformed the crystallographic preferred orientation (CPO) or lattice-preferred orientation (LPO) of the olivine, the most abundant mineral in the upper mantle, produce a directional dependence of seismic wave speeds. The splitting results mirror plate motions and its coupling with the surrounding mantle. Around subduction zones, SKS splitting results in a fast direction turning around the slab and oriented mainly trench-perpendicular and trench-parallel in the wedge and in the sub-slab area, respectively (e.g., Civello and Margheriti, 2004; Long and Becker, 2010).

However, seismological and geochemical observations provide only a snapshot of the present-day condition, and is often limited by the uncertainties in the approximations of the flow–strain–anisotropy relationship (Ribe, 1989).

The long-term evolution of subduction-induced mantle circulation is best understood within the context of lithosphere – mantle interactions. Several modeling efforts, both numerical and analog, have addressed the dynamics of the coupled subduction and mantle deformation and cleared the relevant role of subduction-

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related processes, such as plate bending (e.g. Conrad and Hager, 1999; Capitanio et al., 2009; Capitanio and Morra, 2012), slab migrations (e.g. Funiciello et al., 2003; Stegman et al., 2006; Schellart, 2008; Li and Ribe, 2012), as well as features of the induced flow (e.g. Funiciello et al., 2006; Piromallo et al., 2006; Crameri and Tackley, 2014; Strak and Schellart, 2014). As slabs sink into the mantle, their coupling with the ambient viscous mantle drives a time-dependent three-dimensional (3-D) mantle circulation pattern characterized by the presence of poloidal and toroidal components. The coupling of sinking slabs and mantle drives a poloidal component of the flow in the mantle wedge and beneath the slab, where the flow is mostly contained in a vertical plane aligned with the subduction direction (Forsyth and Uyeda, 1975). In three dimensions, due to the finite lateral width of slabs, the migration of slabs is accommodated by horizontal motions in the mantle, i.e. the toroidal component of the flow, which displaces mantle around the slab edges, as slabs roll back. Furthermore, numerical studies show that the toroidal and poloidal components of the flow have complex spatial distribution, and might create spiral-like flow in the sub-slab area (Crameri and Tackley, 2014). The two main components (toroidal and poloidal) are invoked to explain several processes related to subduction. The poloidal cell provides relevant traction to the back-arc area, driving the deformation of the overriding plate (i.e. back-arc spreading; e.g., Dvorkin et al., 1993; Funiciello et al., 2003; Schellart and Moresi, 2013; Sleep and Toksöz, 1971; Sternai et al., 2014; Uyeda and Kanamori, 1979). The toroidal component contributes substantially to the curvature of subduction zones (e.g., Crameri and Tackley, 2014; Morra et al., 2006; Schellart et al., 2007), to the distribution of temperature around the slab (e.g., Kincald and Griffiths, 2003; Kincaid and Griffiths, 2004) and, in turn, the volcanic activity (e.g. Faccenna et al., 2010; Jadamec and Billen, 2010), and it controls the mantle mixing (e.g., Guillaume et al., 2010). In complex geodynamic systems, where e.g. slab edges approach to each other, the toroidal cells can also determine how slabs interact with each other (Király et al., 2016) and with the upper plates (Sternai et al., 2014) altering the evolution of the margins and the continental tectonics at the surface.

While many factors contribute to the coupled evolution of subduction and the mantle flow, far more uncertain are the relative controls of these two processes, and which of the ingredients of the subduction factory are relevant for the geometry and the strength of mantle circulation remains unclear.

The properties of the subducting plates, i.e., buoyancy and mechanical strength, have been proven to be critical in controlling the rates of subduction and the coupled mantle circulation (Becker et al., 1999; Conrad and Hager, 1999). But the development of flow patterns is also related to mantle properties, not only the density/viscosity stratification of the mantle but also its likely non-linear rheology (Billen and Hirth, 2005). However, a comprehensive 4-D view of the subduction-induced mantle circulation taking into account the role played by both lithospheric and mantle properties is still missing.

Here, we overcome the above-mentioned limitations with the aim to address still open questions about subduction-induced mantle circulation, such as the morphology of the flow around slab edges, the characteristic length scales and its interaction with the subducting plate. We use 3-D numerical models and systematically test the role of lithospheric properties (i.e., density and viscosity contrast and plate width) and mantle properties (i.e., Newtonian vs. non-Newtonian rheology, vertical density and viscosity stratification and mantle thickness) to determine the relative controls on the mantle flow during subduction.

2. Numerical method

Similarly to previous numerical models on subduction dynamics (e.g. Capitanio, 2016; Capitanio et al., 2015, 2010; Király et al., 2016), the subduction framework is modeled in a 3-D Cartesian box as an incompressible viscous flow with a low Reynolds number and an infinite Prandtl number. Consequently, thermal diffusion and any temperature dependence are neglected in the system. In this work, we do not focus on subduction initiation, therefore the subduction starts due to a 250 km long embedded slab with negative buoyancy force, which is high enough to overcome the resistance viscous forces. The subduction is only driven by gravity, thus, no external forces are implied. Based on these assumptions the governing equations are simplified to the conservation of mass and momentum, enforcing an incompressibility constraint:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\nabla \cdot \sigma = \Delta\rho \cdot \boldsymbol{g} \tag{2}$$

where $\boldsymbol{u}$ is the velocity vector, σ is the stress tensor, ρ denotes the density and $\boldsymbol{g}$ is the gravity vector. The stress tensor (σ) splits into a deviatoric part τ, and an isotropic pressure p:

$$\sigma = \tau + pI \tag{3}$$

where I is the identity matrix.

Furthermore, the stress is related to the velocity gradients, i.e. strain rate tensor $\dot{\varepsilon}$, as follows:

$$\tau_{ij} = 2\eta\dot{\varepsilon}_{ij} \tag{4}$$

This allows to define the viscous creep flow law for the viscosity η of the model:

$$\eta_C = \eta_0 \left(\frac{\dot{\varepsilon}_{II}}{\dot{\varepsilon}_0} \right)^{\frac{1-n}{n}} \tag{5}$$

where η_0 is the reference viscosity, $\dot{\varepsilon}_{II} = (0.5\ \dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij})^{1/2}$ is the square root of the second invariant of the strain rate tensor and n is the power-law exponent, which is 1 or 3 for Newtonian and non-Newtonian creep, respectively. The two viscosities are equal at $\dot{\varepsilon}_0$, the transition strain rate, above this value the fluid behaves non-linearly. Equally, we can derive the transition stress ($\tau_{\lim}$) from $\dot{\varepsilon}_0$ by using eq. (4).

Additionally, we define a flow law for (pseudo-)plastic yielding:

$$\eta_Y = (C_0 + C_1 z)/\dot{\varepsilon}_{II} \tag{6}$$

where $C_0 = 20$ MPa is the cohesion at zero confining pressure, and $C_1 = 5$ MPa·m^{-1} the depth-dependent coefficient. The effective viscosity of visco-plastic materials is then:

$$\eta = \min(\eta_C, \eta_{CY}) \tag{7}$$

The equations are solved in their non-dimensionalized form using Lagrangian cells embedded into a Eulerian finite element mesh (i.e. particle in cell method) with the numerical code Underworld (Moresi et al., 2003).

The models are analyzed in order to determine the controls on the toroidal flow around slab edges. We first describe the geometry of the slab, by measuring the slab dip at mid-mantle depth (i.e. half domain depth) and the curvature of the trench. The models are grouped into the following categories: a1) concave trench with a single curve; a2) concave trench with a single curve and a straight center; b) concave trench with double curvature; and c) convex trench (see on Fig. 2E, 3F, 4E).

The toroidal cell's morphology is given by streamlines of the flow around the slab edges. Additionally, we calculate the vorticity vector