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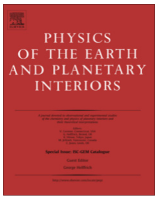

Couette and Poiseuille flows in a low viscosity asthenosphere: Effects of internal heating rate, Rayleigh number, and plate representation

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ABSTRACT

Mantle convection models with a low viscosity asthenosphere and high viscosity surface plates have been shown to produce very large aspect ratio convection cells like those inferred to exist in Earth's mantle and to exhibit two asthenospheric flow regimes. When the surface plate is highly mobile, the plate velocity exceeds the flow velocities in the asthenosphere and the plate drives a Couette-type flow in the asthenospheric channel. For sluggish plates, the flow velocities in the asthenosphere exceed the plate velocity and the asthenospheric flow is more Poiseuille-like. It has been shown that under certain circumstances, flows become increasingly Couette-like as the aspect ratio of the plate is increased in numerical simulations. These models also show an increase in the average surface heat flux with aspect ratio which is counterintuitive, as one would expect that large aspect ratio models would result in older and colder oceanic lithosphere. Previous investigations have used single internal heating rates and Rayleigh numbers and a plate formulation that did not preclude significant deformation within the plate. In this paper, we investigate the conditions necessary for Couette and Poiseuille asthenospheric flows and for surface heat flux to increase with plate aspect ratio by varying the internal heating rate, the Rayleigh number and the representation of surface plates in 2D mantle convection models Plates are represented as a high viscosity layer with (1) a free-slip top surface boundary condition and (2) a force-balance boundary condition that imposes a constant surface velocity within the plate. We find that for models with a free-slip surface boundary condition, the internal heating rate and Rayleigh number do not strongly affect the dominance of Couette or Poiseuille flows in the asthenosphere but the increase in surface heat flux with model aspect ratio in the Poiseuille asthenospheric flow regime increases with internal heating rate. For models using the force-balance representation of surface plates, the flow regime in the asthenosphere is found to be almost independent of the plate aspect ratio and spatially averaged surface heat flux decreases with increasing aspect ratio. The dependence of heat flux on plate aspect ratio is an important consideration in Earth's thermal history while the preponderance of Poiseuille or Couette flows in the asthenosphere may be important for understanding the mobility of surface plates and asthenospheric seismic anisotropy.

1. Introduction

Numerical mantle convection studies have shown that the presence of a low viscosity asthenosphere can lead to flow channelization, promoting larger aspect ratio convection cells by lowering lateral dissipation relative to vertical dissipation (Ahmed and Lenardic, 2010; Bunge et al., 1997, 1996; Busse et al., 2006; Crowley and O'Connell, 2012; Höink et al., 2012; Höink and Lenardic, 2010, 2008; Lenardic et al., 2006; Richards et al., 2001). Earth's large Pacific plate likely overlies a large convection cell and seismological evidence indicates long-wavelength dominated mantle convection (Su and Dziewonski, 1992).

Global radial variations in seismic P and S wave velocities decrease with depth in a 140 km thick layer (Dziewonski and Anderson, 1981) beneath surface plates called the Low Velocity Zone. This region has also been shown regionally to have high electrical conductivity (Naif et al., 2013). These changes in material property may be caused by partial melt (e.g., Schmerr, 2012; Caricchi et al., 2011, Karato, 2012) and/or the effects of water and may be correlated with a low viscosity asthenosphere (Hirth and Kohlstedt, 1996).

Radial viscosity inversions using post-glacial rebound data do not preclude the existence of a narrow low viscosity region

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beneath surface plates (Paulson and Richards, 2009), and rebound studies concerning variations in crustal loading from large lakes indicate very low viscosities at asthenospheric depths (Bills et al., 1994, 2007). However, some authors argue for a broad upper mantle region with only a modest viscosity decrease relative to the lower mantle (Peltier and Drummond, 2008).

Recently, Höink and Lenardic (2010, 2008) have shown that numerical mantle convection models with high viscosity surface plates and a low viscosity asthenosphere above a lower mantle of intermediate viscosity spontaneously produce convection cells that fill the simulation domain. When the simulation domain is smaller and convection cells are forced to have smaller aspect ratios, the surface plates are found to be sluggish and flow velocities in the asthenosphere exceed the surface plate speeds. The asthenospheric flows are driven by pressure gradients caused by the passage of positively and negatively buoyant material through the asthenosphere and by lateral temperature gradients at the top of the asthenosphere (Höink et al., 2011). The small aspect ratio simulations are in the sluggish-lid regime, and the regions of deformation on the ends of the plate are broad, roughly approximating the "diffuse plate boundaries" seen on Earth today (Gordon, 1998). In this regime, the horizontal flow velocity peaks near the middle of the asthenosphere and resembles a Poiseuille flow. For larger simulation domains, Höink and Lenardic (2010) found that the plate became more mobile and its horizontal velocity exceeded velocities in the asthenosphere. The asthenospheric flow in these large aspect ratio convection cells resembles a Couette flow. In simulations within the Poiseuille asthenospheric flow regime, the spatially averaged surface heat flux was found to increase with convection cell aspect ratio. This is contrary to what has been seen in investigations of convection without a modeled low viscosity asthenosphere where spatially averaged surface heat flux is seen to decrease with aspect ratio (Grigné et al., 2005; Lowman et al., 2001).

It is important to understand the conditions necessary to produce Poiseuille flows in the asthenosphere and the dependence of spatially averaged surface heat flux on convection cell aspect ratio. Variations in convective spatially averaged heat flux with aspect ratio have been used to help explain Earth's thermal history (Grigné et al., 2005; Höink et al., 2013). Asthenospheric Poiseuille flows driven by buoyant plumes are the conceptual basis of the plume-fed asthenosphere model of Yamamoto et al. (2007). Poiseuille flows in the asthenosphere would also generate significantly different patterns of seismic anisotropy than Couette flows. Natarov and Conrad (2012) used such patterns to produce a map of regions of suspected asthenospheric Poiseuille flows and to estimate that 40% of the flow in the asthenosphere may be of Poiseuille-type. Asthenospheric Poiseuille flows may also be caused by variations in the thickness of the lithosphere such as continental keels (Harig et al., 2010) – a possibility that we are not modeling in the present study.

Höink and Lenardic (2008, 2010) investigated models with high degrees of mantle internal heating so that most of the buoyancy driving convection, and creating asthenospheric pressure gradients, was caused by cold downwellings. In this contribution, we investigate models with varying degrees of mantle internal heating and so investigate whether asthenospheric Poisseuille flows are efficiently created with varying degrees of positive and negative buoyancy-induced pressure gradients and at more Earth-like internal temperatures.

The behavior of mantle convection models is often strongly dependent on the convective vigor which is parameterized through the Rayleigh number. For instance, the propensity for phase boundaries to induce layering increases strongly with the Rayleigh number (Christensen and Yuen, 1985) while the average temperature decreases with Rayleigh number in simulations that are both basally and internally heated (Sotin and Labrosse, 1999). The generation of long wavelength convection cells and Poiseuille–Couette asthenospheric flows in models with depth-dependent viscosity has not previously been investigated in regards to changes in convective vigor. We will thus test the robustness of these findings and present new results at a higher Rayleigh number.

The rheology that leads to Earth's plate tectonics with almost rigid plate interiors and very high strain-rates at plate boundaries remains poorly understood (Schubert et al., 2001). One method for numerically modeling surface plates with spatially constant horizontal velocities and narrow plate boundaries is the force-balance method (Gable et al., 1991). The force balance method has been shown to give similar spatially averaged heat fluxes and surface velocities to plates that are determined rheologically (King et al., 1992) and it allows for the mobility of the surface plate to be specified. We will investigate models with a low viscosity asthenosphere and a high viscosity surface plate calculated using the force balance method. We expect that plates that are specified to be sluggish will have significant pressure gradient driven asthenospheric Poiseuille flows that drive the surface plate. Models with high specified mobility will exhibit plates that are driven by their own buoyancy that drive Couette-type asthenospheric flows.

2. Model description

We solve the infinite Prandtl number Navier–Stokes equations,

$$\nabla \cdot [-pI + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + T\hat{\mathbf{y}} = 0 \tag{1}$$

$$\nabla \cdot \mathbf{u} = 0. \tag{2}$$

Here, $\mathbf{u}, p$, and T represent the fluid velocity, pressure and temperature. The parameter μ represents the dimensionless viscosity, which is depth-dependent, while $\hat{\mathbf{y}}$ is a unit vector in the vertical direction.

The temperature field is updated using the dimensionless energy balance equation,

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \frac{1}{Ra}\nabla^2 T + \frac{H}{Ra}. \tag{3}$$

Here H represents radioactive heat sources and the Rayleigh number is defined as

$$Ra = \frac{g\alpha\Delta T d^3 \rho}{\kappa\mu}, \tag{4}$$

where $g, \alpha, \Delta T, d$, and κ are the gravitational acceleration, thermal expansivity, temperature difference across the mantle, depth of the mantle, and thermal diffusivity, respectively. The internal heating rate is

$$H = \frac{\chi d^2}{\Delta T c_p \kappa} \tag{5}$$

where χ is the dimensional internal heating rate per unit mass and c_p is the heat capacity. The parameter H can also be considered to be the ratio of an internal heating Rayleigh number to the Rayleigh number that is based on the temperature at the base of the mantle. All mantle properties other than viscosity are assumed to be spatially and temporally constant. The equations are scaled for length, time, temperature and viscosity by $d, d^2/(\kappa Ra), \Delta T$ and μ_0 where μ_0 is a reference viscosity value.

Models were run in a 2D Cartesian geometry with aspect ratios of 1:1, 2:1, 3:1, 4:1, and 5:1. All models have constant temperature top and bottom boundaries and insulating sides (see Fig. 1). The side and bottom boundaries all have free-slip boundary conditions.