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Plug flow in the Earth's asthenosphere

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ABSTRACT

Recent seismic observations, focused on mantle flow below the Pacific plate, indicate the presence of two shear layers in the Earth's asthenosphere. This is difficult to explain under the classic assumption of asthenosphere flow driven by plate shear from above. We present numerical mantle convection experiments that show how a power law rheology, together with dynamic pressure gradients, can generate an asthenosphere flow profile with a near constant velocity central region bounded above and below by concentrated shear layers (a configuration referred to as plug flow). The experiments show that as the power law dependence of asthenosphere viscosity is increased from 1 to 3, maximum asthenosphere velocities can surpass lithosphere velocity. The wavelength of mantle convection increases and asthenosphere flow transitions from a linear profile (Couette flow) to a plug flow configuration. Experiments in a 3D spherical domain also show a rotation of velocity vectors from the lithosphere to the asthenosphere, consistent with seismic observations. Global mantle flow remains of whole mantle convection type with plate and asthenosphere flow away from a mid-ocean ridge balanced by broader return flow in the lower mantle. Our results are in line with theoretical scalings that mapped the conditions under which asthenosphere flow can provide an added plate driving force as opposed to the more classic assumption that asthenosphere flow is associated with a plate resisting force.

1. Introduction

Since the earliest development of plate tectonic theory (Cox, 1973), and into more recent times (Schubert et al., 2001; Turcotte and Schubert, 2014) the prevailing hypothesis regarding flow in the Earth's asthenosphere is that it is driven by the motion of tectonic plates. In this view, the asthenosphere provides resistance to plate driving forces (Richter, 1973; Forsyth and Uyeda, 1975; Richter and McKenzie, 1978). If asthenosphere flow is driven by plate shear from above, then an expectation is that a linear velocity profile should be maintained within the asthenosphere (referred to as Couette flow). In this case, the asthenosphere would be a uniform shear layer that would align olivine crystals in the direction of plate motion and produce an observable seismic anisotropy signal (Ribe, 1989). Detecting such a signal was a goal of a recent seismic study, but the results were not in line with expectations (Lin et al., 2016). The observations of Lin et al. (2016) indicate the presence of two distinct shear layers – one just below the pacific plate, the top of the asthenosphere, and another deeper shear layer inferred to be the base of the asthenosphere. Furthermore, they found the flow direction of the asthenosphere to be offset from the direction of plate motion.

Lin et al. (2016) did not provide a quantitative explanation regarding the physical factors behind their observations, but they did sketch two conceptual scenarios. One revives the old idea of asthenosphere counterflow (Chase, 1979): Plate and asthenosphere flow are part of a closed circuit convection cell in the upper mantle with flow in the lower portion of the asthenosphere moving toward a mid-ocean ridge so as to provide a mass balance for plate and upper asthenosphere flow away from a ridge (a configuration of this sort is a particular form of layered mantle convection). The second scenario invokes small scale convection cells in the upper mantle. This scenario also invokes a component of asthenosphere counter flow, that moves back toward a mid-ocean ridge, in order to explain the presence of two distinct shear layers (Lin et al., 2016). The difficulties with asthenosphere counter flow models have long been noted (e.g., Turcotte and Schubert, 2014 pp. 268–270) and we do not pursue them here in. Rather, we follow, and build upon, a third option (Höink and Lenardic, 2010; Höink et al., 2011; King, 2015).

Fig. 1 is modified from Höink et al. (2011). Density variations, associated with lateral temperature differences, can lead to pressure gradients within the asthenosphere. The idea that pressure gradients in the asthenosphere, associated with rising mantle plumes, could generate a component of asthenosphere flow that

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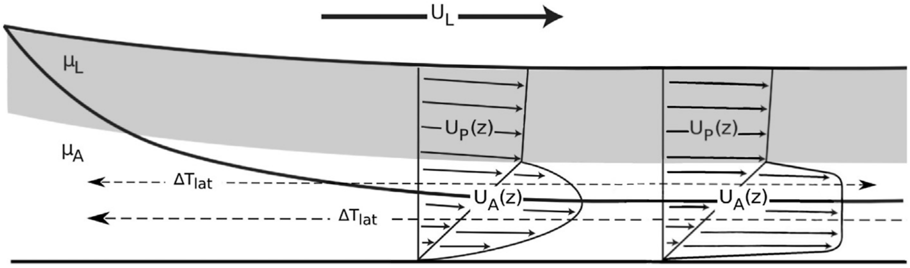

Fig. 1. Modified flow schematic from Höink et al. (2011). The thermal lithosphere thickens with distance from a ridge. This sets up lateral temperature variations in the asthenosphere which affect its density distribution. The density distribution, in turn, generates a lateral pressure gradient which can drive flow in the asthenosphere. If the pressure flow component outweighs that due to plate shear from above then asthenosphere velocity can exceed plate velocity. For a Newtonian asthenosphere, the pressure driven flow is predicted to be of Poiseuille type with a parabolic profile. The full flow theory describing that flow configuration can be found in Höink et al. (2011). Our principal hypothesis is that for a power-law rheology, pressure driven flow in the asthenosphere can transition to a plug flow profile with two regions of concentrated shear bounding a central core of relatively low shear.

exceeds plate flow was put forward by Morgan et al. (1995). The study of Höink et al. (2011) confirmed that possibility but also showed that mantle plumes where not necessary – a conclusion that was also put forward by King (2015). The ability to generate pressure gradients in the asthenosphere independent of mantle plumes is critical for any potential explanation of the Lin et al. (2016) results as their study region was chosen to be away from any proposed mantle plume sites. Höink et al. (2011) developed theoretical scaling expressions for parameter conditions (e.g., relative asthenosphere viscosity) under which these pressure gradients could generate an asthenosphere flow component that could compete with, or potentially outweigh, a flow component associated with plate shear. The theory assumed a Newtonian viscosity. Under that assumption, pressure driven flow would have a parabolic profile (referred to as Poiseuille flow). If that assumption is relaxed, and a power law rheology is allowed for, then the Poiseuille flow component could transition to plug flow. Plug flow is associated with concentrated upper and lower shear layers bounding a central region of near constant velocity. The theory of Höink et al. (2011) also assumed that convection cells could be treated as two-dimensional. However, if a model ridge was, for example, not parallel to a model subduction zone then temperature gradients that are offset relative to plate spreading could be generated. This is expected in a spherical geometry and it would generate pressure gradients with an along ridge component. This, in turn, could generate an offset of flow in a low viscosity asthenosphere relative to a stronger plate.

The extensions to the ideas of Höink et al. (2011), outlined above, have the potential to lead to a mantle flow configuration consistent with the seismic observations of Lin et al. (2016). The remainder of this paper explores this possibility.

2. Modeling methods

We performed numerical mantle convection experiments in 2D Cartesian and 3D spherical domains. Model equations for mass, momentum, and energy conservation are given by

$$\Delta \cdot u = 0 \tag{1}$$

$$-\Delta P + \Delta \cdot [\eta(\Delta u + \Delta^T u)] + RaT = 0 \tag{2}$$

$$\frac{\partial T}{\partial t} + u \cdot \Delta T = \Delta^2 T + H \tag{3}$$

respectively, where u, P, η, T, Ra, H and t are velocity, pressure, viscosity, temperature, bottom heating Rayleigh number, internal heat production, and time. All models assumed mantle convection was driven by a combination of bottom and internal heating with a bottom heated Rayleigh number and a heating ratio given by

$$Ra = \frac{\rho_0 g \alpha \Delta T D^3}{\eta \kappa} \tag{4}$$

$$Q = \frac{Ra_i}{Ra} = \frac{\rho_0 H D^2}{\Delta T K_0} \tag{5}$$

where ρ is the mantle density, α is the coefficient of thermal expansion, g is the gravitational acceleration, ΔT is the temperature drop across the system, D is the system depth, κ is thermal diffusivity, Q is the ratio of the thermal Rayleigh number defined for internal heating, Ra_i, to that defined for bottom heating.

A power law viscosity is assumed for the region of the domain that models an asthenosphere channel. The viscosity, for that region, is given by

$$\eta = \sigma^{(1-n)} A \tag{6}$$

where σ is stress, n is the power law dependence, and A is a material constant. The viscosity of the model lithosphere and lower mantle are Newtonian with reference values that can be set higher than that of the upper mantle.

Model equations are solved using two versions of a community finite element code: Citcom (Moresi and Solomatov, 1995) is used for 2D Cartesian cases and CitcomS (Zhong et al., 2000; Tan et al., 2006; Zhong et al., 2008) for 3D spherical cases.

The 2D Cartesian experiments were performed in 4 × 1 and 8 × 1 domains with wrap around side boundary conditions and free slip surface and basal conditions. The non-dimensional surface and basal temperatures were set to zero and one, respectively. Mesh densities for all cases shown have 64 × 64 finite elements over any 1 × 1 patch of the modeling domain (convergence testing was performed using 96 × 96 finite element resolution to confirm that results were numerically resolved). Over the upper one fourth of the domain the viscosity is multi-valued while it is constant and Newtonian over the lower portion of the domain (the model analog for the lower mantle). If the temperature over the upper fourth of the domain is higher than a non-dimensional value of 0.3, then the material is assigned a non-Newtonian viscosity. This models low viscosity upper mantle, a model analogue for the asthenosphere, and the cooler material then models a cold and relatively strong lithosphere (e.g. Richards et al., 2001). The reference viscosity of the upper mantle, above a temperature of 0.3, is a factor of 2 lower than the lower mantle and lithosphere viscosity (the reference viscosity is the value for a Newtonian, $n = 1$, upper mantle). As n increases, the viscosity in the asthenosphere analogue can dynamically decrease in response to flow gradients.

As per the 2D experiments, the spherical experiments impose three vertically stratified viscosity layers to mimic a strong lithosphere, above a potentially weak (due to a power law viscosity) upper mantle, above a strong lower mantle. The top most layer (lithosphere analog) spans from the surface to a dimensionless