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The feedback between surface mobility and mantle compositional heterogeneity: Implications for the Earth and other terrestrial planets

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Planetary surface mobility depends on lithospheric stresses arising from the mantle's convective vigor. Using a model of thermochemical convection featuring force-balanced plates we examine the effect on surface mobility of different fractions of compositionally dense mantle material. Specifically, we introduce a uniform thickness compositionally enriched basal layer in a system with mobile-lid tectonics and monitor whether an active lid is subsequently maintained. We find that long-term surface mobility decreases when enriched material is present. High mobility is always maintained if the total material volume is no more than 1% of the mantle volume. For the inferred volume of the Large Low Shear Velocity Provinces in the present-day Earth surface mobility is dependent on the buoyancy ratio of the enriched material. If the compositionally dense material self-organizes into provinces, both surface mobility and mantle upwelling vigor become more variable. Generally, upwellings that form at the edges of provinces are more buoyant relative to upwellings that form on the tops of provinces. If enriched material envelops the core, upwelling vigor is diminished so that plates are consumed more quickly than they can fragment, and surface mobility is eventually lost.

1. Introduction

The Large Low Shear Velocity Provinces (LLSVPs) originating within the D″ region below Africa and the Pacific, inferred by seismic tomography studies, may be evidence of compositionally dense material in the Earth's mantle (e.g., Ishii and Tromp, 1999; Masters et al., 2000; Garnero and McNamara, 2008; Lekic et al., 2012). The magnitude of the velocity anomalies is believed to be too large for a simple thermal feature (Karato and Karki, 2001; Brodholt et al., 2007) and sharp lateral changes in shear wave velocity, as well as an anticorrelation in the shear wave speed and bulk sound velocity are also not indicative of purely thermal structures (Ritsema et al., 1998; Ni et al., 2002; To et al., 2005; Karato and Karki, 2001; Saltzer et al., 2001; Brodholt et al., 2007). Possible sources of compositionally enriched material include segregation of oceanic slab material (e.g., Brandenburg and van Keken, 2007) (although Li and McNamara, 2013 suggest difficulty in accumulating the observed LLSVP volume in this fashion), direct interaction with the core (e.g., Humayun et al., 2004), or primordial reservoirs (e.g., Labrosse et al., 2007).

The interaction of chemical heterogeneities with thermally driven convection has been extensively studied, with a focus on whether LLSVPs represent long-lived structures that influence mantle dynamics (e.g., Tackley, 2013, 2002; McNamara and Zhong, 2005; Torsvik et al., 2006, 2008, 2010; Burke et al., 2008; Deschamps and Tackley, 2008, 2009; Davies and Davies, 2009; Schuberth et al., 2009b, 2012; Simmons et al., 2010; Zhang et al., 2010; Tan et al., 2011; Davies et al., 2012; Steinberger and Torsvik, 2012; Li and McNamara, 2013; Conrad et al., 2013). Through correcting the present-day large igneous province locations to the paleo-positions at the time of deposition, Torsvik et al. (2006) showed that the boundaries of the LLSVPs correlate with the projected origin of the deep mantle plumes associated with large igneous provinces (LIPs). Burke et al. (2008) concluded that the steep-sided shape of the LLSVPs were such that their edges would create plume generations zones (PGZs) and that the present-day distribution of kimberlites yields an indication of the behavior of LLSVPs over time. Kimberlite rock forms under high pressure at depth but can be transported to the surface by deep mantle plumes. Utilizing the location and dating of kimberlite sites, Torsvik et al. (2010) proposed the plume generation zones must have been stable over long timescales and that because the sites of LIPs and kimberlite deposits have been relatively fixed for the past

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300 Myr (and perhaps longer) so have plume generation zones and therefore LLSVPs. Furthermore, Steinberger and Torsvik (2012) showed that LLSVPs may control plume dynamics, by demonstrating that circum-supercontinent subduction interacting with plume generation zones would produce large igneous provinces originating from the formation of Pangea.

Nevertheless, recent thermochemical convection studies (e.g., Zhang et al., 2010; Tan et al., 2011; Li and McNamara, 2013) have encountered difficulty in generating stable LLSVPs on the timescales predicted by Torsvik et al. (2006, 2008, 2010), Burke et al. (2008), and Steinberger and Torsvik (2012). Accordingly, an alternative model exists for explaining the present location of the LLSVPs, in which downwellings that reach the core-mantle boundary sweep aside chemical piles (e.g., Tackley, 2013; Kellogg et al., 1999; Jellinek and Manga, 2002; McNamara and Zhong, 2005), so that the current distribution of the material comprising the LLSVPs is explained by the Earth's subduction history having moulded the anomalies into the presently inferred pair of distinct antipodal provinces (McNamara and Zhong, 2005; Bull et al., 2009).

Even more contrary, a number of studies have challenged the very hypothesis of thermo-chemical convection in the Earth's mantle. For example, Adam et al. (2014) explain surface geodetic observations through low-viscosity regions in the asthenosphere, rather than requiring the presence of chemical heterogeneities in the lower mantle, and Tsuchiya (2011) finds LLSVPs (made up of basaltic piles) to be incompatible with current lower mantle seismic characteristics. Similarly, Bouhifd et al. (2013) argue that rather than requiring a mantle reservoir like LLSVPs as a potential source of ^{3}He, the core may be a potential source of ^{3}He erupted at sites of 'hot-spot' volcanism. Measurements of elasticity in the mantle (Schuberth et al., 2009a) and analysis of the ability of tomography to accurately resolve mantle features (Schuberth et al., 2009b) have also been presented to counter arguments supporting thermochemical convection. In high-resolution mantle circulation models, negative shear wave anomalies of ∼4% were generated from high plume temperatures in excess of 1000–1500 K and showed that thermal features, not chemical heterogeneity, could be reconciled with tomographic studies (Schuberth et al., 2009a, 2009b).

The contribution of thermal and chemical features in the lower mantle, in terms of geodynamic observables, has been also assessed in a number of other papers (e.g., Simmons et al., 2009, 2010; Schuberth et al., 2012; Davies et al., 2012). In these studies, thermal effects were found to dominate shear-wave and density heterogeneities when compared to compositional contributions, highlighting the need for joint inversion of velocity and density simultaneously in seismic modeling (Simmons et al., 2009, 2010).

The unsettled debate regarding the longevity, mobility and even the existence of a compositionally distinct component in Earth's lower mantle requires both further analysis of observational data and geodynamic modeling. One unexplored aspect of thermochemical convection is the dynamic feedback between a chemically dense component in the lower mantle and surface mobility. Previously, McNamara and Zhong (2005) showed that both the position and topology of a deep reservoir of compositionally dense mantle material respond to kinematically imposed plate motion. However, the influence of a chemically dense mantle component on surface mobility has received little attention.

If compositionally enriched material exists in the Earth's mantle then it is likely present in other planetary mantles. Planet size (e.g., Valencia et al., 2007), mantle heating mode (van Heck and Tackley, 2011; Stein et al., 2013), mantle viscosity structure (Stein et al., 2011), lithospheric strength (O'Neill et al., 2007), and planetary history (Weller and Lenardic, 2012) have all been cited as fundamental controls on the surface mobility of terrestrial planets. Due to its influence on the buoyancy distribution in the mantle, compositional heterogeneity in a planetary mantle could also affect global velocities and stresses and possibly surface mobility.

Here, we investigate whether a fractional component of compositionally dense material could play a role in facilitating or impeding sustained plate-like surface motion over long geologic time scales. In a vigorously convecting mantle convection model initially characterized by ongoing plate motion, we systematically investigate the influence of introducing a basal layer of high density material, varying both the intrinsic density and volume of the initial layer. Following introduction of the layer, we monitor the effect of thermochemical convection on plate evolution.

2. Method

Mantle convection is modeled using a Boussinesq incompressible infinite Prandtl number fluid in a 2D plane-layer geometry. The system is composed of two chemical species: ambient mantle silicates and compositionally dense silicates. Thermochemical convection is studied by solving the non-dimensional equations for mass, momentum, energy, and composition conservation:

$$\nabla \cdot \boldsymbol{v} = 0, \tag{1}$$

$$\nabla P - \nabla \cdot (\eta \dot{\boldsymbol{\epsilon}}) = (Ra_T T - Ra_C C)\hat{\boldsymbol{z}}, \tag{2}$$

$$\frac{\partial T}{\partial t} = \nabla^2 T - \boldsymbol{v} \cdot \nabla T, \tag{3}$$

and

$$\frac{\partial C}{\partial t} = -\boldsymbol{v} \cdot \nabla C, \tag{4}$$

respectively, where $\boldsymbol{v}$ is the velocity, P is the pressure, η is the dynamic viscosity, $\dot{\boldsymbol{\epsilon}}$ is the deviatoric strain rate tensor, T is the superadiabatic temperature, C is the composition, $\hat{\boldsymbol{z}}$ is a unit vector antiparallel to gravity, and t is time. The surface thermal and compositional Rayleigh numbers are

$$Ra_T = \frac{\rho_0 g \alpha \Delta T d^3}{\kappa \eta_{surf}} \tag{5}$$

and

$$Ra_C = \frac{\Delta \rho_C g d^3}{\kappa \eta_{surf}}, \tag{6}$$

where ρ_0 is a reference density, g is the acceleration due to gravity, α is the thermal expansivity, ΔT is the superadiabatic temperature difference across the system, d is the system thickness, κ is the thermal diffusivity, η_{surf} is the dynamic viscosity at the surface, and $\Delta \rho_C$ is the compositional density contrast between the enriched and ambient materials. Our calculations set $Ra_T = 10^4$, $T = 0$ at the surface, and $T = 1$ at the base. The volume-averaged thermal Rayleigh number, computed *a posteriori* using local viscosity values, is approximately 3×10^7 in all calculations.

The buoyancy ratio, $B = Ra_C/Ra_T$, is equivalent to $\Delta\rho_C/(\rho_0 \alpha \times \Delta T)$. Thus, $\Delta \rho_C = B \rho_0 \alpha \Delta T$ and the Boussinesq equation of state can be written as

$$\rho = \rho_0 \big[1 + \alpha \Delta T (BC - T)\big]. \tag{7}$$

Assuming values appropriate for the Earth ($\rho_0 = 3.3 \times 10^3\ \mathrm{kg\,m^{-3}}$, $\alpha = 1.2 \times 10^{-5}\ \mathrm{K^{-1}}$, $\Delta T = 2500$ K, discussed below) $B = 1.0$ implies $\Delta \rho_C = 100\ \mathrm{kg\,m^{-3}}$.

Utilization of the Boussinesq approximation is appropriate for modeling a planet with a mantle depth that is less than the scale height, $C_p/(g\alpha)$, and when $\alpha T^* \ll 1$, where C_p is the specific heat at constant pressure and T^* is the maximum departure of the superadiabatic interior temperature from the surface temperature