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Dynamics of hidden hotspot tracks beneath the continental lithosphere

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ABSTRACT

The presence of mantle plumes beneath old continental regions may have been underestimated due to the lack of surface expressions. New seismic results reveal a corridor-like low seismic velocity zone at the bottom of the continental lithosphere beneath the eastern United States, interpreted as the erosion of the moving continental lithosphere by a plume conduit. Here we study the dynamics of the interaction between a mantle plume conduit and a moving depleted continental lithosphere. With thermochemical numerical models in 3-D Cartesian geometry, we show that a plume conduit can erode the bottom of the continental lithosphere, generating a corridor-like low seismic velocity zone downstream the plate motion direction. This low seismic velocity corridor is typically ∼300 km in width and ∼50 km in height, with several percent of P-wave velocity reduction within it. It can survive more than 100 Myr and extend thousands of kilometers. The surface swell topography of this corridor is much smaller than those beneath the oceanic lithosphere, forming 'hidden tracks'. We propose that other 'hidden tracks', with little surface expression, may exist beneath old continental regions. Such 'hidden tracks', once found, may provide additional constraints on plate motion history.

1. Introduction

Hotspots are intra-plate volcanic areas thought to be fed from the underlying mantle by a deep-seated plume conduit (Morgan, 1971). Plume–lithosphere interaction can be divided into two stages: (1) the interaction between a plume head and the overlying lithosphere, which causes the formation of large igneous provinces and (2) the continuous interaction between a moving lithospheric plate and a plume conduit, which causes age-progressive hotspot tracks (Campbell and Griffiths, 1990; Olson, 1990; Richards et al., 1989). The plume conduit is considered fixed relative to the mantle, therefore hotspot tracks play a key role in reconstructing plate motions for the Mesozoic and Cenozoic eras (Engebretson et al., 1984; Gordon and Jurdy, 1986; Müller et al., 1993).

Most hotspot tracks are observed on oceanic or thin continental lithosphere (Courtillot et al., 2003; Leeman et al., 2009; Steinberger, 2000). They are often accompanied by significant surface manifestations, including anomalously high topography, relatively high heat flow and surface volcanism (Campbell, 2007; Leng and Zhong, 2010; Phipps Morgan et al., 1995; Richards et al., 1988; Sobolev et al., 2011). For example, the Hawaiian–Emperor hotspot track extends more than 5000 km and has a maximum hotspot swell topography of ∼1.5 km (Crough, 1978).

On the other hand, few hotspot tracks or related swell topography are observed on old continental lithosphere. Recent studies based on seismic data from USArray reveal the existence of a corridor-like low seismic velocity zone (with ∼2.1% P-wave velocity reduction) beneath the eastern United States, azimuthally oriented in agreement with the absolute plate motions 85–50 Ma ago (Chu et al., 2012, 2013). Such a low velocity zone could be a 'hidden hotspot track' caused by the interaction between the North American continental lithosphere and a deep-seated mantle plume (Chu et al., 2013). Other 'hidden tracks' may exist beneath old continental regions. These 'hidden tracks', once detected, may provide extra constraints on lithospheric plate motion history. Understanding the dynamics of plume–lithosphere interaction beneath old continental regions may help us detect these 'hidden tracks'.

To investigate the plume–lithosphere interaction and its related surface expressions, many studies have been conducted (Moore et al., 1998; Phipps Morgan et al., 1995; Ribe and Christensen, 1994, 1999; Zhong and Watts, 2002). The moving lithosphere in these models is typically thin and its composition is identical to the underlying mantle, which is a reasonable approximation for oceanic lithosphere, but not for old continental lithosphere. Old continental lithosphere is thick and chemically more depleted

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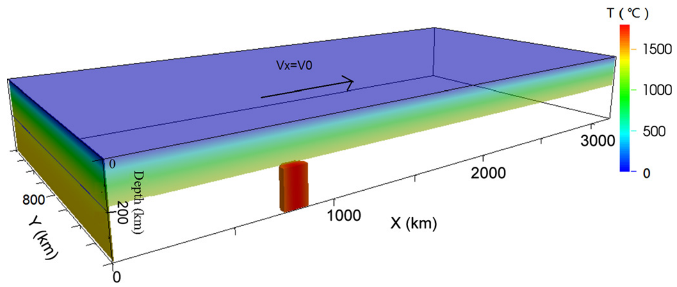

Fig. 1. Model geometry. Velocity along X direction is prescribed for the top boundary to represent the plate motion. The temperature on $X = 0$ plane shows the imposed temperature boundary condition at the inflow boundary. The black line on this plane shows the bottom of the chemical lithosphere at the initial time. Mantle with temperature less than 1260 °C is displayed for comparison. Initially, the plume conduit is represented by a high-temperature cylinder centered at $(X, Y) = (800\ \text{km}, 0\ \text{km})$, with a height of 200 km.

than the underlying asthenosphere. This depletion leads to viscosity increase and density decrease for old continental lithosphere (Hirth and Kohlstedt, 2003; Jordan, 1988; Lee et al., 2011; Pollack, 1986). For example, Archean continental lithosphere (craton) may have a density depletion as large as 2.5% (Kaban et al., 2003; Poudjom Djomani et al., 2001) and a viscosity increase as large as several orders (Peslier et al., 2010). Such density and viscosity contrasts between the lithosphere and asthenosphere should have important effects on plume–lithosphere interaction.

Some groups investigated the interactions between a hot plume and an overlying compositionally different lithosphere (Burov et al., 2007; Jurine et al., 2005; Manea et al., 2009; Sobolev et al., 2011). The lithosphere in these models is more viscous and buoyant, representing an old continent. However, these studies either considered a fixed lithosphere, or focused on the interaction between the lithospheric plate and a plume head. Interactions between a moving compositionally different continental lithosphere and a deep-seated plume conduit have not been fully explored yet.

In this study, we investigate the interaction between a moving, depleted continental lithosphere and a deep-seated plume conduit within 3-D Cartesian geometry. We focus on two important issues: (1) whether the seismically-observed corridor-shape low velocity zone beneath the thick continental lithosphere can be caused by a plume conduit; (2) how different physical parameters of the plume and the lithosphere affect the surface expression and internal structures of this low seismic velocity zone.

2. Methods

Our numerical model is modified from the 3-D mantle convection code CitcomCU (Zhong, 2006). The Earth's mantle is considered as a highly viscous, incompressible fluid with Boussinesq approximation. Our model geometry is similar to that of Ribe and Christensen (1994) and Zhong and Watts (2002) (Fig. 1). The model box is 400 km deep, 3200 km long (along the direction of plate motion) and 1600 km wide. Due to the reflective boundary condition we use at $Y = 0$ plane, our model actually represents a width of 3200 km along the Y-axis direction. The other half part of the model is symmetric to Fig. 1 and not shown here. The bottom boundary has zero horizontal velocity and zero vertical stress to permit vertical flow through it. Temperature at this boundary is set a constant 1400 °C except in a circular region where an excess temperature is assigned to simulate a hot plume conduit. This circular region is centered at $(X, Y) = (800\ \text{km}, 0\ \text{km})$ (Fig. 1). The excess temperature in this circular area is $\Delta T = \Delta T_p \exp(-r^2/R^2)$, where R is the radius of the plume conduit, r is the distance from the circular center and ΔT_p is the plume excess temperature. The upper boundary has a constant plate velocity $V0$ along X direction and zero velocity along Y-axis direction. The temperature at this boundary is set a constant 0 °C. The inflow boundary at the left side has zero shear velocity and zero normal stress. The temperature at this boundary is derived from the half-space cooling model (Turcotte and Schubert, 2002) for a plate age of 200 Ma. The outflow boundary at the right side has zero shear velocity and zero normal stress, same as the inflow boundary. Thermal insulation boundary condition is assigned to this boundary. Reflecting boundary conditions are applied to both the front and the rear boundaries.

Table 1
Constant physical parameters.

Parameters	Value
Mantle density	3.2e3 kg/m^3
Air density	0 kg/m^3
Water density	1.0e3 kg/m^3
Gravitational acceleration	9.8 m/s^2
Thermal expansivity	3e−5 (°C)$^{-1}$
Reference temperature	1400 °C
Box depth	400 km
Thermal diffusivity	1e−6 m^2/s
Plume conduit radius	75 km
Activation energy	120 kJ mol^{-1}
Gas constant	8.31 J(°C)$^{-1}$ mol^{-1}

Initially, we put a plume conduit extending 200 km above the circular region. This plume conduit has the same temperature anomaly as the circular region (Fig. 1). The initial condition, such as the initial height of the plume, initial thermal age of the lithosphere, affects the evolution of plume lithosphere interaction (Olson et al., 1988), as discussed later.

Our models have a uniform 6.25 km vertical resolution and 12.5 km horizontal resolution throughout the whole domain. A large number of time steps (typically 100,000 time steps, corresponding to ~150 Myr) are calculated to obtain the steady-state solutions.

CitcomCU uses tracers to track the compositional evolution (Zhong, 2006). Two kinds of tracers are set in our models, representing the continental lithosphere (the kind 1 tracers) and asthenosphere (the kind 0 tracers) respectively. Initially, each element contains 16 randomly distributed tracers. With the imposed surface velocity along X direction, the tracers will concentrate in the elements close to the outflow boundaries, leaving other elements (especially the inflow boundary elements) vacant as time elapses. This extremely heterogeneous distribution of tracers produces a false compositional field. To solve this problem, at each time step, we add tracers to those inflow boundary elements in which the number of tracers become less than half of their initial value (i.e. less than 8). We also remove the excess tracers from all the overflowing elements when the total number of tracers in the model domain reaches twice its initial value. Our test results show that the processes of adding and removing tracers exert negligible disturbance to the compositional field and that this tracer adjustment algorithm works well for simulating the horizontally moving depleted lithosphere.

The viscosity in our models depends on both temperature and composition according to

$$\eta = \eta_0 \exp\big(E/R * (1/T - 1/T_m) + E_c C\big) \tag{1}$$

where η_0 is the reference viscosity, E is the activation energy, R is gas constant, T and T_m are the temperature and reference temperature, respectively. E_c determines the viscosity increase for the continental lithosphere. C is the composition varying from $C = 1$ (lithosphere) to $C = 0$ (asthenosphere). Table 1 lists the constant parameters we use in this study. To avoid numerical difficulties in solving the Stokes equations, we limit the maximum and minimum viscosity to be $2000\eta_0$ and $0.05\eta_0$, respectively.