Lithospheric Thinning by Mantle Plumes

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SUMMARY

Thermo-mechanical thinning of the lithosphere by mantle plumes is essential for intra-plate volcanism, the initiation of rifting, the evolution of Earth's lower continental crust and the genesis of metals, diamonds and hydrocarbons. To develop a new understanding of how a mantle plume thins the overlying lithosphere beneath moving plates, we use 2-D and 3-D numerical models based on a finite-element discretization on anisotropic adaptive meshes. Our models include Earth-like material properties for the upper mantle (e.g. temperature and viscosity contrasts, non-Newtonian rheology) discretised at a local mesh resolution that has previously been considered intractable. In our simulations, a plume is injected at the base of the model (670 km depth) with a prescribed mass flux that is consistent with surface observations of topographic swells: from 0.5 (e.g. Louisville, Bermuda, Darfur) to 7 Mg/s (Hawaii). We undertake a systematic numerical study, across a wide parameter space, to investigate the effect of plume buoyancy flux, plate velocity, rheology law and Rayleigh number on processes leading to a reduction of the depth of the Lithosphere Asthenosphere boundary (LAB), such as small-scale convection (SSC) ('dripping'), or delamination of the lower lithosphere.

Key words: Mantle plumes, Hotspots, Dynamics of lithosphere and mantle, Geodynamical modelling, Lower lithosphere evolution

INTRODUCTION

Mantle plumes are hot narrow buoyant upwellings rising from Earth's core mantle boundary to the top of the asthenosphere, which account for Large Igneous Provinces (LIPs) and long-lived volcanic hotspot tracks, such as the Siberian Traps and the Hawaiian-Emperor chain, respectively (Morgan, 1972; Richards et al. 1989). The mechanism by which a mantle plume thins the overlying lithosphere so that it can undergo decompressional melting is not understood, despite this being one of the most fundamental processes on Earth. Not only does it have direct implications for such-first-order problems as the origin of LIPs, super-volcanic eruptions and global mass extinctions, but it also plays a key role in Earth's transient topographic expression, the breakup of continents, the evolution of the lower continental crust, regional metamorphism, and the genesis of metals, diamonds and hydrocarbons (e.g. Campbell & Hill, 1988; White & Lovell, 1997; Torsvik et al. 2010; Sobolev et al. 2011).

The plume's increased temperature and reduced viscosity, when compared to surrounding mantle, induces a "head and tail" structure, with a large bulbous head preceding a narrower conduit (Campbell & Griffiths, 1990). Adiabatic melt production associated with plume heads (LIPs) and plume tails (hotspot tracks) would not occur unless the overlying lithosphere has a thickness of less than ~75-100 km, which is not compatible, for instance, with the extensive melting observed under 100 Myr old lithosphere at Hawaii (White & McKenzie, 1995; Foulger, 2005). This implies that locally a plume must thin the overlying lithosphere. Above plume-heads, thinning is thought to have been significant enough to produce substantial crust-derived melts and induce rifting (Campbell & Griffiths, 1990). The thermo-mechanical thinning of overlying lithosphere by a mantle plume is believed to be the result of the combined effect of mechanical removal by: (i) sub-lithospheric small-scale convection (SSC) (see Figure 1); (ii) lithospheric delamination; or (iii) lateral shear stresses resulting from horizontal flow in the asthenosphere away from the plume impact point and, to a lesser extent, of thermal rejuvenation due to heat conduction from anomalously hot plume (Detrick & Crough, 1978; Davies, 1994; Elkins-Tanton, 2005; Agrusta et al. 2013).

Receiver function and surface wave seismological data, beneath hotspots, such as Hawaii and Galapagos, display a Lithosphere Asthenosphere Boundary (LAB) up to 50 km shallower than the surroundings (Li et al. 2004; Lodge and Helffrich, 2006; Rychert et al. 2014; Villagomez et al. 2014). Similarly, gravimetric studies show variation of the geoid-to-topography ratio along the Hawaiian swell, indicating a decrease of the average compensation depth by 20 km (Cadio et al. 2012). However, existing 2-D numerical models of plume-lithosphere interaction have failed to identify the mechanism by which a plume head or tail displaces the cold overlying lithosphere to produce such thinning, at the observed time-scales, within an Earth-like parameter space. Typically, models include unrealistic plume excess temperatures for the Phanerozoic (>300°C) and a relatively 'soft' lower lithosphere (due to the computational challenge of simulating sharp orders of magnitude viscosity contrasts) (e.g. Farnetani & Richards, 1994; 1995; Moore et al. 1999; Herzberg et al. 2007)

In this study we use the recently-developed computational modelling framework, Fluidity (Davies et al. 2011; Kramer et al. 2011) to explore the dynamics and efficiency of SSC above a mantle plume, in 2-D and 3-D simulations with realistic Earth-like material properties and a sub-km local mesh resolution. Specifically, we will build on and complement earlier studies by, for example, Huang et al. (2003), van Hunen et al. (2003) and Agrusta et al. (2013; 2015).

This project is undertaken as part of the completion of Honours at the Australian National University for the year 2016. Final results and conclusions are not yet available, but will be in place prior to the conference.

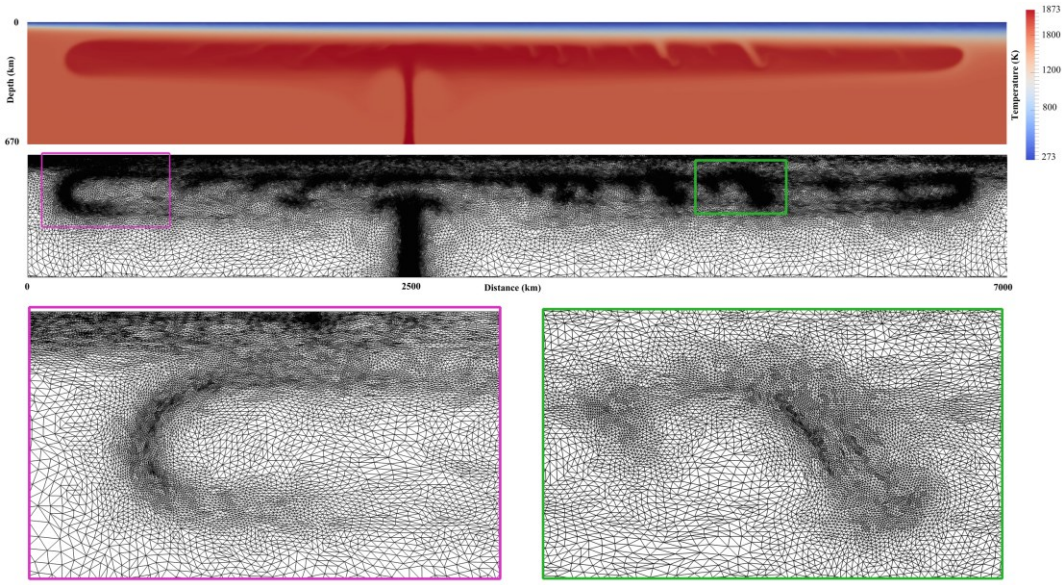

Figure 1: (top) the thermal field from a 2-D Fluidity simulation that examines the interaction between a mantle plume and overlying oceanic lithosphere. The associated adaptive mesh is shown (middle) with zones of high resolution highlighted in the two insets (bottom). The plume has a 250 K excess temperature and impacts a 55 Ma oceanic lithosphere moving to the right at 5 cm/yr. Small scale convection can be seen in the plume fed asthenosphere and is fully resolved by the locally fine mesh (bottom right).

METHOD

We solve the Stokes and energy equations relevant to mantle convection using Fluidity, a finite-element, control-volume model with several features that place it at the forefront of computational fluid dynamics (Davies et al., 2011; Kramer et al., 2012). Fluidity: (i) uses an unstructured mesh, which enables the straightforward representation of complex geometries; (ii) dynamically optimizes this mesh, providing increased resolution in areas of dynamic importance, thus allowing for accurate simulations across a range of length-scales, within a single model; (iii) enhances mesh optimization using anisotropic elements (Davies et al. 2011); (iv) is optimized to run on parallel processors and has the ability to perform parallel mesh adaptivity; (v) utilises solvers linked to PETSc (Balay et al. 1997), that can handle sharp, orders of magnitude variations in viscosity, a feature that is essential for the proposed study; and (vi) employs a free-surface at the outer domain boundary (Kramer et al. 2012). Fluidity, therefore, provide a base for accurately and efficiently simulating plume-lithosphere interaction under Earth-like conditions (see Figure 1).

The 2-D and 3-D computational domain is 670 km deep with an aspect ratio of 10:1. A constant temperature of 273K and horizontal top velocity (V_{plate} ~ 0-12 cm/yr) is imposed on the top boundary. The effect of boundary conditions is investigated for free/no slip bottom and open/Couette inflow and outflow. A plume is injected at the base of the box with realistic imposed excess temperature (ΔT ~ 200-300K) vertical velocity (V_{plume} ~10 cm to 10 m per year depending on the rheology) and radius (Larsen & Yuen, 1997; Herzberg et al. 2007). Moreover, the plume mass flux is prescribed to values of between 0.5 and 7 Mg/s beneath the lithosphere, in agreement with surface observations of topographic swells (e.g. Davies, 1988; Sleep, 1990; King & Adam, 2014).

For Newtonian rheology, a linear Arrhenius viscosity equation is used, where viscosity depends on temperature and pressure. When accounting for the effects of dislocation creep, we use a composite rheology (with diffusion and dislocation creep viscosities combined via a harmonic mean), with a power law representing deformation in the dislocation creep regime (Karato & Wu, 1993). We adopt laboratory constrained rheological coefficients.

OUTSTANDING QUESTIONS

We undertake a systematic numerical study to determine the principal controls upon how, to what extent, and at what time-scale do mantle plumes displace the overlying lithosphere. Initial tests focus on the interaction between a plume and overlying oceanic lithosphere, as the thermal structure and rheology of oceanic lithosphere is generally better understood than continental lithosphere. In this context, we will:

1. Study the effect, in 2-D and 3-D, of the morphology and onset time of SSC produced from shearing under a moving plate first without, then with, a plume. The behaviour of SSC in 2-D and 3-D is likely to be distinctive: longitudinal roll ('Richter rolls') structures, with their axes aligned parallel to plate motion are favoured in 3-D, whilst transverse roll structures, with their axis perpendicular to plate motion, are the only instabilities that can be simulated in 2-D (van Hunen, 2003; Agrusta et al. 2013; Davies et al, 2016). Also, faster onset time of SSC is expected in 3-D in comparison to 2-D.
2. Determine the sensitivity of results to a wide-range of plume characteristics, including plume mass flux, excess temperature, radius and viscosity. Analytical predictions from Davies (1994) suggest that the lower the plume viscosity, the faster should be

the thinning, and that narrower plume conduits (<100 km) would produce faster thinning, while, plume heads would not cause any significant thinning, which is inconsistent with an active rifting scenario (Courtillot et al. 1999). Furthermore, the plume vigour, quantified by the Rayleigh number, is believed to negatively impact the onset time of SSC (Agrusta et al. 2013).

3. Determine the sensitivity of results to a wide-range of lithospheric characteristics, including lithospheric rheology, velocity and age. Plate thickness, related to age, has been shown to negatively influence a plume's ability to thin the overlying lithosphere (Davies, 1994), although our preliminary results seem to demonstrate the opposite, in agreement with Agrusta et al. (2013). We hypothesise that: (i) SSC is inhibited at high plate velocities (< 12 cm/yr), due to a competition between the time-scales required to destabilize the lithosphere and the time-scales required to develop a drip; and (ii) at intermediate plate velocities, SSC thins the lithosphere most efficiently, and generates the associated melting, downstream of the plume conduit.
4. Quantify how the inclusion of a non-Newtonian mantle rheology modifies results. Previous studies demonstrate that the inclusion of dislocation creep, a strain-rate dependent rheology likely to exist within Earth's upper mantle (Karato & Wu, 1993; Freed & Burgmann, 2004), increases the ascent rates of mantle plumes, leading to hotter plumes and intense viscous heating as the plume impinges upon the lithosphere (Karato & Wu, 1993; Larsen & Yuen, 1997). Such local variations may strongly influence plume dynamic and we expect an extreme sensitivity of thinning to rheology calibration.

At each stage, the depth variation of the LAB, the morphology and onset time of SSC will be recorded, across a range of scenarios. We hope to apply the lessons from this study globally and regionally, to the plume-related age-progressive volcanic chains of Eastern Australia (Wellman & McDougall, 1974; Cohen et al. 2008; 2013; Davies et al. 2015) or the Pacific, and to the plume-dominated Archean greenstone belts of Western Australia (e.g. Campbell & Hill, 1988).

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