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Thermally-driven mantle plumes reconcile multiple hot-spot observations

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ABSTRACT

Hot-spots are anomalous regions of magmatism that cannot be directly associated with plate tectonic processes. They are widely-regarded as the surface expression of upwelling mantle plumes. Hot-spots exhibit variable life-spans, magmatic productivity and fixity. This suggests that a wide-range of upwelling structures coexist within Earth's mantle, a view supported by geochemical and seismic evidence, but, thus far, not fully-reproduced by numerical models. Here, results from a new, global, 3-D spherical, mantle convection model are presented, which better reconcile hot-spot observations, the key modification from previous models being increased convective vigor. Model upwellings show broad-ranging dynamics; some drift slowly, while others are more mobile, displaying variable life-spans, intensities and migration velocities. Such behavior is consistent with hot-spot observations, indicating that the mantle must be simulated at the correct vigor and in the appropriate geometry to reproduce Earth-like dynamics. Thermally-driven mantle plumes can explain the principal features of hot-spot volcanism on Earth.

1. Introduction

The theory of plate tectonics successfully explains the large-scale motions of Earth's lithosphere, the solid outermost shell of our planet. It also accounts for the locations of most volcanoes; they occur at plate boundaries. However, a volumetrically minor, yet significant, class of volcanism occurs within plates or across plate boundaries. Such volcanism is often characterized by linear chains of volcanoes that grow older in the direction of plate motion. Classic examples include the Hawaiian–Emperor chain, the Yellowstone–Snake river plain province and the volcanic system centered upon Iceland. As a result of their geometry and age distributions, these volcanic provinces, which are commonly known as hot-spots, are thought to have formed as Earth's tectonic plates moved over long-lived, cylindrical mantle plumes: upwellings of abnormally hot rock within the mantle (Wilson, 1963; Morgan, 1972).

Originally, hot-spot plumes were hypothesized to be spatially fixed, relative to the mantle. However, with improving data, it has become apparent that they do move. For example, palaeomagnetic and radiometric age data demonstrate that the Hawaiian hot-spot plume has intermittently drifted southwards around 10° (1° ≈ 111 km) since the Late Cretaceous, with a rapid phase of motion (>4 cm yr^{-1}) between 81 and 47 Ma (Tarduno et al., 2003). Observational data and dynamic modeling indicate that the Kerguelen plume has drifted 3–10° southwards over the same period (Antretter et al., 2002), whilst the Reunion hot-spot plume has migrated ≈5° northwards since its initiation around 65 Ma (Vandamme and Courtillot, 1990; O'Neill et al., 2003). Relative motion has also been detected between hot-spots in the Atlantic and Indian Oceans (Molnar and Stock, 1987). Taken alongside predictions from geodynamic modeling (Steinberger and O'Connell, 1998), the evidence suggests that, in general, hot-spot plumes migrate slowly, at a fraction of surface plate velocities, with certain plumes exhibiting infrequent and irregular periods of more rapid motion. The Marion hot-spot plume could be a notable exception to this trend; palaeomagnetic data indicates that it has remained fixed for at least 90 Myr (Torsvik et al., 1998), though this apparent fixity may be due to the combination of hot-spot motion and true polar wander acting in opposing directions (Besse and Courtillot, 2002; O'Neill et al., 2003).

Not all hot-spots can be discussed in this framework. Some hot-spot tracks are non-age progressive. Others record simultaneously active volcanism at several places, while a few exhibit irregularly spaced or segmented volcanic centers (Schubert et al., 2001; Ito and van Keken, 2007). This implies that if mantle upwellings are the cause of volcanic hot-spots, as will be assumed for the remainder of this paper, a wide-range of upwelling structures must coexist within Earth's mantle (Courtillot et al., 2003), which differ in their morphology, intensity, migration velocity and longevity. There is strong geochemical (e.g. Bourdon et al., 2006) and seismic (e.g.

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Montelli et al., 2006) evidence to support such wide-ranging dynamics, although, to date, mantle convection models have failed to replicate such a system, with simulations generally displaying singular upwelling behavior, predicting either very stable or highly time-dependent plumes (Jarvis, 1984; Christensen, 1989; Davies, 2005). However, prior to this study, such models had not been examined in global 3-D spherical geometry at the dynamical regime of Earth's mantle, which vigorously convects at a Rayleigh number of order 10^9 (Schubert et al., 2001). We show that this is a key ingredient in generating the diversity of upwellings within Earth's mantle.

2. Modeling the vigorously convecting mantle

Computationally demanding simulations at these high-vigors are enabled by a new, validated, multi-resolution extension to the well-established 3-D spherical mantle convection code TERRA (Baumgardner, 1985; Bunge et al., 1996, 1997; Yang and Baumgardner, 2000). The validated extension (Davies, 2008) is based around a variable level multigrid solver (Brandt, 1977) and allows one to refine and solve on a radially non-uniform grid. TERRA's original icosahedral grid exhibits coarser lateral resolution in the upper mantle than in the lower mantle. The modified version overcomes this limitation, by refining the grid in the upper mantle to yield an equal lateral resolution at both boundaries. Accordingly, element sizes and inter-nodal distances show greater consistency over the entire domain and the dynamically controlled time-step becomes better-suited to the problem under examination (it is not unnecessarily restricted by smaller elements at the base of the shell). For the purposes of this investigation, the upper 25% of the spherical shell is refined to give a lateral spacing of ≈14 km at both upper and lower boundaries. The radial spacing is also reduced at both boundaries, to provide extra resolution in capturing upper and lower thermal boundary layers.

Isochemical, incompressible convection is simulated, with free-slip and isothermal boundary conditions. The mantle is heated internally and through its base, at an almost equal ratio (Bunge, 2005). The model includes a factor of 40 increase in lower mantle viscosity, with a decrease towards the core–mantle-boundary (CMB). This is consistent with several independent lines of geophysical evidence (Hager, 1984; Ranalli, 2001; Forte et al., 2002; Mitrovica and Forte, 2004). As a consequence, fine-scale features dominate upper-mantle convection, with longer wavelength dynamics more prevalent at depth. The discretization utilized, with fine resolution in the upper mantle, fits in perfectly with such a configuration. The model achieves an internal heating Rayleigh number (Ra_H) of 1.4×10^9, based upon the upper mantle viscosity (9×10^{20} Pa s), rendering this the highest vigor global mantle convection simulation to date. The initial condition consists of small-scale, random temperature perturbations. We have verified that results are independent of this initial condition. Model parameters are summarized in Table 1.

Table 1
Model parameters

Parameter	Value	Units
Outer shell radius	6370	km
Inner shell radius	3480	km
Thermal conductivity	4.0	W m^{-1} K^{-1}
Thermal expansivity	2.5×10^{-5}	K^{-1}
Reference density	4.6×10^3	kg m^{-3}
Specific heat at constant pressure	1.13×10^3	J kg^{-1} K^{-1}
Surface temperature	300	K
Core–mantle boundary (CMB) temperature	3000	K
Gravitational acceleration	10	ms^{-2}
Heat generation	4.00×10^{-12}	W kg^{-1}
Upper mantle viscosity, μ_1	9×10^{20}	Pa s
Lower mantle viscosity, μ_2	3.6×10^{22}	Pa s
Basally heated Rayleigh number Ra_T	1×10^8	Non-dimensional
Internally heated Rayleigh number Ra_H	1.4×10^9	Non-dimensional

The model exploited ≈160 million nodes. The simulation was executed across 128 processors, on HECToR (http://www.hector.ac.uk), the UK National Supercomputing Service, for a total of ≈ 400 hours, per process. A calculation matching the upper mantle resolutions achieved here, with the original, uniformly discretized code, would have been unfeasible.

3. Results and discussion

A selection of results from the model are illustrated in Figs. 1 and 2. For the majority of the simulation there are 9–11 coherent plumes, which extend from the CMB to the surface. Although this is much smaller than the number of hot-spots in catalogues, it is similar to the number of deep-rooted plumes imaged seismically (Montelli et al., 2006) and the number of 'primary' plumes selected by Courtillot et al. (2003). Model plume radii vary from 100–400 km. Seismic observations suggest that the mantle plumes underlying the Ascension and Juan de Fuca hot-spots are small (radii of ≈100 km), while those feeding Easter, Hawaii and Tahiti are large (radii of 300–400 km) (Montelli et al., 2006). Although there is some uncertainty in these seismic studies, taken at face value such observations imply that model plume dimensions and their variations are similar to plumes on Earth.

Upwellings show wide-ranging characteristics and varying dynamical behavior. Long-lived cylindrical plumes, whose life-span substantially exceeds a mantle transition time, dominate the planform. These are analogous to the long-lived plumes feeding major hot-spots on Earth, such as Galapagos and Hawaii. However, time-dependent features are also apparent: older plumes fade and die (Fig. 1, a–c); plumes occasionally split in the mid-mantle (Fig. 1, e); newborn plumes continually develop (Fig. 2b, C); whilst nearby plumes often merge and coalesce (Labrosse, 2002) (Fig. 2b, D). Such behavior is consistent with observations on Earth: Large Igneous Provinces (LIPs) are believed to signal the arrival of new-born plumes at Earth's surface (Richards et al., 1989), whilst hot-spot plumes are known to have finite lifetimes (Ito and van Keken, 2007). Developing plumes have been imaged in the present-day mantle beneath Southern Java, Eastern Solomon and the Coral Sea (Montelli et al., 2006), whilst the Azores hot-spot plume is believed to exemplify a present-day dying plume (Silveira et al., 2006). Splitting plumes have also been imaged seismically. For example, the plumes feeding the Ascension and St-Helena hot-spots join at ≈650 km depth (Montelli et al., 2006), upwellings beneath the Azores, Canaries and Cape Verde seem to merge below 1400 km depth, as do Kerguelen and Crozet below 2300 km depth (Davaille et al., 2005).

Short-lived, ephemeral upwellings that could account for temporal and discontinuous magmatic features, such as those recorded in the southern and central Pacific (Ito and van Keken, 2007), also occur (Fig. 1d). In addition, anomalously high concentrations of plumes occasionally arise in certain regions of the mantle (Fig. 1b). These resemble plume clusters (Schubert et al., 2004) There is strong geophysical evidence that such clusters exist (e.g. Davaille, 1999; Davaille et al., 2005), beneath both Africa and the south-central Pacific and, hence, their occurrence here is encouraging.

Model plumes often pulse and vary in intensity. Such behavior is consistent with observations on Earth (Lin and van Keken, 2005) and is caused by the arrival of developing thermal boundary layer instabilities at the base of a mature plume conduit, contributing to an increased buoyancy (Lowman et al., 2004). While upwellings are generally cylindrical, there are exceptions. Some change in shape, often driven by the action of downwelling material, as illustrated in Fig. 2b (B & E), where cylindrical plumes transform to linear, elongate upwellings. Such features could account for synchronous or near-synchronous magmatic events spanning distances of >2000 km, as recorded in the Line-Islands and Cook–Austral volcanic chain (Ito and van Keken, 2007). Furthermore, seismic tomography and isotope geochemistry indicate the existence of a large sheet-like region of upwelling that extends from the Eastern Atlantic Ocean to central Europe and the western