Mantle Convection at Earth-like Vigor: Thermal Plumes Reconcile Hot–spot Observations

D. R. Davies, J. H. Davies

School of Earth and Ocean Sciences, Cardiff University, Wales, UK.

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 hot, columnar plumes, upwelling from deep within Earth's 2900–km thick mantle. Hot–spots have variable life–spans, magmatic productivity and fixity. This suggests that a wide–range of upwelling structures co–exist within Earth's mantle, a view supported by both geochemical and seismic evidence. However, to date, numerical convection studies have failed to reproduce such behavior, predicting either very stable or highly time–dependent plumes. Here, we present results from a global 3–D spherical mantle convection model that better reconcile hot–spot observations. The major modification from previous work is that, owing to a highly–efficient multi–resolution solution algorithm, our model more accurately replicates the dynamical regime of Earth's mantle, which convects at a Rayleigh number of order 10^9. We discover strong upwellings that extend from the core–mantle boundary to the surface. These show a broad range of behavior; some drift slowly, while others are more mobile and ephemeral, displaying variable life–spans, intensities and migration velocities. Such behavior is consistent with observations on Earth, indicating that it is essential to simulate Earth's mantle at the correct Rayleigh number and in the appropriate geometry to reproduce Earth–like dynamics. Thermal processes alone are sufficient to explain the principal features of upwellings on Earth.

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. Because 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 [1, 2].

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° ($1^\circ \approx 111$ km) since the Late Cretaceous, with a rapid phase of motion (> 4 cm yr^{-1}) between 81 and 47 Ma [3]. Observational data and dynamic modeling indicate that the Kerguelen plume has drifted $3-10^\circ$ southwards over the same period [4], whilst the Reunion hot–spot plume has migrated $\approx 5^\circ$ northwards since its initiation around 65 Ma [5]. Relative motion has also been detected between hot–spots in the Atlantic and Indian Oceans [6]. Taken alongside predictions from geodynamic modeling [7], 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 [8], though this apparent fixity may be due to the combination of hot–spot motion and true polar wander acting in opposing directions [5].

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 [9, 10]. 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 co–exist within Earth's mantle [11], which differ in their morphology, intensity, migration velocity and longevity. There is strong geochemical [12] and seismic [13] 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 (see Supplementary Information A for further details). 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 [10]. We show that this is a key ingredient in generating the diversity of upwellings within Earth's 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 [14] (see Supplementary Information B). Isochemical, incompressible convection is simulated, with free–slip and isothermal boundary conditions, at a lateral grid resolution of ≈ 14 km on both boundaries. The model incorporates both basal and internal heating, plus a factor of 40 increase in lower mantle viscosity, which is consistent with several independent lines of geophysical evidence [15]. 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. Further details on the model are provided in Supplementary Information C.

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 core–mantle boundary (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 [13]. 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) [13]. Model plume dimensions and their variations are thus 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 [16] (Fig. 2b, D). Such behavior is consistent with observations on Earth: developing plumes are visible in the present–day mantle beneath Southern Java, Eastern Solomon and the Coral Sea [13], whilst the Azores hot–spot plume is believed to exemplify a present–day dying plume [17]. Splitting plumes have also been imaged seismically; for example, the plumes feeding the Ascension and St–Helena hot–spots join at ≈ 650 km depth [13]. Short–lived, ephemeral upwellings that could account for temporal and discontinuous magmatic features, such as those recorded in the southern and central Pacific [9], 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 [18]. There is strong geophysical evidence that such clusters exist, 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 [19] 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 [20]. While upwellings are generally cylindrical, there are exceptions. Some change in shape, often driven by the action of downwelling material, as

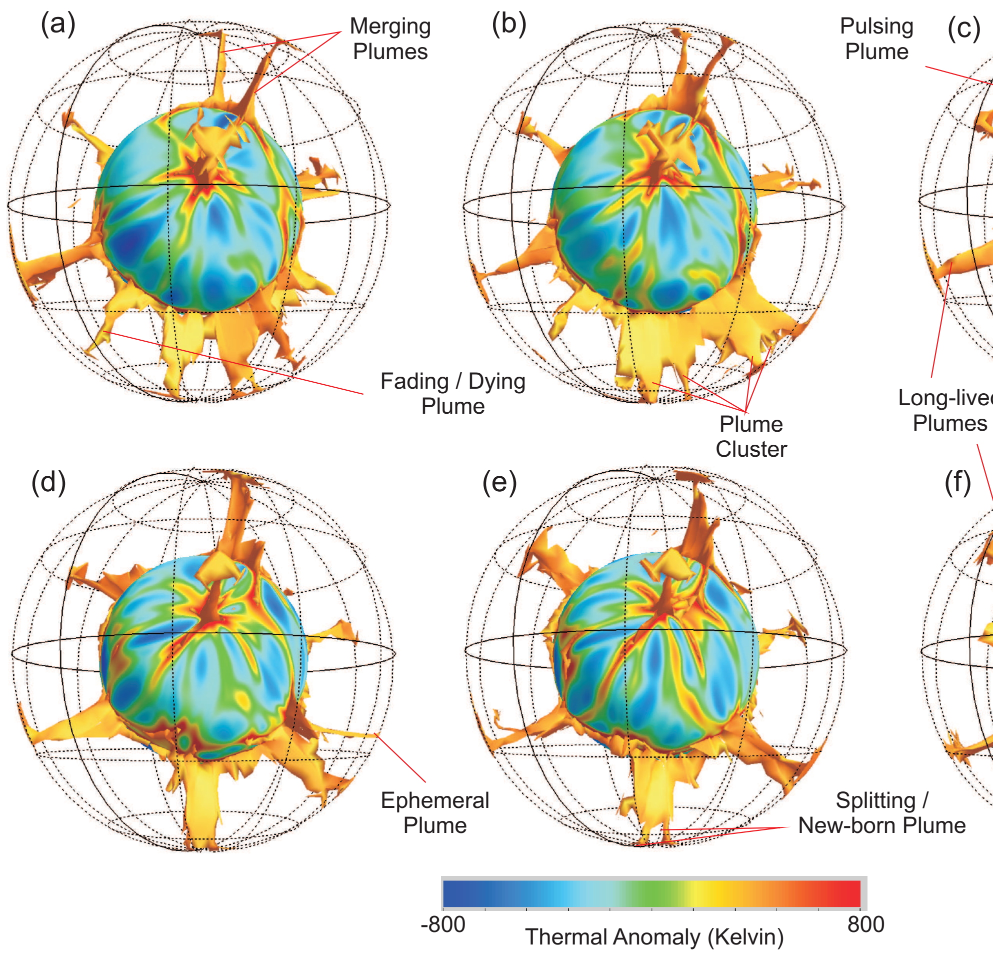

Figure 1: A series of thermal profiles, displaying the temporal evolution of an isochemical, incompressible mantle convection simulation, with free–slip and isothermal boundaries, at $Ra_H = 1.4 \times 10^9$. Snapshots are spaced ≈ 30 Myr apart, and are surrounded by a latitude–longitude grid. The scale illustrates the temperature, away from the lateral average (i.e. the thermal anomaly), in Kelvin. Each snapshot shows a radial surface just above the core-mantle boundary and a hot iso-surface, representing regions of the mantle that are 500K hotter than average for their depth. The most prominent features are hot upwelling plumes (orange columnar features). These display a range of characteristics. The majority are long–lived and migrate slowly across the mantle. Others are more mobile and ephemeral. New plumes form and old ones fade, some of which eventually cease. In addition, smaller plumes merge together and coalesce over time, while long–lived plumes often pulse or vary in intensity.

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 [9]. 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 Mediterranean [21, 22]. The long, linear upwellings observed in our model are comparable to such features.

In general, plumes slowly migrate across the mantle (Fig. 2b, A & B) at velocities of order $0.1°$ Myr^{-1} (≈ 1.1 cm yr^{-1}), which corresponds to $20 - 25\%$ of the overriding surface velocity ($4.2 - 4.7$ cm yr^{-1}). These migration rates are consistent with those recorded for major hot–spots on Earth, such as Kerguelen and Reunion [5]. Interestingly, drifting is not necessarily monotonic. In Fig. 2b (E), a plume migrates towards the southwest initially, only to change direction and drift back towards the northeast. Such behavior may contribute to the non–age progressive volcanism recorded in several volcanic provinces on Earth [23] and warrants further investigation. While the model is dominated by slowly migrating plumes, there are instances of more rapid plume motion. In Fig. 2b (C), a newborn plume emerges and subsequently drifts $\approx 15°$ to the west, at a rate of ≈ 2 cm yr^{-1}. In Fig. 2b (E), a

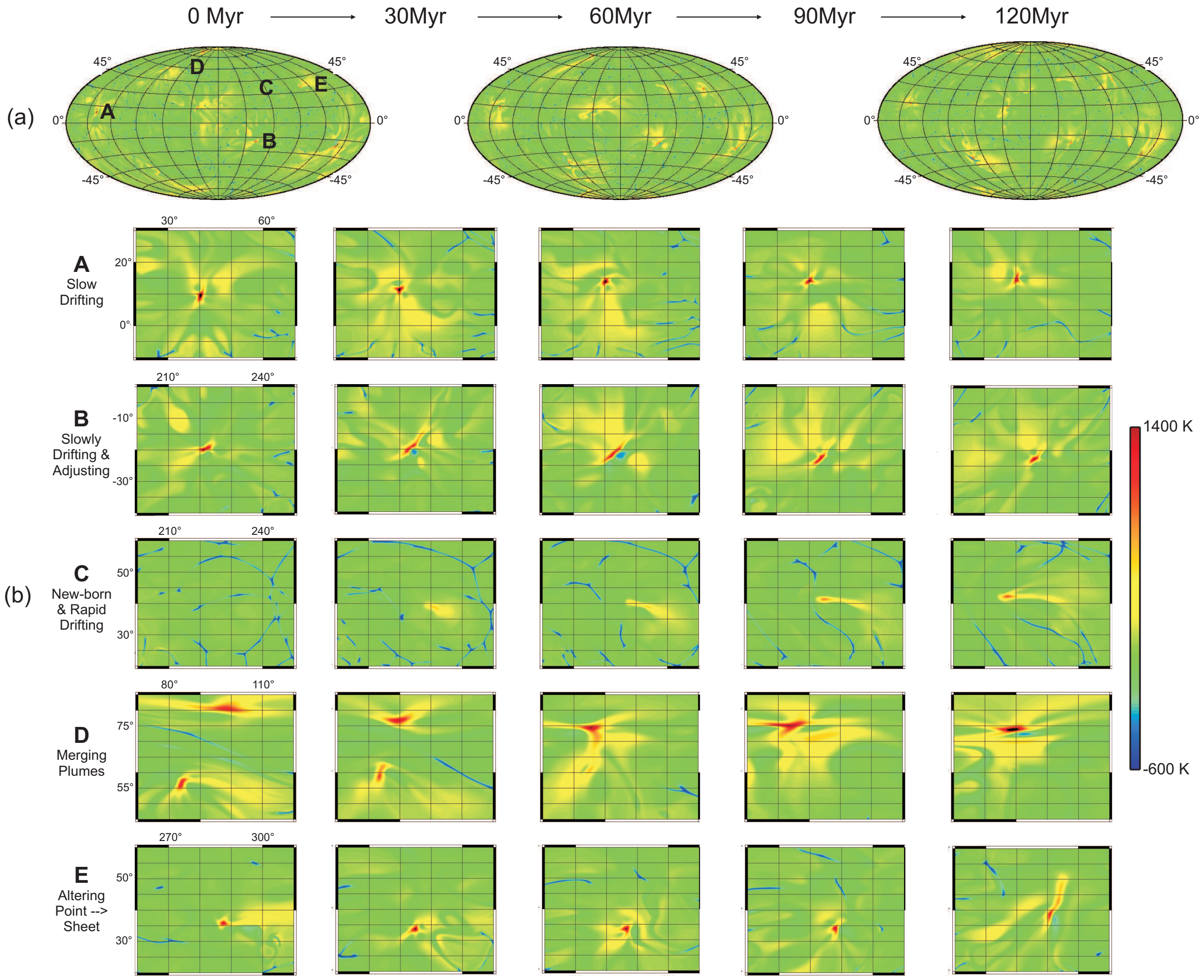

Figure 2: The temporal evolution of our model, displayed as (a) a series of radial slices, taken at the base of the lithosphere, and (b) high–resolution regional plots of specific upwellings, which show wide–ranging characteristics and varying dynamical behavior. Long–lived cylindrical upwellings are prevalent. These drift slowly across the mantle, at velocities that are comparable to hot–spot migration rates on Earth, as illustrated by parts A & B. Upwellings occasionally display elevated migration rates, as shown in part C, where a newborn plume migrates rapidly towards the west. Similar behavior is observed in part D, where two separate upwellings rapidly converge and coalesce. Upwellings frequently change in morphology, as illustrated by parts B & E, where they alternate between traditional columnar plumes and linear, elongate sheets.

cylindrical plume drifts slowly for around 90 Myr, then rapidly migrates $\geq 6°$ towards the northeast, at a rate of ≥ 2.2 cm yr^{-1}, whilst altering in form. Such intermittent and sporadic variations are also displayed in Fig. 2b (D). Here, plumes merge and coalesce, with the lower plume migrating $\approx 20°$ towards the northeast at an initial rate of ≈ 4 cm yr^{-1}. The resulting plume (i.e. the product of the two merging plumes) then remains stationary. Hot–spot plumes on Earth often display rapid and variable rates of drifting; as noted above, the Hawaiian hot–spot plume migrated southwards at > 4 cm yr^{-1} between 81 and 47 Ma. It has remained practically stationary since [3]. Similar behavior has been recorded at the Pukapuka Ridge [24]. Thus, the elevated migration rates seen here, together with discontinuous drifting, are analogous to plume behavior on Earth. While this is an exciting inference, perhaps more importantly, it has implications for our understanding of the relationship between mantle dynamics and plate motion history. Global plate motions remain relatively constant for extended periods of time. However, it is widely–believed that these periods are separated by episodes of abrupt transition, with the great bend in the Hawaiian–Emperor seamount chain often cited as evidence to support this conjecture [25]. It is argued that such an abrupt shift cannot be associated with internal, mantle–derived, buoyancy forces, because these require many millions of years to develop. This has led to the suggestion that plate–boundary forces (i.e. 'top-down' driving mechanisms) may be responsible [25, 26]. While these forces are doubtless important in such events, the results presented here suggest that mantle convection might have a more active role to play than previously envisaged [27]. It might be that these abrupt shifts actually record rapid transitions in hot–spot motion as opposed to plate motion or, probably, a combination of both.

Our model has dynamically reproduced a wide–range of upwellings that vary in their morphology (from traditional cylindrical plumes to linear, elongate, sheet–like upwellings), intensity (plumes of different radii and strength), migration velocity (slow drifting and more rapid motion) and longevity (long–lived and ephemeral), thus replicating hot–spot observations on Earth. Prior to this study, such diverse upwelling features had not been simultaneously reproduced in a global mantle convection model [28]; yet, the only difference between the model presented here and previous models is the convective vigor, or Rayleigh number, of the system. Excluding a depth–dependent rheology, no major complexities were introduced. Indeed, several important aspects of Earth's mantle have not been addressed, the most prominent of which are a temperature–dependent rheology (which would allow large initiating plume heads to develop, thereby accounting for the existence of Large Igneous Provinces [29]), chemical heterogeneities and, perhaps most significantly, the generation and subsequent influence of tectonic plates and continents at the surface. With these facets of mantle convection poorly understood and not very well constrained at present, it is difficult to predict exactly how their inclusion would alter results. Nonetheless, the success of our simple model suggests that thermal processes alone are sufficient to explain many of the principal features of Earth's hot–spots. Our results also demonstrate that the mantle must be simulated at its true convective vigor and in the correct geometry if one is to observe Earth–like behavior. Multi–resolution numerical methods provide a practical and efficient means to solve such problems. The combination of these methods with intelligent, adaptive mesh algorithms [30], will no doubt provide exciting opportunities for geodynamical research.

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