

## Editorial

# The Great Plume Debate: Testing the plume theory

In August 2003 Gillian Foulger, Jim Natland, Dean Presnall and Don Anderson organised a conference on mantle plumes that was held in Iceland. The overwhelming majority of those attending the meeting were not supporters of the plume theory. The aim of the meeting was to find alternatives to the mantle plume theory to explain volcanism such as Iceland, Hawaii and the Deccan Traps, which are normally attributed to mantle plumes. Attendance at this meeting was restricted since it was a Penrose conference. Seventy-nine were accepted for the meeting, 62 attended. Three weeks later another plume meeting, which was conceived before the Iceland meeting, was held at Cardiff organised by a pro-plume group. Only two scientists attended both meetings, although the Cardiff meeting was open to all. Holding meetings that overwhelmingly represent a particular point of view is not the way science should be conducted. Ideas and hypotheses need to be debated to determine which are valid. It was therefore decided that the two sides should meet to debate the critical issues. A meeting was convened at Fort William, Scotland in August/September 2005 entitled The Great Plume Debate.

Prior to the meeting it was agreed to publish a series of review papers dealing with the key issues discussed during the Debate: plume temperature, uplift, seismology etc. Each side was to choose an author or group of authors to present their case for each of the selected topics. Shortly before the meeting the anti-plume group decided to produce their own independent volume, with individual contributions from both sides of the debate. The original plan to publish both sides of the argument in a series of targeted review papers would have constituted a positive step towards resolving the debate. Only one group of plume sceptics, *Falloon et al.* had the courage of their convictions to accept the challenge and write a paper for this special issue: we thank them for doing so. Therefore this volume presents a series of review papers mainly from the pro-plume side that

summarise the case for the existence of mantle plumes. For each of the selected topics the papers are written for the non-expert.

The first paper in the Special Issue is a comprehensive review by *Ian Campbell* of the theory of mantle plumes. This review shows that, contrary to claims made by critics, mantle plume theory makes numerous testable predictions, which are both quantitative and exacting. In the paper it is demonstrated that many of these predictions, which are based on both computational and physical models, hold-up well when tested against observations. For instance the hypothesis correctly predicts that: rapid initial volcanism from the plume head is followed by reduced volcanism from the plume tail, the size of the flattened plume head in the upper mantle is 2000 to 2500 km across, flood volcanism preceded by domal uplift, both mantle plume heads and tails should produce high temperature picrites, plume tails should extend to the core–mantle boundary, and seismically detectable thermal anomalies should persist below flood basalts for at least 100 Ma. Campbell concludes that the excellent agreement between the predictions made from plume theory and the observations made from large igneous provinces and hotspot tracks, leaves little room for doubt that the plume hypothesis is correct.

Perhaps the most controversial aspect of mantle plumes is their temperature. If plumes originate from a thermal boundary layer they must be hotter than the mantle they ascend through. This simple prediction appears to provide a clear and unambiguous test of the plume theory. There are however two opposing views, both of which are represented in this volume. The high temperature case is presented by *Keith Putirka et al.* They use a new olivine/melt geothermometer, infer the pressures of magma sources for selected ocean island and mid-ocean ridges and calculate the  $Kd(Ol-Liq)_{Fe/Mg}$  appropriate to the inferred pressure. From a large data base of rock and glass compositions, and selection of

residual (source) olivine composition, they calculate the excess temperature — the temperature difference between the mantle in the plume and the adjacent mantle — for the Hawaiian, Samoan and Iceland plumes. They obtain values of 268 °C for Hawaii and Samoa, and 162 °C for Iceland; values that are consistent with the plume theory. *Trevor Falloon et al.* use glass and contained olivine phenocryst compositions to calculate crystallization (eruption) temperatures and melt compositions for parental magmas in hotspot and ridge settings. They arrive at a very different conclusion and find no detectable temperature difference between the hottest MORB and parental Hawaiian magmas. They therefore conclude that higher mantle potential temperatures for the source regions of hotspot magmas are unlikely. Both authors compare the key olivine/liquid geothermometers included in the models with existing experimental data; *Falloon et al.* over a pressure range of 1 bar to 1.5 GPa and *Putirka et al.* for pressures up to 15.5 GPa. Both claim excellent agreement and both agree that the mantle potential temperatures of MORB are significantly hotter than the commonly accepted value of 1280 °C. The differences in the calculated excess temperature for hotspots by the two groups arise from differences in the models used and from differences in the melt compositions calculated for MORB and Hawaii, the inferred maximum Fo content of Hawaiian olivines, and differences in the values of  $Kd(Fe-Mg)_{ol-liq}$  used in the calculations. The reader must decide whether petrological arguments are currently definitive either way in this important aspect of the plume debate.

At the suggestion of W Jason Morgan in the early 70's hotspots have been widely used a frame of reference against which to document the movement of plates. Although plume theory does not predict that plumes should be stationary they are expected to move at a slower rate than plates if, as expected, the viscosity of the lower mantle is greater than that of the upper mantle. Although the concept of the hotspot reference frame was questioned almost from the start, it appears to work to a reasonable first approximation, especially for plumes and plates younger than 45 Ma. However, *John Tarduno* uses paleomagnetic analysis to show that the paleolatitude of the Hawaiian plume has changed significantly over the last 80 Ma, which provides clear evidence for significant southward movement of the plume prior to the time of the Hawaiian–Emperor bend. He interprets this observation to mean that position of plumes can be moved by mantle flow and attributes the Hawaiian–Emperor bend to movement of the plume relative to the Pacific plate rather than to a change in plate motion. An important implication of the study is that what has been

interpreted as true polar wander is due more to plume movement than to motion of the spin axis of the solid Earth.

The plume theory makes the unambiguous prediction that plumes should originate from a thermal boundary layer at or slightly above the core–mantle boundary. Seismology can be used to test this key prediction. *Guust Nolet et al.* review recent advances in the application of seismology to the detection of mantle plumes and answer questions commonly raised by non-experts concerning the capability of this method to detect mantle plumes. They also discuss the tomographic interpretation of two case studies: Iceland and Hawaii. The Iceland plume can be clearly resolved from the base of the lithosphere to the transition zone and Hawaii deep into the lower mantle. Deployments of large seismic networks, specifically placed to target narrow mantle plumes, in combination with theoretical advances, are expected to produce improved tomographic images of mantle plumes over the next few years.

The duration of flood basalt volcanism is key to determining eruption rates and hence melt production rates in large igneous provinces, which can in turn help constrain models for the origin of these provinces. *Michael Storey et al.* present new  $^{40}Ar/^{39}Ar$  ages for the Early Tertiary lavas of East Greenland and the Faeroe Islands (parts of the North Atlantic Igneous Province) and use these in conjunction with published data to assess melt production rates leading up to, during and following continental break-up between Greenland and Europe. The authors show that following commencement of volcanism at  $\sim 61$  Ma, volcanic activity was intermittent until  $55.7 \pm 0.5$  Ma when the average melt production rate increased by more than an order of magnitude (from  $< 100$  to  $> 3000$  km<sup>3</sup>/km of rift/m.y.). This increase coincided with continental rifting between Europe and Greenland and shallow decompression melting of hot mantle. It is concluded that a start-up mantle plume head and tail model, with moderate excess temperature ( $\Delta T \sim 100$  °C) and active upwelling, best explains the time, spatial and compositional aspects of volcanism in this province.

An important line of evidence which has been used to support the existence of mantle plumes is the predicted uplift of the lithosphere as a hot mantle plume impacts its base. *Andy Saunders et al.* critically review the geological evidence for regional uplift using five continental flood basalt provinces (Emeishan Traps, Siberian Traps, Deccan Traps, North Atlantic, Yellowstone) as case examples. Each of the five provinces are associated with surface uplift which in each case preceded magmatism. The best biostratigraphic constraints on timing of uplift

and erosion are found in the North Atlantic and Emeishan Provinces, where the time interval between significant uplift and first magmatism is less than 1 million years and 2.5 million years respectively. The authors show that models which try to explain the formation of LIPs without hot mantle plumes have difficulties in explaining the observations of surface uplift, rifting and magmatism. They conclude that start-up plume models remain the most convincing way of explaining the formation of LIPs.

In discussions pertaining to the existence, or otherwise, of mantle plumes the evidence from geochemistry is often used (and occasionally abused), to confirm or deny a mantle plume source. It sometimes appears to non-specialists that the favoured elements or isotopic system which 'demonstrates' a mantle plume origin to one geochemist, can 'prove' a non-plume source to another. Therefore, the review by *Chris Hawkesworth and Anders Scherstén*, which aims to make an objective assessment of the geochemistry of large igneous provinces and ocean islands, and what this can reveal about their mantle source region, is timely indeed. As noted by the authors, because plumes are physical features, they can only be identified geochemically if they are either derived from, or entrain material that has a distinctive geochemical fingerprint. Recent models which attempt to identify a core contribution to mantle plumes (and so prove a deep origin) using Os and W isotopes are reviewed, as are those relying on rare gases to identify contributions from the lower mantle. They conclude that attempts to identify core components using Os and W isotopes are at present inconclusive. However, they note that that mantle plumes derived from the  $D''$  layer might carry ancient signals of subducted oceanic crust such as subchondritic  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios resulting from subchondritic Sm/Nd ratios in the first 30 Myr of Earth history.

*Andrew Kerr and John Mahoney* present a comprehensive review of oceanic flood basalts that summarizes their characteristics. Oceanic plateaus are large areas of thickened ocean crust, which as they point out, are buoyant and therefore resistant to subduction. As a consequence they can be an important component in continental growth. Kerr and Mahoney also discuss the various hypotheses that have been suggested to explain oceanic flood basalts. All have their shortcomings. Although the mantle plume theory does best, it fails to account for the observation that most basalts, particularly in the Ontong Java Plateau, have erupted at water depths of over 1000 m and for the slow subsidence of this particular plateau. They suggest that a thermo-compo-

sitional plume head may explain the eruption depth of the Ontong Java Plateau but note there are also problems with this model. The authors also discuss the important role of oceanic plateau formation in causing global environmental crises and mass extinction events.

The final paper in the special issue by Vicki Hansen focuses on Earth's sister planet, Venus which possesses many examples of large igneous provinces. However, Venus shows no evidence of plate tectonic processes; therefore plate-related hypotheses for large igneous province formation, often advocated by the opponents of mantle plume theories, are not viable on Venus. Four groups of large tectonomagmatic provinces can be identified on Venus: volcanic rises, large coronae, crustal plateaus, and 'plains with wrinkle ridges'. It is argued that volcanic rises represent the most likely possibility of being mantle plume derived large igneous provinces. The distinctive tectonic fabric of crustal plateaus, requires a massive amount of lava to have existed at one time. It is proposed that these plateaus, which have previously been interpreted as forming above deep mantle down-wellings or mantle plumes, are more likely to represent the surface skin of huge lava ponds formed by massive partial melting in the mantle due to large bolide impact on ancient thin lithosphere. Finally, previous interpretations of 'plains with wrinkle ridges' which have been proposed as the solar system's biggest large igneous province, are challenged.

Scientific theories benefit from criticism. The initial criticism of the plume theory by Don Anderson, Gillian Foulger and others was valuable. It caused plume supporters to re-evaluate the theory by testing it against available observations and by making new observations and measurements where the required data were lacking. All of the predictions of the plume theory have now been confirmed by observation as is apparent from this volume. Detractors failed to produce a fatal criticism of the plume theory during the five days of the Great Plume Debate. Most significantly, they have consistently failed to produce a viable alternative hypothesis. Future criticisms of the plume theory will be beneficial only if they draw attention to genuine shortcomings.

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