# *Chapman Conference*

## The Great Plume Debate

### *The Origin and Impact of LIPs and Hot Spots*

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*Introduction*

It is forty years since *Wilson* [1963] first suggested that the Hawaiian Islands were produced by the oceanic lithosphere moving over a stationary "hot spot" in the mantle, and thirty years since *Morgan* [1971] suggested that plumes exist in the Earth's mantle and play an important role in convection. Large igneous provinces (LIPs), volcanic continental margins, large oceanic plateaus and age-progressive aseismic ridges, along with smaller-volume seamount and ocean-island chains, have all been attributed to mantle plumes.

The tendency over the last decade has been to focus research on those features of large igneous provinces (LIPs) and "hot spots" that can be explained by the plume hypothesis and to neglect those that cannot. Many papers have treated the plume hypothesis as an *a priori* assumption, and little in the way of questioning of the hypothesis has been taught. Recently, however, there has been significant critical thought on the subject and a global debate is now in progress concerning the viability of alternative models, the number of deep mantle plumes and even whether any plumes at all exist in Earth (see, for example, http://www.mantleplumes.org/ and http://www.geolsoc.org.uk/template.cfm?name=NakedEmperor). *The Great Plume Debate* Chapman conference was held to bring together scientists with a wide range of viewpoints in order to promote the exchange of ideas and information and to identify the most outstanding questions and the avenues of inquiry that have the greatest potential to address them.

The meeting commenced with statements of the plume and alternative hypotheses, and finished with a discussion and synthesis. In between, six sessions focused on discrete disciplines, each divided into plume-advocate and plume-skeptic sub-sessions. Approximately half the time was devoted to discussion.

*Plume & alternative theories & predictions*

*Campbell* outlined the plume hypothesis, listing its predictions and giving examples of observations that are consistent with them. The primary predictions are (i) that new plumes should have a head approximately 1,000 km in diameter that flattens to form a disk 2,000 to 2,400 km across when it reaches the top of its ascent, (ii) that this head should be followed by a smaller tail 100-300 km in diameter in the upper mantle, (iii) that plumes should originate from the core-mantle boundary (CMB), (iv) that volcanism should be preceded by domal uplift above the center of the upwelling, and (v) that plumes should be hotter than normal mantle. *Morgan* discussed the work of *Stacy & Loper* [1983] who suggested that a low-density, low-viscosity boundary layer above the CMB grows instabilities that give rise to plumes. *Morgan* suggested that because asthenosphere is destroyed by accreting to the bottom of lithospheric plates at a rate of ~250 $km^3$/yr it must be replenished at the same rate. He went on to propose that plumes are the dominant mechanism by which this replenishment takes place. Down-going slabs introduce basalt, sediment and depleted harzburgite into the mantle, leading to its being heterogeneous on a scale of centimeters to kilometers. Low-melting-point “plums” embedded in plumes melt to form ocean-island basalt (OIB), leaving behind depleted mantle material that later melts to form mid-ocean ridge basalt (MORB).

*Foulger* described the Plate Tectonic Processes hypothesis for the generation of melting anomalies. This hypothesis suggests that melting anomalies develop where the lithosphere extends, and that the amount of melt produced is related to the fusibility of the source material beneath. The lithosphere extends at mid-ocean ridges (MORs), back-arc regions, and in the interiors of both continents and ocean basins where variations in stress due to plate-wide thermal and/or boundary processes cause local extension. Mantle inhomogeneity, and thus variations in fusibility, result from processes such as melt extraction at MORs, slab subduction, lithospheric and lower-crustal delamination and lithospheric metasomatism. The locus of melt extraction may migrate as plate-tectonic-related processes that induce extension evolve *e.g.*, the configuration of plate boundaries. *Elkins-Tanton* described lithospheric removal via gravitational Rayleigh-Taylor instability, popularly known as delamination. This can produce continental magmatism of a range of volumes and can explain observed geochemical compositions and accompanying topographic expressions. In combination with mantle potential temperatures of the order of 1350 to 1400°C, it can produce short-duration eruptive episodes on the scale of a LIP. Amongst many other localities, loss of the lower lithosphere has been suggested to explain the Siberian LIP, in particular the subsidence that accompanied the first kilometer of eruption. *Sandwell* presented new satellite-based marine gravity maps and highlighted linear volcanic ridges that are widespread in the deep ocean basins and associated with 150-km-wavelength gravity lineaments. He proposed that cooling and contraction of the lithosphere produces both extension parallel to the ridge axis and concave–down bowing. This thermal bending stress is optimally released by lithospheric flexure between regularly spaced parallel cracks, and the pull of subducting slabs around the Pacific plate may trigger cracking which is amplified by thermoelastic flexure. Such cracks may provide conduits for the formation of volumetrically small volcanic ridges.

*Posters: Goes* argued that the predicted seismic signature of thermal whole-mantle plumes as generated in dynamic models with pressure- and temperature-dependent viscosity are consistent with observations, assuming that the seismically-identified dense chemical heterogeneity in the deep mantle stabilizes part of the boundary layer above the CMB.

*Lithosphere & mantle physics & dynamics*

*Davies* gave an overview of mantle convection, stressing aspects relevant to the plume debate, including both simple and complex models and the influence of parameters that vary with depth and/or pressure, such as viscosity and the thermal expansion coefficient. He concluded that the Earth generates a lot of heat which requires upward flow which in most models is cylindrical. *Ulrich Hansen* presented the results of numerical experiments in which the amount of internal heating, the effects of temperature and pressure on the viscosity and thermal expansion coefficient were varied independently. He showed that strongly temperature-dependant viscosity leads to episodic plumes with an initially massive head and that subsequent flow follows the established low-viscosity pathway with little entrainment. Both *Davies* and *Ulrich Hansen* stressed that laboratory and numerical models are carried out under conditions that simplify the mantle. *Tarduno* discussed the relative motion of the plumes that have been proposed to underlie the Pacific plate. A number of studies have shown motion of the Hawaiian-Emperor "hot spot" with respect to the spin axis between 81 and 47 Ma, but a first-order consistency between the Hawaiian-Emperor volcanic chain and the Louisville chain suggests that the movement is caused by a Pacific-wide component of mantle flow. However, the mismatch between these chains and chains in the central Pacific suggest that smaller scale, shallow flow must also occur.

*Burov* modeled surface topography predicted by the plume hypothesis using realistic lithosphere rheology. Continental lithosphere involves (i) a free surface, (ii) an elastic-viscous (ductile)-plastic (brittle) rheology and (iii) a stratified structure. Numerical experiments reveal major differences compared with conventional models, *i.e.* transient topographic uplift and subsidence on large (> 500 km) and small horizontal scales (50-400 km). Detectable long-wavelength topographic highs may not be expected but alternating smaller-scale surface features that could otherwise be attributed to regional tectonics are more likely. *King* discussed "edge" convection, whereby fluid near a vertical wall of uniform temperature, *e.g.*, a continent-ocean boundary, drives local, small-scale convection. The 660-km discontinuity is a barrier to small-scale flow, and convective instabilities form nearly unit-aspect-ratio cells. Thus "hot spots" within 600-1,000 km of a continent-ocean boundary may be attributable to edge convection. Seismic tomography suggests that ~20 "hot spots", mostly in the Atlantic and on the African plate, might be candidates. *van Wijk* focused on how continental rifting often follows weak zones in the lithosphere, such as orogenic belts. She showed numerical modeling of Atlantic-type passive margin formation. The results show that old structures influence the location of rifting, lithosphere deformation and thermal evolution during rifting, and decompressional melting. Also, the pre-breakup magmatic characteristics of rifted margins (timing and volume of melt intrusions, extrusions and underplating) can be explained with numerical models adopting normal mantle temperatures – they are dependent on the inherited structure of the lithosphere. *William Stuart* showed modeling results for a hypothetical propagating crack beneath the Hawaii-Emperor volcano chain. Three-dimensional thermoelastic stress rates were calculated for a model Pacific plate cooling according to seafloor age. Horizontal tensional stress is predicted normal to the entire Hawaii chain, and strong tension near Samoa. Plate stress, and features dependent on it, are expected to be approximately stationary with respect to the plate boundary reference frame in this model.

*Posters: Sears* presented an hypothesis proposing that Gondwanan and Rodinian fractures and associated LIPs define geometrically regular, energy-minimizing arrays of interspersed hexagons and pentagons fitting the spherical projection of a truncated icosahedron. *Tiwary* proposed a genetic relationship between the 65-68 Ma old Deccan volcanic province, extensional tectonism and Precambrian magmatism and suggested that a plume is not required. *Beutel* suggested that large volumes of melt can be produced by overpressuring mantle material trapped between the transition zone, ringing subduction zones, capping continents, and/or advancing cratonic roots behind regressing slabs, *e.g.,* the Afar "hot spot". *Davies* discussed "splash plumes", a new class of cylindrical thermal upwellings discovered in numerical spherical models which are not rooted in thermal boundary layers.

*Temperature*

An obvious prediction of the plume hypothesis is that mantle plumes should be hotter than the adjacent mantle and should therefore produce higher temperature magmas. Petrologists use glass and whole-rock compositions, and the forsterite content of phenocrysts, to calculate the temperature of the mantle sources of mafic and ultramafic rocks. Using this method, *Arndt* obtained temperatures for the Hawaiian and Gorgona magmas that are 100-150°C, and 200°C hotter than the MORB source respectively. Archaean komatiites yield temperatures that are 300°C higher than the modern MORB source. *Rhodes* used the same approach to calculate the temperature of the Hawaiian source. However he used constant distribution coefficients (Kd) for the partitioning of Fe and Mg between olivine and melt whereas *Arndt* used values that varied with composition. Both results found that the Hawaiian source is appreciably hotter that the MORB source. *Lesher* used the maximum MgO of magmas to show how the source temperature varied through time. He found that the maximum MgO of Phanerozoic magmas is 22%, compared with 32% in the Archaean. He postulated that the hottest magmas were much hotter in the Archean – too hot to have formed from ambient mantle – and that the change was abrupt and not gradual, indicating a fundamental change at that time.

*Harris* discussed heat-flow data collected on "hot spot" swells and suggested that shallow fluid flow can obscure thermal conditions within or at the base of the lithosphere. Heat flow data collected with seismic reflection profiles at Hawaii and Reunion reveal great scatter and short-wavelength spectral peaks consistent with fluid flow. He suggested that bathymetric relief is capable of driving significant fluid flow that may suppress the background thermal field and cautioned that fluid flow may mask variations in sublithospheric heat flux. *Presnall* re-examined the model of *Klein & Langmuir* [1987; 1989] and *Langmuir et al.* [1992] that interprets MORB magmas as fractionated aggregates of melts from a wide range of pressures in melting columns. Data from

MOR and Icelandic basalt glasses show no hint of the olivine-controlled fractionation required by this model. The data are consistent with magma generation in the range 1-1.5 GPa from a heterogeneous mantle, implying magma-generation temperatures of ~1260-1280°C. *Falloon* modeled magmatic crystallization temperatures of tholeiitic magmas from Kilauea and MORB rocks and glasses from ODP Leg 148 (hole 896A) using PETROLOG. The results show that there is little difference (< 10°C) in the magmatic temperatures at 1 bar, and temperatures and depths of origin, between two well-studied OIB and MORB tholeiite suites. Indeed, the MORB suite has a slightly higher temperature. The results find no evidence for a temperature contrast of ~200-250°C between "hot spot" or "deep-mantle plume" sources and ambient (MORB source) asthenospheric mantle.

*Posters: Foulger* reviewed temperature estimates for the mantle beneath Iceland from ~15 seismic, petrological and other analyses, showing that almost all required or permitted temperature anomalies of < ~100 K. *Keays* presented results suggesting that the high concentrations of Pd and Ir in komatiites, komatiitic basalts, picrites and some continental LIPs require both high temperature and high-degree partial melting of their mantle source reservoirs. *Mashima* argued against a hot mantle plume source for the Cenozoic basalts of NW Kyushu, SW Japan, pointing out that tomography suggests the 660-km discontinuity beneath NW Kyushu is cold and the petrochemistry of primitive NW Kyushu basalts indicates that their source is not hot. *Stein* revisted the question of whether hydrothermal circulation masks anomalously high heat flow at "hot spots", comparing heat flow data and other factors from both "hot spot" regions and areas of similar ages far from "hot spots". She found no clear evidence for the proposed suppression of heat flow by hydrothermal circulation, except for some sites within about 200 km of the swell axes.

*Geochronology*

*Duncan* discussed the eruption rate of LIPs, with special emphasis on the North Atlantic Igneous Province. He argued that the available radiometric and magneto-stratigraphic data point to major LIPs, such as the North Atlantic Igneous Province, forming in about 1 Myr. Volcanism occurs over an area several thousands of kilometers in diameter as several large discrete flows, each with a volume of $10^3$ to $10^4$ $km^3$, rather than as a continuous flow, and then contracts to more focused flow. These observations are consistent with the starting plume hypothesis for LIPs. *Hoernle* described an age progression on seamounts NE of the Canary and Madeira islands that agrees with age progressions on the Walvis and St. Helena chains. This can be explained by rotation around a common Euler pole, consistent with the plume hypothesis. The Hikurangi plateau, NE of New Zealand, has the same 120-Ma age and geochemistry as the Ontong Java and Manihiki plateaus, requiring two Ontong-Java-sized plateaus of similar age in the Western Pacific or one combined plateau double the size of present Ontong Java plateau. Cenozoic intraplate volcanism in New Zealand does not fit the plume hypothesis. *Koppers* described two types of seamount trails in the Pacific; long chains that show well-developed age progressions, such as the Hawaiian and Louisville chains, and numerous shorter chains that do not. The deep-plume hypothesis can explain the former but not the latter.

*Baksi* critically assessed radiometric ages for oceanic “hot-spot tracks”. The argon-dating methods are most commonly used. However, samples from oceanic islands and the seafloor, tend to be altered and as a result the literature contains many unreliable ages. According to his interpretation, there is no reliable evidence for a linear progression of “hot spot” track ages from the Indian and Atlantic oceans, including the Ninetyeast Ridge, the Chagos-Laccadive and Mascarene Plateaus (Reunion “hot spot”), the New England Seamounts (Great Meteor “hot spot”) and the Rio Grande Rise and Walvis ridge (Tristan da Cunha “hot spot”). *O’Connor* reviewed the relative merits of shallow/local vs. deep/global “hot spot” theories. An important question regarding a proposed plume at any locality is: “where is the mantle plume”? The fundamental, simple assumption inherent in the plume hypothesis for small “hot spots” marking the location of narrow plume “tails” seems not to be holding up in light of age dating of new dredge samples from seamounts and aseismic ridges *e.g.,* at the Galapagos and Foundation seamount chains.

*Posters: Tegner* described secular variations in the pressure of fluid inclusions in the Skaergaard intrusion, east Greenland, that constrain the timescale of volcanic build-up and subsidence. He surmised that 7.3 ± 1.5 km of flood basalts were emplaced over the Skaergaard intrusion in less than 0.3-0.4 Myr. *Watts* presented work on global gravity and bathymetry and the spatial and temporal history of submarine volcanism deduced from estimates of the elastic thickness of the oceanic crust at the time seamounts were emplaced. *Widdowson* reported high-precision $^{40}Ar/^{39}Ar$ ages from the stratigraphically highest and lowest basalts of the Deccan lava succession. He proposed that these new data suggest a duration of 2-3 Myr for the eruption of the main Deccan province.

*Seismology*

An unambiguous prediction of the mantle plume hypothesis is that strong plumes such as Hawaii, Reunion and Iceland should originate from a thermal boundary layer, probably the CMB. As a consequence, it should be possible to use seismic images to trace these strong plumes to the CMB. Recent advances, especially the development of finite-frequency ("banana-doughnut") tomography [*Montelli, et al.*, 2004], have been used to produce images of plumes at all mantle depths. *Allen* presented the results of resolution tests designed to constrain the low-velocity structure below Iceland. His results suggest that Iceland is underlain by an anomaly 100-200 km wide that can be traced to a depth of at least 350 km. He suggested that a plume model was appropriate for Iceland but not for the Newberry (High Lava Plains) chain. *Zhao* showed local, regional and global tomographic images interpreted as mantle plumes and subducting slabs. He argued that plumes beneath Hawaii and Iceland could be traced to the CMB and that superplumes underlie Africa and the South Pacific. He also showed images interpreted as small-scale, weak plumes originating at higher levels. The anomalies are not vertical, suggesting that plumes are deflected laterally by mantle convection currents. *Nolet* argued that well-constrained seismic images can be used to estimate the heat- and volume flux of mantle plumes if their viscosity and chemical density are known. This approach yields a plume flux that is an order of magnitude higher than accepted values. He suggested that the plume volume flux should balance the flux of down-going slabs. This would mean that the Earth's two principal modes of convection are in balance, as also suggested by *Morgan*.

*Deuss* emphasized the limitations of global mantle tomography. Body waves are suitable to search for narrow plumes, but data coverage is limited, a particular problem in oceanic areas where most plumes are proposed to lie. Body waves are only sensitive to velocity perturbations and it is unknown whether imaged features are caused by temperature-, phase- or compositional anomalies. Normal-mode data can separate temperature and composition varations in the mantle, but only on a large scale. *Trampert et al.* [2004] used such data to show that the African and Pacific "superplumes" are compositional and dense and not thermally bouyant. *Julian* expressed concern that the "plumes" claimed to have been imaged by *Montelli et al.* [2004] might be artifacts of non-uniform sampling of the mantle by seismic waves. He proposed a new seismic method that might be able to detect narrow plumes – "plume-guided" waves. Low-wave-speed channels act as waveguides, and "plume-guided" waves would be little affected by bends or other geometric complexities, but would behave in a similar way to light in fiber-optic cables. The main question is whether such waves are excited sufficiently to be observable. *Lay* gave an overview of the D" region, a layer above the CMB several hundred kilometers thick that is widely invoked as the putative mantle plume source. A ~1,000°C thermal boundary layer is expected there. Large-scale seismic heterogeneities exist in D", with two massive low-shear-velocity provinces beneath Africa and the South Pacific. Both have unusual $Vs/Vp$, with much stronger decreases in $Vs$ than in $Vp$. They may be anomalously dense rather than anomalously hot.

*Posters: Laske* reported on the SWELL ocean bottom seismometer deployment around Hawaii. A deep, low-velocity anomaly suggests that the cause for the swell relief is sub-lithospheric but not centered beneath the island chain. *Ritter* described seismic imaging of the Eifel region, central Europe. Low-wave-speed anomalies for both *P*- and *S*-waves extend down to the transition zone, where the 410-km discontinuity is depressed by 20±5 km while the 660-km discontinuity is unperturbed, consistent with a temperature anomaly near the top of the transition zone only.

*Planetary*

*Hamilton* argued that all circular features on Venus, over 5,000 in number, are meteorite impact craters and not due to Venusian mantle plumes. He claimed that the plume hypothesis was applied to Venus to explain an assumed need for loss of heat from a planet that lacks plate tectonics and asserted that Venusian plumology became dogma by repetition and self-citation and lacks convincing evidence-based justification. He argued that Venusian circular structures have the characteristics expected of eroded, buried impact structures and impact-melt constructs, and likely record late-stage planetary accretion older than 3.9 Ga. *Hansen* proposed that Venus, which is expected to have a heat budget similar to Earth and lacks plate-tectonic processes, preserves an excellent surface record, and was not catastrophically resurfaced < 1 billion years ago, as is widely acccepted. She proposed that volcanic rises represent plume-lithosphere signatures based on size, morphology, apparent depth of compensation and geologic history. Crustal plateaus represent crystallization of huge lava ponds which may result from bolide impacts causing massive partial melting of the mantle. Coronae comprise at least three different geomorphic groups. These include those > 1000 km diameter which represent plumes on thin lithosphere, radial coronae which represent compostional (as opposed to thermal) diapirs, and circular lows, which form a previously unrecongnised style of impact crater. *Adrian Jones* discussed meteorite impacts as a possible mechanism for LIP formation and "hot spots" on Earth. The combined effects of impact melting, enhanced by sub-crater decompression melting in computer simulations for ~200-km-diameter craters produce characteristic high melt volumes of approximately $10^6$ $km^3$ derived from the uppermost ~150 km of Earth's mantle. The Ontong Java Plateau was successfully modelled as an impact-induced LIP and testable characteristics were predicted. *Reese* presented work on impact-induced melting as a possible mechanism for creating Tharsis Rise on Mars, a major center of volcanism and tectonism characterized by large gravity and topography anomalies. It has been suggested that Martian mantle convection is dominated by a single, large, long-lived upwelling that created Tharsis Rise, but an alternative is that the upwelling was produced by a large impact during planetary formation. Fully three-dimensional spherical shell simulations of thermochemical mantle convection suggest that this model is viable.

*Posters: Jurdy* presented a study of uplift and rifting on Venus, examining the relationships between chasmata, coronae and impact craters. On the basis of distribution and topography, and relating rifting and uplift, she favored a diapir origin for coronae as opposed to an impact origin.

*Field Evidence*

The plume hypothesis predicts about a kilometer of domal uplift prior to LIP volcanism. *Saunders* discussed uplift associated with the Siberian Traps, where it has been claimed that there was pre-eruption subsidence and therefore no associated plume. He showed evidence for up to one kilometer of uplift in the West Siberian Basin-Khatanga Trough, but pointed out that edge convection could produce uplift of similar magnitude. *Steven Jones* used sedimentary stratigraphy to map out transient uplift associated with the North Atlantic Igneous Province. An early phase of intraplate igneous activity was accompanied by relatively minor, localised uplift, while a late phase related to Europe-Greenland break-up was accompanied by widespread, kilometer-scale uplift. He reasoned that the short (< 1 Myr) onset of both uplift phases is best explained by rapid injection of hot mantle into a low-viscosity asthenospheric channel. *Xu* described the erosion of mid-Permian limestone below the Emeishan LIP province in China. He also identified two phases of uplift. The first occurred about 3 Myr prior to volcanism, was domal, and reached a maximum of about one kilometer near the center of the dome. The shape of the uplift agrees well with that predicted by some laboratory and computer models of uplift associated with a plume head. He attributed the second phase of uplift to the injection of magma into the crust at the crust-mantle boundary.

*Sheth* described several contradictions between observations from the Deccan – Reunion system and the plume model. He suggested that the interplay of intersecting continental rift zones caused the circular outcrop of the Deccan and the Lakshadweep-Chagos Ridge, Mauritius and Réunion are located along leaky fracture zones. He argued that the planation surfaces on the varied basement rocks of the Deccan lavas, and the typical absence of basement-derived conglomerates under the first lavas throughout the province, are evidence against plume-head-generated pre-volcanic uplift. *Sallares* described seismic and gravity data from the Galapagos volcanic province that had been used to investigate whether a mantle density anomaly is required. The results showed that it is difficult to account for the seismic structure of the ridges if it is assumed that the source is a thermal anomaly. A compositional heterogeneity for the primary source of the Galapagos "hot spot", possibly a mixture of depleted mantle and recycled oceanic crust, fit the data better. *Winterer* pointed out that in addition to fresh fracture systems, younger midplate volcanism commonly occupies older lines of weakness such as fracture zones, ridge-parallel faults, abandoned spreading centers and pseudofaults created during spreading-ridge propagation. The emplacement ages of such volcanoes are typically not a linear function of distance. He proposed that pre-existing magmas beneath the lithosphere can be tapped by the opening of new fissures, especially where the lithosphere is in tension.

*Posters: Abt* reported data in support of a delamination origin for the Columbia River LIP, in particular the absence of significant crustal uplift preceding eruption. *Breivik* studied the Moere Margin to the Aegir Ridge in the north Atlantic and concluded from ocean-bottom seismometer data that the igneous productivity was low once breakup-related magmatism had subsided, and that the influence of the Iceland "hot spot" was very weak in the Norway Basin. *Cawthorn* described the Kaapvaal craton in southern Africa, the home of some of the oldest komatiites and best-preserved Proterozoic LIPs in the world. Much of the 200 km-thick Archaean lithosphere survived these magmatic events, suggesting that the magma source did not ascend above a depth of 200 km. *Dalziel* investigated whether LIPs had formed at random locations on Earth's surface throughout geological time, as predicted by the plume hypothesis, and concluded that they had. *Jordan* reported that propagation of the Brothers fault zone could not be responsible for time-progressive volcanism at the Oregon High Lava Plains, and advocated models that relate the volcanism to the Yellowstone melting anomaly. *Khodayar* reported that compressional structures are absent in west and south Iceland. Tectonism is extensional with dykes, normal- and strike-slip faulting comprising six fracture families. These strike parallel, perpendicular and oblique to the rifts.

*Norton* proposed a classification for "passive" continental margins based on the timing of onset of volcanism, with "volcanic" margins simply a result of early onset of volcanism and "non-volcanic" margins resulting when volcanism did not precede sea-floor spreading. *Sager* reported that the revised Pacific apparent polar wander path is consistent with previous findings that the Emperor melting anomaly moved southward by 15-20 degrees while the plate itself had little northward movement, contrary to "hot spot" models. The Emperor chain formed at a time bracketed by rapid polar movement and then polar standstill (*i.e.*, some sort of geodynamic or tectonic reorganization of the plate). *Tsikalas* used regional transects across the Norwegian margin to show that it can be divided into a series of rifted, sheared, and oblique segments that appear to have experienced different structural, magmatic and temperature histories. *Vogt* summarised plume and non-plume models for Bermuda, the difficulties with each and suggested possible ways to test these hypotheses. *Widdowson* synthesized evidence from the Deccan Traps in support of a southward migrating locus of volcanism and local uplift.

*Petrology & Geochemistry*

*Hawkesworth* pointed out that a plume is a physical process and cannot be identified on the basis of geochemistry. Basalts from Auckland, the Cape Verde islands, certain seamounts and Hawaii have similar, geochemically enriched characteristics but it is unlikely that they were all derived from plumes. Plume-derived magmas are identified better by their high eruptive volumes and eruption rates, which require a zone of anomalously high melting in the mantle that is presumed to be anomalously hot. *Rhodes* discussed the evolution of Hawaiian basalts in terms of a compositionally and thermally zoned plume.

*Takahashi* discussed the role of melting recycled oceanic crust (eclogite) in the mantle. He showed that the degree of interaction between the eclogite-derived melts and adjacent peridotite decreased with temperature leading to alkalic picrites at high temperature, olivine tholeiites at intermediate temperature and basaltic andesite when eclogite melting occurs below the peridotite solidus. Ignoring the role of eclogite in a plume source may lead to temperature being overestimated by as much as 100ºC.

*Fitton* pointed out that nearly all OIB has positive $\Delta$Nb [*Fitton, et al.*, 1997] that probably derives from recycled subducted oceanic crust. This characteristic is shared by many LIPs, small MOR seamounts clearly not plume-related, and basalts in some continental rifts. Some rifts have erupted geochemically uniform lavas continually while the region drifted through tens of degrees of palaeolatitude. He concluded that the geochemical diversity of "hot spot" basalts requires that if mantle plumes do exist they cannot all share a common mantle source. *Keskin* described the Eastern Anatolian region, one of the best examples of a continental collision zone in the world. The region contains abundant thick eruptives and a regional domal shape comparable to that of the Ethiopian High Plateau, although the Anatolian dome has a north-south shortened asymmetrical shape. Although these have been interprted as plume-derived, geologic and geochemical data provide evidence against a plume origin, but suggest instead passive upwelling associated with the mechanical removal of much of the mantle lithosphere as a result of slab-steepening and breakoff. *Scherstén* reviewed the subject of proposed CMB tracers and discussed the coupled $^{186}$Os/$^{188}$Os and $^{187}$Os/$^{188}$Os system and the extinct Hf-W isotope system. Hawaiian lavas do not have any resolvable W isotope anomalies, even when possible masking by a recycled component is considered. He concluded that a case for a CMB origin cannot be made on the basis of Os isotopes either.

*Posters: Class* suggested that high $^3He/^4He$ comes from old depleted mantle, isolated from convection and upper mantle degassing for 1-2 Gyr. *Frezzotti* reported $CO_2$-$H_2O$-$H_2S$-diamond fluids in garnet pyroxenite xenoliths from Hawaii and argued that they represent a strong metasomatic agent able to induce partial melting at the base of the lithosphere at normal mantle temperatures, obviating the need for plumes beneath "hot spot" volcanoes. *Griffin* described the Balcones Igneous Province of south central Texas and suggested it represents a small portion of a Cretaceous diffuse igneous province and is not plume-related. *Ivanov* reported on the atypical Pliocene-Quaternary alkaline basalts of the Sredinny Ridge of Kamchatka. He concluded that typical island-arc high-field-strength-element-depleted magmas were generated from a spinel-bearing mantle source. However, atypical within-plate magmas originated from a deeper garnet-rich source with the composition of recycled oceanic crust. *Mashima* argued on geochemical grounds that partial melting of basalt/peridotite hybrids could not have formed NW Kyushu basalts and that recycling of Archean oceanic crust with a peridotitic komatiite composition is the best candidate source.

*Meyer* presented data from the Vøring Plateau in the north Atlantic from ODP Leg 104, Site 642E, emphasising that the diversity of samples offers opportunity to distinguish geochemical signatures related to crustal contamination from those related to intrinsic mantle source variations. *Sensarma* described the ~2.5 Ga Dongargarh Group in the Central Indian Craton, a ~10 km thick volcano-sedimentary sequence with both mafic and felsic lavas covering an area at least ~250 km x ~90 km in extent. He suggested a model of an anomalously hot plume head melting in an extensional environment. *Finlay Stuart* made a statistical comparison of $^3He/^4He$ distributions in MOR and OIBs, concluding that the source of high $^3He/^4He$ is distinct from the MORB mantle source. *Pandey* presented a numerical study of a source for the Deccan Traps in large volumes of magma stored in magma chambers at shallow crustal depths. *Takahashi* described experimental constraints on garnet pyroxenite as a contribution to high-Fe melts from the Cretaceous Parana-Etendeka LIP. He presented a model to explain the limited occurrence of ferropicrites at the base of continental LIPs and their apparent absence in OIB successions.

*Jordan* contributed a poster and a short oral presentation on communicating the plume debate to undergraduate geoscience students. He described a classification of theories as central, frontier, and fringe, all theories beginning as fringe theories. Most physical geology textbooks present mantle plumes as accepted and only one suggests it might be contested. He solicited views on if and how the present controversy regarding the existence of mantle plumes should be presented in undergraduate textbooks and subsequently established a web-based questionnaire with which he solicited opinion.

*Summary*

Substantial discussion periods followed each sub-session and the enthusiasm of debate illustrated that it is scarcely possible to schedule too much discussion time in a meeting of this kind. Many assertions made by both plume-advocate and plume-skeptic speakers were challenged from the floor. The assertion that a plume must come from the

CMB was contested on the grounds that numerical convection modeling can produce plumes originating from within layers. Propagating cracks is a popular alternative mechanism proposed for Pacific volcanic chains but the question was posed whether this model can explain the Hawaii and Louisville chains, which have the most robust time-progressions. It was also questioned how the hypothesis could be tested, and how sufficient volume of melt could be produced by the relatively small pressure release expected from cracking. It would seem that such cracks would have to tap pre-existing melt reservoirs in the asthenosphere.

Numerical convection modeling readily produces plumes, but critics questioned whether the physical properties of the deep mantle are sufficiently well known and sufficiently realistically modeled, by computer programs that cannot yet simulate self consistently surface plate motions. Whether the absence of domal uplift can negate the plume theory was challenged by recent modeling using realistic continental lithospheric rheologies, which suggests that complex patterns of uplift are expected. The problem of how melt is extracted from the mantle via hypothetical cracks through the lithosphere was raised, as such models predict only narrow rifts into which asthenosphere can rise.

The question of the source temperature of primary melts was particularly vigorously debated. End-member opinions proposed on the one hand a temperature anomaly for the source of Hawaiian lavas relative to MORB of ~200 K, with a smaller anomaly for the source of Icelandic lavas, and on the other hand no significant temperature difference for Hawaiian, Icelandic, and MOR lavas. Most of the discrepancy can be attributed to variations iin olivine compositions, partition coefficients and oxidation states used, and which methods were used to "correct" the compositions for high-level fractional crystallization. An impromptu workshop was later held to discuss the detailed differences in the various computation approaches.

The geochronology of seamounts and chains, in particular on the Pacific sea floor, reveals a spectrum of behavior from the regular, linear age-progression of the narrow Hawaiian chain to no recognizable temporal patterns in regions of diffuse volcanism. Alternative (non-plume) mechanisms *e.g.,* related to slowly evolving plate boundary configurations, also predict time-progressive chains. Those present generally agreed, though not unanimously, that volcanic time-progression is not required by, nor diagnostic of, a plume. Nevertheless robust dating of geologic events is critical, in particular in view of the large errors in many old dates, given that age constraints underpin many models of volcanic regions.

Both seismic models presented and interpretations of them were vigorously debated. Concern was expressed about the reliability of recent images obtained using finite-frequency ("banana-doughnut") tomography and interpreted as plumes. The problem of non-uniform sampling was a particular focus. Concerns were also expressed regarding the correspondence between seismic velocity and physical parameters such as temperature, composition and melt content, particularly in the light of the recent finding that the Atlantic and Pacific "superplumes" are not thermal in origin [*Trampert, et al.*, 2004]. Notwithstanding these caveats, the necessity of explaining the common observation of low-velocity anomalies under "hot spots" such as Iceland and Eifel was highlighted, along with possible correlations between "hot spot" locations and seismic anomalies in the D" layer above the CMB.

Study of the effect of meteorite impacts on Earth, Mars and Venus is a rapidly developing subject with wide scope for further testing. Debate was particularly enthusiastic over plume vs. impact models for the circular features on Venus. Plume and compositional-diapir models for the coronae have been most popularly supported during recent years. Detailed development of the impact hypothesis is urgently needed, in order that its predictions may be compared in detail to those of the plume/diapir model.

Many researchers consider substantial domal uplift to be a robust diagnostic of an impinging plume head, notwithstanding recent modeling predicting instead a complex pattern of vertical motion. There was disagreement regarding whether uplift occurred prior to the emplacement of the Siberian Traps and the Deccan Traps. Uplift of the north Atlantic region contemporaneous with ocean opening occurred over a wide area but was not centered beneath Greenland, the most popularly suggested plume center. The Deccan Traps – Reunion "hot spot" system is considered by many to be an ideal example of a plume-head/plume-tail system. This model was criticised, but many present felt that the challenge to alternative models remains, both there and at all "hot spot" localities, to explain quantitatively how the melt volumes observed can be extracted from the mantle given the sometimes modest amounts of lithospheric widening proposed in crack-type models.

There was broad agreement that the presence of OIB is not a plume diagnostic, as is compellingly illustrated by the observation highlighted by a number of people that OIB is widespread where no-one would seriously argue in support of plumes. There was also widespread agreement that OIB geochemical signatures originate in recycled near-surface materials such as oceanic and continental crust and mantle lithosphere, possibly metasomatised, and wedge material. High $^3He/^4He$ isotope ratios are still argued by some to come from the lower mantle, but their use as a plume diagnostic is limited since their absence is generally not considered to significantly weaken a plume model.

In general there was a tendency for those present who advocated the plume model to favor fewer than have been considered in the past. Some popular "hot spot" lists involve up to ~ 50 plumes. Many of those present at the meeting favored less than ten, and often less than five. Opinion differed regarding which these were, however.

The last afternoon was devoted to synthesis and discussion. *Campbell* summarized his view that any hypothesis for the origin of LIPs must explain the sudden appearance of basalt over large areas, high eruption rates, sudden contraction to a narrow chain of volcanoes, age progression along a chain, high-MgO basalts and thickened oceanic crust. He synthesized the predictions of the edge, crack, eclogite-melting and bolide-impact theories, and questioned their ability to explain thickened oceanic crust and high MgO basalts. He opined that the main problems with the plume hypothesis are the lack of a linked head and tail at some localities and the absence of an identified seismic anomaly beneath some volcanic chains. In the light of the week of presentations and discussions, *Foulger* again questioned whether the plume hypothesis could be tested, in particular if the absence of observations *e.g.*, precursory domal uplift, petrological evidence for high temperature or a downward-extensive seismic anomaly, was not accepted as disproving the presence of a plume.

Substantial time was devoted to attempting to define a plume. A *plume* is a well-defined fluid-dynamics term, but there were widespread variations in opinion regarding how the term *mantle plume* should be defined. A suggested definition was "*a narrow, dominantly vertical flow driven by buoyancy*". However, after considerable debate the effort to attain agreement faltered. *Morgan* expressed the viewpoint that the term cannot be defined because all mantle plumes are different. This is the crux of a major objection that skeptics have leveled at the plume hypothesis – that in the extreme it is defined *a-posteriori* at individual localities by what the local observations are and is, in practice, not disprovable. This approach characterizes plume science in the broad sense, though it does not necessarily apply to every researcher. It is also related to the diverse usage of the term "plume" to mean different envisaged phenomena – a practice considered by some to be a necessity and by others to be a problem.

Plume-advocates pressed for clear statements and definitions of the alternative hypotheses, which some felt were still unclear. Concern was expressed that the alternatives comprise a high-entropy assemblage of *ad-hoc* models that are different for each locality. *Foulger* emphasised that a single, generic, one-size-fits-all replacement model for the plume model was not envisaged, for precisely the reason that *Morgan* gave for his reluctance to define precisely a mantle plume, *i.e.*, the great diversity of "hot spots".

The bolide-impact theory forms a special category of alternative theory that is rigorously predictive and quantifiable. However, the others share the common generic element of being linked to shallow, plate-tectonic-related processes that involve extension and tapping of mantle made variably fertile by the recycling of near-surface materials. Beyond this broad commonality, the features at individual melting anomalies are predicted to be related to local features.

The envisaged relationship between plate tectonics and plumes was discussed. The hypothesis that plume impingements on the base of the lithosphere cause supercontinents to break up seems to imply that plumes have a major role in driving plate tectonics. *Morgan* confirmed his opinion that plate tectonics is driven by plumes. This view was not held by many others.

The question of rigor in reporting observations and exploring permitted suites of candidate interpretations was considered. The importance of maintaining quality in reporting was emphasized. This requires careful reviewing and editorial work at the publishing stage. The publication of poor-quality data can seriously mislead and be counter-progressive. Subject reviews should ideally be inclusive of contradictory data and highlight problems, an approach which will bring to the attention of others the most important problems that need further work.

The discussion and synthesis session finished with a review of the most important research challenges for the future. These may be summarized:

- *Mantle physics:* Self-consistent models that can reproduce plate tectonics are required, along with a better understanding of critical mantle physical parameters, *e.g.,* CMB heat flow, lower-mantle viscosity and understanding the importance of small-scale convection. Better predictions of the temperatures, masses and compositions of postulated plume- and alternatives-derived magmas are required.
- *Lithosphere physics:* Understanding is required of lithosphere behavior during a major thermal event, *e.g.*, the arrival of a plume or a bolide, delamination, cracking, or rifting. The response of the lithosphere to stress, *e.g.,* cracking, needs

to be clarified, along with the character of lithospheric stress and the cause of rifting.

- *Temperature*: Geothermometers need to be refined. Our understanding of the phase equilibria of $CO_2$-bearing systems and the influence of composition on the partitioning of Fe and Mg between olivine and silicate melt needs to be improved. Understanding of the physics of melting at various depths is required and refinements in other geothermometry methods *e.g.,* seismology.
- *Geochronology*: More high-quality age constraints, including re-analysis of important island chains and LIPs, is required.
- *Seismology*: Interpreting mantle seismic anomalies in the mantle and D" is a challenge – are they hot, cool, buoyant or dense? We need to understand the transfer of material between the upper and lower mantles, and develop innovative high-resolution experiments to improve seismic imaging of the deep mantle. Experiments are required to image seismically the plume heads that are predicted to remain hot for ~300 Myr and to underlie young LIPs, along with stalled plume heads. Seismic mapping of anomalously thick oceanic crust and continental and oceanic crustal underplating is needed.
- *Planetary*: Hypotheses for the various circular structures on Venus should be critically compared and tested. Geological field evidence for terrestrial meteorite impacts is required to test whether there is a direct relationship to volcanism.
- *Field evidence*: Observations that are diagnostic of proposed mechanisms of formation, *e.g.*, vertical motions, temperature and mantle structure, should be preferentially targeted. Quantitative models of uplift associated with plumes and continental rifting need to be refined and tested against field observations. Lists of potential plume localities need to be refined. Distinguishing cause and effect, *e.g.,* rifting and volcanism is a challenge. Unexplained characteristics of the Hawaiian-Emperor system should be a focus of continued study.
- *Petrology & Geochemistry*: Improved melt generation models are needed to explain diffuse volcanism *e.g.*, on the Pacific plate, and the largest oceanic and continental LIPs. Experimental and theoretical determination of high-pressure trace-element partition coefficients and eclogite-peridotite interactions is required. The enigma concerning the origin(s) and source(s) of OIB is a problem of fundamental importance.

Two books are in preparation as a result of this meeting. It is expected that they will be published as an AGU monograph and a special issue of Chemical Geology.

The meeting closed with warm votes of thanks for the numerous organizations and individuals who contributed to the running of the meeting. These included the American Geophysical Union for sponsoring the meeting and the staff involved (Melissa Ficek and Marlie Brill), NSF, Statoil, University of Durham and IAVCEI for financial support, Godfrey Fitton and University of Edinburgh for much logistic help, Godfrey Fitton, Ian Dalziel, Henry Emeleus, Valentin Troll and Brian Bell for leading successful and enjoyable pre-, syn- and post-meeting fieldtrips in Ballachulish, Glen Coe, Arisaig (the "Road to the Isles") and on the islands of Rum, Mull and Skye.

This report was prepared in consultation with all the meeting participants, many of whom contributed to writing it.

For more information and resources pertaining to this Chapman meeting, including some of the posters and slide sets presented, visit http://www.mantleplumes.org/Chapman/Information.html

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