The row over earth's mantle plume concept

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Five blind men wanted to have an idea about an elephant. Feeling its long tail, the first man said that the elephant is like a rope; 'No, it is like a trunk of a tree', exclaimed the second blind man, feeling one of its legs. 'Elephant is like a wall,' said the third man sweeping his hands across its massive sides. The fourth felt its broad ears and asserted that the elephant is like a fan while the fifth blind man stroked its trunk and shouted 'Even a blindest man can tell the elephant is like a snake'.

– An old Indian tale

The concept of mantle plumes, which like the elephant in the tale, has drawn conflicting opinions, was advanced in 1970s in the wake of plate tectonic theory to explain mid-plate or hot spot volcanism erupting far from the usual sites along the plate boundaries (ridge volcanism). This was proposed, initially to explain string of volcanic islands exhibiting a trend of age progression, such as the Hawaii-Emperor chain in the Pacific Ocean (mid-Pacific plate) and subsequently applied to explain the Chagos–Laccadive–Reunion chain in the Indian Ocean (Indian Plate) and similar tracks elsewhere. These island-chains are supposed to have formed by eruptions from a fixed hot spot plume in the mantle, over which the plate moved. Over the years, the mantle plume concept gained acceptance and was applied to explain diverse magmatism and also for major geographic, environmental, climatic and biotic events in earth's history.

Mantle plumes are considered as solid-state narrow upwelling currents originating from a thermal and compositional boundary at the core–mantle boundary (CMB 2900 km deep) or higher from the junction of the upper and lower mantle. Upon reaching the base of the lithosphere, the plume flattens into a broad head and finally erupts to form volcanic rocks. The trace element, isotopic and geophysical data of these rocks (ocean island basalts or OIB) are found to differ from those of plate boundary volcanism (mid-ocean ridge basalts (MORB), and this led to the belief that their melt-sources must be different, the former believed to tap lower mantle reservoirs and the latter, MORB, the upper mantle ones.

Plume heads erupt rapidly (< 1 million years), and are supposed to form large igneous provinces (LIPs) covering > 1 million km[2], such as the Phanerozoic continental flood basalts (CFBs), oceanic plateaus, immense radiating and linear dyke swarms, e.g. Deccan Lavas, Kerguelen plateau, Ontong–Java Plateau, Caribbean Oceanic Plateau, Mackenzie and Grenville dyke swarms (Canada), Rajmahal Traps (India), Siberian Traps, Yellowstone (USA) and the large volcanic island of Iceland[1]. High-Mg basaltic rocks, komatiites, picrites, ophiolites and other mafic and ultramafics, as well as sulphide ores, diamond deposits and giant hydrothermal ore deposits present in Archaean and early Proterozoic greenstone belts in India, Canada, S. Africa and Australia are considered remnants of plume delivered oceanic plateaus[1].

Many of the alkaline magmatism around the world and carbonatite occurrences are linked to flood basalt events. The Deccan event is credited for the carbonatite occurrences at Mer, Mundwara, Ambadongar in western India and the Kerguelen event for those in Sung Valley, Sampchampi and Jasra in eastern India[2]. Similar carbonatite occurrences are associated with the Parana-Etendeká (South America), Siberian and Keweenewan (Africa) events[1]. The parent carbonated magmas for these rocks are believed to form by liquid immiscibility processes from silica undersaturated melts at depths[2] and their Nd, Pb, Sr and He isotope data are comparable to the OIB rocks. Felsic magmatism giving rise to rhyolites, dacites and granites in the intraplate setting, as in NW Indian Malani magmatism, are considered products of a hotspot related to Pan-African thermal event[3]. Silicic LIPs of South America, eastern Australia, Al-granites in southern Australia are other examples of such volcanism[1].

Apart from eruption of magma of varied compositions, plume heads invariably uplift the regions above them thereby altering existing drainage patterns. Examples of such plume dynamics are the Rocky Mountain uplift and the Columbian Plateau in USA, both far away from plate boundary, and in India, the Reunion plume-caused Western Ghats elevation, uplift of Dhanjori sedimentation (eastern India) by a Proterozoic age plume and the uplift of NE India by the Kerguelen plume[4]. Similar uplifts in North Atlantic Ocean crust and parts of South America are linked respectively to the Tertiary North Atlantic Igneous Province and the Parana-Etendeká flood basalt events[1]. The circular faults and depressions (calderas) in the Snake River Plain (USA) are attributed to Yellowstone plume and a similar one in Ethiopia-Yemen to Afar mantle plume[1].

Rifting in intraplate setting takes place after upwelling or doming by the plume head and this ultimately leads to continental break up. Also, some of the CFB events are found synchronous with opening of oceans such as the Central Atlantic, South Atlantic, SW and NW Indian Oceans[5]. One model conceives that after the subducted slabs, held long in the transition zone, slide into the lower mantle (slab-avalanching) superplumes arise leading to the rifting and continental break up and such events are believed to have occurred during 2.7, 1.9 and 1.2 Ga and minor ones in the late Palaeozoic and Cenozoic, coinciding with growth and break up of supercontinents[6].

Plume theorists are emphatic about a deep lower mantle source for most of the LIPs, CFBs and many high temperature rocks. Such rocks, free from crustal or lithospheric contamination, show enriched LREE, lack negative Nb, Ta, and Ti anomalies and high MgO (e.g., picrites, Komatiites) characteristic of lower mantle origin. But clinching evidences cited are the high ^{3}He/^{4}He ratios, characteristic noble gas signatures and presence of high-pressure inclusions like majorite-garnet, coesite, ferropericlase, Fe, FeC and Sic in some of the kimberlitic and peridotitic diamonds[7].

Though plume model has been extensively applied for explaining midplate magmatism, recent seismological and other studies have come up with alternate non-plume models. Anderson, California Institute of Technology, Pasadena, rejects the idea of the ascent of magma plumes from CMB on the grounds that the pressure, viscosity, coefficient of thermal expansion, thermal conductivity, interatomic distances at these depths forbid such a mechanism of magmatism[8]. He argues that the high pressure and viscosity here suppresses heat flow from the core and slows down generation of mantle convection cells at the thermal boundary near CMB, which in turn impedes buoyancy effects for initiating plumes. Further, the high mantle temperature theorized for plume involvement for the Precambrian komatiites, picrites and other rocks are not supported by heat flow data or petrology and in fact, calculations indicate that the early mantle was merely 120°C hotter than now (1300°C) and hence these rocks could as well have formed by partial melting of upwelling mantle accompanying passive rifting[9].

Large volume of melt, considered typical of plume magmatism, is also now questioned. In terms of lateral spread, volume and duration of eruption as well as from fluid dynamical calculations for athermal mechanisms for magmatism[8], the magnitude of plate boundary volcanism (ridges and island arc basins) arising from mantle upwelling far exceeds plume eruptions. High volume of melt can also arise at normal mantle temperature under the oceanic crust and such melts with lower mantle geochemistry, considered typical of plume derivation, can be generated at much shallower depths in the upper mantle itself from the melting of recycled crust[10].

One of the basic tenets for basaltic flooding by mantle plume heads is their rapid eruption. Yet, this fails in the case of the Deccan eruption, one of the largest CFBs, which lasted for 8–9 million years, barring a few minor flows erupting for a short 0.5–1 million years; also, the eruptions forming the Kerguelen Plateau, the second largest oceanic flood basalt formation, lasted for 130 million years[11]. Removal of blockages to the upward progress of magma, plate reorganization, mantle convection changes, partially molten asthenosphere, midplate mantle melting due to continental insulation can also lead to sudden expulsion of large volume of magma[8]. In the same token, Reunion plume dynamics for the uplift of the west coast of India (Western Ghats) is dismissed as the latter is now ascribed to combined surface erosion and magmatic underplating processes[12]. The Yellowstone (USA) example is now ascribed to mantle convection and regional tectonics[13].

Even though all LIPs are claimed to be products of plume heads, opponents of plume model have drawn attention to absence of such plumes for Ontong-Java, Fiji or Siberian Traps and they also doubt the suggested genetic links to remote Louisville hotspot (for Ontong-Java, Fiji LIPs) and Hawaii and Jan Mayen hot spots (for the Siberian Traps). Likewise, several hundred seamounts distributed in the Pacific Ocean having hot spot derived chemistry do not have hot spots beneath them and are more likely to have shallow level melt-source in lithosphere[10].

Superplume triggered continental break-up and development of new ocean basins[6], especially during the last one billion years, are also discredited in view of the earth's decreasing mantle potential (Raleigh number). Superplume tectonics do not seem to have operated during the growth of Rodinia and Gondwana, two major supercontinents in earth's history, judged from volumetrically minor juvenile crust production during Grenvillian (Rodinia) and Pan-African (Gondwana) periods[14]. Likewise, superplume events were absent also when Australia and Antarctica separated from Gondwana. Alternatively, non-plume agencies like plate boundary driving forces, 'top-down' plate tectonic dynamics or combination of latter and mantle upwelling could as well have brought about these episodes[8].

Another bastion of plume theorists to come under the onslaught of plume opponents is the elevated ^{3}He/^{4}He ratios cited as strong evidence for the origin of several plume derived rocks from an undegassed ^{3}He-rich lower mantle reservoir retaining primordial composition. The opponents consider this improbable as earth's pre- and post core-formation periods were noted for high incidence of bolide impacts, including a major one that formed the moon, all of which would have extended early earth's hot magma ocean phase long enough for the escape of primordial gases. Secondly, it is now argued that such high ratios can result also from the helium present in CO_2 fluid inclusions in olivines and from U, Th retained in the mantle melt. They may also be contributed from old caught up olivine-gabbroic rocks in the upper mantle involved in partial melting or during shallow-mantle partial melting of recycled, radiogenic and non-radiogenic regions of different ages[8].

Another much debated issue, is the observed bend midway in the Hawaii-Emperor chain in the Pacific Plate and the shift in the Chagos–Lacccadive–Reunion chain in the Indian Plate. According to the plume model, these changes reflect the shift in direction of movement of the concerned plate with respect to the hot spot fixed in the mantle below. But plume opponents explain that forces on plates arise from combined effects of all driving and resisting forces and hence changes to plate motion are bound to be too slow for the abrupt shifts noticed. On the other hand, local stresses inside the plate, influenced by the subduction geometry, can rapidly alter fracture trends in the plate thereby shifting the eruption along the new direction. Such fracture tectonics operating in the Pacific plate, around 43 m.y. ago, resulted in Hawaii-Emperor chain bend[8]. Likewise, the Reunion plume connection is rejected for the shift of Chagos-Lacadive-Reunion Island track, which instead is attributed to the southward deviation of crack propagation through oceanic lithosphere[12].

At this stage, when non-plume models are questioning the very existence of hot spot plumes, studies by a Princeton University team have shown how the currently used seismic technique based on the ray concept is incapable of detecting narrow plumes due to 'wave front healing effect' on the travel-times of seismic waves passing through such plumes. Now, by adopting an alternate finite-frequency tomography, this effect could be overcome and they could detect some of the elusive plumes, all of them several hundred kilometers in diameter, for six well-known hot spots – Ascension, Azores, Canary, Easter, Samoa and Tahiti and less-resolved one for Hawaii reaching up to the lower mantle[15]. Views of the plume opponents are further jolted by fresh seismic anisotropic studies which have found onset of vertical flow, referred to as 'superplumes', from the base of lower mantle for two well-known low-velocity regions below Pacific Ocean and Africa[16].

Similarly, another non-plume explanation[8] for the bend in Hawaiian track may have to be re-examined against the recent findings by Steinberger and others[17] who studied global plate motions with intraplate deformation and movement of hotspot through distortion by mantle flow. They have concluded that relative to the deeper mantle, the Pacific Plate did change its motion during 43–52 m.y period at the time the Hawaii-Emperor bend was taking place. In a like manner, non-plume explanations[8] rejecting the uniqueness of high ^{3}He/^{4}He ratio for a lower mantle origin may have to reviewed considering the views about ^{3}He additions from the core, postulated recently by Hollenbach and Herndon[18]. They have pointed out how increments of ^{3}He to the lower mantle can come from nuclear reactions in the inner core, where uranium is thought to have entered during core formation, to the extent of 64%, enough to start nuclear reaction.

Many of the mantle involved geological and geochemical processes are explained on the basis of layered mantle convection with a boundary separating a depleted upper mantle and a lower mantle retaining primordial geochemical abundances. However, ample trace element and isotopic data indicate mantle heterogeneity due to recycling of oceanic crust deep into lower mantle, so well highlighted in several tomographic studies which imply whole mantle mixing. Some of the recent geophysical findings about mantle dynamics have also shaken our understanding of many of the magmatic processes, making one to ponder which of the two – plume or non-plume models, are closer to truth. Perhaps both these models have to recognize the impact of changes to the mantle structure and chemistry with time and consequent limitations they impose on the temporal viability of the respective models[19]. The row over mantle plume conception has not ceased and may be, in the forthcoming Special Session of the AGU in December this year when many fundamental aspects and different opinions about the mantle plume and other models will be discussed, a composite picture of the unseeable 'plume elephant' may emerge.

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