The unsettled plume hypothesis

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A simple explanation advanced more than forty years ago[1] for the origin of a line of age sequential volcanic islands in the Pacific plate (Hawaiian Islands), which was later developed to explain several intraplate volcanic eruptions (Large Igneous Provinces or LIPs such as flood basalts and large oceanic plateaus), evolved in course of time as the 'plume hypothesis'. The proponents of this hypothesis defined several characteristic features of plume manifestations which found ready acceptance initially. However, with the emergence of new data from advanced research techniques, the hypothesis came to be debated and soon snowballed into a controversial topic dividing the concerned scientists into pro- and anti-plume groups. Taking note of the barrage of growing criticisms over the years, a team of scientists have now defended the plume hypothesis and rejected the alternate non-plume explanations given for the considered products of plume processes.

According to the plume hypothesis, plumes are columns (~100–200 km diameter) of hot magma that are supposed to be initiated as a spherical blob or head, from an unstable thermal boundary layer developed near the core–mantle boundary (CMB) due to the lowering of density here by heat transfer from the hotter core. The plume head is further envisioned to enlarge gradually to a diameter (~400 km) buoyant enough to overcome the mantle viscosity and possible background mantle 'wind' (dissipation), and ascend towards the surface. Critics[2,3] have now questioned this concept about plume initiation, since according to the scaling laws relating pressure, volume and temperature, the viscosity of the mantle is less sensitive to temperature under high pressure of the lower mantle and hence core heat will have little impact on density and buoyancy to initiate plumes. Plume defenders disagree and argue that since viscosity is a thermally activated process, an equation of these physical parameters at the CMB actually shows that the relative effect of temperature on the viscosity increases with pressure promoting the generation of narrow plumes[4], and its slow ascent unimpeded by existence density interfaces as assumed by some researchers[2].

A 'tail' trailing behind the plume head is presumed to continuously feed the head with additional flux while it ascended towards the surface, forcing it to swell to a disk of enormous size (2000–2500 km diameter). On its entry into the low-pressure shallow depths, the plume head decompresses and erupts forming the LIPs, e.g. Deccan flood basalts[4,5]. Further, the hotter head is conceived to melt and incorporate (entrainment) thin layers of chemically differing cooler mantle adjacent to its path of ascent. This entrainment is attributed to the close association of high-temperature komatiites and picrites with low temperature basalts occurring in many LIP areas[5]. Thus, the plume tail flux is claimed to reflect the lower mantle chemistry whereas the plume head melt, a mixture of lower mantle and entrained mantle material[6]. Plume theorists emphasize that these concepts of plume generation, ascent, entrainment and eruption are all built on sound physics of fluid material and analytical boundary layer theory in the mantle and have been verified through several experimental studies and numerical modelling[4]. The plume model is further claimed to have enabled studies on viscosity stratification, background mantle flow, compositional layering at source, mixing within plume and a host of other mantle properties[4–6].

Among the major surface expressions of plume activity highlighted by the plume advocates are the large topographic swells (up to 2 km height and hundreds to a few thousand square kilometre spread) and subsidence of crust. The uplift is ascribed to the buoyancy forces of the plume head as it nears shallower levels (~250 km depth), while subsidence is thought to result from the fall in density of the mantle residue after extraction[5,7]. The uplifted crust, now under tension, rifts and widens, heralding the birth of new ocean basins like the present-day NW Indian Ocean, Red Sea, the Gulf of Aden, South Atlantic and the SW Indian Ocean. Decompression melting of the plume head follows and the melt flows into the spreading region adding new crust like those seen off the west coast of India associated with Reunion-Deccan plume and off the east coast of South America and west coast of Africa associated with Parana-Etendeka (Tristan da Cunha plume) and the North Atlantic Province (Faeroes-Iceland plume)[6,7]. Uplift, followed by eruption is the normal sequence of plume activity observed in most of the LIP areas, though this is contested with respect to Iceland, Ontong Java and a few others. In rare cases, for example, in the early eruptive phase of the North Atlantic Province, where the eruption had preceded uplift and rifting or as in the Siberian Province, where the crustal flexure was not adequate, a lithospheric thinning mechanism through gravitational instability or delamination of lower lithosphere is thought to allow the hot mantle to decompress and erupt, the products exhibiting shallow mantle geochemistry[4,7].

Uplifts and subsidences are recognizable through geomorphological records they leave such as development of terrain topography due to relative uplift and tilting as in the Yellowstone site, or sea-level changes like stepped deposits progressively outward and downward as in North Atlantic eruptions. Evidences for the pre-eruption uplift of the Deccan are seen as marine regression features present in the upper Cretaceous sediments lying below the basalt formation in the Cambay–West Narmada region as well as from the sudden increase in sedimentation rates (3–5 times) noted in Kutch, Krishna–Godavari and Cauveri basins and from development of radial drainage patterns, all pre-dating the main phase of the volcanism[6,7]. However, all these interpretations about pre-eruption uplift are questioned and in fact, it is pointed out how the Deccan Lava/basement contact at several places is actually far below the surface and also how some of the local uplifts reported in a few places really post-date volcanism[8].

Another aspect of plumes is their rapid eruption forming thick crusts, a feature observed in all the major LIPs. The Reunion plume eruption forming the Deccan Lavas, is reckoned to have lasted only 1–2 m.y. forming ~175 km thick crust linked to the source plume through an age-sequential chain – the 2200 km long and 200–300 km wide Chagos–Lakshadweep volcanic ridge-system, believed to have evolved from the tail of the plume.

However, data on the age progression and palaeolatitude positions dispute this conclusion[8]. Though non-plume process like upwelling of partial melt of a chemically heterogeneous mantle[3,9] can form similar crust, plume supporters doubt if crusts of comparable thickness and spread can be formed by such a process[6]. Also, such partial melts will have a high-density basaltic content, which would make the melt sink and not be drawn into the spreading centre.

Recent data from seismic tomographic studies of the mantle have revealed plume-like structures traversing the entire mantle region, and these are highlighted as vindication of the plume postulate[6,10]. This technique has traced the origin of the Hawaiian plume to the lowermost mantle (CMB)[11] with great certainty, helped by the excellent resolution obtained by the island's location in the Pacific with innumerable earthquake sources and seismic stations, and through the use of frequency arrival times of various reflected and transmitted waves in the mantle and outer core[10]. As for the Iceland plume structure, technical limitations had confined its detection all these years to the upper mantle only, but now a latest seismic study of 60 hotspots reports imaging of plume-like structures continuously in both the upper and lower mantle, some of them suggesting an origin from the CMB, under Iceland, Hawaii, Louisville, Reunion, Kerguelen and several more hotspots around the world[12]. However, some have reservations in accepting the tomographic images of plume structures, since it is felt that interpretations of such data are highly pliable to accommodate one's conclusions[13]. The successful detection of thermal anomalies beneath the plume heads of Deccan, Parana, Ontong–Java and the long survival (~200 m.y.) of the hot buoyant melt are all considered to affirm the plume-based predictions[6].

The much debated question whether plumes remain stationary or not in the mantle space is not considered a key issue of plume hypothesis nor a test for the existence of the plume, though initially the explanations for intraplate age-sequential volcanisms invoked stationary plume against a moving plate. According to this hypothesis, if the mantle viscosity with depth does not change, the plume moves with the plate matching its rate and direction of motion. However, with the prevailing viscosity variations between the lower and upper mantle and consequent influence on the convection velocities in these two regions (almost stationery in the upper mantle but moving slowly in the lower mantle), relative motion of the plume is expected to be affected[6].

In the context of the debate on the fixity of plumes, the volcanic chains in the Pacific plate, such as the Hawaiian–Emperor chain, Louisville chain and other seamounts exhibit mismatching age progression with respect to the direction of motion of the Pacific plate. This has remained a contentious issue contradicting the plume tenets[3]. Data on the palaeolatitude positions and argon ages for the Hawaii–Emperor and Gilbert Ridge–Tokelau seamounts conflict the basic explanation of a fixed hotspot plume. Their trends, denoted by the bends in the trail, are in different directions – NW for the former and NNW for the latter group, the bends forming at different times – 67 Ma for the Gilbert Ridge seamount, 57 Ma for the Tokelau seamount and 47 Ma for the Hawaii–Emperor. These indicate that they cannot be coeval or attributable to fixed plume, but may have resulted due to eruptions from drifting plumes or due to magmatism caused by short-term local lithospheric extensions[14]. Plume supporters speculate that these may be derived from headless thermochemical plumes, which shift in the upper mantle space faster than those with heads[6]. Also, the mismatched age progression, they point out, may arise due to superposition of time-separated eruptions or jumps from adjacent ridge locations or to prevailing complexities in the crust or disproportionate match of plate motion and eruption[4]. Actually, heterogeneities in the composition of the lowermost mantle support coexistence of plumes of different shapes and sizes, which are seen as different seamounts on the surface[15].

A lower mantle source for the plumes, conceived by the hypothesis, is another of the issues disputed by many on grounds of petrology, trace element and isotopic chemistry, and instead they are assigned an origin from mid-mantle. However, plume advocates stress the lower-mantle origin for plumes based on the results from computer modelling. The latter reveals that when a weak thermochemical plume rising from the deep lower mantle has a head with high-density basaltic component derived from subducted crusts stagnating at the heterogeneous D″ layer near the CMB, it can stall at the mid-mantle discontinuity (670 km) and undergo compositional separation owing to the instabilities introduced by the cold downwelling oceanic basaltic crust. Two fractions result, a heavier one representing the basaltic component of the subducted material and a second lighter fraction formed by the residue. This lighter fraction penetrates the discontinuity as a secondary plume and develops a small head as it ascends the relatively small distance to the surface, thus giving an impression of an origin from the mid-mantle discontinuity[6,15]. Against this background, the recent discovery[16] of a new type of a plumeless midplate seamount in the Pacific plate originating from a shallow-level melt erupting through flexures produced by the bending of the subducting Pacific plate, has further exacerbated the ongoing bitter plume debate.

Plumes erupt typically high temperature (~1520–1570°C) products like picrites, which are invariably confined to the centre of the plume head or its axis. Such occurrences in many areas including the Deccan[3,8] are disputed on petrological grounds, but plume patrons maintain that the petrology of mantle melts, in general, is still not clearly spelt out, given the heterogeneity of mantle sources, intricacies of magma migration and disequilibrium processes[4]. Further the trace element and isotopic geochemistry – low $^{86}Sr/^{87}Sr$, high $^{143}Nd/^{144}Nd$ and LREE depletion, typical of MORB-type source, often used to reject plume connection are not considered ideal guides to judge the origin. For example, mantle plume-derived picrites in some areas like the Carribean–Columbian Igneous Province show three types of lavas – LREE-depleted, LREE-enriched as well as constant LREE, comparable to the Ontong–Java LIP chemistry, indicating a heterogeneous state of their respective mantle plume source. Hence plume materials do not have any specific or unique composition and they reflect only the composition of the source thermal layer, which may be either geochemically enriched or depleted[6].

As for the Deccan magmatic province, it is ascribed to non-plume magmatism associated with continental rifts and plate dynamics involving possibly eclogitized oceanic crust trapped in ancient Indian suture zones and erupting voluminous basalt[8,9]. Plume theorists do not agree to this and are of the opinion that the relative age of the onset of off-shore rifting is not clear for the Deccan Traps, and also it is not considered a requirement for the onset of LIPs, though rifting can increase melting rate appreciably apart from magma generated through lithospheric thinning caused by the plume head[7]. Further, current geodynamic, geochemical and isotopic data are inconsistent with models invoking pre-Deccan rifting and separation (plate break-up and separation) of Seychelles–Mascarene microcontinent from India, which post-date the main flood basalt volcanism – and this post-eruptive rifting is confirmed by the presence of extensive parallel dyke swarms along the coast cutting the upper part of the Deccan succession[5].

The debate for and against the plume hypothesis appears unending. Presently, for every argument upholding the hypothesis, a counter argument is advanced rejecting the contention and a consensus appears elusive. Major objections to the plume hypothesis are that the postulate is flexible regarding its source, width, mode of eruption and its duration, its shape and structure, fixity, longevity and geochemistry[3]. It emerges from the prolonged plume debate that intraplate volcanism, undoubtedly, can arise through a number of routes besides plumes and hence the plume concept possibly cannot be totally ignored. As described by a pro-plume scientist[4], 'because a mature physical theory of plumes developed rather slowly over two decades, plumes have been invoked perhaps excessively by some enthusiasts, while skeptics complained not without justification, that plumes were ill-defined concept that could neither be tested nor well justified'. Far from it, 'plume hypothesis is relevant enough to observations and supporting knowledge to be a fruitful one to pursue further'.

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OPINION

Methane emission, rice production and food security

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The three major greenhouse gases (GHGs) – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – have significant fluxes from agro-ecosystems. Methane is the second most important GHG after CO_2. Its concentration in the atmosphere has more than doubled over the last 200 years, and in particular has increased by about 50% in the last 40 years. Irrigated rice production, a major food source for a large portion of the world's population, has been reported to be a major anthropogenic source of methane[1]. Global emission estimates for this source range from 20 to 100 Tg yr^{-1}, which may be 4–30% of the total anthropogenic contribution to the atmosphere, making it one of the sources with the largest uncertainty[2]. Rice-field soils, characterized by waterlogging, O_2 depletion, high moisture and relatively high organic substrate levels, offer an ideal environment for the activity of methanogenic bacteria[3].

Now methane has been designated as the climate culprit. According to Reiner Wassmann, coordinator of the Rice and Climate Change Consortium at International Rice Research Institute, Philippines, rice is the only crop that emits such a large amount of GHGs. There is also a stress that Asian countries have to look at rice production to reduce GHG. The recently concluded Intergovernmental Panel on Climate Change (IPCC) summit has also recommended improved rice cultivation techniques, and livestock and manure management to reduce CH_4 emissions[4]. It is explicit that rice and livestock are targetted for CH_4 emission reduction. It is high time that rice cultivation is looked into as an important activity that is not related to food security but as the global climate change agent.

Globally rice production has been estimated to double by the year 2020 in order to meet the demand of an increasing population, which may increase methane production[4] by up to 50%. India should also increase food production by 5 million tonnes per year to keep pace with this increasing population and to ensure food security. India has recently indicated that it would reject proposals to limit GHG emissions because stricter limits would slow its booming economy and have serious implications for poverty alleviation programmes. These observations could