The new experimental findings have confirmed the previous estimate of SBSL flash widths being in picoseconds regime; however, they have now been resolved and found to depend on experimental parameters. The most important observation is that, the flash widths and times of emission of SBSL are independent of wavelength of light. This fact rules out simple adiabatic heating as a mechanism for sonoluminescence since adiabatic compression followed by blackbody radiation would have resulted in flash width being much larger in red than ultraviolet. Further, since the SBSL spectra is broadband and devoid of any features which would suggest line or band emissions, the only possible mechanism for optical radiation is thought to be thermal bremsstrahlung. This, however, would require considerably higher temperatures than theoretical predictions of about 10,000 K on the basis of observed and also computed collapse of a typical sonoluminescing bubble from a maximum radius of about 40 µm to submicron size. Much higher temperatures are predicted if one includes the possibility of formation of a shock wave inside the bubble, during the bubble collapse phase. Then there is a mechanism for secondary energy focusing in the form of shock strengthening as it converges to the centre of the bubble and formation of high energy state in the form of 'cold' plasma for a very brief duration. Therefore, although the mechanism of emission in SBSL is still to be identified conclusively, the 'plasma' model of Moss *et al.*[9] which includes the above feature, seems to predict more aspects of SBSL than other models.

1. Arakeri, V. H., *Curr. Sci.*, 1994, **66**, 213–218.
2. Gaitan, D. F., Crum, L. A., Church C. C. and Roy, R. A., *J. Acoust. Soc. Am.*, 1992, **91**, 3166–3183.
3. Barber, B. P. and Putterman, S. J., *Nature*, 1991, **352**, 318–320.
4. Moran, M. J. *et al.*, *Nucl. Instrum. Methods*, 1995, **B96**, 651–652.
5. Barber, B. P. *et al.*, *Phys. Rep.*, 1997, **281**, 65–143.
6. Gompf, B., Gunther, R., Nick, G., Pecha, R. and Eisenmenger, W., *Phys. Rev. Lett.*, 1997, **79**, 1405–1408.
7. Hiller, R. A., Putterman, J. and Weninger, K. R., *Phys. Rev. Lett.*, 1998, **80**, 1090–1093.
8. O'Conner, D. V. and Phillips, D., *Time-correlated Single Photon Counting*, Academic Press, New York, 1984.
9. Moss, C. W., Clarke, D. B. and Young, D. A., *Science*, 1997, **276**, 1398–1401.

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Drifting mantle plumes, mobile hot spots and island chains

A. V. Sankaran

An examination of the global pattern of volcanisms shows that they are mostly connected with tectonic plate boundaries (divergent and convergent), while a few are located far away from such boundaries, as intra-plate or mid-plate volcanoes. The magma for most of the plate-boundary related volcanism arises from the asthenosphere, a seismically low velocity mushy or soft layer at the bottom of lithosphere; they may also be eruptions of refined fractions of basalt differentiating in a magma chamber or remelted continental rocks or oceanic crust sinking into the asthenosphere. The mid-plate volcanoes, on the other hand, appear as elevated domes, far from these plate boundaries and compositionally too, they do not seem to be related to plate margin volcanism. These intra-plate volcanoes, better known as hot spots, have their source direct from the mantle. Classic examples of intra-plate volcanoes are the many island chains dotting the Pacific plate, prominent among which is the Hawaiian group, stretching from Hawaii all the way up to the Aleutian trench (Figure 1 *a*). Most members of this chain appear above the sea-surface as extinct, aseismic volcanic islands, except for the island of Hawaii, where the volcanism is still active and associated with seismicity. A few in this chain, however, remain as undersea mountains and ridges of varying heights. Presently, more than 120 hot spots have been reported around the world, on both oceanic and continental plates (Figure 2).

With the advent of plate tectonic concept during 1960s, geologists began to recognize links between the plate motions and development of island chains. Tuzo Wilson, the Canadian geophysicist, explained that the intra-plate volcanic ridges or islands are actually upwellings of ascending plumes of magma, as the plate moved over a mantle hot spot (see inset, Figure 1 *a*), this volcanism ceasing as the plate moved away from the hot spot[1,2]. Developing these ideas in the 1970s, Dietz and Holden[3] demonstrated, how the trend of these ridges indicated the direction of plate motion, while Jason Morgan[4,5] introduced the notion of fixed hot spots and showed that the island chains of Hawaii–Emperor, Tuamota-Line and Austral-Gilbert-Marshall are volcanic products arising as the Pacific plate rotated around a pole-axis over three fixed hot spots. Such plate movements result in progression of age of the islands away from the hot spot, as seen very well in the Hawaiian and Emperor Seamount chains. Here, the oldest of the islands, dated 80 m.y., is farthest from the present day hot spot site and the youngest one, just 800,000 years old, is at the hot spot site, beneath the island of Hawaii. Likewise, the Kerguelen Plateau hot spot volcanism, in the far south Indian Ocean, is supposed to have given rise to the Kerguelen islands (oldest of which is about 115 m.y. and youngest 38–0 m.y.) and also the N–S trending Ninetyeast Ridge, stretching from Broken Ridge (30°S, 38 m.y.) northwards to the Andaman group (13°N, > 83 m.y.) in Bay of Bengal, the former associated with separation of India from Australia–

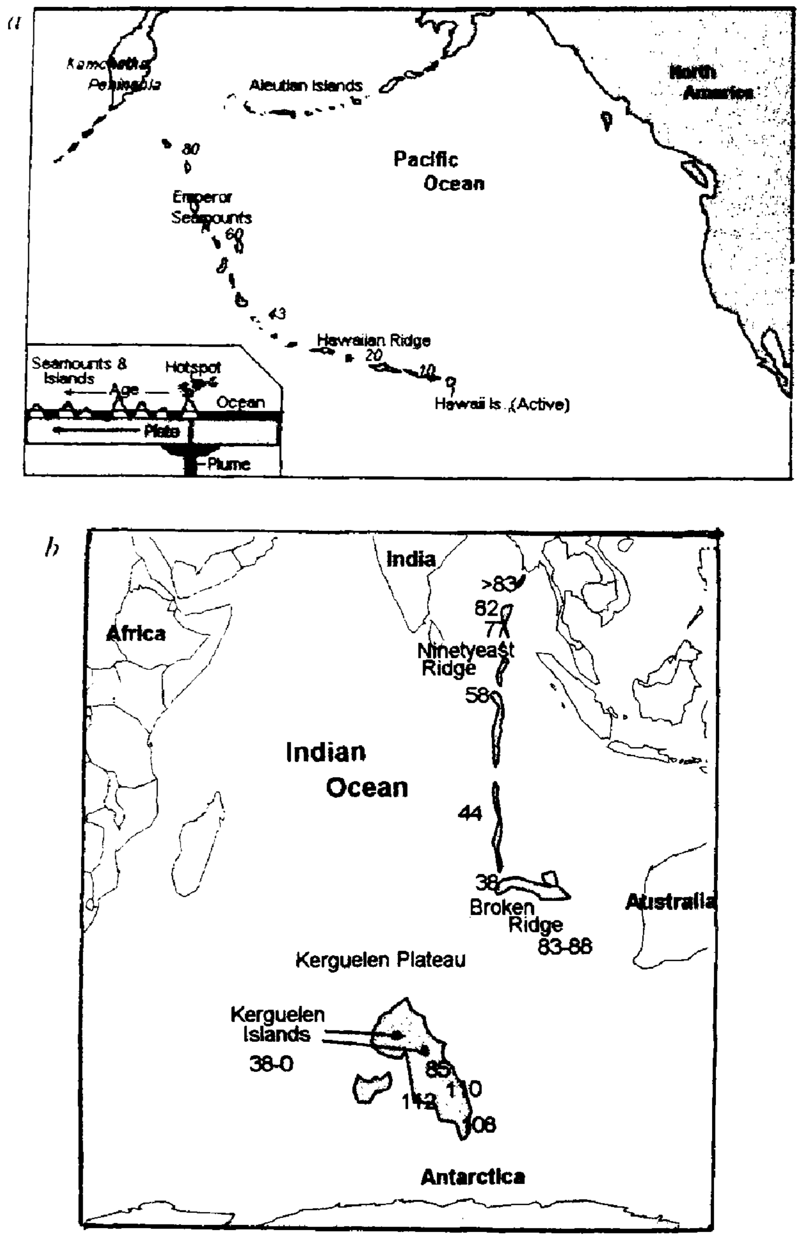

Figure 1. Intra-plate volcanic activity. ***a***, Hawaii–Emperor Seamount Chain in Central Pacific Ocean showing a sharp bend due to sudden shift in the direction of plate. Inset: Standard hot spot theory of origin of mid-plate islands and seamounts. ***b***, Mid-plate ridges and islands generated by the Kerguelen hot spot volcanism in the Indian Ocean; shaded regions shown in this figure indicate submarine plateaus. (Numbers in both *a* and *b* indicate age in m.y. of the volcanic island.)

Antarctica while the latter with the northward drift of Indian plate[6] (Figure 1 *b*). Other examples of mantle plume islands are Samoa, Bikini, Tahiti, Easter, and Galapagos in the Pacific, Reunion and Mauritius in the Indian Ocean, and in fact, many of the large islands, like Iceland, in mid-oceans are thought to owe their existence to mantle plumes. Apart from these, thousands remain as submerged peaks of varying heights called seamounts. These are particularly abundant in the Pacific Ocean floor, and they are believed to be products of dozen or more hot spots. Interest about mantle plumes, hot spots and seamounts has been gathering momentum with the explosion of data generated by ocean-bottom surveys using side-scan sonar imaging and satellite mounted radars having extraordinary sensitivity and precision. These have brought to light many new undersea rifts, submarine plateaus, ridges, fractures, and in particular, existence of thousands of hitherto undetected seamounts, many just about a kilometer high. In the Pacific region alone, a maze of seamounts, 8000 or more, generated probably by a group of hot spots, is known to occur. Mid-Cretaceous (about 100 m.y. ago), was a notable period in earth's past for enormous mantle plume activity, called superplumes, ascending from deep below the mantle. They were responsible for the piling up of such vast expanses of oceanic crust, particularly in the Pacific, Indian, S. Atlantic, Caribbean oceans, as to raise the world wide sea-level by 250 meters[7,8] causing the well documented world-wide Cretaceous marine transgression.

The concept of plate movement across fixed hot spots[1–3] had enabled earlier geologists to reconstruct by backtracking (a) direction of the plate motion, (b) changes in its direction, (c) its velocity or rate, and (d) derive the site of the hot spot. For example, reconstruction of the Hawaiian and the Emperor Seamounts Chain by backtracking had revealed that the Pacific plate initially moved northward since 80 m.y. ago and abruptly changed its direction about 43 m.y. back and shifted to a westerly movement. This abrupt shift is reflected in the bend or kink seen midway in this island chain (Figure 1 *a*), which according to Jason Morgan, is the result of a shift of the existing pole of rotation to a new one. Backtracking technique has also enabled location of the present site of hot spot in this chain beneath the island of Hawaii. Needless to point out, this is a simple way of tracing the past movements of the plates, provided hot spots had remained stationary and had not ceased to erupt. But such a belief was found to be unsound in the light of findings that the hot spots also moved slowly along with the mantle current. It was also noticed that where multiple hot spots were present beneath a plate, they were stationary relatively between themselves, but moved together, independent of the movements of the plate above them or elsewhere. Besides, their motion when compared to those of the lithospheric

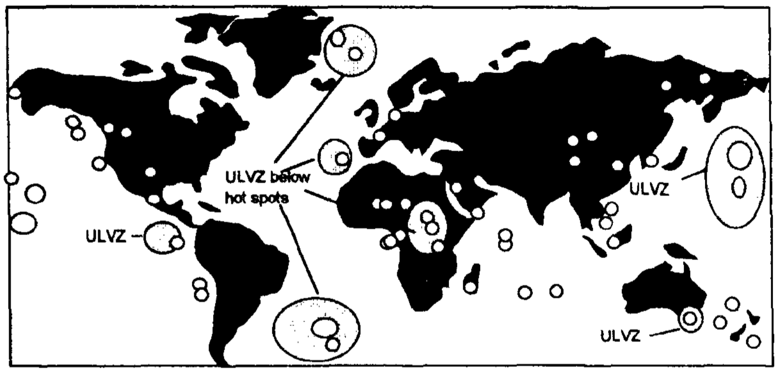

Figure 2. Map of the world showing some of the major hot spots (unshaded circles). Shaded zone around some of the hot spots are seismically-inferred ultra low velocity zones (ULVZ) in the lower mantle considered as the magma source for the hot spots.

plates above them, was slower and different in direction.

Now, bypassing some of the above constraints, Paul Wessel and Loren Kroenke (University of Hawaii) proposed a new age-independent method to locate hot spots. They found a geometric relationship between seamounts and their parent hot spots and have used undated seamounts to refine the motion of tectonic plates, and assess the hot spot mobility, locate extinct ones and define status of one hot spot relative to others in the region[9]. From a few reliable seamount dates available around Line Islands in the Pacific, where five hot spots were proposed by researchers to explain hundreds of seamounts crowding the area, they could derive the plate motion. Computer plotting of the probable paths of the seamounts here revealed two trends, one tracing their paths before shift of plate direction and the other, after the shift. The two trends intersected to form an X indicating the one position crossed by every seamount, which represented the site of the hot spot. Using this technique, the authors were able to fix the positions of some of the hot spots around this region, on the assumption that the positions of the seamounts on the oceanic crust were precisely mapped. They could thus locate Hawaiian, Louisville (far S. Pacific) and Rarotunga hot spots and could even hint presence of more such hot spots in the region.

Though the fixed hot spot concept was useful initially as a frame of reference to measure absolute plate motions, global studies of their movements induced by mantle circulation led to doubts about hot spots remaining stationary in a convecting mantle. Also, studies have shown that the movements of different tectonic plates do not match, either in their rate or in their direction, with those of the mantle below them. For example, hot spots in the Atlantic or the Indian plates are found to move quite differently from those in the Pacific. Hence, calculation of plate motion can no longer be based on a stationary hot spot concept. Steinberger and O'Connell[10,11] have used a kinematic model to show that the plumes, while retaining their connection with mantle below and earth's surface above, also drifted and shifted, induced by the mantle flow. To establish this, the authors first derived the pattern of mantle circulation using data obtained by seismic tomography and plate motions for past 68 million years and described how the plume conduits were also carried horizontally with the 'mantle wind' – just as fog or smoke drifted horizontally by advection. As a result, the plumes twisted and tilted, but buoyancy straightened them out ultimately; however, when the tilt exceeded 60°, the conduit snapped from the hot spot and magma upwelling ceased. Plume advection is sensitive to variations in the mantle viscosity, a parameter influenced, apart from mantle depth and prevailing P–T conditions, also by subducting plates, as they plunged into the lower mantle gradually. In their model, all Pacific hot spots moved toward southeast, about 1 cm yr^{-1} relative to zero mean plate shift. The plume drift is calculated for low viscosity prevailing at 100–400 km depths of the mantle which shows higher viscosity below 1500 km. Such drifts under low viscosity conditions, they say, are also responsible for the sharp bend in Hawaiian–Emperor chain, though according to Ulrich Christensen (Institut für Geophysik, Göttingen), this kink can also be explained by sudden drift in the hot spot rather than due to shift in the plate motion[11].

Another approach to determine plate and hot spot motions, avoiding uncertainties involved in mantle-related reference frames, has come from Torduno and Cotrell[12] who feel that the plotting of palaeo-latitudes of the plates, based on the palaeomagnetism of minerals, is a reliable technique to trace their absolute motions. They feel that true polar wander[13–15] resulting from movement of entire earth relative to the rotation axis on long time scales (10^3–10^9 years) can cause latitude shifts. This is made out by examination of the orientation of iron-bearing magnetic minerals in the lavas of progressively later eruptions, which align themselves to the N–S direction prevailing at the time of eruption, in effect, a palaeomagnetic record of latitude shifts in time and space. Using such records, the authors detected 9° southward latitude shift (36°N to 27°N) between two seamount eruptions – an 81 m.y. old one and an younger 16 m.y. one in the northern end of Emperor Seamount chain. Since polar wander involves motion of entire earth relative to the rotation axis, it does not, however, explain the hot spot's movement during the interval between formation of these two seamounts. The palaeomagnetic data also agreed with the southward drift of hot spot in the Emperor–Hawaii chain at a rate of at least 3 cm yr^{-1} before 43 m.y. and very little drift subsequently, a feature that challenges conventional assumptions regarding mantle circulation and plate motions[11].

The age progression attributed to the drift of plates over hot spots, while working well in the Hawaiian chain, is found to break down in the case Cook-Austral chain in south Pacific ocean and lying within the same Pacific plate, further south of the Emperor Seamounts-Hawaii chain. Similar inconsistent age sequences among hot spot volcanic island lavas have also been noticed elsewhere in other tectonic plates also. Marcia McNutt (Massachusetts Institute of Technology) and co-workers[16], who studied the Austral chain of volcanic islands and incidentally located a few hitherto undetected undersea volcanic chains (Ngatemato and Taukina chains) in this region, have pointed out how radiometric dates of many of the island samples from this chain departed from the expected age progression; this departure is also paralleled by variations in their geochemical make up – features that, undoubtedly, weaken the assumed view that a 'single plume currently located at the volcanically active MacDonald seamount' was the source for all these islands. The authors have now shown them to be products of 'three distinct volcanic chains with a range of ages spanning 34 million years and with inconsistent age progression' and that these volcanic islands probably materialized when magma erupted as a result of stresses in the lithosphere rather than through conventional plate drift over hot spots. They have arrived at this view after analysis of gravity anomaly data and radiometric dates of ocean floor around the volcanoes. They explain the observed mix-up of younger and older age as due to eruptions arising from a broad spread of the buoyant plume material that was dragged laterally, as the plate moved, along the base of lithosphere up to the relatively thinner regions of the lithosphere, close to the mid-ocean ridge axis. This had resulted in a broad region of plume material, which subsequently vented out through fissures or cracks that developed in course of time in the plate under enormous load stresses from the maze of seamounts on the ocean floor. In an alternate mechanism proposed for the origin of these islands, they assume that the upper mantle is 'enriched in different easily melted components that have been injected by earlier subduction of oceanic crust, continental crust and sediments'. These, they say, are also clearly indicated in the seismic tomographic imaging of the upper mantle in the south Pacific. Such exotic melts pervade beneath the plate on account of diffuse upwelling mantle currents and are 'preferentially channeled to the surface by pre-existing cracks or older volcanic conduits'. These views are supported geochemically by 'totally different isotopic signatures' of the individual islands in the chain, a feature pointing to different mantle source regions[16], not matching with the lower mantle material composition.

Scientists have also, long debated whether the mantle plumes rise from the top few hundred kilometers of the upper mantle or whether they are tappings from farther deep in the lower mantle, some 2900 km down. If the upper mantle were the source, it would mean that the lower mantle material is forever sealed and hence would represent primitive mantle composition of early earth. However, geochemical and isotopic studies carried out on the rocks derived from the lower mantle have shown that its composition has departed from the pristine state and some mixing between the two mantles appeared certain[17]. Recent geophysical investigations also tend to consider that the two-layered concept held by many is untenable and that whole mantle convection is prevalent (a) in the light of seismic tomographic pictures of subducting slabs plunging into the lower mantle[15,18,19] and (b) although earth's mantle, to begin with, 4.5 b.y. ago, was two layered with the lower mantle retaining its pristine composition for considerable geological span, this had changed during the past 500 million years, and far from being layered, the intermixing between the two mantle regions appeared inevitable leading to a state of whole mantle convection[20].

In late 1996, some interesting findings were presented during the annual American Geophysical Union meeting about the source of the mantle plumes[21,22]. Quentin Williams and Edward Garnero (University of California, Santa Cruz) as well as Donald Helmberger (California Institute of Technology, Pasadena) reported that both compressional and shear seismic waves passing through lowermost ~ 5 to 40 km of the mantle (core–mantle boundary, CMB) slowed down, the former by about 10% and the latter shear or S-waves by 30%, when passing beneath central Pacific. This, according to them, indicated prevalence of hotter rock or a partially molten zone, a suspicion also expressed earlier by Stephen Grand (University of Texas, Austin), while studying South American earthquakes[15]. Williams and Garnero recognized this as an ultra low velocity zone (ULVZ) (Figure 3), and ruled out, on basis of observations and theoretical calculations, discontinuity or phase transition at the CMB for the anomalous zone. Instead, they considered partial melting at the CMB as the cause for the ULVZ, and this partial melt resulting from 'vigorous small-scale convection or the instability of a thermal boundary layer at the base of the mantle'[21]. Such ULVZ or partially molten zones, far below in the lower mantle, were also identified in several other places around the globe, particularly where the molten rocks had reached earth's surface to form volcanic hot spots, e.g. beneath southwest Pacific, Pitcairn, Hawaii, Iceland, central America, south Africa, Tasmania, southern Alaska (Figure 2). These were considered as proofs of links between surface hot spots and deepest parts of lower mantle – the ULVZ. Far from being solid, the mantle at places at the bottom is semi-molten and serves as a faster escape route for confined heat and this will trigger motion in the solid portion of the mantle above ULVZ to start rising upwards, generating a plume of superheated rock to create hot spots.

Even though the various hot spot-plume theories explain the age-progression among several of world's island and seamount chains, the relative motions of hot spots, plumes and plates, the mechanism of plume's ascent from the core-mantle boundary aided by the magma's buoyancy (controlled by temperature and viscosity relative to the surrounding mantle), and the probable source of the plume material in the lower mantle, some anomalous occurrences crop up somewhere on the globe that do not fit into these notions. Further, views about mantle convection are getting more refined in the light of fresh geophysical and chemical data; as a result, parameters that come up for its evaluation in relation to hot spot volcanism include depth-dependent viscosity of the mantle, movements of mantle influencing the plate motions, effects due to true polar wander (TPW), heat from core, mineral phase changes within mantle and the much debated seismic wave slowing at the CMB[21,22] whether due to a chemical phase change or a thermal anomaly[23]. With the current increased tempo of ocean bottom sur-

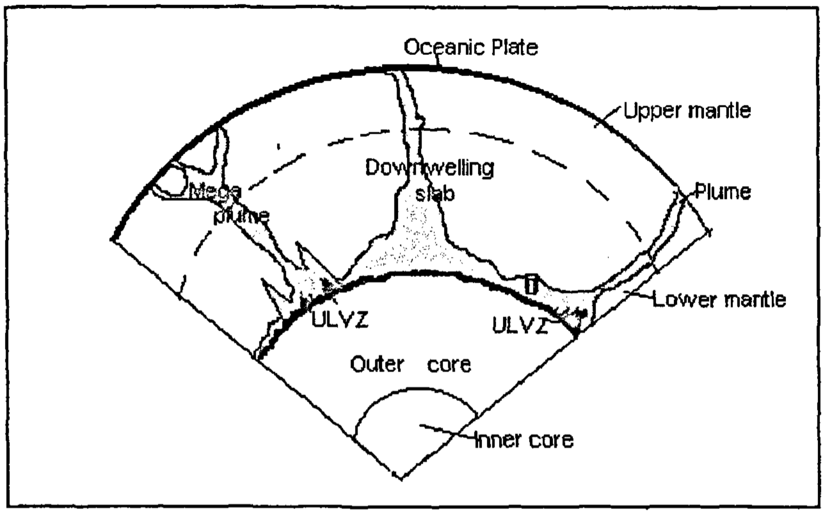

Figure 3. Diagrammatic representation of earth's core-mantle boundary (CMB) showing partial melt at the base of the mantle – ultra low velocity zone (ULVZ), giving rise to hot spots and mantle plumes.

veys, satellite mapping of submarine topography, seismic, tomographic and palaeomagnetic studies, and above all availability of hitherto scarce and inaccessible oceanic-crust samples, obtained by drilling programmes, for isotopic and other and geochemical investigations, firm answers to the evolution of hot spot volcanism can be expected. Considerable earlier geochemical (trace element) and isotopic (^{3}He to ^{4}He) studies at spreading ridges (Azores and Iceland hot spot volcanisms) have enabled recognition of compositional differences in the magma generated and linked these to the mechanism of deriving basalt through partial melting of the mantle periodotite under 'wet' or 'dry' environments as well as to their locations, either in upwelling (hot) or downwelling (cold) currents of mantle convection cycle[24,25]. Recent contributions on the Kergulean Plateau hot spot volcanism in the Indian Ocean using rhenium-osmium isotopic ratios have also indicated diverse mantle provenances for the region's volcanism. Yet another aspect that affects the mantle convection, related magmatism, plume structure and composition, is the influence exerted by true polar wander (TPW). This is a phenomenon linked to plate drifts and arising out of mass imbalance caused by drifting plates, density inhomogeneity and viscosity in the mantle (attributed to the sinking cold slabs). Also, some recent data coming out of joint studies by a 16-member team – the MELT experiment (Mantle Electromagnetic and Tomography Experiment)[26] about magma production and formation of new oceanic crust at inter-plate boundaries (spreading ridges) are bound to shape the thinking, at least about some of the intra-plate volcanism connected with upwelling mantle. However, inasmuch as there can be more than one way of generating the magma for this volcanism, including the recently-proposed cosmogenic magma generation through annihilation of dark matter earth accreted in its core during its passage through their clusters in our galaxy[27], and so long as the mantle's dynamic processes and its fine structure – physical and chemical, below the various plates are not identical globally, many aspects of hot spots and mantle plumes are bound to be much debated.

1. Wilson, J. T., *Can. J. Phys.*, 1963, **41**, 863–870.
2. Wilson, J. T., *Philos. Trans. R. Soc.*, 1965, **A258**, 145–153.
3. Dietz, R. S. and Holden, J. C., *J. Geophys. Res.*, 1970, **75**, 4939–4944.
4. Morgan, W. J., *Nature*, 1971, **230**, 43–44.
5. Morgan, W. J., *Mem. Geol. Soc Am.*, 1973, **132**, 7–10.
6. Hassler, D. R. and Shimizu, N., *Science*, 1998, **280**, 418–421.
7. Calderia, K. and Rampino, M. R., *Geophys. Res. Lett.*, 1991, **18**, 987–990.
8. Larson, R. C., *Sci. Am.*, 1995, 66–70.
9. Wessel, P. and Kroenke, L., *Nature*, 1997, **387**, 365–369.
10. Steinberger, B. and O'Connell, R. J., *Geophys. J. Int.*, 1998, **132**,
11. Christensen, U., *Nature*, 1998, **391**, 739–740.
12. Tarduno, J. A. and Cotrel, R. D., *Earth Planet. Sci. Lett.*, 1997, **150**, 171–180.
13. Gold, T., *Nature*, 1955, **175**, 526–529.
14. Anderson, D. L., *Science*, 1984, **223**, 347–355.
15. Grand, S. P., Van der Hilst, R. D. and Widiyantaro, S., *GSA Today*, 1997, 1–10.
16. McNutt, M. K., Caress, D. W., Reynolds, J., Jordahl, K. M. and Duncan, R. A., *Nature*, 1997, **389**, 479–482.
17. Hofmann, A. W., *Nature*, 1997, **385**, 218–229.
18. Van der Hilst, R. D., Widiyantaro, S. and Engdahl, E. R., *Nature*, 1997, **386**, 578–584.
19. Sankaran, A. V., *Curr. Sci.*, 1997, **73**, 901–903.
20. Allégre, C. J., *Earth Planet. Sci. Lett.*, 1997, **150**, 1–6.
21. Williams, Q. and Garnero, E. J., *Science*, 1996, **273**, 1528–1530.
22. Wen, L. and Helmberger, D. V., *Science*, 1998, **279**, 1701–1703.
23. Bunge, H. P., Richards, M. A., Bertelloni, C. L., Baumgardner, J. R., Grand, S. P. and Romanowicz, B. A., *Science*, 1998, **280**, 91–95.
24. Bonatti, E., *Science*, 1990, **250**, 107–110.
25. Bonatti, E., Seyler, M. and Nadia Sushevskaya, *Science*, 1993, **261**, 315–320.
26. The MELT seismic team, *Science*, 1998, **280**, 1215–1218.
27. Abbas, S. and Abbas, A., *Astroparticle Phys.*, 1998, **8**, 317–320.

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