WHAT IS A PLUME ?

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A plume is often invoked, as an explanation of magmatism, because of some perceived difference with “normal” volcanism. This difference can be volume, chemistry or tradition. In discussing the origin of”melting anomalies” it is necessary to have precise definitions. Workers in different fields have different ideas of what constitutes a plume so it is important to agree on the concept.

normal volcanism

Spreading ridges involve pressure-release melting. As ridges spread the space is filled with adiabatically upwelling mantle which is close to or above the melting point. The release of pressure causes melting or an increase in the melt content.

Island arc volcanism is attributed to reduction of the melting point by the release of volatiles from the downgoing slab. Melting is not entirely due to the increase of temperature or the release of pressure but by reduction of the melting point.

Hotspot volcanism, by contrast, is attributed to locally high temperatures.

melting anomaly

Excess or long-lived volcanism. This can be due to wet or fertile mantle (compared to normal mantle), focusing, small-scale convection, or high-temperatures. The plume hypothesis focuses on the high-temperature explanation. Some of the other mechanisms are athermal - that is, melting anomalies can be generated from normal temperature mantle.

plume

A narrow thermal feature, which can be either hot or cold, which rises or sinks because of its anomalous temperature compared to the surrounding fluid. In fluid dynamics a jet has the same meaning. A plume. or jet, arises from the instability of a thermal boundary layer, which is heated from below or cooled from the top.

mantle plume

A hot narrow buoyant upwelling rising from deep in the mantle and generally attributed to thermal instability of a thin layer near the core-mantle boundary (CMB). In Earth sciences a plume is also defined as a form of convection independent of other kinds of convection or plate tectonics. Plumes are considered to be the way the core gets rid of its heat, while plate tectonics is defined as the way the mantle gets rid of its heat.

Properties of Plumes

Plumes are hot. The primary thermal diagnostics are temperature, heat flow, uplift, and thermal erosion of the overlying lithosphere. Normal variations of potential temperature associated with plate tectonics are of order 200 degrees or more. The core is hotter than the mantle and the thermal boundary layer at the base of the mantle involves a larger temperature change than the one at the top. Deep thermal plumes are expected to have temperature excesses of more than 300 degrees compared to normal upper mantle basalts. Plumes have been predicted to cause thermal uplifts of 1 to 2 kilometers prior to volcanism. The heat flow at midplate plumes should be equivalent to very young oceanic lithosphere.

Plume heads. Injection experiments show that a large bulbous plume head is required to start a plume from deep in the mantle. There should be a one-to-one correspondence between a proposed hotspot track and a large igneous province (LIP) and this LIP should be generated at high elevation. "Plume Head" basalts should be colder than OIB.

Plume heads spread out. Tomography and heat flow should reveal slow seismic velocities and thermal anomalies over at least a 1,000 km radius in the upper 100-200 km. Of the mantle under proposed plume sites.

False Plume Proxies

Some characteristics of provinces with magmatic anomalies have been taken as proxies for plumes. These include non-MORB geochemical characteristics, high $^{3}He/^{4}He$ ratios, rapidity of extrusion, volumes of basalt and crustal thickness. Some geochemical models predict high ^{3}He contents and high $^{3}He/^{4}He$ ratios have been taken as a proxy for that.

Tomography

Seismic anomalies in the lower mantle are sometimes related to surface features. Continuity to the surface must be demonstrated. Statistical methods, such as Monte Carlo, should be used to confirm that the coincidences (between, say, a deep low-velocity-zone and a surface volcano) occur at a higher level than random chance.

Geochemical Diagnostics

The best chemical diagnostics would be those that have something to do with interaction with the core, at the appropriate time. Much of the mantle has probably been in equilibrium with molten iron at some point in the accretion/differentiation process (except in the extreme inhomogeneous accretion models). But if some magma was in contact with the core less than 500 myr ago this would be a good diagnostic of a deep upwelling. On the other hand if the upper mantle trace siderophiles occur in chondritic proportions this would indicate isolation of the deep mantle (the irreversible chemical differentiation model). Recycled materials in the mantle are intrinsic to plate tectonics and do not imply a deep or plume origin.

Characteristics of Melting Anomalies

The accompanying table summarizes the physical and chemical characteristics of many proposed hotspots. Many of the proposed Primary Plumes do not have the characteristics most closely associated with thermal anomalies.

Table: Summary of candidate plume-diagnostic observations. **PDF viewers: Expand screen magnification to at least 200% for optimal viewing.**

Assumptions & Fallacies

" The method of postulating [assuming] what we want has many advantages. They are the same as the advantages of theft over honest toil."

(Bertrand Russell, Introduction to Mathematical Philosophy)

Among the more critical assumptions that have been made in developing the plume hypothesis are:

° *"normally" the mantle is below the melting point*
° *melting anomalies are due to localized high temperature (not low melting point)*
° *the mantle is almost isothermal (adiabatic)*
° *cracks will not be volcanic unless the local temperature is anomalously high*
° *high temperature requires importation of heat from the CMB in the form of narrow jets.*
° *the upper mantle is vigorously stirred and is chemically homogeneous.*
° *steady state - hotspots are supplied by a steady stream of deep mantle material (rather than tapping melt lens that have accumulated over long periods of time).*
° *steady state - plate tectonics is steady state and one does not expect more magmatism or different components at the onset of seafloor spreading.*

These assumptions need to be continuously tested. The proximity of the upper mantle to the melting point and the variable fertility of the mantle due to plate tectonic processes, may call into question the validity of some of these assumptions and may make the plume hypothesis unnecessary. Evidence now used in support of plumes includes the absolute volume of erupted basalts, the rapidity of eruption, the chemistry of the magma, the elevated helium isotope ratios of some of the basalts at some hotspots, and the observation that inferred hotspot tracks cross ridges.

The most convincing arguments for a "hotspot" or a plume would be high magma temperature, uplift, thick crust, high heat flow, thermal erosion of lithosphere, or a deep mantle tomographic signal. These are indicators of a thermal mechanism, as opposed to athermal mechanisms which have also been proposed for oceanic plateaus, swells and CFB. Athermal mechanisms include focusing, fertility, ponding, the edge and rift mechanisms, and mechanisms involving lithospheric stress and dikes, and a partially molten shallow mantle. The time element (transients, long-term ponding), the stress element (litospheric valves) and the fertility element (recycled crust, volatiles), in many respects, serve as substitutes for high temperature.

The absolute amount of magma is often used as an argument supporting plumes but, usually, no comparisons with other mechanisms are made. For example, ridges also produce large quantities of basalt and do so for much longer periods of time. Focusing, ponding and edge-driven effects can increase rates, for short periods of time. The current eruption rates at Hawaii are certainly impressive but prior to 6 myr ago, the output of the Emperor-Hawaii chain were not impressive. Most "hotspot" tracks are only active for 15 myr or so. CFB are transients and 3D while most ridges are steady state and 2D. These factors alone increase eruption rates and volumes by large factors over ridges, with no increase in temperature. Also, some plateaus clearly have a continental base and are not entirely recent features as often assumed. Other processes that can give results similar to plumes are small-scale convection, an intrinsic part of plate tectonics, and convection induced by lithospheric architecture (corner flow).

Stress-controlled rates (the lithospheric valve) and fertility and volatile variations in the shallow mantle (all athermal mechanisms) received a boost from these calculations. Large volumes, and large eruption rates, especially if only temporary, can be caused by decrease in melting point, increase in basalt content of the shallow mantle (the recycling mechanism), increase in volatile content, edge and rift induced convection, and focusing. High temperature alone does not seem to be adequate.

Arguments & Counterarguments

What are some of the arguments (A), and counter arguments, (C) used in support of a mantle plume as the standard model for the origin of flood basalts?

A1. *Exceptionally large volume of tholeiitic magma.*
C1. One must compare the observed rates with something. The absolute value by itself means nothing, particularly since it is trivial, and not long-lived, compared to the output of ridges, island arcs, and backarc basins.

A2. *Flood basalts are erupted in an extremely short time.*
C2. The short time actually implies stress or lithosphere control, a valving action. Plume theorists have shown that in the plume model the timescale is controlled by the viscosity of the deep mantle and they get time scales of 10 myr or longer. A stress mechanism can be instantaneous. The transient nature of magmatic bursts also suggests pre-eruptive ponding. Global synchronism of volcanism seems to favor a stress explanation, one that involves a global plate reorganization.

A3. *Huge volumes and high eruption rates are unique to continental flood basalt provinces. As such they appear to require a unique tectonic/magmatic event.*
C3. This unique event can be a change in stress or a plate reorganization. The EDGE and rift-induced convection mechanisms are, by nature, episodic, and flux rates vary enormously so there may be no "event", just as no causative event is responsible for a continent-continent collision or a ridge-trench annihilation or variations of eruption rates along volcanic chains (although these MAY be caused by stress variations). A mantle plume is often assumed necessary to get the volumes and rates, assuming a steady-state mechanism.

A4. *From the prospective of flood basalt provinces, no other model appears to provide for the unique volumes and eruption rates of these large magmatic provinces.*
C4. The recent literature seems to offer viable alternatives (following up on earlier suggestions of a partially molten asthenosphere, a fertile source (eclogite, piclogite), focusing, EDGE convection, continental insulation (midplate mantle is warmed up), refertilization of the shallow mantle, melt ponding, and ultimate release by stress control, diking and so on. These must be tested.

A5. *These huge eruptions can be shown to frequently occur at the beginning of a long trail of lesser eruptions which end at a currently active volcanic center. The Deccan is by far the best example of this correlation.*
C5. Fewer than half the LIPs have even a postulated tail and the most prominent examples are contentious

A6. *Hotspots often cross ridges, showing that a fixed plume underneath the plate is responsible.*
C6. Plate reconstructions based on the fixed hotspot assumption have this feature but other plate reconstructions do not show ridges crossing hotspots. The association of some linear volcanic features (*e.g.,* 90 E. ridge, Chagos-Laccadive Ridge) with CFB has been used to assert that the LIP is now separated by a ridge from the hotspot. These associations have been disputed by other plume specialists.

A7. *A line of evidence in support of the mantle plume - hot spot model for the origin of continental flood basalt provinces lies in the composition of the magmas. Here, again, the evidence is not unambiguous and certainly does not prove the existence of mantle plumes. But it does fit the mantle plume model. Some eruptions contain those elevated helium isotope ratios that are equated with an origin deep in the mantle.*
C7. This involves the circular argument that, because Yellowstone, Hawaii and Iceland are products of a hot spot then elevated helium isotope ratios must be produced in the lower mantle. High $^3He/^4He$ ratios are found in many places but when found they are attributed to deep mantle plumes. In all case the absolute ^3He abundances are orders of magnitude less than in MORB. In other words, by definition, the elevated ratios are from the lower mantle. The only reason elevated helium ratios were associated with plumes in the first place was because Yellowstone, Iceland and Hawaii had some high ratios and they were thought to be plumes. This again is a circular argument.

A8. *The problems with the thermal plume idea can be fixed up by adopting aspects of the chemical plume idea. A more iron-rich or fertile source has long been advocated and supported by experimental evidence. An eclogite-bearing mantle plume source derived from subducted ocean basalts recycled through the deep mantle appears to satisfy this requirement and to satisfy the trace element concentrations.*
C8. The chemical plume idea, and the eclogite and recycled crustal source idea are old ones and are alternative mechanisms to deep hot plumes. Introduction of eclogite into a plume was thought to be necessary to get the observed volumes but when this is done one no longer needs the plumes or deep recycling. If the shallow mantle is close to the solidus of peridotite it will be near the liquidus of eclogite and melting anomalies can be created at "normal" mantle

temperatures. A shallow fertile source is one alternate to plumes, and may give the necessary volumes at low T, especially if combined with the ponding/stress-release idea.

A9.*There is lack of geologic evidence for extension prior to eruption of CFB.*
C9. There is abundance evidence for extension, but usually not uplift (the plume diagnostic), prior to volcanism. Dikes can also take up extension. Only 1 cm of extension, with magma viscosities, is all that is needed to provide the volumes and rates from a fertile and partially molten mantle. Meter wide dikes can certainly provide the necessary flow rates and this can be below geologic resolution for extension.

Fallacies

Some of the common arguments in support of particular models of mantle convection or geochemical box models can be cast into the form of logical arguments and analyzed for their validity. Some well known fallacies are categorized below, with examples from the recent literature.

Circulus in demonstrando

Mid-ocean ridges are able to migrate over hotspots, which implies that the hotspot source is deeper than about 200 km.

(plate reconstructions not using the fixed hotspot reference frame do not demand that ridges cross hotspots)

argumentum ad populum

"For many geoscientists, the mantle plume model is as well established as plate tectonics".

False Dilemma and Affirming the Consequent, plus rhetoric and Bifircation

"The apparent controversy can be broken down into two questions. Is there evidence that deep mantle plumes exist? And do all volcanoes not associated with plate boundaries require a deep mantle plume? The answers seem most likely to be "yes" and "no" respectively."

(A limited number of options (usually two) is given, while in reality there are more options (or perhaps even one). A false dilemma is an illegitimate use of the "or" operator. Putting issues or opinions into "black or white" terms is a common instance of this fallacy.)

The actual question is, "Is there evidence that any volcano requires a deep mantle plume?" Deep mantle plumes, in the sense of thermal instabilities of a thermal boundary layer, certainly exist but do they rise to the surface and are they narrow? Pressure (and chemical layering) at the CMB causes them to be broad, sluggish, long-lived and slow to form, apparently consistent with the large features seen by tomography. The probable existence of a deep mantle TBL is not the same as the assumption that these must be the source of OIB. The discovery of deep mantle low-velocity zones is not evidence for connection to the surface; even a chemically stratified mantle will have variable temperature (and composition?) in each layer.

Bifurcation

Also referred to as the "black and white" fallacy and "false dichotomy", bifurcation occurs if someone presents a situation as having only two alternatives, where in fact other alternatives exist or can exist.

Red herring and fallacy of Irrelevant Conclusion

The upwelling mantle under Hawaii must also be 200-300 K hotter than the surrounding mantle to achieve the required large melt fractions at depths below the 80-km-thick lithosphere. Such hot rock material must come from a thermal boundary layer. The CMB is the most likely source, unless there is another interface within the mantle between compositionally distinct layers.

(these are requirements of the steady-state thermal plume hypothesis, not general requirements).

The Ratio Fallacy and the Slippery Slope Fallacy

The chemistry and isotopic composition of many hotspot lavas, especially the high $^{3}He/^{4}He$ ratios, indicate that the hotspots sample a part of the mantle distinct from that sampled by mid-ocean ridge basalts. High $^{3}He/^{4}He$ ratios imply high ^{3}He contents and therefore an ancient undegassed reservoir and therefore the deep mantle.

Fallacy of Irrelevant Conclusion

Numerical simulations of plumes reproduce many of the geophysical observations, such as the rate of magma production and the topography and gravity anomalies produced by plume material as it spreads beneath the lithosphere. Therefore, plumes exist.

Modus Moron

Midocean ridge basalts come from the upper mantle.
Therefore, ocean island basalts come from the lower mantle.
Plumes come from the lower mantle.

Fallacy of Irrelevant Conclusion, Affirming the Consequent and Permissivity

Theoretical and laboratory studies of fluids predict that plumes should form in the deep Earth because the core is much hotter than the mantle. Therefore hotspots are caused by plumes from the CMB.

(confusion of "should" with "do" or "must".)

Ignoratio Elenchi and Circulus in Demonstrando

The persistence of flow through the plume tail for 100 myr or more (several times the number of years required for plume heads to rise through the mantle) implies that the plume is much less viscous than the surrounding mantle.

(this has nothing to do with whether plumes exist or the characteristics and requirements of other models).

Continental flood basalts erupt a million cubic kilometers of basalt or more in 1 myr or less. Therefore plumes erupt a million cubic kilometers of basalt or more in 1 myr or less.

(this characteristic is now used to prove that continental flood basalts are caused by plumes).

The above two conclusions are contradictory. The rate of plume magmatism is controlled by lower mantle viscosity while in the plate theory it is controlled by lithospheric stress (the valve).

Table: Summary of candidate plume-diagnostic observations. PDF viewers: Expand screen magnification to at least 200% for optimal viewing.

HOTSPOTS	BF	Princeton	JP	Malamud	3He/4He	lowHe	He/Ne	Courtillot	TZ	Temperature	ULVZ	negative	flux	geoid	crack?	TOMO			Ritsema &	Clouard &	Wessel &	Koppers	HOTSPOTS
	10^3kg/s		Morgan	Turcotte	R				effect	/heat flow	(D")	studies	reliability			110 km	290 km	000 k	Allen	Bonneville	Kroenke	et al	
Hawaii	6.5	YES!	ge(0-5M	large	igh/variable		low	primary	?	no anom.	yes			5		km		no	UM				Hawaii
Tahiti	3.3	YES!	medium	large	low			2			yes		poor	2				no	NO	NO	NO	not fixed	Tahiti
Marquesas	3.3		medium	large		low		2				McNutt	poor	2.25	yes	no			shallow			not fixed	Marquesas
Macdonald	3.3		small	large				2					poor						UM	NO	NO	not fixed	Macdonald
Easter	3.3	YES!	small	large	normal			primary	thin	< 150 C		no swell	Favela	0	yes	no		no	UM			not fixed	Easter
Louisville	2	no!	small					primary				no swell	poor		yes	no		no	UM		relocate	not fixed	Louisville
San Felix	1.6			medium				1							yes				shallow				San Felix
Caroline	1.6		very small					3											NO			not fixed	Caroline
Juan Fernandez	1.6		small		high			2							yes				shallow				Juan Fernandez
Samoa	1.6	YES!	medium	medium	igh/variable		low	primary???			yes	Natland			yes			no	UM	NO		not fixed	Samoa
Pitcairn	3.3		small	large		low		2	thin			poor	poor	0.4	yes				shallow	NO	NO		Pitcairn
Yellowstone	1.5	no			variable			2	none										NO				Yellowstone
Reunion	1.4	no!	small		moderate		low	primary				Hirn		2.6	yes	no			NO		Burke,no		Reunion
Galapagos	1.4		large		high/variable			2		<70 degrees		no swell		0.4	yes		no	no	NO				Galapagos
Bermuda	1.3							0	0		no			5.5	yes				NO				Bermuda
Iceland	1.2	no	large	small	igh/variable		low	primary	small	<70 degrees	yes				yes				UM				Iceland
Azores	1.2				low	low		1		<70 degrees	no			3	yes				NO				Azores
Afar	1.2	no			average			primary	none		no				yes			no	UM				Afar
Cape Verde	1.1	YES!	small	small		med.		2			no			8	yes			no	NO		no track		Cape Verde
E.Africa	1.1														yes								E.Africa
Tristan	1	no			low	low		primary		<150-162 C	no		poor		yes	no			NO				Tristan
Canary	1				low	low		2			yes			6.8	yes								Canary
Ascencion	0.9							0				no swell	poor	0.4	yes								Ascencion
Kerguelen	0.9	YES!	large	very small	low	med.	low	2					poor		yes			no	shallow				Kerguelen
Lord Howe	0.9							1															Lord Howe
E.Australia	0.9							1															E.Australia
Tasmanid	0.9							1			yes		poor										Tasmanid
Trinidade	0.7																						Trinidade
Jan Mayen								1			yes				yes				NO				Jan Mayen
Bowie	0.3		small					2					poor						UM			not fixed	Bowie
Balleny								0															Balleny
Bouvet	0.4	YES!		very small	MORB			1				no swell		0	yes	no		no					Bouvet
Cameroon							low	0				crack			yes								Cameroon
Cobb/JdF								2							yes							not fixed	Cobb/JdF
Comores								0															Comores
Crozet	0.5							0															Crozet
Darfur								0															Darfur
Discovery								1					poor										Discovery
Eifel	0.5							0			no												Eifel
Fernando								0					poor										Fernando
Guadalupe			small		low			0							yes							not fixed	Guadalupe
Hoggar								1															Hoggar
Marion								1															Marion
Meteor																							Meteor
New England												McHone			yes								New England
Raton															yes								Raton
St.Helena						low	low	0			no				yes								St.Helena
Socorro					low							Favela											Socorro
Tibesti	0.4																						Tibesti
Vema	0.4																						Vema
Baja								0					poor		yes								Baja
Gulf of Alaska																							Gulf of Alaska
Foundation smts															yes							fixed	Foundation smts
Amsterdam/St.Paul					low							no swell		0									Amsterdam/St.Paul
Circe										278 C		no swell			yes								Circe
Caroline											yes		poor										Caroline
San Felix													poor		yes								San Felix
Cook-Australs					MORB				normal			Dickinson	,McNutt							NO			Cook-Australs
Macdonald																				NO			Macdonald
Rarotonga																				NO	NO	not fixed	Rarotonga
Gough					low	low																	Gough
Madeira																							Madeira
Shimada						low																	Shimada
Shona					MORB		high																Shona
Great Meteor																							Great Meteor
Erebus																						not fixed	Mangaia
																						not fixed	Rurutu
Pasadena									220 km														Pasadena
Sumatra									181 km														Sumatra
Java									306 km														Java
Brazil-Andes									290 km														Brazil-Andes