The EDGES of the Mantle

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The core-mantle boundary region is often considered to be the source of narrow upwellings which drive or influence plate motions and continental breakup, fuel large igneous provinces and generate volcanic chains. The plume hypothesis has influenced most fields of geochemistry, petrology, geodynamics and mantle evolution. The key axioms underlying the plume paradigm are identified: Axioms are self-evident truths and are seldom stated explicitly. When they are, they are sometimes not so self-evident. The role of the surface boundary layer is discussed in connection with large igneous provinces and volcanic chains. Partial melting is the expected natural state of the upper mantle and only abnormally high seismic velocities imply absence of melting (slabs, cratons). Plume theoreticians have underestimated the average temperature of the mantle and have overestimated melting temperatures. Extensive melting in the upper mantle does not require abnormal temperatures or plumes. The dynamics and chemistry of midplate volcanism are explainable by near-surface processes. "Midplate" volcanism starts at plate boundaries or discontinuities, at lithospheric "edges", in regions of extension generated by plate processes. The chemistry of "hotspot" basalts implies contamination by processes and materials that occur near the surface of the Earth. A buoyant metasomatised layer at the top of the mantle, near the melting point, removes the need to import heat and chemical inhomogeneity from D" to explain midplate volcanism. D" is an interesting and important region, but any connection to surface processes or chemistry is speculative.

INTRODUCTION

"It is only after you have come to know
the surface of things
that you can venture to seek what is underneath . . .
The surface is already so vast and rich and various
that it more than suffices
to saturate the mind with information and meanings."
Mr. Palomar
Italo Calvino (1983)

"But then, to what end" said Candide,
"was the world formed?
"To make us mad," said Martin.
Candide

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The core-mantle boundary (CMB) region is one of the most important boundaries in the Earth. The changes in density and viscosity across the CMB are larger than at the surface. The dross of mantle and core processes collect there. Molten metal contacts crystalline oxide there. Temperature variations of hundreds of degrees are damped to near zero. But, because of pressure, buoyancy is hard to come by, and heat is transmitted readily by conduction. D" and E' are important and fascinating parts of the CMB neighborhood. But does D" drive the plates and fill up the asthenosphere with giant plume heads and control the chemistry of ocean islands? Or does outer Earth control its own fate? Do narrow volcanic roots extend to CMB or only to the base of a cracked plate? Are volcanic chains part of the surface mosaic, or are they imposed from deep in the Earth? Does Earth dynamics start and end at D"? To many Earth scientists, the concepts of hotspots, plumes, primitive mantle and D" are inextricably intertwined in a thread that weaves throughout the tapestry of mantle

dynamics, evolution and chemistry. Herein I explore the connections.

Some of the assumptions underlying global Earth dynamics are treated as axiomatic; these are collected in Appendix I. The role of plumes vs. plates is discussed in Appendix 2. The focus on the deep mantle by geochemists is treated as an exercise in deductive logic in Appendix 3. The issues of partial melting, passive ridges, reference frames, radioactivity of the lower mantle and linear volcanic chains are discussed. These have all been considered by some authors to be relevant to the base of mantle. Each one of these "side issues" is particularly compelling to some in formulating views of the Earth. For example, the fixed hotspot reference frame has convinced some that hotspots are due to deep mantle plumes rather than propagating cracks or leaky transform faults. The passivity of ridges and mass balance calculations have convinced some that a deep source is required for ocean island basalts. Many linear volcanic chains, however, are due to surface tectonics and lithospheric architecture. Only when these are understood can we "venture to seek what is underneath . . .".

THE BASE OF THE MANTLE

It is unlikely that the lower mantle is entirely homogeneous. A compositionally distinct D" is expected on several grounds:

1. During accretion, material denser than the mantle, but less dense than the core, will settle into D".
2. As the core cools and the inner core grows, light material which can no longer be held in solution, or suspension, will rise to the top of the core and may become part of the lower mantle.
3. The Earth accreted, in part, in the inhomogeneous accretion mode. The deep mantle may have more Ca-Al-Ti-rich refractory material than the top of the mantle [Ruff and Anderson, 1980].
4. The early formed nucleus of a planet may be able to retain more volatiles than the outer parts. Later impacts result in complete devolatization. On the other hand, the final assembly of a planet may involve a volatile-rich late veneer, brought in from the far reaches of the solar system. A big planet can retain low molecular weight species.
5. Subduction on a small planet, or the sinking of dense cumulates, may have brought the products of near-surface fractionation to the CMB, even if this is not possible today.
6. FeO-rich phases may be able to separate from MgO-rich phases and, perhaps, form a layer at the base of the mantle.

Many of these processes make the CMB denser than normal lower mantle, and stable stratification is the likely result. In this situation, the chemically distinct layer will not be uniform in properties or thickness. The top is expected to have high relief and the layer may be missing in places as it is swept toward mantle upwellings. Because of the large density contrast between the mantle and core, and the thermal and viscosity properties of the core, the bottom of D" is expected to be isothermal and low relief. A high thermal gradient and a silicate-iron slurry may make a thin, low shear velocity, layer at the boundary. In Dante's "Inferno", DIS is the boundary between Upper and Nether Hell, and this is an appropriate name for the base of the D" layer.

The intensely slow region (DIS), recently found at the base of the mantle [Garnero and Helmberger, 1995], may be another analogy between the top and bottom of the mantle; both are thermal boundary layers, both collect material of extreme density and both may be close to or above the melting point. The upper part of the Earth contains thick accumulations of basalt or residual peridotite. These are called continents, plateaus, swells and cratons. D" can be expected to be equally variable.

Whether or not D" is important for the understanding of mantle dynamics and geochemistry depends on which of the following statements is more nearly true:

"Plumes are secondary flow superposed on mantle wide plate scale flow [Davies, 1988]."

or

"Hot upwellings are part of the main mantle flow. Surface expressions of volcanism are controlled by plate tectonics, subduction and rifting."

This issue is discussed in Appendix 2. Plates and cracks certainly modulate expressions of magmatism at the Earth's surface; the question is, can D" do so as well? Are volcanoes caused by concentrated jets of hot fluid, or are they the result of lithospheric failure? Is DIS relevant to surface tectonics and volcanism?

LOW VELOCITIES AND MELTING

The most plausible explanation for the occurrence of intensely slow regions of the mantle is partial melting or the presence of a fluid phase [Anderson and Sammis, 1970; Anderson and Bass, 1984]. Partial melting, dehydration, dislocation relaxation and change in crystal orientation are the main mechanisms by which extremely low seismic velocities can be generated [Anderson, 1989; Minster and Anderson, 1981].

Dislocation relaxation is a viable velocity reduction mechanism and, formally, has the same effect as thin grain boundary melts [Anderson, 1989]. If the fluid does not wet grain boundaries, and occurs in spherical or cylindrical inclusions, then small amounts of melt do not cause large reductions in velocity. If at lower mantle pressures (in DIS) the viscosity of silicate melts is very high, or if they do not wet grain boundaries, then extensive melting is required to substantially lower the seismic velocity. According to Zerr et al. [1997] melting of silicates in D" is unlikely, but this is still an open question.

An alternative to partial melting in DIS is the incorporation of molten Fe. If metallic fluids wet silicate grain boundaries, then the melt should drain out. Fe-melts, however, may be trapped in silicates. Although Fe may not diffuse or percolate far up into the base of the mantle, a

silicate slurry at the top of the core, formed by stopping and entrainment, may be able to trap metal as it joins the base of the mantle. DIS may represent a transition region between mantle and core and therefore be intermediate in density and seismic velocity. The lowermost layer of the mantle is usually thought of as a mantle silicate but it may be a metal-oxide mix with very high density.

A large part of the upper mantle above 300 km has such low seismic velocities than partial melting is implied [Anderson and Bass, 1984]. It is only cratons and slabs that appear to be subsolidus. Oceanic mantle and mantle under tectonically active areas have seismic velocities that are lower than any combination of stable minerals at reasonable temperature. Lithospheric architecture and volcanic regions show excellent correlation with upper mantle seismic velocities [Scrivner and Anderson, 1992; Wen and Anderson, 1995a,b, 1997]. There is very poor correlation with the lower mantle [Ray and Anderson, 1994].

Cratonic roots remain dry and buoyant (and strong) because they are deeper (~200 km) than the dehydration depth in slabs and are protected from refluxing [Polet and Anderson, 1995]. The MORB reservoir is probably deeper than 200 km, except at ridges, and is immune from contamination, remaining depleted, dry and homogeneous [Anderson, 1996]. Slabs sinking below 200 km are efficiently demetasomatized and do not contaminate the MORB reservoir or craton roots. On the other hand, MORB mantle rising to the surface at newly extending rifts will react with the shallow mantle and recover some of the recycled material, thereby generating enriched magmas, common at the inception of continental rifting, seafloor spreading and island arc formation. Conditions near the top of the mantle need to be understood before the base of the mantle is implicated in magmagenesis. If variations in temperature of 100°C are associated with plate tectonics (slab cooling, continental insulation, craton roots), and variations of tens of degrees in melting temperature are plausible (water content, fertility, composition) and if extents and volumes of melting depend on focusing and lithospheric thickness as well as temperature, then there is little need to look deeper than the upper mantle to explain the various styles of magmatism.

The existence of a widespread partially molten layer in the upper mantle [Anderson and Sammis, 1970] eliminates the need to import deep hot material into this region to explain magmatism. It is conditions in the lithosphere that mainly control the locations of volcanoes. Magmatism attributed to hotspots and convective processes in the mantle may be opportunistic invasions of magma from an already partially molten mantle [Bailey, 1992]. It is hard to construct a geotherm that does not intersect the damp solidus [White and Wyllie, 1992]. The seismic LID acts as a strong impenetrable barrier to melt migration. In brief, melting is the expected and observed normal state of the upper mantle, volcanoes are probably the result of lithospheric cracking and melt focusing [Vogt, 1974a,b], and shallow mantle geochemistry is appropriate for midplate volcanoes [Anderson, 1996]. Midplate volcanism is a normal result of plate tectonics. Plates are not rigid or homogeneous or uncracked.

It is commonly assumed that deep strong plumes are required to explain large igneous provinces (LIP). However, these are usually found at lithospheric discontinuities, such as craton boundaries, or at new ridges, triple junctions, and migrating ridges. These regions focus the flow and are weak points of the lithosphere. Since the upper mantle is partially molten almost everywhere, a conclusion obtained both from seismology and experimental petrology, and magmas are less dense than the overlying mantle and crust, only small extension is required to allow ascent of magma to the surface. Using the heights of volcanoes as a guide to the pressure differential (~1 kb) and using estimates of magma viscosity (~103 c.g.s.) a crack of the order of 1 cm in width is all that is required to generate the inferred flow rates of large igneous provinces (~10-7 km3/sec). The heights of volcanoes imply a magma source near the base of the lithosphere [Vogt, 1974]. A crack 1 cm wide implies a strain of only 10-8 if it is the result of extension over 1000 km. Gravitational stresses associated with topography, slab pull or slab roll-back may be the source of extension. The absence of uplift prior to LIP eruption rules out the thermal plume explanation [e.g., Kamo et al., 1996; Fedorenko et al., 1996]. Other problems with current plume models for generating LIPs are summarized in Cordery et al. [1997].

TEMPERATURES IN THE MANTLE

Seismic velocities and properties of upper mantle phase changes are the main geophysical constraints on mantle temperature. A potential temperature of 1400°C is an appropriate average temperature [Anderson, 1989; Anderson and Bass, 1984]. A range of about 200°C is expected from normal plate tectonic processes [Anderson, 1998]. McKenzie and Bickle [1988] adopt a "normal" mantle potential temperature of 1280°C. Evidence for higher temperatures is taken as evidence for plumes. The plume hypothesis, then, to some extent, is based on a straw man. Mantle temperatures are higher than in the "standard model" and "hotspot" magmas probably have lower melting temperatures than assumed because of the presence of volatiles. The highest temperature magmas (komatiites, picrites) may only require 1400°C in order to melt [Stone et al., 1997; Parman et al., 1997], well within the range of "normal" mantle temperatures.

MASS BALANCE

The large-ion lithophile (LIL) elements are partitioned strongly into the crust and upper mantle. Although the crust is only 0.5% of the mass of the mantle, it contains more than 50% of some of the most incompatible elements. Almost all of the most incompatible elements are in the

crust and upper mantle. These include U, Th, Pb, Ba, Cs, K, I and Cl [Anderson, 1989; Rudnick and Fountain, 1995; Dérvelle, et al., 1992].

Highly incompatible elements such as I, Cl and 40Ar are strongly concentrated into the atmosphere, oceans and pelagic sediments. U, Th, K, Ce and Pb are highly concentrated into the crust and require extraction from 60 to 100% of the mantle. There is no mass balance argument that requires only the upper mantle be depleted in LIL to form the crust or that only the fertile MORB reservoir is depleted. Most of the mantle, in fact, appears depleted and there is evidence of strong upward concentration of the LIL elements. Lead isotopes and ratios such as U/Nb and Pb/Ce show that no sampled reservoir is primordial or unfractionated [Hofmann et al, 1986]. The lower mantle, the refractory residue of upper mantle and crustal extraction, apparently is not sampled by current processes. In contrast to the MORB reservoir, it is predicted to be both depleted and infertile.

The volatile elements are depleted in the Earth by two orders of magnitude relative to chondritic abundances. The abundance of elements such as H, Cl and I suggest that volatiles could have been brought in by a late veneer representing 1% or less of the mass of the Earth [Anders and Owen, 1977; Dérvelle, et al., 1992]. The high content of siderophiles in the upper mantle plus the chondritic relative ratios of the trace siderophiles suggest that they too were brought in as a late veneer [Dreibus and Wänke, 1989]. Much of the atmosphere and oceans could have been from a late veneer. The same may hold true for the noble gas budget of the Earth. Deep sea sediments today are high in noble gases because of the high concentration of interplanetary dust particles (IDPs). The sediments are retentive of trapped 3He but not 4He [Farley, 1995]. Therefore sediments are subducted with 3He/4He ratios comparable to those found in Loihi basalts. Today's IDPs flux cannot account for today's volcanic 3He flux but neither quantity is constant in time [Anderson, 1993]. Most of the late veneer probably accreted prior to 2 Ga. IDPs are remarkably retentive of noble gases and it is the fate of the fluid in sediments after subduction that matters. Noble gases are transported by fluids and are trapped in secondary minerals and fluid-filled inclusions. Loosely bound 10Be and OH make their way into the mantle. The high 3He/4He ratios and high iodine contents of Loihi basalts suggests that a pelagic source may be involved. There is no evidence, however, that Loihi basalts are particularly high in 3He. The high 3He/4He ratios of Loihi basalts apparently reflect low 4He abundances, and therefore, a U-depleted refractory reservoir [Anderson, D. L., The Helium Paradoxes, submitted to Earth and Planetary Science Letters for publication, 1997].

3He plays an important role in discussions of mantle evolution. The presence of 3He in the mantle must be explained since it is difficult to accrete and retain the light volatile elements. Both midocean ridge basalts and hotspot magmas contain 3He. Either this is brought into the Earth during the primary high-temperature accretion, or as a late veneer. The easiest place and time to degas the Earth is at the surface during initial accretion. The easiest time to incorporate volatiles is during a drawn out late accretion stage.

The other aspect of helium geochemistry is the high 3He/4He ratio of some OIB such as at Hawaii, Loihi, Iceland and Samoa. OIB typically have two orders of magnitude less 3He than MORB, and midocean ridge volcanism supplies more than 300 times the amount of 3He provided to the atmosphere by hotspots [Sano and Williams, 1996]. A late veneer and cold subduction can explain the presence of 3He in the mantle but high 3He/4He ratios imply, in addition, a low U and Th storage tank for OIB gases. The lithosphere is such a storage tank [Anderson, D. L., The Helium Paradoxes, submitted to Earth and Planetary Science Letters for publication, 1997]. Thus, another argument for a deep plume source is brought into question.

RADIOACTIVITY OF LOWER MANTLE

Mass balance, heat flow and Pb-isotope data suggest that most of the lower mantle is depleted in the heat producing elements [Birch, 1965; Patterson and Tatsumoto, 1964; Spohn and Schubert, 1991; Anderson, 1989]. This was probably accomplished by upward concentration of volatile and incompatible elements during accretion [Anderson, 1989]. The crust contains more than 50% of the terrestrial inventory of U, Th and K and the atmosphere contains about 70% of the 40Ar produced over the age of the Earth from 40K [Rudnick and Fountain, 1995; Wedepohl, 1995; Anderson, 1989]. These observations are consistent with a strongly differentiated and degassed Earth and with a lower mantle that is infertile (low in basaltic elements such as Al, Ca and Ti), depleted (low in U, Th, K, Ba, etc.), and degassed. The various paradoxes that occur in geochemical mass balance calculations (e.g., the Pb-paradox) imply that there is an unsampled reservoir [e.g., Hofmann et al., 1986]. I suggest that this is the lower mantle.

REFERENCE FRAMES

Oceanic plates move rapidly in the paleomagnetic and paleogeographic reference frames. The plates are part of the surface boundary layer and are expected to be mobile. Markings on the surface are not expected to provide a good reference system. For the same reason, D" is not a good reference system; not only is it a boundary layer but it has very low viscosity and motions may be fast because of the small area. Plumes arising from D" are not expected to define a fixed reference system, particularly after having risen through various shear layers and phase boundaries in the overlying mantle. The relative fixity of hotspots is not an argument for a deep-mantle plume origin or for a source at the base of a high-viscosity layer.

Ridges and trenches migrate. It is of interest to compare motions of candidate fixed points, such as hotspots, to other reference frames which are known to be flexible.

Continents move episodically; stationary periods occur when they are over downwellings. Relative motions of slowly moving continents provide a standard to which hotspots reference frames can be compared. These are comparable to inferred motions of hotspots.

The hotspot hypothesis as a means of determining an absolute reference frame for lithospheric plate motions seems to be somewhat of a tail-wagging-the-dog, since the volumes of material produced by volcanoes is small in comparison to the amount produced at other tensional features in the plate tectonic system [Kaula, 1975]. An absolute reference frame defined by minimizing the transitional motion of plate boundaries differs by only 0.6 cm/yr from a frame defined by hotspot traces and by 0.4 cm/yr from a frame defined by drag forces on plates [Kaula, 1975]. Although ridges are expected to be mobile, there is a remarkable spatial correlation of ridges with hotspots, suggesting a relation between the two. Many hotspots which are not currently on ridges were on-ridge within the past 60 Ma. A spreading ridge creates space and updrafts, and permits extensive melting of rising mantle. Even at linear ridges the induced convection is three-dimensional, with some regions, both along- and off-axis delivering more melts than others. Some of these productive regions have been called "hotspots" with the implication that they differ from normal ridge induced convection and that they have deep roots. In spite of their expected mobility, a reference frame based on ridges is just as stationary as one based on hotspots [Kaula, 1975]. The validity of the fixed hotspot reference frame is in dispute [Stock and Molnar, 1987; Cande et al., 1995; Norton, 1995]. Very few island chains are either parallel or have consistent age progressions with other tracks on the same plate.

The Hawaiian is the best studied volcanic chain. It is parallel to some features on the Nazca and Antarctic plates and some of the boundaries of the Pacific plate, but there is a notable absence of parallel island chains. The Louisville chain, an oft quoted analog of the Hawaiian chain, in fact is not a fixed magmatic center [Norton, 1995]. It appears to terminate on the Eltanin Fracture system although the actual location of the Louisville "hotspot" is in dispute. The Hawaiian melting anomaly is not fixed relative to other hotspots [Cande et al., 1995; Norton, 1995].

NON-PLUME MODELS

Recent discussion about hotspots suppose that they are the result of convective phenomena; i.e., intense narrow upwellings. The surface locations of volcanoes, however, may be almost entirely due to lithospheric conditions and have little to do with deep small-scale convective processes (Appendix 2). Propagating cracks were discussed some time ago [Turcotte and Oxburgh, 1978] but dismissed because of the perceived fixity of hotspots. The propagating crack idea was based on homogeneous plates and uniform mantle. Detailed gravity and magnetic maps, however, show an extensive fabric to the seafloor [Smith and Sandwell, 1997]. Island and seamount chains are often along, or parallel to, fracture zones or are near subduction zones (Samoa, Juan Fernandez, San Feliz, Galapagos) where plate tearing stresses are highest. Some hotspots occur along abandoned ridges or where oceanic plates are fragmenting (E and NE Pacific). Many island chains originated at a spreading ridge and all continental flood basalts occur at cratonic boundaries. These regions tend to focus melts resulting in larger volumes of magma than in an extending situation involving uniform plates. Other large igneous provinces occur at new ridges or triple junctions, and at times of plate reorganization. These all indicate lithospheric control of volcano locations, and a role for transient drainage effects.

The opening of leaky transform faults, or the propagation of cracks toward the interior of a plate from a ridge or a subduction zone, can also cause linear volcanic chains. Such cracks may explain hotlines and rejuvenated volcanism as well as non-parallel tracks. Rates and durations of magmatism depend on stress conditions in the plate. These in turn depend on boundary conditions such as slab pull, ridge push and thermal contraction, and local conditions such as volcanic loads. If plates act as stress guides, areas of maximum tensile stress will tend to be fixed relative to the boundary configuration; stagnation points in mantle flow will be as well. Volcanic chains tend to propagate counter to the direction of plate motion. Lithospheric tears due to lateral changes in subduction dip (Nazca plate, Samoa) or trend (Galapagos) also propagate counter to the plate motion, and therefore appear to be relatively fixed. The Easter "hotline" appears to be propagating counter to plate motions [Kruse et al., 1997].

Time progressive magmatism is a characteristic of ridge "propagators", leaky transform faults, crack propagation and progressive opening of oceans, such as the south to north unzipping of the North Atlantic. Nevertheless, the existence of age progressive volcanism is often taken as evidence for a mantle plume. Most long volcanic chains do not exhibit age progression or are not parallel to plate motions [e.g., Okal and Batiza, 1987; McHone, 1996b; Anderson, 1996; Vogt, 1995]. The ubiquitous presence of melt in the low-velocity zone, ponding of melt at the base of the lithosphere and the rapid extrusion of melt through narrow conduits suggests that only moderate extension is required to form large and transient igneous provinces. The hydrostatic head inferred from volcano heights and the thickness of the lithosphere, combined with estimates of magma viscosity, is consistent with inferred rapid extrusion rates. The composition of near-surface and subducted materials, and the shallow mantle are appropriate for midplate volcanics [Anderson, 1996]. The concept of a non-rigid plate plus a partially molten upper mantle (at "normal" mantle temperatures), is an alternative to plumes.

THE PASSIVE RIDGE DIVERSION

It was once believed that ridges and trenches were the up- and down-wellings of mantle convection. It then became

clear that ridges were passive; plate tectonic forces caused the plates to separate and mantle passively upwelled to fill the cracks. Ridges migrate about the Earth's surface and become annihilated as they approach trenches. The idea took hold that ridges were entirely passive; that active, convective upwellings were elsewhere; and that ridges could form essentially anywhere.

However, ridges and trenches are the largest source and sink of material on Earth. Slabs cause entrainment and cooling of the mantle and control the locations of the most significant downwellings in the mantle. Plates are strong and have high viscosity and contain an element of chemical buoyancy. They are thicker and colder than a normal thermal boundary layer and have a larger influence on mantle thermal properties than a simple unstable TBL. The locations of subduction zones are fundamental in controlling the planform of mantle convection. Trenches provide a good reference frame, comparable to hotspots [Kaula, 1975; Chase, 1978].

Upwelling under thin lithosphere causes adiabatic melting and creates buoyancy. Flow is focused toward ridges. The mantle in the vicinity of a ridge becomes a sink for mantle flow and "active" upwellings are attracted to the ridge. Although the ridge, from a plate tectonic point of view, may be passive, and entirely driven by "ridge-push" and "slab-pull", it will certainly influence the locations of the major mantle convective upwellings. It is no accident that most hotspots occur on young lithosphere (most of the others being at lithospheric discontinuities such as transform faults, old ridges and craton boundaries). This is where the plate is thin and under tensile stress, and where upwelling mantle and melts are focused. It is also no accident that most of the world's ridges (and hotspots) overlie mantle that has not experienced subductive cooling since at least the breakup of Pangea [Wen and Anderson, 1995a]. Ridges (and hotspots) occur over hotter than average mantle, and mantle not cooled from below [Anderson, 1996]. Spreading ridges not only induce localized upwelling by plate divergence, adiabatic melting and focusing (upslope migration) but they also provide sites where the lithosphere is most vulnerable to penetration.

Therefore, while ridges are technically passive and they do migrate and "jump", they seldom migrate far or fast. In fact, the "fixed-ridge" assumption provides as good a reference system as the "fixed hotspot" assumption [Kaula, 1975]. Ridges and trenches can annihilate, but overridden ridges show up as regions of low seismic velocity and extensive volcanism; for example, Western North America. Subducted ridges may be responsible for some volcanic chains. Slab windows are implicated in many regions of continental magmatism.

Long-lived ridges are no longer processing chemically diverse mantle that may have initially been at the top of the system (the perisphere). New ridges, slowly spreading ridges, migrating ridges and continental rifts all sample mantle that is enriched relative to that providing N-MORB at rapidly spreading, and long-lived, ridges. New ridges and triple junctions form when there is a major plate reorganization, such as the breakup of Pangea, and it is at these times and places that there occur transient episodes of enriched non-MORB magmatism. These are the times and places where the shallow mantle is being sampled and it is at later times that the deeper MORB reservoir becomes available, and the shallow enriched layer becomes depleted or attenuated [Anderson, 1996]. The ultimate source of the enriched layer is probably refractory residue permeated by fluids from dehydrating subducting slabs and trapped interstitial residual melts. The MORB reservoir is generally thought to be well mixed because of its homogeneity. It, in fact, is probably depleted and homogeneous because it is deep, and protected from the contaminating effects of subduction. Low-melting and shallow constituents have been removed by prior magmatism. MORB are depleted and homogeneous because they do not encounter pre-existing crust, lithosphere or sediments as they rise. The anomalous mantle that appears at the onset of rifting is often attributed to a plume or plume head. It could as well be shallow mantle, and probably is.

A similar idea has been put forth by Jason Phipps Morgan [1997]. He proposes a "compositional lithosphere", the refractory residue of melting at midocean ridges. Such a shallow infertile (refractory) explains the age dependence of oceanic bathymetry and the puzzle that plume flux does not depend on age of the lithosphere. This model is similar to the perisphere model except that the perisphere is formed by billions of years of melt extraction and a chemical buoyant layer may also be a relic of crystallization of a magma ocean. Additionally, the perisphere is the ultimate repository of slab fluids which carry the OIB recycled signatures and trapped small volume melts such as lamproites and kimberlites. Carbonatites may derive from this region. A shallow enriched layer, sampled at new rifts and at the onset of seafloor spreading, explains temporal and spatial relations between enriched and depleted magmas and predicts a MORB reservoir which does not extend to the base of the plate except at spreading ridges. "Plume heads", and "fossil plume heads" have been used in a similar way but the underlying assumption is that, otherwise, only MORB would come from the upper mantle (Appendix 1). A refractory layer also extends the conductive geotherm, making it possible to reduce the size of the melting column and increase "normal" mantle temperatures over those assumed by McKenzie and Bickle [1988].

THE PLUME HYPOTHESIS

In order for narrow thermal plumes to rise almost 3000 km from D" or DIS through a convecting, internally heated mantle without deflection or cooling, they must be strong. In the laboratory, the plume fluid must be removed from the system, heated externally and then reinjected; narrow plumes with low viscosity do not arise spontaneously in a heated fluid [Nataf, 1991].

Morgan [1972a] required 20 plumes, 150 km in diameter, rising at 2 m/year in order to influence the motion of surface plates and dominate over ordinary convection. He calculated a plume volume flux of 500 km3/yr and this served to drive the asthenosphere at 5 cm/year. The heat flow associated with plumes was calculated to be half the total heat flow of the Earth. If plumes were much weaker, ridges would close up and the return flow associated with plate tectonics would dominate plume flow.

The mass fluxes and heat flow associated with plumes have now been estimated [Davies, 1988]and are only a fraction of those required by Morgan [1972a]. The minimum plume flux inferred by Morgan is about two orders of magnitude higher than the observed flux and about 25 times the theoretical flux from D" [Stacey and Loper, 1983]. The strong plume theory has therefore been falsified, and no weak plume theory has been put forward that has the attributes needed if plumes are to be a significant form of convection.

Narrow plumes, or jets, are an unusual form of convection [Tackley, 1995, 1996], usually simulated in the laboratory by injecting hot fluids at the base of a tank of non-convecting fluid, or by puncturing a membrane which has isolated a layer of hot fluid. In systems that are internally heated, or convecting, small instabilities tend to get swept toward the main upwelling and isolated independent narrow upwellings do not exist. Normal thermal convection tends to buffer the temperature rise in the TBL so that narrow plume-like instabilities do not form [Nataf, 1991].

It is generally assumed that thermal instabilities in a deep thermal boundary layer are the only possible source of upwelling but this is not true (Appendix 2). Most of the globe's magmatism is due to passive, or opportunistic upwelling, or due to flux induced lowering of the melting point. Lithospheric architecture (craton boundaries, fracture zones, etc.) generate focusing and vertical motions (i.e., upwellings). Adiabatic melting and bubble exsolution contribute to buoyancy once an upwelling gets close to the surface. Focusing of magma, updip or toward thin lithosphere, and 3D effects can increase the volume of magmatism without increasing temperature or extent of melting. If melting of the upper mantle is widespread, as implied by the low seismic velocities, then the existence and magnitude of extrusion may be entirely a function of lithospheric conditions, and time (transient vs. steady-state). Finally, convection can be driven by cooling from above, in the absence of heating from below [King and Anderson, 1995].

Modern plume models attribute massive volcanism to localized, and deep, processes that are independent of plate motions and mantle convection. They are not so easily falsified as Morgan's plume theory since they are less specific and testable. The idealized plume has two components: plume heads which are supposedly responsible for very short-lived massive igneous events, and narrow plume tails which generate long-lived hotspot tracks. The plume head heats the lithosphere and causes or localizes continental breakup. Plume head magmatism is predicted to be very brief [Campbell and Griffiths, 1990; Richards et al., 1989].

This idealized behavior is not observed. Large igneous provinces (LIP) are seldom accompanied by hotspot tracks. Most hotspot tracks do not terminate in LIP. LIP are always deposited at major lithospheric boundaries at times of plate reorganization or major plate boundary changes. The lithosphere is presumably under extension at the time. LIP are often unaccompanied by precursory uplift. This observation alone falsifies the plume hypothesis since uplift is an unavoidable consequence of insertion of hot material into the upper mantle. Rift induced circulation or lateral temperature gradients, however, can drive a large amount of mantle material through the melting field [King and Anderson, 1995].

EDGES

Excess volcanism at margins does not correlate with the presence of hotspots [Mutter, 1993; Holbrook and Kelemen, 1993] but with proximity to thick cratonic lithosphere (e.g., Brazil, Congo, Greenland, north Australian margin), ancient sutures (Narmada-Son, Cochambanba-Paraná, etc.) or rapid pull-apart [Hopper et al., 1992]. Basalt thickness in the Red Sea and Afar contradict a plume influence [Altherr et al., 1988]. The initiation and focusing of igneous activity at lithospheric discontinuities, particularly cratonic boundaries, continental margins, ridges and triple junctions, is an argument against deep mantle plumes, and an argument for plate control. Some LIP are the result of passive plate pull-apart. Rapid lithospheric extension induces short-lived small-scale convection in the mantle, resulting in a pulse of magmatism at the inception of seafloor spreading. Crustal stretching, a slow process, is not adequate and is not required. In plate theory, magmatism should not be uniform all along newly formed ridges [Mutter et al., 1988; Sawyer and Harry, 1991].

The correlation of CFB to cratons and lithospheric discontinuities is much stronger than to hotspot tracks. Every CFB province is adjacent to an Archean Craton or on a shear zone [Anderson, 1996]. Many hotspot tracks are along, or influenced by, fracture zones, sutures and ridges. The lithosphere plays a major role in magma ascent, mantle convection and LIP [Mutter et al., 1988; Mutter, 1993; Zehnder et al., 1990; Bailey, 1992]. Edge-driven gyres and eddies (EDGE) are a form of convection driven by lateral temperature gradients [King and Anderson, 1995].

"Hotspots" which are related to pre-existing fractures, sutures or lithospheric boundaries [A. S. Davis, 1989] include Line, MacDonald, Louisville, Cobb, Bowie, Yellowstone, Galapagos, Bermuda, Canary, St. Helena (Cameroon), Cape Verde, E. Australia, Erebus, Easter and the New England Seamounts. Pre-existing fracture zones or sutures are implicated in Deccan, North Atlantic, Ascension, Cape Verde, Columbia River and Paraná volcanism. The Line Islands, Socorro Island and the Manihiki Plateau may be related to

ridge jumps. The Hess and Shatsky Rises appear to be related to migrating triple junctions. These rises bracket the Emperor seamount chain and all three features terminate at the Mendocino fracture zone. "Midplate" volcanoes are not in random places. They are concentrated at "edges" such as margins, sutures, mobile belts and fracture zones.

LINEAR VOLCANIC CHAINS

Linear volcanic chains in the Pacific were the motivation for the hotspot and plume theories [Wilson, 1963; Morgan, 1972a,b] and the idea that the deep mantle was involved in their genesis. Viewed as the results of thermal instabilities, the logical place for them to originate was a thermal boundary layer in D". Since D" is almost 3000 km from the surface and plumes must penetrate through a convecting mantle and multiple changes in phase and viscosity, they should certainly emerge at random places on the surface. In order to test the deep mantle or D" origin of volcanic chains, it is important to place them in a tectonic context. Many midplate volcanoes occur on pre-existing boundaries and can be attributed to changes in plate stress or separation that are ongoing plate tectonic controlled processes.

The active or recently active volcanoes in the eastern Pacific are mostly within 600-800 km of coastlines of the Americas, usually a trench. Some are related to recent ridge jumps (Socorro). Juan Fernandez and San Felix bound the flat slab section of the Nazca plate and fall at the ends of the volcano gap in Chile. They seem clearly to be related to tearing of the plate due to dip angle changes. The same is true for the Samoan chain. This chain is at the northern end of the Tonga trench where the dip of the Pacific plate changes from steep to horizontal. This region is where the convergence rate changes from the fastest rate in the world to zero. The Galapagos appear to be due to fragmentation of the young portions of the Nazca plate, due to complex trench geometry.

Well defined hotspot tracks with consistent age progressions are uncommon. Many seamount chains are active long after passage over a conjectured hotspot, are simultaneously active over their entire length or have trends inconsistent with plate motions. Examples include Line, Marquesas, Samoa, Cruiser, Marshall, Marcus-Wake, Bowie, and Cameroon. The median duration for volcanic chains in the Pacific is only 15 million years [Pringle, 1993]. Hotspot tracks often start and end at times of plate reorganization. Many isolated seamounts with no obvious connection to chains share geochemical characteristics with long-lived hotspots such as Hawaii. There are only a few old, or long-lived, age-progressive volcanic chains. Most of these were built on ridges. The Musician hotspot track contains only 6 seamounts and has a total duration of 13 million years; it terminated at a FZ at a time of Pacific plate reorganization [Pringle, 1993]. No LIP is involved. These are typical characteristics of "hotspot tracks" and are not readily explained by plume theories. They are consistent with stress in the plate-controlling onset (and shutdown) of volcanism.

Most long hotspot tracks (aseismic ridges) were built on young oceanic lithosphere, implying control by ridges. Some (90° E ridge) are clearly related to long linear fracture zones, or age offsets on the seafloor. The possibility that the Emperor chain was built on a pre-existing fracture zone or ridge is hard to test because of the lack of magnetic anomalies during the long Cretaceous normal polarity interval. Part of it is bounded by deep troughs, not a swell. It terminates at a trench and a fracture zone (Mendocino).

It appears that the orientation of island chains is controlled by pre-existing features, such as fracture zones, transform faults and ridges, and by divergent pulls of subduction zones and that volcanoes are a better guide to stress conditions than to plate motions. If far field stresses control the motions of plates, and stresses in the interiors of plates, then regions favorable for volcanism (extensile strains) will be relatively fixed with respect to the boundaries. Volcanism will propagate counter to the plate motion, modulated by stresses of volcanic loads and orientation of fracture zones.

THE RELATION TO CONTINENTAL TECTONICS

Midocean ridges are not uniform sheets of rising magma. They exhibit a basic three-dimensionality [Morgan and Forsyth, 1988]. Ridges are segmented by offsets and fracture zones and by variations in magma flux. When magma supply rates are particularly high a hotspot is often invoked. The spacings of major fracture zones and gravity anomalies in the oceans are comparable to upper mantle depths. The spacings of volcanoes and small-scale fracture patterns are comparable to lithospheric thicknesses [Vogt, 1974a]. Large fracture zones can often be traced inland onto adjacent continents. Continental tectonics appear to impress itself onto the structure of a newly opening ocean [Sykes, 1978]. Rarely do volcanic chains originate in the middle of an ocean. Ridges, fracture zones and shear zones or mobile belts are implicated at the starting end. Large volcanoes on pre-existing lithosphere contribute their own stresses and may cause self-propagating fractures. Large volcanoes probably stop growing because of hydrostatic head considerations not because they drift off of a hotspot [Vogt, 1974b]. Some island chains stop when they reach a major fracture zone (Emperors, Louisville, Socorro).

Seamount chains in the Atlantic are related to leaky transform faults or extensional fractures, rather than to hotspots [McHone and Butler, 1984; Smith, A. D., 1993; Meyers and Rosendahl, 1991]. The Canaries are on the continental passive margin, near the border of the Eurasian and African plates. Geochronological and geophysical data do not support a hotspot origin for the Canary Islands. The

periods of magmatic activity correspond to the three main tensional phases in the nearby Atlas mountains [Anquita and Hernan, 1975]. Geoid anomalies and bathymetry provide no support for any swell, lithospheric heating or mantle plume [Filmer and McNutt, 1989]. The entire Canary chain has been active in recent times. A propagating fracture model is consistent with the data. The Azores owe their origin to a plate reorganization [Searle, 1980]. The Bouvet and Conrad "hotspots" are related to fracture zones of the same names, near the South America, Africa and Antarctic plate stable triple junction [Sclater et al., 1976]. Walvis ridge and Rio Grande rise may be the result of early transform faults with components of extension [Sykes, 1978; Martin, 1987]. Deccan magmatism is related to reactivation of the Narmada-Son lineament, a 1000 km long active feature that splits the Indian Peninsula [Verma and Banerjee, 1992]. Other hotspot tracks appear to be overridden, or "ghost" ridges [Sutherland, 1983]. None of the midplate igneous activity and topographic swell patterns in the western North Atlantic and eastern North America can be easily reconciled with simple plume concepts [Vogt, 1991]. Global or regional plate reorganization seems to be implicated. The numerous plateaus in the Atlantic and Indian Oceans are coast-parallel, about 1000 km offshore and were active when the ocean was only 2000-3000 km broad. They appear to be EDGE effects (Vogt, 1991).

Many aseismic ridges and seamount chains in the Atlantic are extensions of shear zones in the adjacent continents. The extension of the Walvis Ridge corresponds to the southern boundary of the Congo craton, the Damara tectonic belt, and a line of alkalic basalts. Canaries, Cape Verde [McNutt, 1988] and the Cameroons are on trends of cross-African rift zones. The Rio Grande rise is a continuation of the Cochabamba-Paraná shear zone [Eyles and Eyles, 1993]. Intracratonic rift zones accommodated deformation in the continents during the early opening of the Atlantic and apparently also affected oceanic lithosphere.

The Red Sea-Afar-Gulf of Aden region appears to be the passive response to plate tectonic forces, in particular the rotation of Arabia from the African plate [Coleman, 1993]. The Red Sea and Gulf of Aden are rifts propagating toward the Afar depression. The ocean crust is thin near the Afar and is abnormally thick at points along the Red Sea far removed from the conjectured plume influence. These observations are all in conflict with the plume hypothesis. Mantle upwelling, concomitant uplift and timing of magmatism all follow the passive rifting scenario. Premagmatic uplift at "hotspots" is rare, a clear violation of the thermal plume hypothesis.

Giret and Lameyre [1985] point out that the timing of the New England, Nigerian, Afar and Kerguelan magmatic provinces are not consistent with plume theory. They propose that melting is triggered by systems of lithosphere shear openings. The Monteregean Hills-White Mountains province is not easily reconciled with plume theory [Foland et al., 1988; McHone, 1996a,b], but is consistent with rejuvenation of lithospheric fractures.

Other proposed hotspot tracks associated with lithospheric cracks do not exhibit the shallow reheating expected for a mantle plume [Filmer and McNutt, 1989]. The NW African plate hotspots (Canaries, Madeira, Cape Verde) show episodic, non-time progressive volcanism and seem to be tectonically related to convergence of Africa and Europe and to lithospheric features such as fracture zones and continent-ocean margins [Schmincke, 1982; McNutt, 1988; Vogt, 1974b].

Bowie seamount is not a hotspot; it is part of a crude alignment of seamounts (Bowie-Kodiak) with an origin at the Tuzo Wilson Volcanic Field (TWVF), a complex diffuse, leaky transform-ridge triple junction [Allan et al., 1993]. Geological and geochemical data contradict the Bowie plume hypothesis. There is no evidence of an enriched plume component in the seamount magmas; they are indistinguishable from MORB. The purported deep mantle plume imaged tomographically [Nataf and van de Car, 1993] is to the north of the Bowie Seamount and far to the northeast of the origin of the seamount chain. The deep mantle plume should be to the SE of the seamounts.

A seismic image of the Iceland mantle was recently presented [Wolfe, Solomon and van de Car, 1997]. A cone-shaped anomaly is apparent which has the appearance of upflow being focused toward the ridge by passive spreading. No plume head is evident. Thus, this may be a passive rather than active upwelling. The seismic experiment, as designed, cannot distinguish between the competing hypotheses for the North Atlantic; passive upwelling, edge-driven convection or plume. The shape and inferred depth extent (400 km) need to be checked by less vertical rays since along-ray smearing can give a similar image. The North Atlantic is a new and narrow ocean and is bounded by thick Archean cratons. It has not yet evolved to a mature spreading center. It was recently covered and insulated by thick lithosphere. Iceland may be a double-EDGE feature, similar to Bermuda, Rio Grande, Kerguelen, etc. rises when these were active (i.e., in a new narrow ocean, close to cratons).

The Chagos-Laccadive ridge, the conjectured volcanic trace of the Réunion hotspot, was built on very thin lithosphere, near a spreading ridge-transform junction [Martin, 1987]. The 90°E ridge is on or near fracture zones and is only 5° from the 85° E ridge. Many hotspot tracks and fracture zones are only about 600 km apart (Bouvet, Shona; 85°E, 90°E ridges) about the depth of the upper mantle. This is very close together for plumes from CMB. The proposed hotspots at Ascension and Circe are close to the mid-Atlantic ridge and the Ascension FZ and are a likely result of small-scale convection associated with the temperature gradient across the FZ [Freedman and Parsons, 1990].

Along some ridge segments, quite substantial magmatism has occurred apparently without the influence of crustal stretching, elevated mantle temperatures or proximity to a

hotspot [Ellam, 1991a,b]. Lithospheric conditions apparently can affect the style and amount of eruption, as well as the location.

These are just a few examples of plate tectonic, rather than convective, control of what have been called "hotspot tracks." A fixed anomaly in the mantle does not appear necessary, any more so than is required to explain the relatively slow motions of ridges and trenches. This lengthy discussion of surface effects seems necessary since linear volcanic chains and "fixity" of hotspots are two of the main arguments that have been advanced to support a D" origin.

If cracks, or tears, propagate away from the consuming trench, as seems to be the case for San Felix, Juan Fernandez and Samoa, then the volcanic chain will propagate counter to the plate motion and may appear fixed in the trench reference frame, which Kaula [1975] has already shown to be slowly moving. If interior stresses in a plate are controlled by the geometry of the surrounding boundaries then the maximum tensile stress region may also appear relatively fixed.

It should be pointed out that there are few unambiguous examples of time progression in volcanic chains and long-lived progressions are extremely rare. The propagating crack, or leaky transform, models of volcanic chains should be studied in more detail. They seem to explain several paradoxes of the plume hypothesis (hot lines, many hotspots on same track, rejuvenated volcanism, absence of swells and geoid highs, non-age progression, absence of parallelism, track offsets, etc.). On a more local scale, volcanoes in a group or chain are often controlled by a fracture grid [Vogt, 1974a].

CHEMISTRY OF PLUMES

At one time, the chemistry of ocean island and continental flood basalts was thought to reflect primitive undifferentiated mantle. The location of this primordial reservoir was placed below the "convecting layer", it being thought that only in the lower ("non-convecting") mantle could primordial material survive for the age of the Earth, and only the lower mantle could serve as a fixed reference system. It was subsequently found that isotopically "primitive" basalts were just part of a continuum that extended from enriched to depleted, relative to expected primitive compositions [e.g., Anderson, 1989]. Much of the isotopic and trace element chemistry of ocean island basalts (OIB) can be attributed to pelagic and continental sediments, altered oceanic crust and seawater contamination. The oxidization state and oxygen isotopic signatures point toward a surface origin for at least some components in so-called hotspot magmas. OIB chemistry is often intermediate between MORB and island arc volcanics (IAV). It is now generally agreed that, for most trace element and isotopic systems, the geochemistry of OIB reflects recycling, primarily of oceanic crust and sediments. This material, of course, is provided to the system from the top and the question arises, how deep is it circulated before contributing to OIB magmatism? Continental flood basalts (CFB) show evidence for interaction with the underlying lithosphere, crust and sediments. Even the noble gas composition of "hotspot" magmas and xenoliths exhibit strong contamination by the atmosphere or seawater or seawater infiltrated crust and upper mantle [Farley and Poreda, 1993].

Nevertheless, in spite of this strong evidence for near-surface sources of the non-MORB characteristics of OIB and CFB, the old idea that "hotspot" magmas require a deep mantle source has survived. Material is believed to be recycled deep into the mantle, heated up and then brought to the surface in narrow plumes. The widespread evidence for OIB-like material at ridges, rifts and island arcs is attributed to pollution from a point source (plumes), channeling by and to ridges, long distance channeling by "grooves" in the lithosphere, flattened plume heads, incubating plumes and fossil plumes. The evidence is even more consistent with a universal enriched layer underlying the lithosphere, and widely available at new rifts, spreading centers and off-axis volcanoes [Anderson, 1996]. This enriched layer has been called the "perisphere" (all-around, close) to distinguish it from the lithosphere and asthenosphere, which are rheological terms. Models invoking a deep source for OIB and CFB tacitly assume that the whole upper mantle is depleted (yet fertile) and suitable only for providing MORB (Appendix 3).

The *coup de grace* for the chemical part of the plume hypothesis is the widespread occurrence of basalts identical to OIB in extending terranes in all tectonic environments, including local extension at consuming margins [e.g., numerous references in Smellie et al., 1994 and Anderson, 1996, 1998]. OIB-like basalts are associated with cessation of subduction, slab window formation, slab roll-back, thin spots in the lithosphere and extensional tectonism in general. Quite often no precursory uplift is observed, ruling out a thermal anomaly. In this context, the alternatives to plume, or thermal, magmatism include passive upwelling, convective partial melting, displacive upwelling, flux induced melting, and flow driven by lateral temperature gradients [Mutter et al., 1988; King and Anderson, 1995].

To my knowledge, there is no evidence that suggests that any basalt source has been in contact with the core or with the lower mantle. Although partition coefficients (and the siderophile nature of elements) depend on temperature and pressure, it is likely that mantle which has been in contact with the molten core or a perovskite lower mantle would have chemical characteristics quite unlike mantle that has not. There is abundant evidence, however, that much of the geochemistry of OIB was acquired at or near the surface. The main remaining argument for a primordial source is the high 3He/4He ratio of some basalts, assuming that it is the 3He that is in excess rather than 4He (or U and Th) that is in deficit.

THE PB-PARADOX AND THE HE-PARADOX

Lead isotopes, and other source specific ratios such as U/Nb, Pb/Ce and Lu/Hf show that a primordial reservoir has not been sampled and may not exist [Bichert-Toft and Albarede, 1997; Hofmann, et al., 1986]. The presence of such a reservoir is fundamental in mass balance box models that attribute the continental crust to extraction of all of the incompatible elements out of the top 30% of the mantle. Modern mass balance calculations imply that most or all of the mantle has been processed to form the crust and upper mantle [Anderson, 1989; Hofmann, et al., 1986; Zhang and Zindler, 1989; Bichert-Toft and Albarede, 1997].

Plumes play a central role in noble gas models of the mantle. Some hotspots have a subset of their eruption products with 3He/4He ratios in excess of MORB. These have been assumed to contain excess 3He. If so, calculations suggest that the source mantle must be enriched in helium by two-orders of magnitude compared to other less volatile species [Kellogg and Wasserburg, 1990; Porcelli and Wasserburg, 1995]. A gas-rich primordial lower mantle has been proposed.

However, hotspots have low 3He abundances and low ratios of He to other noble gases and CO2. The low He/Ne, He/CO2 ... ratios of high 3He/4He ratio magmas indicate that these do not represent degassed magmas but may be related to the vesicles in degassing magmas. High 3He/4He apparently represents a deficit in 4He and therefore in U and Th. The lithosphere is a low U, Th environment and CO2-He rich fluid-filled inclusions are common in lithospheric xenoliths. There seems to be no support for the standard assumptions that high 3He/3He ratios imply excess 3He and that hotspot magmas are low in 3He because they have been extensively degassed compared to MORB. There is therefore no support for the conjecture that high 3He/4He ratio basalts are from a deep primordial undegassed reservoir. The number of atoms of 3He associated with "hotspot" volcanoes and basalts is trivial compared with those at ridges and island arcs [Anderson, D. L., The Helium Paradoxes, submitted to EPSL for publication, 1997].

DISCUSSION

Hopefully, it is clear by now why so much attention has been paid to surface tectonics. All the tectonic and geochemical features discussed have been attributed by one author or another to deep mantle processes including plumes and D" instabilities. Sometimes correlations are claimed between surface processes or chemistry and deep mantle tomography, or magnetic field variations. The correlations of hotspot locations (but not volume) with lithospheric age, fracture zones and cratonic boundaries are expected if plate architecture, rather than deep mantle convection, controls the locations of magmatism (Appendix 2). The deep Earth correlations, however, have received much more attention. Ridges, slabs and cratons provide a template which controls the planform of mantle convection. Past subduction controls the large scale temperature, melting point and chemical structure of the mantle. Past ridges and rifts control the fertility and volatile content of the upper mantle. Thickening plates, slabs and lateral temperature gradients due to lithospheric architecture probably provide adequate stresses to drive the plates, and to provide the extending stresses conducive to extrusion. These near surface and plate tectonic effects must be understood and removed [Wen and Anderson, 1995a,b] before the role of unrelated deep mantle processes on surface processes can be understood (Appendix 1.G).

The assumptions that ridges are entirely passive, that the ridge reservoir fills up the whole mantle, that melting requires importation of deep heat, that magma volumes depend only on temperature, that the hotspot reference frame is fundamental, that recycling of surface contaminants is deep and that the lower mantle is more primitive and fertile than the upper mantle underlie much of the current deep Earth literature (Appendix 1). The prevailing idea that the deep mantle readily communicates with the surface through narrow plumes is based on the above assumptions. The fact that these assumptions ("axioms") are not generally discussed is the motivation for the emphasis in the present paper.

Normal mantle geothermal and melting curves are such that partial melting is the normal state of the upper mantle. The exceptions are in regions of refractory dry peridotite (craton roots) and cold advected geotherms (slabs). Regions which have experienced melt extraction or refractory cumulate formation, such as the perisphere or compositional lithosphere, may dominate the shallow mantle and these regions may also be subsolidus. Melts migrate to thin regions of the lithosphere and to lithospheric discontinuities. Lithospheric strength and compression keep melts in the mantle until there is extension and development of centimeter to meter-size cracks at which point rapid drainage, transient, events occur. When stress conditions are appropriate, the magma itself may participate in opening these cracks by magma fracturing. Some extending regions evolve to rifts and spreading ridges. The basic three dimensionality of passive upwellings gives regions with excess volcanism, often at plate boundaries, or edges. Lithospheric architecture imposes itself on the opportunistic upwellings and on the mantle flow. Some volcanic chains are on old lithospheric flaws, fracture zones, transform faults, abandoned ridges and sutures. Others are on new or reactivated cracks near plate boundaries. As extension (magmatism) evolves to rift and to drift the magma chemistry changes from shallow contaminated (hotspot) to deep "pure" (MORB). Newly opening areas (North Atlantic) may be expressing a temporal phase rather than a spatial feature (deep active upwellings). This is a self-consistent topside alternative to D" driven volcanism.

The questions now are: which end of the mantle is the tail and which is the dog, or are they on separate animals? Are ocean islands the result of fluid dynamics, intense hot

jets and thermal instabilities deep in the system, or are they the result of cracks in the LID, opened by far field and nearby stresses?

Are volcanoes permitted by the lithosphere (passive or opportunistic upwellings driven by the hydrostatic head from a partially molten asthenosphere, regenerated by subduction) or are they the tops of narrow convective features from the bottom of the system? "To what end" do we look? Is the mantle a Top Down system, or Bottoms Up? Do we so understand the surface of things that we can venture to seek what is underneath?

"All I want to do," I said
"is open a few specific eyes.
Warn a couple of people
about the path they're treading."
Dick Francis
The Edge (1989)

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APPENDIX 1

The Plume Paradigm

A paradigm is the infrastructure of a culture of ideas and thought processes that is shared by the practitioners in a given discipline. It includes assumptions, techniques, language and defense mechanisms. Every paradigm has paradoxes; as paradoxes multiply a paradigm can become vulnerable. It can only be overthrown from the outside and, ironically, only when the tenets become unfalsifiable (Just-So Stories are not falsifiable). It is useful to periodically collect together the key assumptions or axioms of a current paradigm, to see if they can shed light on the current paradoxes. The key axioms of the plume paradigm are:

Physical (P)

1. Midplate volcanoes require a convective instability that arises from a thermal boundary layer at the base of the system (rather than opportunistic utilization of lithospheric fractures, sutures, or tensile stress regimes).
2. Mantle melting (away from ridges and island arcs) requires the importation of heat from a deep TBL (rather than being a natural state of the upper mantle, utilizing normal temperature and chemical variations).
3. An instantaneous steady state exists between heat productivity and heat flow (some geochemical models use this assumption and conclude that there must be a primordial undifferentiated reservoir; i.e., lower mantle).
4. Volume of melting depends only on mantle temperature.
5. The Earth accreted cold and there is no primordial heat (a corollary of P.3).

Kinematic (K)

1. The hotspot reference frame is fixed, implying a deep source.
2. Volcanic chains on a plate are age progressive concentric circles.
3. Ridges are passive and can move about at will.
4. The source of ocean ridge volcanoes is shallow.
5. The upper mantle provides midocean ridge basalts and can only provide midocean ridge basalts; ocean island basalts require a source external to the convecting upper mantle.
6. Hotspots occur at random places and times, unrelated to plate tectonics and large scale convective flow.

Geometric (G)

1. The dimensions of midplate volcanoes, and widths of volcanic chains are related to dimensions of convective features below the plate (rather than to cracks or other lithospheric features).
2. The dimensions of Large Igneous Provinces and associated volcanics and of subsequently uplifted regions are related to dimensions that plume heads acquire as they rise 3000 km (rather than being the convective scales of the upper mantle).

Chemical (C)

1. The crust is a product of the upper mantle and only the upper mantle.
2. The crust and the upper mantle are complementary.
3. Non-MORB characteristics of ocean island and other "hotspot" volcanics are either primitive (undifferentiated mantle) or recycled material that has been taken deep into the mantle.
4. High 3He/4He ratios imply excess 3He and require a deep undegassed or primordial reservoir (rather than implying a deficiency in 4He and therefore, U and Th).
5. The characteristics acquired by plates at the surface (sediments, seawater alterations, oxidization state) are carried deep into the mantle (rather than stripped out of the slab at shallow depth).
6. The lower mantle differs chemically from the upper mantle.
7. Volatiles are incorporated into the bulk of the Earth in chondritic abundances, rather than as a late veneer.

Few readers will believe most of these axioms, as stated, but unstated they underlie much of modern deep Earth science. The widespread belief in deep mantle plumes rests on

the validity of these statements. Sometimes beliefs outlive the axiomatic framework they were based on. It is useful, therefore, to isolate the key assumptions and reevaluate them as data and theory advance.

APPENDIX 2

Plume vs. Plates

Large igneous provinces, lateral variations in mantle temperature, geoid highs, hotspot tracks, rapid sea-floor spreading and rises in sea level have all been attributed to plumes rising from the core-mantle boundary. Plumes, as used in the current literature, are secondary forms of convection superposed on, and independent of, the plate scale flow. In a convecting Earth, heated from within, there are broad scale upwellings, but plumes are a hypothetical smaller scale phenomenon, thought to arise from a thermal boundary layer at the base of the mantle, driven by core heat. The presence of a broader scale of convection can destroy this layer, or advect instabilities toward the broader upwelling, so very specific circumstances are required in order for a plume to rise rapidly through a convecting mantle. Broadscale flow, and narrow cold downwellings, can also remove heat from the core, a role generally attributed exclusively to narrow, thermal upwelling plumes. The presence of compressibility, pressure-dependent properties and phase changes also affect the ability of a plume to form or to rise rapidly through the mantle. Plates and slabs also impose a large wavelength structure on mantle convection. Plate-related phenomena and normal mantle convection can cause all of the effects that have been attributed to narrow deep plumes. Subduction and instabilities in the thermal boundary layers of plates can introduce thermal and chemical inhomogeneities into the mantle. These thermal anomalies are of the order of 200°C or greater. Mantle unaffected by subduction for a long period of time will be hotter than mantle elsewhere.

Plate-generated forces (slab pull, ridge push, trench suction, slab roll-back) create extension and plate separation which can induce upwellings and adiabatic melting. Boundary effects can penetrate deeply into plate interiors, causing basins or uplift, or extension. Changes in plate motions and boundary conditions can cause extension across fracture zones and transform faults or pre-existing sutures. Leaky transform faults can open progressively, giving the appearance of time-progressive hotspot tracks. New ridges, or supercontinental breakup, can cause sea level to rise.

Large Igneous Provinces such as continental flood basalt provinces (CFB) and oceanic plateaus, typically occur at triple junctions or ridges, and occur at times of plate reorganizations, ridge jumps or continental breakup. Lithospheric architecture can cause convection and can focus melts. Edge-driven convection is a dynamic alternative to the passive thermal plume hypothesis.

The question is, how can one distinguish these passive and active plate-related processes from the conjectured deep mantle hydrodynamic instabilities? Plume theories are local. A plume must be focused on one part of the lithosphere for a long period of time; long sustained heating, stretching and thinning are implied. Eruption associated with the plume head should be rapid and follow a long period of uplift [Campbell and Griffiths, 1990]. In many large igneous provinces, the evidence for uplift, heating or stretching is missing. In fact, many CFB occur on top of deep sedimentary sequences and in depressions.

There is evidence for high temperatures and high degrees of melting far from the influence of any "plume" [Johnson and Dick, 1992], suggesting large-scale thermal conditions, or hot regions [Anderson, 1993; 1996].

Flood basalt provinces may be generated in response to regional tectonic forces and do not require external influences such as plumes [Ziegler, 1992; Dickinson, 1997; Smith, A.D., 1993]. Some CFB provinces are in back-arc basin locations (CRB) and sites of ridge-trench collisions or slab-windows. Some are associated with margins having experienced a long history of subduction (Gondwana Mesozoic CFB provinces). The shallow mantle in these regions has been fluxed with volatiles and sediments. All CFB provinces are associated with pre-existing lithospheric fractures, sutures, continent-ocean boundaries or craton edges.

Convective and plate motions can be driven or influenced by variations in lithospheric thickness. No critical Rayleigh number is associated with convection driven by lateral temperature gradients at the top of the system. Mantle upwellings will focus at lithospheric discontinuities [King and Anderson, 1995].

Plates therefore play several roles in mantle dynamics and magmatic activity. Without plates, one tends to focus on convective control of surface magmatism. It is likely that lithospheric architecture and stress-state of the surface layers are more important in controlling the locations of volcanoes that a deep thermal boundary layer, such as D" [e.g., Vogt, 1974b].

There are two endmember views of the driving forces of plate tectonics, and the planform of mantle convection. In one view the plates drive themselves by plate tectonic forces (ridge push, slab pull) and the planform of mantle convection is controlled by the plates. Stresses in the plates form a slowly evolving pattern as long as the ridge and trench systems are slowly evolving. Volcanism is expected to be focused at regions of extension (ridges, leaky transforms, lithosphere boundaries) and mountain building and island arcs are at converging boundaries. If hotspots and hotspot tracks are newly extending regions, and ridges are long-lived extending regions, then they both should be slowly moving until boundary forces change by, for example, ridge-trench interactions. In this view, it is no surprise that there is a close spatial relationship between hotspots and ridges and that most hotspots start at ridges, or end up as ridges.

In the other endmember view, convection drives plate tectonics and, in particular controls the locations of "midplate" volcanoes (i.e., hotspots). D" controls the locations of volcanoes and the near-surface simply modulates the "plume flux". Motions of hotspots are due to motions of plumes.

APPENDIX 3

Deductive Logic

The main geochemical argument for a deep source for non-MORB is as follows:

MORB are from the upper mantle
OIB are not-MORB
Therefore OIB do not come from the upper mantle.

Symbolically:

If M then UM
OIB are not-M
So if OIB then not-UM

That is, only MORB can come from the upper mantle. This is the well known Modus Moron fallacy [Margaris, 1967]. It is this fallacy that has led to proposals that non-MORB come from the continental lithosphere (technically outside the "convecting upper mantle"), the lower mantle, D" or the transition region.

It is this fallacy plus the view that the MORB reservoir must be immediately below the plate, if ridges are passive, that has given support to the geochemical aspects of the lower mantle reservoir and plume hypotheses. The geochemical signatures of OIB include MORB, sediments, oceanic crust and, for the noble gases, seawater and atmospheric components. All of these, of course, are near the surface.

The limitations of geochemical approaches in determining source provenances are reasonable well-known but not widely appreciated. The reason for dwelling on this obvious point is the following; the only reason for invoking a deep mantle, or plume source, in much of the current geological and petrological literature is the presence of a non-MORB basalt or component in a basalt. That is to say, in many papers, a non-MORB component (or an OIB-component) is considered a sufficient condition to invoke a deep-mantle plume [e.g., Hart et al., 1997; Wendt et al., 1997; Arndt et al., 1997]. Necessary conditions, such as precursory uplift, or high temperatures, are almost always overlooked. Secondary characteristics such as rifting or time progression are sometimes discussed.

To some extent, D" plumes entered the geochemical literature because of the need for a non-MORB source and the belief that the upper mantle could only provide MORB. However, the plume head aspect of the plume hypothesis makes this assumption self-contradictory. If plume heads are of order 1000 km in radius, the whole central Atlantic upper mantle is contaminated by plumes and ridges will not have access to the MORB reservoir. Likewise, the large plume heads thought to be responsible for the Atlantic bordering CFB would displace a large part of the "MORB asthenosphere". In the perisphere model, a thin enriched layer is available everywhere at the onset of rifting and seafloor spreading until it is replaced by the process of extensive and long-sustained magmatism. Enriched magmas represent transient magmatism; ocean ridge magmatism is the steady-state. One does not need to import the plume components into the upper mantle from the deep mantle; they are already there. On the contrary, one needs to eliminate the shallow enriched layer in order for uncontaminated MORB to be the dominant magma. The lack of sediments, old crust and thick lithosphere at ridges make MORB less susceptible to contamination than "midplate" volcanoes.

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