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Hotspots, Basalts, and the Evolution of the Mantle

Don L. Anderson

Hotspots, or plumes, have not yet been fitted satisfactorily into either the tectonic or the geochemical framework for the evolution of the mantle. A hotspot is a relatively stationary and long-lived thermal anomaly in the mantle and provides a variety of trace element enriched magmas to oceanic islands and continental interiors. From the point of view of mantle processes and the chemical evolution of the mantle, the alkali volcanism associated with hotspots is a very important process even if the abundance of such rocks is small as compared to the volume of abyssal tholeiites (*1*). The processes of creation and subduction of oceanic crust and lithosphere clearly account for most of the mass transport into and out of the upper mantle, and the study of mid-ocean ridge basalts (MORB) has placed important constraints on the part of the mantle that is providing these magmas. Trace element and isotopic considerations show, however, that the source region for MORB cannot be representative of the average composition of the mantle, nor can it have existed as a separate entity with its present characteristics for the full age of the earth.

The composition, location, and volume of this source region, which I designate as MORBS, are still uncertain. It appears to be very large, homogeneous, global in extent, and the result of an earlier differentiation or fractionation process that depleted it, relative to other source regions, of most of the incompatible elements, that is, those trace elements that are strongly concentrated into partial melts. On the other hand, it is clearly not lacking in a basaltic component. The continental crust is complementary to MORB in both trace elements and isotopic ratios (*2, 3*). Formation of the continents has presumably been at least partially responsible for the depletion of the so-called oceanic mantle. If the continental crust is the only enriched reservoir, then mass balance calculations indicate that only about 30 percent of the mantle has been processed, the rest remaining undifferentiated and primoridal (*3, 4*).

A large primitive reservoir would be difficult to reconcile with other evidence regarding the early thermal evolution of planetary interiors. There is, however, evidence for an additional enriched reservoir in the mantle. Magmas from conti-

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The author is director of the Seismological Laboratory, California Institute of Technology, Pasadena 91125.

nental interiors, rift zones, oceanic islands, anomalous ridge segments and island arcs, mantle xenoliths from kimberlites and alkali basalts, and kimberlites themselves all indicate the presence of a mantle reservoir with trace element concentrations that are also complementary to trace element concentrations in MORB. This reservoir apparently is also global and can provide magmas to a variety of tectonic environments including all types of plate boundaries as well as plate interiors. These magmas, of which alkali basalts are one example, are not nearly as voluminous as MORB, but they indicate the presence of an enriched region or layer that may be substantially larger than the continental crust. I shall designate this as the hotspot or plume reservoir, or simply PLUME (*5*), and assume that it is the source of alkali basalts, nephelinites, melilitites, basanites, kimberlites, and continental tholeiites, which it provides by varying degrees of partial melting (*6, 7*). One of the diagnostic signatures of these basalts is the pattern of rare earth elements, which implies a source enriched by about a factor of 10 in the light rare earth elements and 3 in the heavy rare earth elements, relative to chondrites (*6–8*).

PLUME basalts also have high Rb/Sr, Rb/K, Ba/K, Nd/Sm, Ba/Nd, Ba/Sr, Nb/Zr, ^{87}Sr/^{86}Sr, and ^{144}Nd/^{143}Nd ratios and high concentrations of H_2O, CO_2, Ti, K, Rb, Sr, Ba, La, Nd, Th, and U relative to MORBS. These characteristics are shared by continental and ocean island basalts and are also evident, albeit diluted, in backarc basins, island arcs, and transitional or anomalous ridge tholeiites. Other characteristics that may be common, although they have been studied in only a few hotspot locations, are high abundances of Cl, F, Br, and primordial helium (*9*). The process that led to the enrichment of PLUME will have depleted other, presumably deeper, regions of the mantle. The absolute and relative sizes of these enriched and depleted reservoirs bear directly on the problems of the evolution of the mantle and, in particular, on the question of whether there is a large primitive reservoir in the mantle.

Basalt Source Regions

The continental crust is extremely enriched in the incompatible trace and minor elements. Continental tholeiites, basanites, nephelenites, alkali basalts, kimberlites, and basalts from oceanic islands are also enriched. The complement to the depleted MORBS may therefore be much more voluminous than just the continental crust. The trace element and isotopic affinities of these rocks, regardless of their tectonic setting, suggest that they are all derived from a similar source region. This reservoir, PLUME, has been referred to as continental mantle, the enriched source region, or primitive mantle. Its location is uncertain, but it appears to be a global layer. Proposals for its location include the uppermost (*6, 10*) and lowermost (*11*) mantle. In trace element ratios such as Ba/Nd, Nd/Sm, Ba/Sr, Ba/K, and Rb/K there is a progressive increase from ocean island and island arc basalts, basalts from anomalous ridge segments, continental tholeiites, alkali basalts, to kimberlites. MORB have much lower ratios than PLUME basalts, and tholeiites from backarc basins have generally slightly higher ratios than MORB. Trace element concentrations vary systematically through the compositional spectrum olivine melilitite, olivine nephelinite, basanite, alkali basalt, and olivine tholeiite and can be explained in terms of varying degrees of partial melting ranging from 4 to 25 percent from a common source region that is enriched in the strongly incompatible elements (Ba, Sr, Th, U, and light rare earth elements) by ten times the chondritic value and in the moderately incompatible elements (Ti, Zr, Hf, Y, and heavy rare earth elements) by a factor of about 3 (*6–8*).

MORB are derived from a very different source, which is depleted in the large-ion lithophile (LIL) elements. The complementary nature of the two source regions is possibly due to the migration from the MORBS of a melt or fluid with incompatible element concentrations similar to those of kimberlite. This fluid depletes the MORBS and enriches the complementary mantle reservoir. The upper mantle, low-velocity zone (LVZ) is a likely repository of these volatile and trace element–enriched fluids and therefore a possible source region for the enriched magmas that are characteristic of the PLUME or hotspot source. Kimberlites come from depths as great as 220 kilometers, consistent with an origin near the bottom of the LVZ. The xenoliths in kimberlites and alkali basalts represent mantle fragments from various shallower depths and also generally exhibit enrichment of the type inferred for PLUME. There is now a wealth of evidence for upper mantle metasomatism (*12–14*) and enrichment events at various times. The source of the enriching fluid has not been much discussed.

The complementary nature of continental and oceanic tholeiites is illustrated in the bottom part of Fig. 1. Alkali basalts, nephelinites, melilitites, and basanites have similar but more enriched patterns than continental tholeiite, consistent with their derivation from the same source region by smaller degrees of partial melting. Continental and abyssal tholeiites exhibit reflection symmetry about a line (horizontal line in Fig. 1) corresponding to a six- to sevenfold enrichment over average mantle concentrations.

Continental and ocean island basalts are relatively depleted in those elements that are retained by garnet and clinopyroxene. The reverse is the case for abyssal tholeiites. Since garnet and clinopyroxene are reduced or eliminated during the large amounts of partial melting usually inferred for the formation of tholeiites (*6*), the inverse garnet-clinopyroxene pattern of PLUME basalts must be related to a prior history that included eclogite fractionation or invasion of PLUME by a fluid, such as kimberlite, that was in equilibrium with a garnet-clinopyroxene assemblage.

The origin of island arc basalts is still controversial, but they have PLUME affinities in such trace element ratios as Rb/K, Rb/Sr, Ba/K, Ba/Sr, and Ba/Nd. These ratios are closer to those of ocean island basalts, alkali basalts, and continental flood basalts than to those of

Summary. The trace element concentration patterns of continental and ocean island basalts and of mid-ocean ridge basalts are complementary. The relative sizes of the source regions for these fundamentally different basalt types can be estimated from the trace element enrichment-depletion patterns. Their combined volume occupies most of the mantle above the 670 kilometer discontinuity. The source regions separated as a result of early mantle differentiation and crystal fractionation from the resulting melt. The mid-ocean ridge basalts source evolved from an eclogite cumulate that lost its late-stage enriched fluids at various times to the shallower mantle and continental crust. The mid-ocean ridge basalts source is rich in garnet and clinopyroxene, whereas the continental and ocean island basalt source is a garnet peridotite that has experienced secondary enrichment. These relationships are consistent with the evolution of a terrestrial magma ocean.

MORB. Backarc basin basalts are intermediate to MORB and hotspot magmas; this result suggests a mixture from a deeper MORB source and an overlying enriched source region. Ocean island tholeiites also appear to be mixtures both in trace element and isotopic ratios (*2*). The fact that both MORB and basalts with continental or PLUME affinities are available at ridge environments, island arcs, oceanic islands, and well-developed continental rifts suggests a compositionally stratified mantle. The order of appearance of these basalt types is consistent with enrichment of the shallower layer in the incompatible trace elements. In a stratified mantle the deeper layer should be denser and therefore more garnet-rich. The ratio of concentrations in MORB to those in continental tholeiites indicates that MORBS, although depleted in most of the incompatible trace elements, has selectively retained those that are most comfortable in the garnet and clinopyroxene lattices. This suggests that MORBS is an eclogite or garnet-pyroxenite cumulate. It may be an olivine or picritic eclogite.

The Composition and Volumes of the Two Source Regions

The concentrations of some key incompatible trace elements in various magma types, normalized to average mantle concentrations, are shown in Fig. 1. Relative to the average mantle, continental tholeiites, alkali basalts, kimberlites, and the continental crust are most enriched in K, Rb, Ba, La, and U. These are the elements that are most strongly rejected by the major mantle minerals, olivine, orthopyroxene, clinopyroxene, and garnet; that is, they have the lowest mineral/melt partition coefficients. The other incompatible trace elements in Fig. 1 are also strongly rejected by olivine and orthopyroxene, having partition coefficients of less than 0.03 for these minerals (*6*). On the other hand, garnet and clinopyroxene have partition coefficients greater than about 0.1 for Y, Nd, Sm, Sr, and Yb. These are the least-enriched elements in the magmas with continental and ocean island affinities and the most enriched in MORB. It appears that garnet and clinopyroxene are abundant minerals in MORBS, and that the fluid that enriched PLUME was formerly in equilibrium with a reservoir rich in garnet-clinopyroxene.

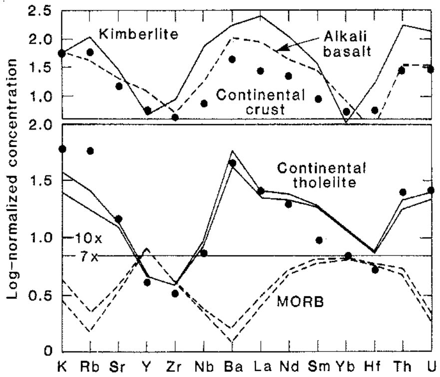

Fig. 1. Normalized trace element concentrations in the continental crust (dots), continental basalts (kimberlite, alkali basalt, and continental tholeiite), and mid-ocean ridge basalts (MORB) (*2, 6, 8, 41*). All concentrations are normalized to the terrestrial values of Ganapathy and Anders (*19*), recalculated to mantle equivalents. The lower curves for continental tholeiites and MORB are normalized to mantle concentrations after removal of the continental crust, as are the curves for alkali basalts and kimberlites. The complementary nature of MORB and the other magma types is evident. The continental crust is not the only "enriched" reservoir.

The high concentration of Y and Yb in MORB (Fig. 1) relative to other elements and relative to concentrations in basalts from PLUME, the enriched source region, is particularly significant. These elements have mineral/melt partition coefficients greater than unity for garnet. Mass balance calculations suggest that most of the terrestrial inventory of Y and Yb may be in MORBS. This can only be accomplished if garnet is a dominant phase and if most or all of the mantle has experienced differentiation. Partial melting of primitive mantle concentrates Y and Yb into the melt; crystallization of this melt at moderate pressure would concentrate these elements into an eclogite cumulate.

The relative volumes of the two source regions can be inferred from Fig. 1 if it is assumed that they, plus the continental crust, give an undifferentiated terrestrial pattern for the very incompatible elements. Using 0.56 percent for the mass of continental crust relative to the mantle (*3*), I compute that the mass of MORB must exceed the tholeiitic fraction of PLUME by a factor of 12 to 15. Continental tholeiites represent about 20 percent melting of a peridotitic source region (*6*), and MORB must be mixed with at least 15 percent olivine to recover the composition of its parent magma (*15, 16*). The residual crystals in both cases are assumed to be depleted because of their very low partition coefficients (*6, 8*). MORBS is, therefore, at least 2.8 to 3.5 times the mass of PLUME, and the enrichment of the combined source regions, relative to the primitive mantle, is about 3.3 to 3.8. Note that MORB are depleted only in a relative sense. Compared to average mantle abundances, MORB are enriched. This suggests that MORBS plus PLUME are complementary to the remainder of the mantle from which they presumably have been removed by partial melting. The enrichment factor implies whole-mantle differentiation and a residual mantle about 2.5 times the size of the combined reservoirs. I show later that this is equivalent to the volume of the lower mantle.

If we assume that the very incompatible elements have been entirely fractionated into the two source regions, it is possible to estimate their total mass. For example, if La is depleted in the lower mantle, the combined source regions represent 26 to 30 percent of the mantle. This corresponds to a thickness of 560 to 640 km in the upper mantle, or a region extending upward from the 670-km discontinuity to a depth of 27 to 110 km. If we take the transition region, 220 to 670 km, to be the depleted source region (*17*), then PLUME is 130 to 160 km thick, about the average thickness of the LVZ.

A similar calculation for the other strongly incompatible elements (K, Rb, Ba, U) gives a range of 21 to 38 percent for MORBS plus PLUME. These are upper bounds since it has been assumed that the whole mantle has been processed and depleted. This, however, is a good approximation if olivine and orthopyroxene are the main residual phases. It is significant that the above estimates of the relative and absolute sizes of the principal mantle reservoirs correspond to the main subdivisions of the upper mantle, the LVZ and the transition region. The 670-km depth corresponds to a major seismic discontinuity and the maximum depth of earthquakes. The seismic data imply a change in chemistry near this depth (*17, 17a*).

Other elements can be used to estimate the sizes of the individual reservoirs. The partition coefficients of Yb and Y are such that they strongly prefer the garnet structure (*18*). Both are enriched in MORB relative to PLUME, suggesting a higher portion of garnet in the former. If the entire mantle complement of Y and Yb reside in MORBS, then this would represent 14 to 17 percent of the mantle or an upper mantle equivalent thickness of 300 to 364 km. Scandium is partitioned into garnet and clinopyroxene by a factor of 8 relative to olivine and orthopyroxene. If we use this ratio of enrichment for MORBS relative to the rest of the mantle, MORBS would constitute 26 percent of the mantle.

The elements with the highest relative concentrations in PLUME are K, Rb, Ba, La, and U. These are the elements with the lowest partition coefficients for the major mantle minerals and those that are most likely to be concentrated into PLUME by melts or metasomatic fluids. The PLUME abundances of these elements can account for the entire mantle inventory if PLUME is 9 to 19 percent of the mantle.

Using the above estimates of the relative sizes of the two source regions and the values of Ganapathy and Anders (*19*) for terrestrial abundances, we can now estimate the total abundances of the trace elements in the various reservoirs. The continental crust contains more than 26 percent of the mantle plus crust inventory of K, Rb, and Ba and less than 8 percent of Sr, Y, Zr, Nb, Sm, Yb, and Hf. The "depleted" MORBS contains more than 50 percent of the earth's inventory of Y, Zr, Nd, Sm, Yb, Hf, and Th and more than 20 percent of Nb, La, and U. PLUME, although generating highly enriched magmas, contains only about 10 to 20 percent of the earth's K, Rb, Sr, Nd, Sm, Yb, Th, and U. It is the primary repository for Ba and La and has small total abundances of Y, Zr, Nb, and Hf (less than 7 percent). The crust and the two upper mantle reservoirs account for about 75 percent of the terrestrial heat flow. Therefore, only 25 percent of the earth's heat flow comes from the lower mantle, the core, or by cooling from higher temperatures. About 40 percent is due to MORBS. The continental crust and PLUME each contribute about 18 percent. The lower mantle may be essentially devoid of K, Th, and U.

This distribution of heat sources affects the style of convection in the two reservoirs. If PLUME is the shallower reservoir, it is heated primarily from below and will therefore be characterized by narrow ascending plumes. By contrast, MORBS is heated primarily from within and will be characterized by broader ascending regions and narrow descending jets or "slabs." If MORBS was underlain by a substantial volume of undepleted or primitive mantle, one would expect MORB to be erupted in narrow plumes because of the strong heating from below.

Mineralogy of the Two Source Regions

If the two source regions are related, one can determine an apparent partition coefficient by forming the ratio of the concentrations in MORB to those in continental tholeiites or continental flood basalts. This ratio is shown in Fig. 2 along with mineral/melt partition coefficients for garnet, clinopyroxene, orthopyroxene, and olivine. Tholeiites are used in this comparison since they presumably are products of large degrees of partial melting. They will therefore have the trace element pattern of their source and a relatively uniform enrichment. The ratio of the concentrations in the two reservoirs can be explained if MORBS is composed mainly of garnet and clinopyroxene and PLUME has been enriched with fluids that were in equilibrium with this layer and therefore depleted in such elements as Zr, Nb, Y, Yb, Hf, and the heavy rare earth elements.

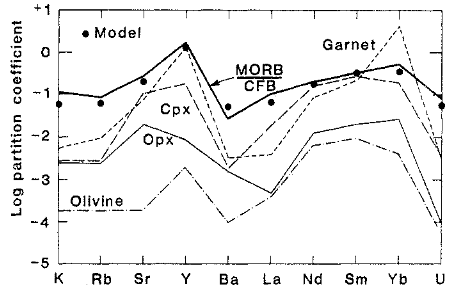

Fig. 2. Crystal/liquid partition coefficients for garnet, clinopyroxene, orthopyroxene, and olivine (*6*). The heavy line is the ratio of concentrations in primitive MORB (*42*) to that in continental tholeiites (*2, 6*). This indicates that MORB result from the melting of a source region rich in garnet and clinopyroxene and that the continental tholeiite or continental flood basalt (*CFB*) source region has experienced eclogite extraction. The points are for a model (*21*) in which the proto-MORB source region is an eclogite orthocumulate from the initial melt fraction of primitive mantle differentiation. The continental and ocean island basalt, or PLUME, source region is a shallow cumulate enriched by a late-stage melt from the proto-MORB cumulate layer. *Cpx*, clinopyroxene; *Opx*, orthopyroxene.

MORB are enriched with respect to continental tholeiites in Y and Zr and only slightly depleted in Hf and Yb. Both MORB and continental tholeiites represent rather large degrees of partial melting of their respective source regions. A garnet peridotite would be expected to lose most of its garnet and clinopyroxene under these circumstances. The above results indicate that primary garnet must be a minor mineral in PLUME but a major component of MORBS. MORB are depleted in the most incompatible elements, such as K, Rb, Ba, and U but not as much as would be expected if the source region of these basalts were composed entirely of residual crystals. This suggests that MORBS evolved from a melt, presumably the result of an early differentiation event, and consists of a mixture of melt with excess garnet which has settled into it during crystallization; that is, it is an orthocumulate. The upper part of the mantle would consist of lighter, cumulate and residual, crystals and late-stage fluids which impart an inverse garnet signature to this region.

This sequence of events, based on trace elements, is precisely what O'Hara *et al.* (*16*) proposed on the basis of petrological and major element considerations. They concluded that the parent magma for ocean island tholeiites had experienced a history of eclogite extraction. The remaining magma evolved to ocean island tholeiite by olivine fractionation. On the basis of major element (*17*) and trace element chemistry, I suggest that the eclogite cumulates constitute MORBS. The parent magma from which both MORBS and PLUME evolved by crystal fractionation would be picritic, the result of extensive partial melting of a primitive garnet peridotite mantle. Similar considerations have led to the concept of a magma ocean on the moon (*20*). Because of the higher pressures in the earth's mantle, a deep eclogite cumulate is the analog of the floating plagioclase cumulate that forms the lunar highland crust.

In order to determine if this explanation holds up quantitatively for the trace elements, let us investigate the following model. The primitive mantle is split into two reservoirs by 15 percent partial melting and melt extraction to the surface. The melt fraction reservoir is enriched by about a factor of 6 in the incompatible elements but, because of the low partition coefficients, has nearly primitive Rb/Sr and Sm/Nd ratios. Crystallization of the melt yields an eclogite cumulate layer that is modeled as a 50:50 mix of garnet and melt, proportions appropriate for an orthocumulate. Part of the final 5 percent melt fraction, a melt that is in equilibrium with eclogite, is removed to deplete the cumulate layer and enrich the overlying mantle. The mixing ratios were adjusted so that the former can yield MORB by 15 percent olivine fractionation and the latter can yield continental flood basalts by 20 percent partial melting (*21*). Detailed mass balance calculations to be presented elsewhere show that MORBS may contain up to 50 percent olivine. It may therefore be a picritic eclogite.

Results of this model are shown as dots in Fig. 2. They are consistent with the idea that MORB are the result of extensive melting of a source region which represents high-pressure cumulates from the melt fraction of the primary differentiation, that is, eclogite or garnet pyroxenite.

Prior to providing depleted MORB, this region lost its late stage fluids or, alternatively, crystallized completely

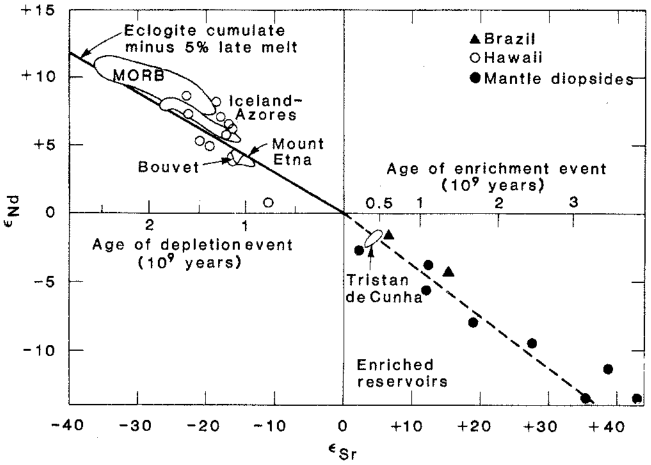

Fig. 3. Present $\epsilon_{Nd}-\epsilon_{Sr}$ values (*43*) for an eclogite cumulate (solid line) that has been depleted at various times by removal of a melt fraction (*35*). This melt fraction enriches the complementary reservoir (dashed line) (*13, 14, 30, 31, 34*). Observed magmas may be from variously aged reservoirs or may represent mixtures of depleted and enriched magmas.

and then lost its early melt fraction on a subsequent reheating cycle. The upward migration of this fluid enriched PLUME. Thus, two stages of differentiation and fractionation are required in order to concentrate the LIL elements in the two upper mantle reservoirs. Isotopically, MORBS evolves as nearly primitive mantle until it transfers its incompatible elements to PLUME. It subsequently evolves as a depleted reservoir. Basalts from PLUME will have time-integrated depleted, enriched, or "primitive" isotopic ratios, depending on when the enrichment occurred and the extent to which they have been mixed with MORB. Since the MORB reservoir contains many convection cells, it does not necessarily deplete at the same time at all locations. If kimberlites are the depleting fluid, they will appear to have come from a relatively unfractionated or "primitive" reservoir.

Locations of the Two Source Regions

A variety of evidence suggests that PLUME is shallow. Anomalously low seismic velocities can be traced to a depth of about 250 km under Yellowstone, but deeper velocities appear to be normal (*22*). The variable and small amounts of partial melting required to generate melilitites, nephelenites, basanites, and alkali basalts (*6*) from a common source region are consistent with diapirs rising from various shallow depths. Tholeiites are the result of larger degrees of melting, consistent with adiabatic ascent from deeper levels. The xenoliths entrained in kimberlites and alkali basalts are rich in volatiles and trace elements, and these are samples from the upper 200 km of the mantle (*12*). Intuitively, we expect that volatiles will migrate upward and be trapped by the cold upper mantle. Magmas enriched in volatile and LIL elements occur not only under continents but also at island arcs where the downgoing slab perturbs the upper mantle. Basalts of the PLUME type occur in continental rifts. These rifts evolve to oceanic ridges, with isolated oceanic island hotspots, when the rifting has led to the formation of an ocean basin.

There are also some suggestive geometric constraints. The volume of the LVZ is adequate to provide the PLUME basalts but not the voluminous MORB (*10*). The preferred mode of convection in a region with a high-temperature gradient and a rapidly varying viscosity takes the form of hexagonal cells with upwelling centers (*23*). This seems to be consistent with hotspot patterns (*24*) and the small areal extent of hotspots. In more homogeneous regions of the mantle, where the temperature gradient is smaller and the viscosity more uniform, linear rolls are a possible mode of heat transport. Linear ridge systems and the uniformity of oceanic tholeiites therefore suggest a deeper source, one that is below the large vertical and lateral variations that occur in the upper 200 km. The sink of oceanic lithosphere, judging from the depth distribution of earthquakes, appears to be between 200 and 670 km. The distinctive isotopic and trace element signature of MORBS can be maintained if it is also between these depths. Upper mantle temperatures are closest to the melting point between depths of about 150 and 250 km, and this is therefore the depth range where it is most likely for diapirs to originate.

It is difficult to estimate the depth at which partial melting first occurs. Seismic data from several hotspots give low velocities down to at least 150 km (*22, 25*). Eruption temperatures of 1300°C and large degrees of partial melting require initiation of melting below 150 to 200 km (*26*). There is some evidence for crystal fractionation in melts as deep as 280 km (*27*). Mantle fragments brought up by alkali basalts and kimberlites do not, in general, have the trace element pattern required for MORBS. Therefore, PLUME magmas may originate from shallow depths but MORBS must be deeper than 200 km. In a gravitationally stratified mantle, one would expect the deeper layer to be denser and therefore rich in garnet. The inability of young buoyant lithosphere to subduct below about 220 km suggests a density increase at this depth, and this may be the boundary between the two source regions (*17*). If we take all the evidence into account, it appears that PLUME may be coincident with the LVZ and that diapirs rising from the top of the transition region supply the magmas that evolve to MORB.

A Terrestrial Magma Ocean

The complementary LIL element patterns of the major terrestrial magma types are reminiscent of lunar data that have led to the widely accepted concept of crystal fractionation and cumulate formation in a magma ocean or vast lava lakes (*20*). The various source regions are attributed to cumulate and residual fluid layers that resulted from the crystallization of a magma ocean ~ 300 km thick; this magma ocean, in turn, was derived from very early melting of at least half the moon. If a body as small as the moon experienced such extensive differentiation and fractionation, then the earth should have as well. The amount of partial melting required, ~15 to 25 percent, to explain the enrichment of the upper mantle reservoirs on the earth, is, in fact, relatively modest. Although the energy of accretion of the earth is much greater than that of the moon, the greater size of the earth results in high Rayleigh number convection and rapid increase of the melting curve with depth. This plus the latent heat buffer and the high melting temperature of olivine may prevent more extensive melting on a global scale. A 15 percent melt implies a magma ocean ~ 400 km deep. The pressures in the earth are greater than on the moon. Early eclogite fractionation at depth therefore preempts the extensive plagioclase fractionation that resulted in the early lunar anorthositic crust.

Crystallization of a magma ocean will proceed from the base because of the relative slopes of the adiabat and the liquidus. The near liquidus phases at depths greater than 60 km are garnet and clinopyroxene (*16, 28*), and they will form an eclogite or garnet pyroxenite cumulate layer. Although there is a seismic discontinuity in the mantle near 400 km, eclogite is denser than residual peridotite to depths of 670 km (*17*). These cumulates will therefore sink to this depth, displacing residual mantle upward. The shallower part of the mantle will therefore consist of olivine and pyroxene cumulates and residual fluid from the magma ocean and displaced residual lower mantle. The top of the eclogite layer could be as shallow as 220 km (*17*) or as deep as 370 km on the basis of the considerations presented in this article. The mantle discontinuity near 400 km, which is usually attributed to the olivine-spinel phase change could therefore either be a chemical discontinuity or could represent the completion of the phase change from garnet pyroxenite (eclogite) to garnetite (garnet solid-solution) (*29*).

Isotopic Ratios of the Two Source Regions

The study of Sr and Nd isotopes places important time constraints on the evolution of mantle reservoirs (*30-32*). The continental crust and the depleted reservoir have mean ages of 1.5 billion years (*3*). Kimberlites and continental flood basalts, although enriched in LIL elements, have been attributed to a primitive reservoir (*2, 3, 30, 33*). This interpretation is not required by the data, as I show below. Some mantle samples have been derived from ancient enriched reservoirs (*14*). Other samples come from reservoirs that apparently have been enriched only recently (*14, 34*).

Consider a primitive mantle that partially melts and separates into two reservoirs, as before, by upward removal of the melt. The lower mantle consists of residual crystals and is therefore depleted in the incompatible elements. The melt fractionates into a deeper garnet-rich cumulate layer and a shallow peridotite layer. A 5 percent melt fraction is transferred from the deeper to the shallower layer at various times (*35*). The Nd and Sr isotopic ratios for the two reservoirs are shown in Fig. 3. The central horizontal scale gives the ages of the depletion and enrichment events. The theoretical $\varepsilon_{Nd} - \varepsilon_{Sr}$ correlation lines agree with the data and indicate that MORBS was depleted at times between 1.5 and 2.5 billion years ago. A redistribution of LIL elements makes it possible to satisfy the mantle isotopic data even if the primary differentiation occurred early in the history of the earth. The inferred enrichment ages can be brought into correspondence with the depletion ages if enrichment has been progressive with a time constant of about 2 billion years. The Rb/Sr and Nd/Sm ratios of the residual fluids in a crystallizing eclogite cumulate will, in fact, increase with time. Thus, the trace element, petrological, and thermal constraints on the evolution of the mantle and the various reservoirs are not contradicted by the isotopic data. The type of model investigated here is similar to earlier ideas of mantle metasomatism and trace element redistribution (*13, 14*). Because of the isotopic data, enrichment is often assumed to be a recent precursor to eruption. Enriched magmas exhibiting time-integrated depletions may also represent mixtures of enriched and depleted magmas.

Implications for Mantle Evolution

Isotopic studies indicate that the two major mantle reservoirs have been isolated for more than 1 or 2 billion years (*2, 3*). The evidence presented here from trace elements, and from major element and seismic considerations (*17*), suggests that the mantle is chemically stratified and that the various regions of the mantle are complementary products of terrestrial differentiation. The present emphasis has been on magmas from these reservoirs, but similar conclusions result from the study of solid fragments from the mantle (*16, 17*). O'Hara *et al.* (*16*) pointed out that the restricted number of phases found in bimineralic eclogites from kimberlites indicate that they are either crystal accumulates or crystalline residue developed in contact with a liquid. This is exactly the situation inferred from the trace element patterns for the source region of abyssal tholeiites. Eclogite and garnet peridotite xenoliths from kimberlites may represent samples from MORBS and PLUME, respectively. They give satisfactory average mantle compositions for the major oxides when combined in the proportions indicated by the trace elements (*17*).

Although whole mantle convection, in the conventional sense, is precluded in a chemically stratified mantle, transfer of material into and out of the various upper mantle reservoirs is possible because of the large volume change associated with partial melting and phase changes, for example, basalt-eclogite. The oceanic part of the plate tectonic cycle may be summarized as follows. Partial melting in the eclogite layer allows diapirs to rise to the base of the oceanic lithosphere. Extensive melting occurs during adiabatic ascent. This is possible because of the proximity, in temperature, of the liquidus and the solidus in eclogite. Peridotite diapirs can melt only partially because of their high liquidi. The resulting melt fractionates in near surface magma chambers to form tholeiitic melts that are light enough to rise to the surface. The pyroxenite residue forms the lower oceanic lithosphere. As the lithosphere cools and thickens, the lower part transforms to garnet pyroxenite or eclogite, which is denser than the underlying mantle. The oceanic lithosphere becomes gravitationally unstable, and it returns to its source region which lies between depths of about 220 km or deeper and 670 km. Partial melting in the shallow enriched pe-

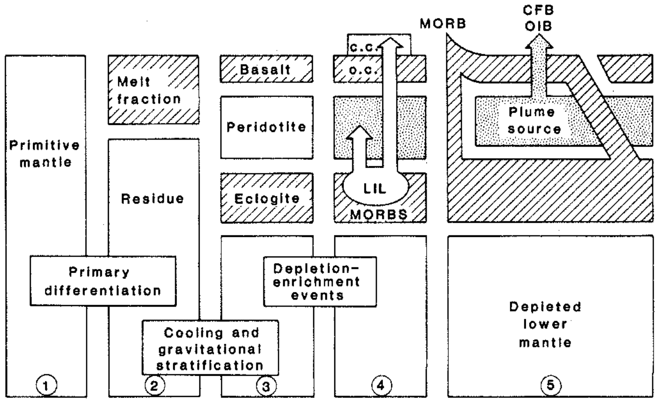

Fig. 4. A model for the evolution of the mantle. Primitive mantle (part 1) is partially molten either during accretion or by subsequent whole-mantle convection, which brings the entire mantle across the solidus at shallow depths. The large-ion lithophile (*LIL*) elements are concentrated in the melt. The deep magma ocean (part 2) fractionates into a thin, plagioclase-rich surface layer and deeper peridotitic and garnet-rich cumulate layers (part 3). Late-stage melts in the eclogite cumulate are removed (part 4) to form the continental crust (*c.c.*), enrich the peridotite layer, and deplete the MORB source region (*MORBS*), the source region of oceanic crust (*o.c.*) and lower oceanic lithosphere. Partial melting of PLUME (part 5) generates continental flood basalts (*CFB*), ocean island basalts (*OIB*), and other enriched magmas, leaving a depleted residue (harzburgite) that remains in the upper mantle. Erupted magmas may be mixtures of magmas from MORBS and PLUME.

ridotite layer generates continental and ocean island basalts and a harzburgite residue, both of which are lighter than their source region. These PLUME products remain in the crust and upper mantle. Some volatiles are returned to PLUME by subducted sediments and hydrothermally altered oceanic crust. The high temperature gradient in the thermal boundary layer at the PLUME-MORBS interface brings temperatures there close to the melting point (*17*). A perturbation in the elevation of the boundary, caused, for example, by convection in MORBS, may trigger partial melting and diapiric ascent. A thermal perturbation, discussed below, is another possible trigger. When mature oceanic lithosphere passes over a hotspot, it is quite likely that the lower pyroxenite part will contribute xenoliths to the alkalic magmas and, by remelting, contribute to the trace element and isotopic signatures of ocean island basalts. The evolution of the mantle is shown schematically in Fig. 4.

It has generally been assumed that basalts of all kinds represent partial melts of peridotites. Mantle compositions based on this premise have much lower abundances of SiO_2, Al_2O_3, and CaO than models based on cosmochemical considerations. The evidence used to construct the petrological models is obtained from the upper 200 km of the mantle, and the models are therefore strictly valid only for the uppermost mantle. A thick eclogite layer serves to increase the abundances of the above components and can serve to reconcile the cosmochemical and petrological interpretations. The possibility of an eclogite layer in the upper mantle was also discussed by Press (*36*).

The idea that eclogite may be the source for oceanic basalts is an old one (*37*) but has not been in favor in recent years. The main objection is that limited partial melting of eclogite does not generate a tholeiite. Extensive or complete melting is required, and this has been thought to be unlikely.

However, eclogite has an extremely small melting interval (about 60°C) compared to peridotite (*28, 38*). Since diapirs cannot rise out of an eclogite layer into a less dense peridotite layer until they are already extensively molten, it requires only a small additional temperature rise, relative to the liquidus, to complete the melting. This can be accomplished in a rising diapir (*39*). If the source region is an olivine eclogite, a picritic parent magma can be formed by smaller degrees of partial melting. It is still unknown why melting begins in the first place. One possibility is insulation by the thick continental lithosphere.

Hotspots and ridges in the Atlantic and Indian oceans were beneath continental lithosphere before 200 million years ago. A large number of hotspots are presently under the relatively stationary continent of Africa. This suggests that continental insulation, which prevents mantle heat from being efficiently removed to the surface, may be the cause of the partial melting that ultimately results in ridge and hotspot volcanism. The thick, 150 km, continental lithosphere (*17*) prevents diapiric uprise, and extensive melting may be possible until the continent rifts and rapid spreading and heat removal can take place. It is not so obvious that this explanation holds for the ridges and hotspots in the Pacific. The thick crust under the oceanic plateaus in the central Pacific or a thick oceanic lithosphere, due to a period of slow spreading, could also serve to insulate the mantle, raise temperatures, and cause extensive in situ melting prior to diapiric ascent. Parts of the Pacific rim continents such as Alaska, Mexico, Central America, and southeastern Asia may also have been located in the central Pacific prior to 200 million years ago. Once initiated, the rise of upper mantle diapirs should be rapid (*40*), possibly rapid enough to avoid crystal fractionation en route (*39*).

Small-scale convection dominates in the type of chemically stratified mantle discussed here. Hotspots will be relatively stationary since they are locked into position by the underlying convection cell.

Conclusions

Garnet and possibly clinopyroxene control the complementary trace element patterns of MORB and PLUME magmas. I suggest that MORBS was formed from an eclogite cumulate layer resulting from crystallization of the picritic melt fraction of the original differentiation of the earth. The PLUME source is enriched in those elements that would be concentrated in a melt that was removed from a garnet-rich region. This fluid, the result of an early partial melt or a late-stage fluid from crystallizing eclogite in MORBS, infiltrated the shallow-mantle PLUME source at various times over the past 2 billion years. This gives PLUME basalts an inverse garnet signature of trace elements relative to MORB. Taken together, MORBS and PLUME make up about 25 to 30 percent of the mantle. This requires that most, if not all, of the mantle has been processed to obtain the observed enrichment. There is no need to invoke a large primitive reservoir in the mantle or deep, lower mantle PLUME sources. On the contrary, PLUME appears to be shallow and may be coincident with the LVZ. The upper mantle transition region, 220 to 670 km, represents about 21 percent of the mantle, and the LVZ is about one-third as large. This is about the ratio of the sizes of the two upper mantle reservoirs that is required to satisfy the trace element data. The MORB source is probably an eclogite cumulate, possibly picritic eclogite, whereas the PLUME source is probably garnet peridotite. Crystallization of a magma ocean would give this kind of upper mantle stratigraphy. The Nd and Sr isotopic data indicate that the depletion of that part of MORBS being sampled today occurred over the interval from 1.5 to 2.5 billion years ago. The fluid that participated in the depletion-enrichment events, and in the formation of the continental crust, appears to be a partial melt or late-stage residual fluid from an eclogite cumulate layer. Kimberlite magmas have the trace element characteristics required of this fluid. The lower mantle is residual peridotite, and, although it may be convecting, it no longer communicates with the shallower reservoirs. The 670-km discontinuity appears to be both a phase change and a chemical discontinuity (*17a*). This is consistent with the present model.

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21. The two source regions (MORBS and PLUME) are constructed as follows. For primitive mantle (PM) we use the Ganapathy-Anders (*19*) values and extract 15 percent melt (ME). The concentrations of LIL elements in ME and residual mantle (RM) are calculated with the use of partition coefficients appropriate for a peridotitic residue (*3*, *6*). The eclogite cumulate (EC) is a 50 : 50 mix of garnet and equilibrium intercumulus fluid. To obtain the depleted LIL pattern for MORBS, half of the final 5 percent melt (LSM) is removed. Partition coefficients for an eclogite residue are used at this stage; LSM is the enriching or metasomatic fluid for PLUME, which is composed of 10 percent LSM and 90 percent RM. Thus, PM evolves to ME and RM by partial melting; ME evolves to EC and a silica-undersaturated fluid by eclogite fractionation. Finally, EC minus LSM yields MORBS; RM plus LSM yields PLUME.
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Application of Space Technology to Geodynamics

Edward A. Flinn

Despite the rapid progress achieved within the last decade, there are many important questions in geodynamics that we cannot yet answer. For example, How are the plates moving at the present time? Is the movement smooth or jerky? How do the local movements caused by earthquakes at active plate boundaries contribute to the gross movement of the plates? How do the plates deform in response to the driving forces? How is strain distributed near active plate margins, and how does the strain change with time? What relationship, if any, is there between variations in polar motion and other geodynamical phenomena such as great earthquakes? What is the rheology of the lithosphere and the asthenosphere? Are large-scale vertical movements taking place at the present time?

What these questions have in common is that progress in finding their answers depends, at least to some extent, on measuring the relative position and movement of points on the earth's surface, over distances ranging from a few kilometers to many thousands of kilometers. An accuracy of at least 2 to 3 centimeters is required because of our desire to measure average plate movements (a few centimeters per year) within a reasonable time and because of the necessity to detect episodic changes in motion.

There are several reasons why classical ground-based geodetic surveying methods—leveling and trilateration—are impractical for making frequent measurements of station position over distances greater than about 100 km (these methods, of course, cannot be used at all over the oceans). The major reason is that ground surveys must be made in a sequence of line-of-sight measurements between points up to a few tens of kilometers apart, and the resulting accumulation of random (and possibly systematic) errors soon brings the uncertainty in position above the required level of a few centimeters. The best trilateration measurement is good to about three parts in 10^7, an error that exceeds 3 cm beyond about 100 km; the best leveling measurement accumulates random error at the rate of about 1 millimeter multiplied by the square root of the length of traverse

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The author is Chief Scientist of the Geodynamics Program, National Aeronautics and Space Administration Headquarters, Washington, D.C. 20546, and Secretary-General of the International Lithosphere Program.

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