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Paul T. Robinson et John Malpas

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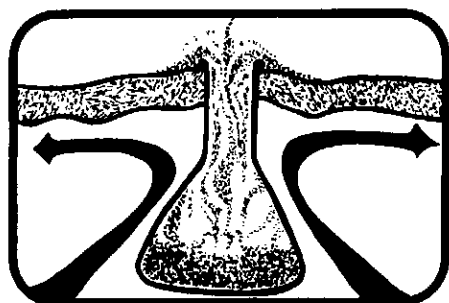
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Résumé de l'article

Les laves océaniques constituent les matériaux volcaniques les plus volu-mineux de la Terre. Seulement le long de l'axe d'expansion des fonds océaniques, entre 15 et 20 km³ de croûte océanique sont créés à chaque année par l'éruption de basaltes des crêtes médio-océaniques (BCMO). Ces laves de BCMO sont des tholéïtes à olivine et hypersthène normatifs, fortement appauvries en éléments traces incompatibles tels le Rb, Sr, Ba, K, Zr, Y ainsi que les terres-rares légers. Leur contenu isotopique se caractérise par la présence de Sr et Pb faiblement radiogéniques et de Nd fortement radiogénique. Ces laves sont produites par fusion de décompression de matériaux mantelliques peu profonds, lors de leur ascension sous les axes d'expansion océaniques. Tôt dans l'histoire de la Terre, ces matériaux mantelliques ont été appauvris en éléments incompatibles par extraction de matériaux crus-taux continentaux. À l'échelle du globe, ces laves ont une composition qui est remarquablement uniforme, quoiqu'il existe des variétés enrichies (BCMO-E) aient été reconnues dans tous les segments de crête. Dans l'échelle de composition, ces laves enrichies occupent des positions inter-médiaires entre la composition des laves d'îles océaniques (LIQ), dont le contenu en éléments incompatibles est beaucoup plus élevé, et le contenu isotopique beaucoup plus varié que celui des laves de type BCMO. On estime que les basaltes des îles océaniques sont formés par la fusion partielle de panaches de matériaux ascendants issus du voisinage de la frontière entre le noyau et le manteau. Ces panaches entraînent au passage des matériaux mantelliques qui auraient été relativement enrichis au contact de matériaux crustaux recyclés dans les zones de subduction. Le mélange, en des proportions variées, de matériaux de panaches mantelliques avec des BCMO mantelliques appauvris peut expliquer l'existence de laves BCMO-E. On estime que de grands super-panaches seraient à l'origine de ces grands plateaux océaniques qui sont formés par de volumineuses éruptions de basaltes d'îles océaniques.

SERIES



Oceanic Lithosphere 3. The Origin and Evolution of Oceanic Lithosphere: The Geochemistry and Origin of Oceanic Lavas

Paul T. Robinson¹ and John Malpas
*Department of Earth Sciences
The University of Hong Kong
Hong Kong*

SUMMARY

Oceanic lavas are the most voluminous volcanic products on Earth. Between 15 and 20 km³ of new oceanic crust is created every year by eruption of mid-ocean ridge basalt (MORB) along sea-floor spreading axes. MORB lavas are olivine- and hypersthene-normative tholeiites highly depleted in incompatible trace elements such as Rb, Sr, Ba, K, Zr, Y and the light rare earth elements. Isotopically, they are characterised by low radiogenic Sr and Pb and high radiogenic Nd. They are formed by

decompressional melting of shallow mantle material as it rises beneath spreading axes. This upper mantle source was previously depleted in incompatible elements by extraction of continental crustal material early in Earth history. On a global scale MORB lavas are remarkably uniform, but relatively enriched varieties (E-MORB) are known from all ridge segments. These enriched lavas are transitional in composition to ocean island basalts (OIB) which have much higher contents of incompatible elements and much more varied isotopic compositions than typical MORB lavas. Ocean island basalts are believed to form by partial melting of mantle plumes that rise from near the core-mantle boundary. These plumes entrain mantle material that has been relatively enriched by recycled crustal materials in subduction zones. Mixing of plume mantle and depleted MORB mantle on a variety of scales can explain the occurrence of E-MORB lavas. Large-scale superplumes are believed to be responsible for the formation of oceanic plateaus, which are built by voluminous eruptions of ocean island basalts.

RÉSUMÉ

Les laves océaniques constituent les matériaux volcaniques les plus volumineux de la Terre. Seulement le long de l'axe d'expansion des fonds océaniques, entre 15 et 20 km³ de croûte océanique sont créés à chaque année par l'éruption de basaltes des crêtes médio-océaniques (BCMO). Ces laves de BCMO sont des tholéiites à olivine et hypersthène normatifs, fortement appauvries en éléments traces incompatibles tels le Rb, Sr, Ba, K, Zr, Y ainsi que les terres-rares légers. Leur contenu isotopique se caractérise par la présence de Sr et Pb faiblement radio-

géniques et de Nd fortement radiogénique. Ces laves sont produites par fusion de décompression de matériaux mantelliques peu profonds, lors de leur ascension sous les axes d'expansion océaniques. Tôt dans l'histoire de la Terre, ces matériaux mantelliques ont été appauvris en éléments incompatibles par extraction de matériaux crustaux continentaux. À l'échelle du globe, ces laves ont une composition qui est remarquablement uniforme, quoique l'existence des variétés enrichies (BCMO-E) aient été reconnues dans tous les segments de crête. Dans l'échelle de composition, ces laves enrichies occupent des positions intermédiaires entre la composition des laves d'îles océaniques (LIO), dont le contenu en éléments incompatibles est beaucoup plus élevé, et le contenu isotopique beaucoup plus varié que celui des laves de type BCMO. On estime que les basaltes des îles océaniques sont formés par la fusion partielle de panaches de matériaux ascendants issus du voisinage de la frontière entre le noyau et le manteau. Ces panaches entraînent au passage des matériaux mantelliques qui auraient été relativement enrichis au contact de matériaux crustaux recyclés dans les zones de subduction. Le mélange, en des proportions variées, de matériaux de panaches mantelliques avec des BCMO mantelliques appauvris peut expliquer l'existence de laves BCMO-E. On estime que de grands super-panaches seraient à l'origine de ces grands plateaux océaniques qui sont formés par de volumineuses éruptions de basaltes d'îles océaniques.

INTRODUCTION

Nearly all of the available geochemical data on oceanic lavas have been obtained in the last 35 years. Prior to 1963

¹Permanent Address: Centre For Marine Geology, Dalhousie University, Halifax, Nova Scotia B3H 3J5

the only data on such lavas were from volcanic islands, which we now know to be completely unrepresentative of the ocean basins as a whole. These volcanic island data were interpreted to reflect three distinct lava suites, the Atlantic, Pacific and Mediterranean (*e.g.*, Rittmann, 1962). The Atlantic suite, heavily biased by data from Iceland, was thought to consist chiefly of tholeiitic lavas, whereas the Pacific suite was thought to be alkalic. The leucite-bearing lavas of the Roman Province were used to postulate a potassic suite for the entire Mediterranean Basin.

Problems with this simple classification became apparent as detailed studies of individual ocean volcanoes were undertaken. For example, Macdonald and Katsura (1964) showed that the alkalic basalts on Hawaiian volcanoes form only thin caps on the tops of the volcanoes and that the shields consist primarily of tholeiitic lavas.

In 1963, a few lava samples dredged from the northeast Pacific Ocean floor revolutionized our understanding of seafloor basalts. These basalts had a uniform, highly depleted composition distinct from any lavas known at that time (Engel and Engel, 1963; 1964). In a stupendous, but essentially accurate, extrapolation Engel and Engel postulated a new class of basalts which they suggested might be characteristic of the seafloor everywhere.

This once common view that there is a widespread uniformity in composition of oceanic basalts has now given way, however, to the realization that they exhibit considerable diversity in their major element, trace element and isotopic compositions. It is now accepted that there are different geochemical source regions for the basalts, that there is a range of parental magmas, and that these lavas show variable degrees of differentiation from place to place on the ocean floor.

Nevertheless, for the purpose of the present discussion, oceanic basalts are considered to fall into two major geochemical groups; those generated at mid-ocean ridges and those forming ocean islands and seamounts. Here, we exclude lavas generated in island arcs, which will be discussed in a separate paper dealing with collisional plate boundaries.

With the recognition of seafloor spreading and plate tectonics, it became clear that the oceanic crust is generated

largely at mid-ocean ridge spreading centres. Indeed, the mid-ocean ridge system is the largest single supplier of magma to the surface of Earth. Rocks dredged from these spreading centres have compositions similar to those described by Engel *et al.* (1965) and are termed mid-ocean ridge basalts (MORB) (Kay *et al.*, 1970).

A small proportion of the oceanic crust is represented by oceanic island volcanoes and seamounts which are the result of intraplate volcanism associated with hotspots in the mantle (Wilson, 1963). In volume, this volcanism is relatively insignificant compared to that which forms the oceanic basement on which these edifices sit. Some of these volcanoes, such as the Hawaiian Islands, occur in linear chains in which individual volcanoes become progressively older away from the hotspot (Dalrymple *et al.*, 1987; Clague and Dalrymple, 1989). Others, such as the Canary Islands, occur in clusters without spatial age relationships. Typically, these intraplate volcanoes occur far from active spreading centres but a few, such as the Azores, Iceland and Bouvet, lie on, or close to, mid-ocean ridges.

Detailed stratigraphic studies of these island volcanoes have shown that most of them have a complex history involving construction of a shield, formation of a collapse caldera, and post-caldera volcanism. Lavas erupted during the shield-building stage are mostly tholeiitic basalts, albeit quite different in composition from mid-ocean ridge basalts (Table 1), whereas the later lavas are alkali-olivine basalts and their differentiated products such as phonolites and trachytes.

LAVA CHARACTERISTICS

All oceanic basalts are enriched in incompatible elements relative to primitive mantle because they originate as melts which concentrate the incompatible elements from the mantle source. Incompatible elements are those that are excluded from common silicate minerals because of their large ionic radius and/or high ionic charge and therefore preferentially enter, or remain in, any available melt phase. The fundamental difference between MORB and OIB lies in the degree of enrichment of the highly incompatible elements compared to the moderately incompatible elements. Trace element ratios between highly incompatible to moderately incompatible

elements provide an indication of the source composition and, in the 1970s, led to the concept of a layered mantle, with MORB derived from an upper layer depleted in all the incompatible elements as a result of an earlier melting event, and OIB coming from a deeper, primitive layer that was less depleted or even enriched in the highly incompatible elements (see discussion in Hofmann, 1997).

An additional notable difference between MORB and OIB is the degree to which each magma type fractionates. Whereas MORB undergoes very little differentiation, OIB fractionates to a far greater extent and is found commonly with highly evolved lavas.

LAVAS ERUPTED AT MID-OCEAN RIDGE SPREADING CENTRES

Mid-ocean ridge lavas are typically silica-undersaturated tholeiitic basalts characterized by a marked relative depletion in large-ion lithophile or incompatible elements such as Cs, Rb, Ba, Th, K, La and Ce relative to more moderately incompatible elements such as Sm, Hf, and Y (Figs. 1, 2).

These lavas are produced by partial melting of shallow mantle upwelling beneath spreading ridges and are erupted as pillow lavas and massive or sheet flows, commonly with thin accumulations of hyaloclastite. Pillow lavas are typically fine- to very fine-grained with well-developed quench textures and many have fresh glassy rinds up to several centimetres thick. Massive and sheet flows are typically coarser-grained and better crystallized but some also have narrow glassy margins. Very few of these basalts crystallise under equilibrium conditions. All are erupted into cold seawater on the ocean floor and cooled rapidly. Thus, very few of the minerals observed in the lavas can be thought of as liquidus assemblages.

Most MORB lavas are aphyric to very sparsely phyrical although some contain large and abundant phenocrysts (*e.g.*, Flower *et al.*, 1977). Calcic plagioclase and olivine are the common phenocryst phases; spinel occurs only in the most mafic MORB lavas as small, subhedral phenocrysts and as inclusions in olivine. Close examination of the phenocryst phases reveals that magma mixing and mingling are major causes of variation amongst the basalts, and may be more important than fractionation processes in shallow magma chambers. For ex-

Table 1 Geochemistry of oceanic lavas. N-MORB values from Sun and McDonough (1989). E-MORB major oxide data from Humphris *et al.* (1985) and trace element data from Sun and McDonough (1989). OIB major oxide data from Hughes (1982) and trace element data from Sun and McDonough (1989).

| | N-MORB | E-MORB | OIB |
|--------------------------------|--------|--------|-------|
| SiO ₂ | 50.4 | 51.2 | 49.2 |
| TiO ₂ | 1.36 | 1.69 | 2.57 |
| Al ₂ O ₃ | 15.2 | 16 | 12.8 |
| FeO* | 9.31 | 8.46 | 11.4 |
| MnO | 0.18 | 0.16 | 0.17 |
| MgO | 8.96 | 6.9 | 10 |
| CaO | 11.4 | 11.5 | 10.8 |
| Na ₂ O | 2.3 | 2.74 | 2.12 |
| K ₂ O | 0.09 | 0.43 | 0.51 |
| P ₂ O ₅ | 0.14 | 0.15 | 0.25 |
| Total | 99.34 | 99.23 | 99.82 |
| Sc | 40 | | |
| V | 262 | | |
| Cr | 346 | | |
| Co | 50 | | |
| Ni | 177 | | |
| Cs | 0.007 | 0.063 | 0.387 |
| Rb | 0.56 | 5.04 | 31 |
| Sr | 90 | 155 | 660 |
| Ba | 6.3 | 57 | 350 |
| Nb | 2.33 | 8.30 | 48.0 |
| Zr | 74.0 | 73.0 | 280 |
| Hf | 2.05 | 2.03 | 7.80 |
| Y | 28.0 | 22.0 | 29.0 |
| La | 2.50 | 6.30 | 37.0 |
| Ce | 7.50 | 15.0 | 80.0 |
| Pr | 1.32 | 2.05 | 9.70 |
| Nd | 7.30 | 9.00 | 38.5 |
| Sm | 2.63 | 2.60 | 10.0 |
| Eu | 1.02 | 0.91 | 3.00 |
| Gd | 3.68 | 2.97 | 7.82 |
| Tb | 0.67 | 0.53 | 1.05 |
| Dy | 4.55 | 3.55 | 5.60 |
| Ho | 1.01 | 0.79 | 1.06 |
| Er | 2.97 | 2.31 | 2.62 |
| Tm | 0.456 | 0.356 | 0.350 |
| Yb | 3.05 | 2.37 | 2.16 |
| Lu | 0.455 | 0.354 | 0.300 |
| Pb | 0.30 | 0.60 | 3.20 |
| Th | 0.12 | 0.60 | 4.00 |
| U | 0.047 | 0.180 | 1.02 |
| Li | 4.3 | 3.5 | 5.6 |
| Mo | 0.310 | 0.470 | 2.40 |
| Ta | 0.132 | 0.470 | 2.70 |
| Tl | 0.001 | 0.013 | 0.077 |

ample, where present, clinopyroxene phenocrysts are typically rounded and corroded indicating that they are out of equilibrium with the surrounding groundmass. They appear to have crystallised from a different magma composition than that erupted, and to have been incorporated in the MORB lava through magma mixing (Natland, 1989). Low-Ca pyroxene is very rare in spreading centre basalts, but pigeonite has been recorded in some lava flows (Thompson and Humphris, 1980). Theoretically, olivine should be replaced by low-Ca pyroxene late in the crystallisation sequence of MORB lavas, but there are arguments that such extensive fractionation is only rarely seen (Walker *et al.*, 1979).

Mid-ocean ridge basalts are typically silica-undersaturated tholeiites with normative olivine and hypersthene; a few have normative quartz. Although relatively uniform on a global scale, they are now known to show many small-scale spatial and temporal compositional variations. The varieties are recognized on the basis of their major and trace element geochemistry (Table 1). Most voluminous are normal or N-MORB lavas, characterized by low abundances of incompatible elements, such as K, Rb, Sr, Zr, and Y (Fig. 1), by low radiogenic Sr and Pb and high radiogenic Nd (Fig. 3). Another distinguishing characteristic of N-MORB is a relative depletion of the light rare earth elements such as La, Ce, Pr and Nd (Fig. 2). The

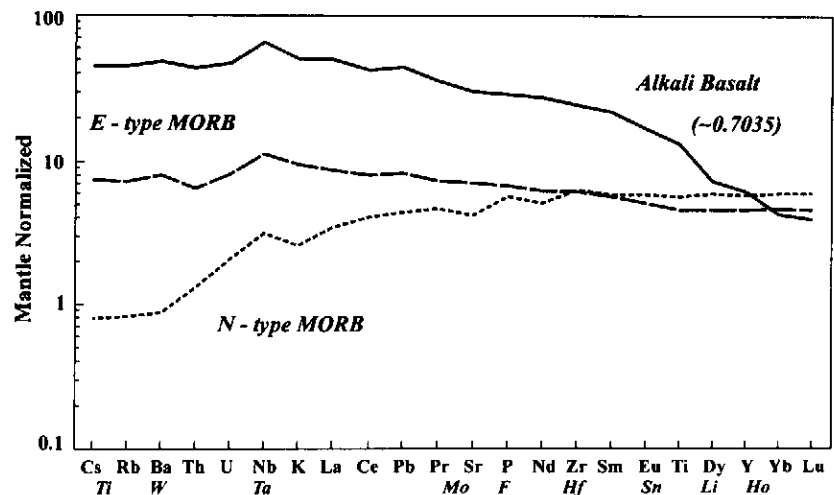


Figure 1 Primitive-mantle normalized abundance patterns for moderately to highly incompatible elements in average N-type and E-type MORB and oceanic alkalic basalts with ⁸⁷Sr/⁸⁶Sr = 0.7035 (values for lavas after Sun and McDonough, 1989, normalizing values after McDonough and Sun, 1995).

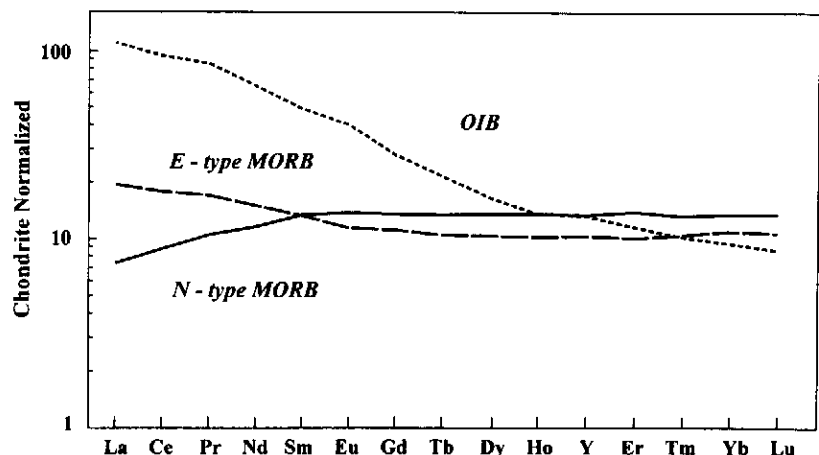


Figure 2 Chondrite-normalized rare earth element patterns for N-MORB, E-MORB and OIB (data are from Table 1 and normalizing values are from McDonough and Sun, 1995).

very low abundances of incompatible elements in these lavas are believed to reflect the depleted character of the upper mantle from which they are derived. The upper mantle was already depleted relative to the deeper mantle, probably during formation of the continental crust (Gast, 1968; O'neils *et al.*, 1977; Zindler and Hart, 1986; Hofmann, 1988).

Significant regional variations in major element compositions, REE, and isotopic signatures were recognized first on the northern Mid-Atlantic Ridge (*e.g.*, Schilling *et al.*, 1983; White and Schilling, 1978; Sigurdsson, 1981) where it was found that La/Sm ratios and ^{87}Sr contents increase toward Iceland and the Azores platform. These basalts, which have significantly higher contents of incompatible elements than normal MORB, are termed enriched or E-MORB. They may be considered to be compositionally intermediate between N-MORB types and ocean island basalts. Typically, E-MORB lavas are somewhat more evolved than N-MORB and have notably lower MgO and higher TiO_2 , Na_2O and K_2O (Table 1), higher

incompatible element contents, greater radiogenic Sr and Pb and lower radiogenic Nd (Ito *et al.*, 1987) (Fig. 3).

Some workers also recognize a transitional or T-MORB intermediate between normal and enriched varieties (Langmuir *et al.*, 1986; Reynolds *et al.*, 1992). These are distinguished largely on the basis of relatively high Al_2O_3 and Na_2O and intermediate incompatible element contents.

In the Atlantic Ocean, the degree of incompatible element enrichment increases with decreasing ridge axis depth and proximity to on- or near-ridge hotspots such as Azores, Bouvet and Iceland (Sun *et al.*, 1975; Schilling *et al.*, 1983; Dosso *et al.*, 1993). This transition from N-MORB to E-MORB along the ridge axis has been attributed largely to the interaction of plume magmatism with that of a normal spreading centre. However, similar E-MORB lavas are distributed ubiquitously along well-studied segments of the East Pacific Rise, far from any known hotspots (Langmuir *et al.*, 1986; Fornari *et al.*, 1988; Thompson *et al.*, 1989; Natland, 1989; Hekinian *et al.*, 1989; Prinzhofer *et al.*, 1989;

Sinton *et al.*, 1991; Batiza and Niu, 1992; Reynolds *et al.*, 1992; Perfit *et al.*, 1994; Mahoney *et al.*, 1994; Niu *et al.*, 1996; Niu *et al.*, in press). Many seamounts along the East Pacific Rise also show enriched incompatible element compositions (Batiza and Vanko, 1984; Zindler *et al.*, 1984; Niu *et al.*, 1996; Niu and Batiza, 1997). These enriched magmas are believed to be derived from small-scale heterogeneities, such as dykes or veins of enriched material in the more pervasively depleted upper mantle (Niu and Batiza, 1997).

There are several places where more fractionated lavas have been discovered on the seafloor. Some of these rocks contain low-Ca pyroxene, more than 12% total Fe as FeO and as much as 3.5% TiO_2 . They have been described from intermediate- to fast-spreading ridges in the eastern Pacific Ocean (Morel and Hekinian, 1980) and along slow-spreading ridges close to hot spots (Schilling *et al.*, 1983), and are termed ferrobasalts. In the Galapagos Rift, Perfit *et al.* (1983) have described even more evolved rocks containing high SiO_2 (up to 60%) and high total alkalis

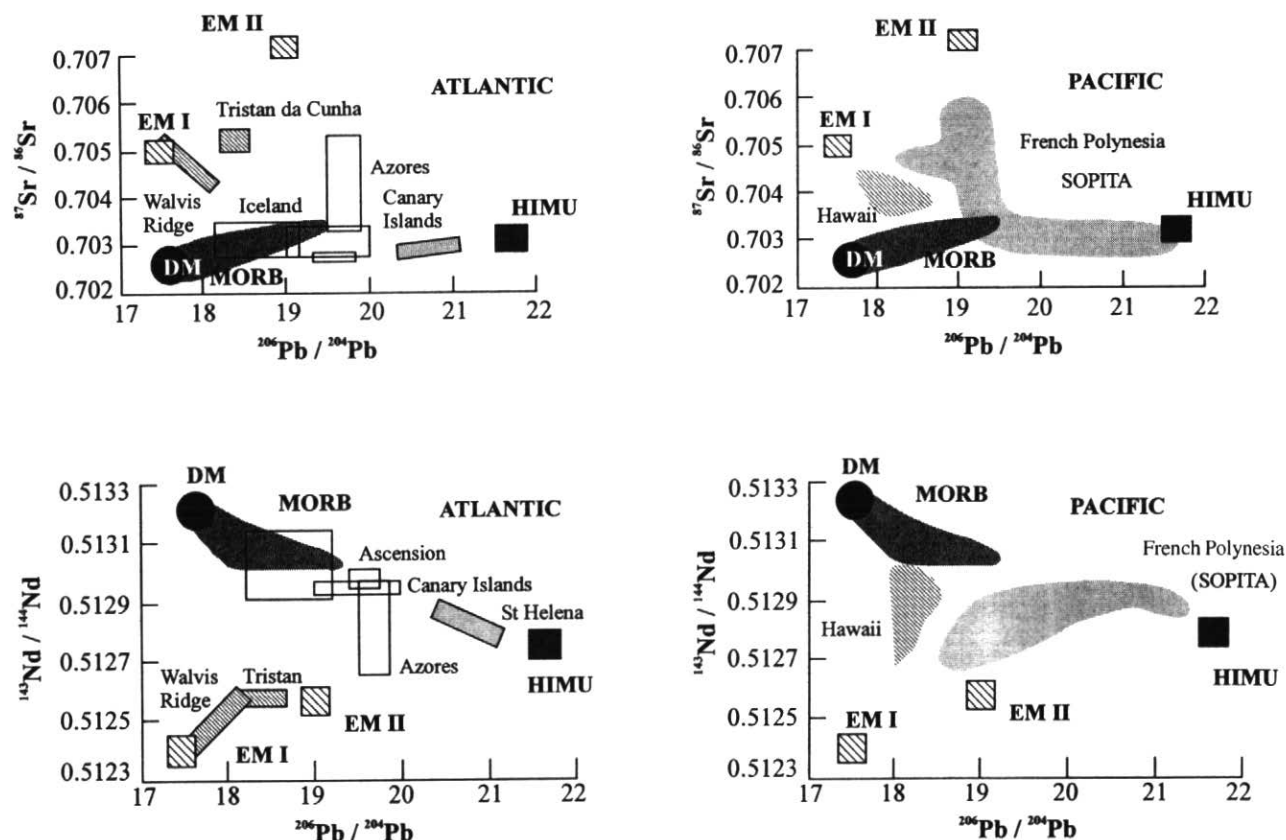


Figure 3 Sr-Pb (A) and Nd-Pb (B) isotopic characteristics of ocean basalts from the Atlantic and Pacific Ocean basins (after Wilson, 1993). DM, EM I, EM II and HIMU endmember compositions are from Hart *et al.* (1992).

(up to 4%). In these rocks, crystallisation of titanomagnetite leads to a decrease in FeO in the most fractionated examples. Similar rocks have been described elsewhere on the East Pacific Rise but are generally absent in the Atlantic Ocean.

Magmatic Segmentation of the Mid-Ocean Ridge System

The geochemical variations of lavas along ridge crests appear to correlate well with structural segmentation of the sea floor (*e.g.*, Melson and Thompson, 1971; Thompson *et al.*, 1985; Langmuir *et al.*, 1986; Langmuir and Bender, 1984; Batiza, 1996). Typically, ridge-crest lavas adjacent to major fracture zones are enriched in Fe and Ti as well as a number of incompatible trace elements (Zr, Sr, REE) relative to those farther from ridge-transform intersections. Designated the "transform fault effect" by Langmuir and Bender (1984), these differences may reflect lower degrees of partial melting near the transform fault which would also explain the presence of thinner crust at many ridge-transform intersections (*e.g.*, Chen, 1992). Langmuir and Bender (1984) also recognized "transform discontinuities" in which ridge crest lavas on opposite sides of major transforms have distinctly different compositions (*cf.* Schilling *et al.*, 1995; Niu and Batiza, 1991) (Fig. 4).

The close correlation between magmatic and tectonic segmentation on mid-ocean ridges reflects differences in the history and composition of the mantle beneath the ridges on a variety of scales (Batiza, 1996). On a global scale, there appears to be a first-order relationship between lava geochemistry, crustal thickness and axial depth of spreading ridges (Klein and Langmuir, 1987; 1989; Brodholt and Batiza, 1989). When the compositional effects of low-pressure fractionation are removed by normalizing the geochemical data to a fixed value of MgO, basalt compositions show a good correlation with axial depth. In shallow regions, MORB lavas have relatively high CaO, low Al₂O₃, low Na₂O, and high FeO whereas along deeper ridge segments the opposite trends are observed. Crustal thickness also correlates well with axial depth, being greatest near shallow midpoints of ridge segments. These variations are interpreted to reflect mantle temperature variations on a regional scale (Klein

and Langmuir, 1987; 1989; Niu and Batiza, 1991; 1993; Langmuir *et al.*, 1992)

Local variations in lava geochemistry and the degree of partial melting have also been related to such tectonic features as propagating rift tips (Christie and Sinton, 1981; 1986) and on-ridge seamounts (Batiza and Vanko, 1984). Other small-scale temporal and spatial variations have also been recognized on some ridge segments. For example, on the East Pacific Rise (EPR) at 12°N small variations in N-MORB occur normal to the ridge axis and both N-MORB and T-MORB lavas have been found within the axial graben (Reynolds *et al.*, 1992). Between 9°N and 10°N on the EPR both N-MORB and E-MORB lavas have been found in a 600 m area just off the ridge axis (Perfit *et al.*, 1994) and these variations have been taken as evidence of contemporaneous axial and off-axis eruptions from distinct melt sources (Fig. 5).

Primary MORB Magmas

An important observation is that the oldest seafloor lavas, of Jurassic age, are compositionally indistinguishable from those being erupted today along mid-ocean ridges. Thus, MORB lavas have been produced unchanged at least since the Middle Mesozoic, and geochemically similar lavas are known as far back as the Archean. Currently, about 15-20 km³ of lava are produced each year along the 54,000 km-long ridge system. Thus, the volume of MORB produced over geologic time has been enormous.

A fundamental question is, "are any of these lavas representative of primary melts from the mantle"? Because MORB lavas are modified by a variety of processes as they rise through the mantle, including crystal fractionation, magma mixing, melt-wall rock reaction and assimilation, it is unlikely that many eruptive compositions correspond to primary melts. It is generally assumed that only the most primitive (up to 10 wt% MgO) lavas approach primary compositions but even these, known as P-MORB, have likely undergone some modification while rising through the upper mantle. Based on their study of global ocean-ridge basalt chemistry, Klein and Langmuir (1987) suggested that primary MORB lavas should range in composition from about 10-15 wt% MgO and would be formed by roughly 8-20% melting of the depleted mantle

at mean pressures of 5-16 kbar. They further showed that primary magma compositions correlate with axial depths of the spreading ridges. Basalts occurring on shallow ridges are formed by larger degrees of partial melting at greater mean pressures of melt segregation than those formed on deeper ridge segments.

OCEAN ISLAND LAVAS

Ocean island lavas have a number of unique characteristics that distinguish them from MORB. Most of our knowledge of the volcanic and petrologic evolution of ocean island volcanoes is based on extensive studies of the islands of the Hawaiian group (Macdonald and Katsura, 1964; White, 1966; Macdonald, 1968; McDougall and Swanson, 1972; Moore *et al.*, 1982). In these islands the initial period of volcanism appears to consist of alkali basalts (*e.g.*, Loihi seamount), but these early lavas are totally enveloped by the second stage of growth which forms large shield volcanoes composed of tholeiitic basalt, which is more enriched than MORB. The basal parts of these shields are presumed to consist of pillow lavas, since they were clearly built under water, but the exposed portions consist chiefly of massive flows, a few metres to a few tens of metres thick.

The shield-building flows are commonly porphyritic with large and abundant phenocrysts of olivine and augite, sometimes accompanied by plagioclase. In the late shield-building stage the lavas become more olivine-rich and a collapse caldera may form in the summit area. Continuing eruption of lava fills and overflows the caldera and small parasitic cones may form on the flanks of the volcano. At this stage the magma composition changes and the late lavas become distinctly alkaline in character. These lavas include highly olivine- and augite-phyric picrites and ankaramites, which may pass upward into more differentiated alkalic lavas such as hawaiites and mugearites. The transition from tholeiitic to alkalic lavas may occur in the upper part of the shield (Macdonald and Katsura, 1964) or it may post-date caldera collapse.

Following a period of extensive erosion over a period of 1-2 million years, highly alkaline mafic lavas, such as nephelinites, mellilite basalts and basanites, may be erupted. This is the case on four of the Hawaiian islands where

this period of volcanism is referred to as the post-erosional stage. In addition, ocean island basalts generally undergo extensive differentiation, resulting in late-stage trachytes and phonolites.

This scenario is often considered to represent the typical evolution of an ocean island volcano. However, closer examination of the islands of the South

Pacific, which are generally much smaller than those of the Hawaiian archipelago, suggests that their evolution is somewhat different. Tholeiitic basalts are conspicuously absent on nearly all of the ocean islands of the South Pacific (the Marquesas are an exception) and the oldest exposed rocks are alkali basalts. In some cases (*e.g.*, Western

Samoa) the post-erosional stage lavas form the bulk of the exposed edifice.

Compared to MORB, ocean island tholeiites have lower SiO_2 , Al_2O_3 and CaO and distinctly higher TiO_2 and $\text{FeO}_{\text{total}}$ (Table 1). Among the trace elements, Rb, Sr, Ba, Nb, Zr, Pb, Th, U and the light REE are strongly enriched, as shown in Figure 1. The alkali-olivine

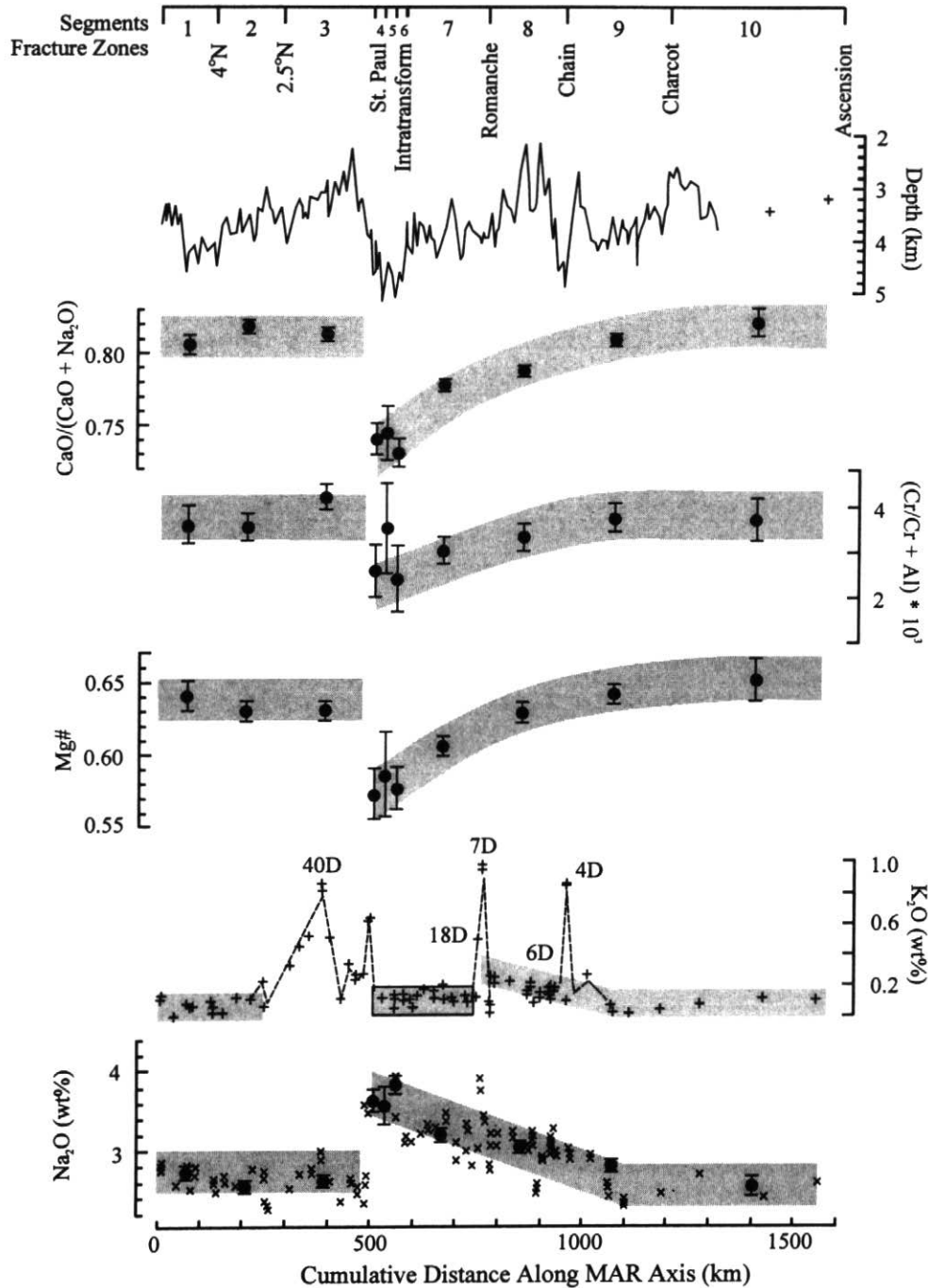


Figure 4 Variations in chemistry and depth along the equatorial Mid-Atlantic Ridge (from Schilling *et al.*, 1995). The bottom two panels show raw data and the middle three show segment averages. Note the major edge effect associated with the St. Paul transform and the long distance of its effect on the chemistry of axial lavas (modified from Batiza, 1996).

basalts have even lower SiO_2 and higher TiO_2 , $\text{FeO}_{\text{total}}$, Na_2O and K_2O than the ocean island tholeiites and are markedly enriched in all incompatible trace elements. These compositional differences are accompanied by marked differences in Sr, Nd, and Pb isotopic compositions (Fig. 3). Compared to MORB, ocean island lavas have much more variable isotopic compositions but typically they are relatively enriched in ^{87}Sr and ^{206}Pb and depleted in ^{144}Nd .

Oceanic plateaus, such as the Kerguelen, Ontong-Java and Manihiki, are broad, relatively flat-topped features on the sea floor. Drilling of these features has shown that beneath a carapace of sediment they are built of lava flows whose composition is similar to that of ocean island basalts. All of these features are roughly equivalent in age, ranging from about 124 Ma to 115 Ma (Early Cretaceous). Because they represent vast outpourings of lava on the sea floor, Larson (1991a; 1991b) has suggested that they formed from one or more "superplumes" rising from the core-mantle boundary. He suggested that this superplume activity disrupted the normal mantle convection system and led to vastly increased spreading rates and ocean crustal production rates. These plateaus are thought to be the oceanic equivalents of continental flood basalts, some of which formed at roughly the same time.

Mantle Sources of Ocean Island Lavas

Following the acquisition of a plethora of geochemical data from oceanic islands, the model of a simple two-layered mantle is no longer tenable. Ratios of incompatible trace elements and isotope abundances of ocean island basalts indicate that the mantle from which they are derived is heterogeneous on a variety of scales. It is now generally accepted that mantle convection and crustal recycling are the primary mechanisms by which these compositional heterogeneities are generated (Allègre, 1984; Hofmann *et al.*, 1986; Zindler and Hart, 1986; Saunders *et al.*, 1988; Hart and Zindler, 1989; Sun and McDonough, 1989; Weaver, 1991; Wilson, 1993; McKenzie and O'Nions, 1995; Hofmann, 1997). The detailed patterns of mantle convection are still controversial, but whole-mantle, single-layer circulation is widely accepted (Hofmann, 1997). This model, however, is difficult to reconcile with evidence that many isotopic anomalies in the mantle have persisted for millions of years.

At shallow mantle levels, convection must involve the recycling of crustal material. As oceanic crust is subducted into the mantle, basalts and gabbros are converted to eclogites, which have higher densities than the surrounding peridotites, causing them to sink. The depth to which the crustal material sinks

is debatable (Fig. 6) but it appears that the lithospheric plates play a crucial role in organizing mantle convection and that plate-scale flow penetrates the full depth of the mantle (Davies and Richards, 1992). Mantle plumes are thought to reflect convective upwelling of deep material into the shallow melting zone.

Four end-member mantle sources have been proposed to explain the isotopic diversity of ocean island basalts (Zindler and Hart, 1986; Hart, 1988; Hart *et al.*, 1992). These are termed DM (depleted MORB mantle), HIMU (high $^{238}\text{U}/^{204}\text{Pb}$), EM-I and EM-II (enriched mantle 1 and 2) and are combined in various proportions to provide the mantle source material for a variety of primary melts (Fig. 3). For example, in the Atlantic Ocean such island volcanoes as St. Helena, the Azores, Canary Islands, Ascension and Iceland lie along a relatively linear mixing line between DM and HIMU sources (Fig. 3). However, such linear arrays are not always simple binary mixtures of end-member components but also reflect the fractionation history of the parent/daughter element ratios (Hart *et al.*, 1992). Possible sources of the enriched mantle material include recycled oceanic crust, hydrothermal or abyssal sediments, and subcontinental lithosphere (Hofmann, 1997). Continental sediments and hydrothermally altered sea floor basalts are thought to contribute only small amounts to the recycled material, although the crustal contribution is difficult to measure directly. The MORB source itself must be heterogeneous at a certain scale, containing zones of recycled material and local anomalies caused by plume injection. Thus, it is not surprising that the Indian Ocean MORB source differs from those of the Atlantic and Pacific, apparently containing a greater component of subcontinental lithosphere and/or old continent-derived abyssal sediments.

A variety of very large-scale isotopic anomalies is recognized in the ocean basins. Dupré and Allègre (1983) noted that ocean island basalts from a large area of the Indian Ocean have anomalous isotopic mantle source signatures equivalent to EM-II. Hart (1984) traced this isotopic anomaly throughout the Southern Hemisphere using its characteristic high $^{87}\text{Sr}/^{86}\text{Sr}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios, and he named it the Dupal anomaly. He postulated that the

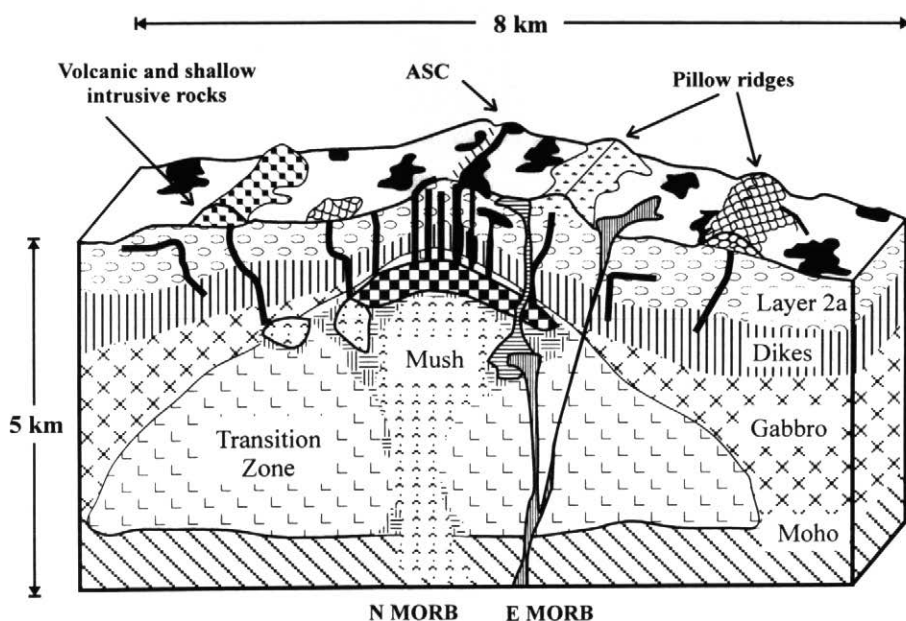


Figure 5 Petrogenetic model for the East Pacific Rise in the 9-10° N area, showing one possible relationship between axial N-MORB and off-axis E-MORB lavas (from Perfit *et al.*, 1994).

anomaly was world encircling and centred between 30° and 40° south latitude. However, Castillo (1988) suggested that the anomaly was focussed at two localities, one in the Indian Ocean and one in the Pacific, corresponding to regions where the mantle has low seismic velocities, perhaps due to plume upwelling. Another region in the southern Pacific termed the South Pacific Isotopic and Thermal Anomaly (SOPITA of Staudigel *et al.*, 1991), is characterized by extreme diversity of isotopic compositions among its islands and seamounts (Fig. 3), which apart from Pitcairn and Rarotonga, lie on a mixing line between HIMU and EM-II. These very extensive anomalies have been related to large-scale plume upwelling, although the details await refinement of Earth's interior by seismic imaging techniques.

Both Pitcairn and Rarotonga have an EM-I component in their mantle source, making them very different from other islands in their respective chains. Indeed, not only may islands within a single group or chain tap different mantle sources, but mantle source heterogeneity has been observed within a single island (Dupré *et al.*, 1982; Barling and Goldstein, 1990). How these different mantle source regions are related is still debatable.

CONCLUSIONS

The most voluminous lavas on Earth are mid-ocean ridge basalts. Normal or N-MORB lavas are olivine- and hypersthene-normative basalts characterized by relative depletion in incompatible elements, particularly Rb, Sr, Ba, K, Zr, Y and the light rare earth elements. Enriched varieties (E-MORB) contain higher abundances of incompatible elements and are transitional to ocean island basalts. MORB lavas are derived by decompressional melting of previously-depleted mantle material at relatively shallow levels beneath oceanic spreading axes. Mixing of depleted mantle material and recycled crustal material gives rise to enriched and transitional MORB compositions.

Ocean island basalts are much less voluminous than MORB and form intraplate volcanoes built upon the seafloor. These lavas include both tholeiitic and alkalic varieties, both of which are strongly enriched in incompatible elements and the light rare earth elements. Ocean island lavas typically evolve from tholeiitic to alkalic within individual vol-

canoes and undergo extensive fractionation to form highly evolved derivative melts. They are believed to form by partial melting of deep mantle plumes, which entrain recycled crustal materials. Superplumes of Early Cretaceous age are believed to have generated the voluminous ocean island lavas, which make up oceanic plateaus.

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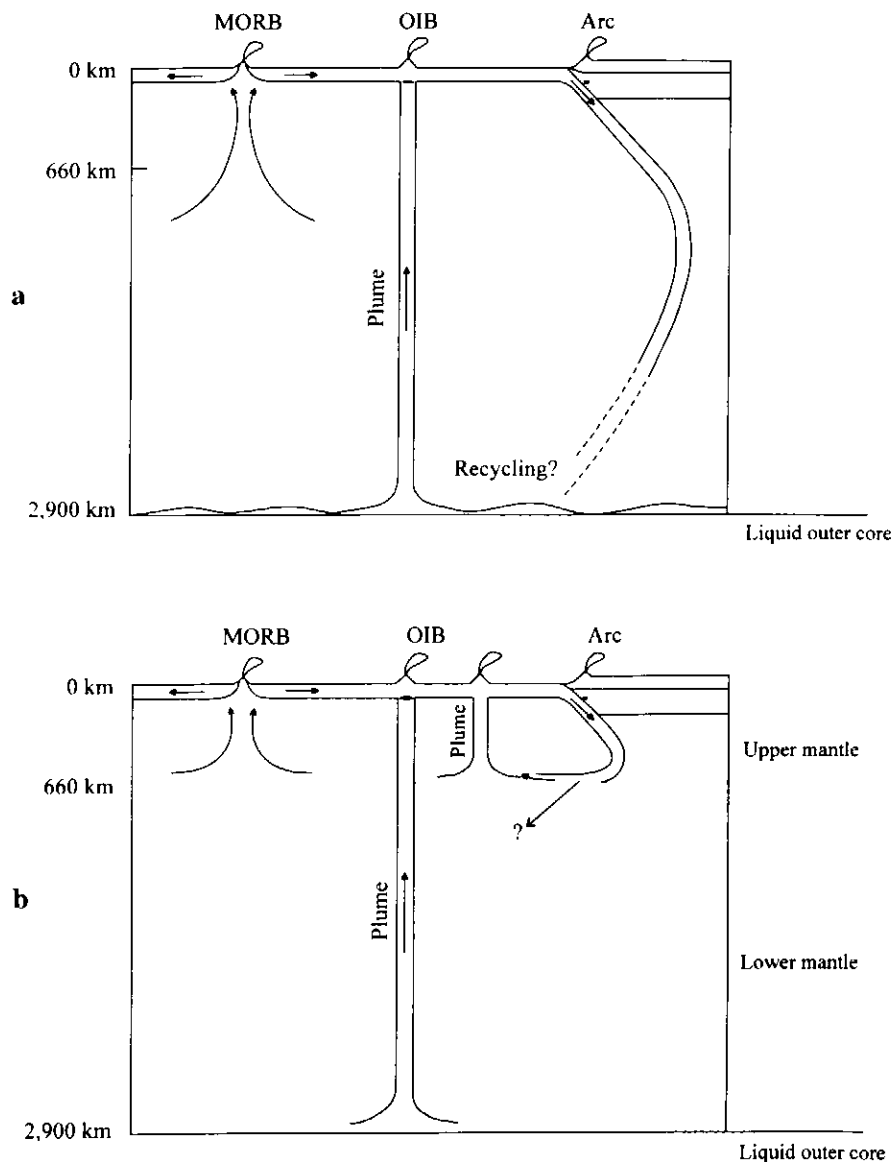


Figure 6 Models of mantle circulation (after, Hofmann, 1997) (a) Whole-mantle, single-layer circulation with plumes rising from the core-mantle boundary. Plume sources are created by subduction of ocean lithosphere (b) Two-layer, circulation model with small plumes rising from the 660 km depth and strong plumes from the core-mantle boundary. In this model there is only limited contribution of subducted lithosphere to the deep mantle sources.

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