

Origin of ocean island basalts: A new model based on lead and helium isotope systematics

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Abstract. Current models of ocean island basalt (OIB) Pb isotope systematics based on long-term isolation of recycled oceanic crust (with or without sediment) are not supported by solutions to both terrestrial Pb paradoxes. It follows that the linear arrays of OIB data in Pb isotope diagrams are mixing lines and have no age significance. A new model is presented that takes into account current solutions to both terrestrial Pb paradoxes and that explains combined Pb and He isotope evidence in terms of binary mixing. The key feature of this model is a two-stage evolution: first, long-term separation of depleted mantle from undepleted lowermost lower mantle. Mixing between these two reservoirs results in the wide spread in $^{207}\text{Pb}/^{204}\text{Pb}$ ratios and generally high (but variable) $^3\text{He}/^4\text{He}$ ratios that typify enriched mantle 1 (EM1) OIBs. The second stage involves metasomatism of depleted upper mantle by EM1 type, lowermost mantle-derived melts. Evolution in the metasomatized environment is characterized by variable but generally high $(\text{Th}+\text{U})/(\text{Pb}+\text{He})$ ratio that leads to a rapid increase in $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios and decrease in $^3\text{He}/^4\text{He}$. Mixing between depleted mantle and melts from metasomatized mantle portions reproduces the characteristics of high μ (HIMU) OIBs. The Sr versus Nd isotope array is compatible with binary mixing between depleted mantle and near-chondritic lowermost mantle because of the large variation in Sr/Nd ratios observed in EM1 and HIMU OIBs. OIBs contaminated by subcontinental lithospheric mantle (EM2) exhibit more complex isotope systematics that mask their primary geochemical evolution.

1. Introduction

The vast majority of ocean island basalts (OIB) are not only enriched in incompatible trace elements but also carry isotopic signatures interpreted to reflect evolution in enriched mantle (variable but high $(\text{U}+\text{Th})/\text{Pb}$, high Rb/Sr , low Sm/Nd , and low Lu/Hf). A plethora of models have been proposed to explain these features, but no consensus has been reached in spite of more than three decades of geochemical research into OIBs. Among the debated issues two questions stand out: first, can the isotopic signatures of OIBs be interpreted to reflect the existence of chemically distinct domains in the mantle that escaped convective homogenization; and second, if such domains exist, where in the mantle are they located, what is their origin, and how have they withstood homogenization?

One popular view is based on the work by Zindler and Hart [1986], who proposed that chemically distinct domains do exist in the mantle and that over time such domains would evolve characteristic isotopic signatures. Apart from the mid-ocean ridge basalt (MORB)-source-depleted mantle, the following mantle reservoirs have been suggested to contribute to OIB magmatism: (1) recycled oceanic lithosphere, both ancient (up to circa 2 Ga) and young; (2) recycled sediment; (3) subcontinental lithospheric mantle (SCLM); and (4) an enigmatic “plume component” probably derived from the lower mantle.

There is now strong isotopic and trace element geochemical evidence that SCLM is a component in some OIBs. It is

important to note that SCLM can remain isolated from the convective asthenosphere for billions of years and hence evolve to isotopic signatures that deviate strongly from those of the depleted mantle. SCLM can extend past the present-day shoreline of continents, and OIBs that erupt in their proximity may be contaminated. Furthermore, subcontinental lithospheric mantle can be entrained into the convecting oceanic asthenosphere upon continental breakup. The geodynamic significance of a SCLM OIB source component is therefore very different from that of recycled components.

The claim for the existence of (subducted) recycled components that have remained convectively isolated over billions of years is problematic if these domains are envisaged to reside in the depleted mantle. One very strong argument against the persistence of such domains is the second terrestrial Pb paradox. It is now firmly established that the secular decrease in Th/U ratio of the depleted mantle reflects increased recycling of continent-derived U (and Pb) back into the mantle after establishment of a pandemic oxidizing hydrosphere and atmosphere at circa 2.2 Ga [e.g. Kramers and Tolstikhin, 1997; Collerson and Kamber, 1999; Elliott et al., 1999]. On the basis of the homogeneity of the Pb isotope-inferred Th/U ratio and the observed Nb/Th and Nb/U ratios in MORB it has to be concluded that recycled components are well mixed into the MORB source mantle and that substantial chemical and isotopic heterogeneity in the depleted mantle is relatively short-lived [Collerson and Kamber, 1999]. The range in $^{207}\text{Pb}/^{204}\text{Pb}$ ratios of OIBs (excluding those with a SCLM component) requires, however, that sources remained isolated for billions of years. The consensus that has been reached on the significance of the second terrestrial Pb paradox therefore necessitates a reevaluation of OIB Pb isotope systematics.

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An independent test of OIB Pb isotope models is possible by combined consideration of Pb and He isotope systematics since these are coupled through their parent isotopes. At present, the He isotope characteristics of those OIBs with radiogenic Pb can only be explained by open system behavior [Hanyu and Kaneoka, 1998].

In this paper we present a review of OIB Pb and He isotope systematics and show that they require a two-stage evolution. First, long-term separation of primitive undegassed lowermost mantle from depleted mantle leads to a significant difference in the $^{207}\text{Pb}/^{204}\text{Pb}$ ratio. Second, short-term modification of Pb and He isotope systematics in localized, metasomatized portions of the upper mantle, characterized by variable but high $(\text{Th}+\text{U})/(\text{Pb}+\text{He})$ ratio that leads to an increase in $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios and a decrease in $^3\text{He}/^4\text{He}$

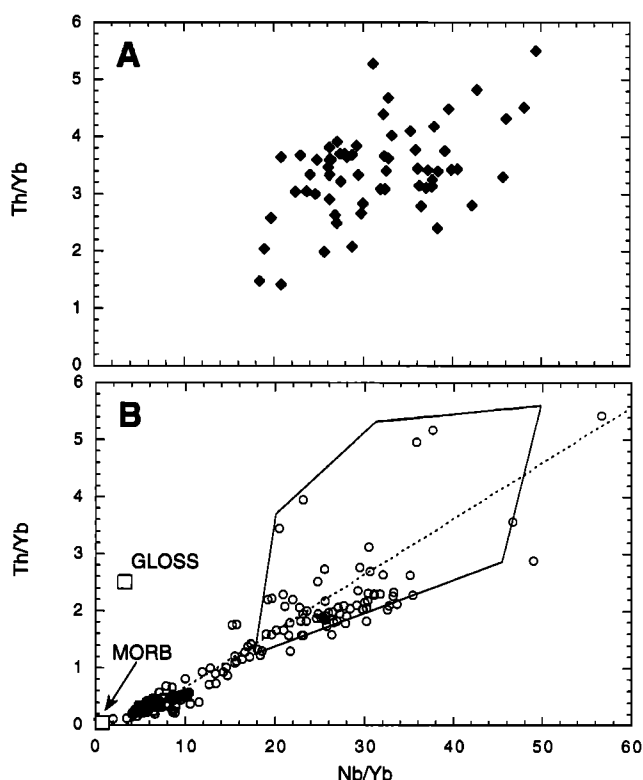


Figure 1. Th/Yb versus Nb/Yb plot for global ocean island basalt (OIB) dataset. All samples have MgO > 6 wt % to minimize effects of fractional crystallization. (a) OIBs with subcontinental lithospheric mantle (SCLM) contamination (solid diamonds) are Canaries [Elliott, 1991], Comores [Späth et al., 1996], Heard [Barling et al., 1994], and Inaccessible [Cliff et al., 1991]. On average, these clearly plot at high Th/Yb values for a given Nb/Yb ratio, irrespective of the degree of melting. (b) Data sources for OIBs without SCLM contamination (open circles) are given in caption to Figure 2. Plot includes additional data for Easter Island [Haase et al., 1997], Hawaii [Fodor et al., 1992], Réunion [Fisk et al., 1988; Albarède et al., 1997], Tristan da Cunha [Weaver et al., 1987], and Walvis Ridge [Humphris and Thompson, 1983]. Only four out of 257 samples used in the Pb isotope database plot clearly above the regression line (dotted line). SCLM contamination or a subducted sediment component can therefore be excluded. Average of global subducted sediment (GLOSS [Plank and Langmuir, 1998]) and field defined by SCLM-contaminated OIBs are plotted for comparative purposes.

ratio. It is concluded that OIBs are a mixture of only two long-lived components, one being the undegassed deepest portion of the lower mantle and the other being the depleted MORB source mantle. We discuss implications of this model for chemical evolution of the mantle and convection dynamics.

2. Selection of OIB Database

Like continental crust, its underlying SCLM root remains isolated from the asthenosphere for substantial periods of time and plays a key role in stabilizing and preserving continental crust. Even though SCLM may be entrained into the asthenosphere by delamination, this process has no bearing on the Pb isotope composition of the oceanic mantle [Kramers and Tolstikhin, 1997]. The effect of SCLM on OIB isotope and trace element geochemistry is contamination during magma ascent. SCLM is thus not a source component in the stricter sense, and we have excluded from the global OIB database all SCLM-contaminated ocean islands. Using the interpretation of isotopic and trace element data by original authors we have omitted data from the following ocean islands: Canaries [Elliott, 1991; Hoernle and Schmincke, 1993]; Comores [Späth et al., 1996]; Heard [Barling et al., 1994]; and Inaccessible [Cliff et al., 1991].

The distinction between subducted sediment component and SCLM is difficult. Figure 1a shows that the omitted OIBs define a field at high Th/Yb ratios for a given Nb/Yb ratio which extends over almost the entire range of enrichment indicated by the Nb/Yb ratio. This could either reflect contamination with sediment or SCLM. According to Hilton et al. [1995] the Heard Island OIBs were contaminated with ^4He at shallow levels due to interaction with buoyant SCLM. They argued that other ocean islands, whose sources were previously considered to carry the signature of subducted sediment, may only have been contaminated at very shallow levels by SCLM. These conclusions have recently been supported by Os isotope data from Kerguelen [Hassler and Shimizu, 1998] and the Canaries [Widom et al., 1999]. In fact, many ocean islands (Comores, Cape Verde, and Canary Islands) that occur close to the African continent have geochemical characteristics which can be interpreted to reflect involvement of SCLM [Späth et al., 1996]. As neither Africa nor Antarctica are surrounded by subduction zones which could inject sediment into the mantle, the SCLM signature is likely to be due to contamination by remnants of sub-Gondwana lithosphere. For these reasons we exclude the above mentioned data from our investigation.

3. Pb Isotope Characteristics of OIBs

Pb isotope systematics of OIBs show two prominent features in common Pb space (Figure 2a). First, all OIBs plot to the right of the meteoritic isochron. Second, OIBs define a linear array that is emphasized by data from individual archipelagos.

In an important contribution, Chase [1981] concluded that linear OIB Pb isotope arrays of individual oceanic islands were secondary isochrons that date timing of melt extraction from a common source. The increase in U/Pb and Th/Pb during melting resulted in OIB Pb plotting to the right of the Geochron. Chase [1981] interpreted the common source of OIBs to be oceanic crust from ancient depleted mantle, defined by a single-stage Pb isotope evolution with a $^{238}\text{U}/^{204}\text{Pb}$ ratio (μ) of 7.91 ± 0.04 . Figure 2a illustrates that a linear regression

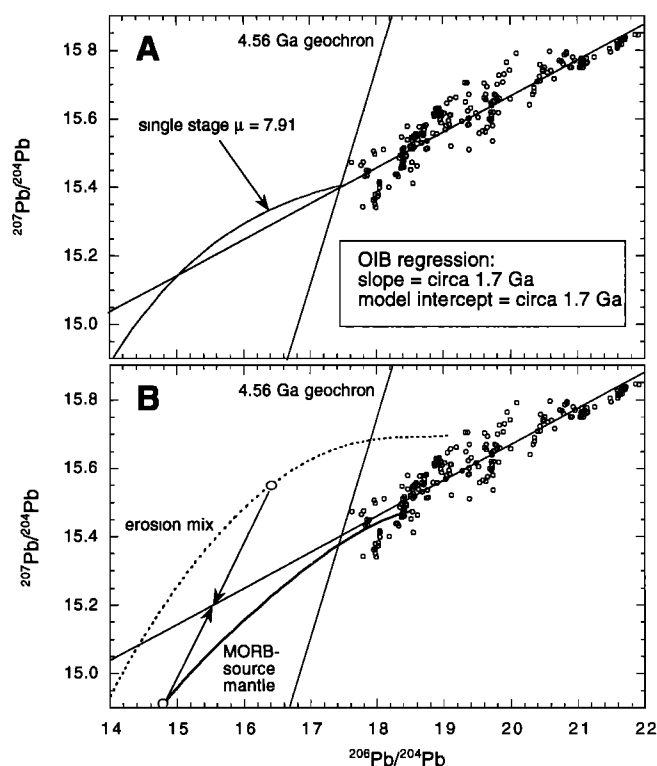


Figure 2. The $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ isotope compositions of ocean island basalts from Azores [Turner *et al.*, 1997; Widom *et al.*, 1997], Balleny [K.D. Collerson *et al.*, manuscript in preparation, 1999], Cameroon [Lee *et al.*, 1994], Cook-Austral [Palacz and Saunders, 1986; Chauvel *et al.*, 1992, 1997; Hémond *et al.*, 1994; Woodhead, 1996; Kogiso *et al.*, 1997], Galapagos [White *et al.*, 1993; Reynolds and Geist, 1995], Hawaii [West *et al.*, 1992; Frey *et al.*, 1994; Chen *et al.*, 1996; Garcia *et al.*, 1996], Iceland [Elliott, 1991; Hards *et al.*, 1995], Pitcairn [Woodhead and McCulloch, 1989; Woodhead and Devey, 1993], St. Helena [Chaffey *et al.*, 1989], and Tristan da Cunha [le Roex *et al.*, 1990]. All samples have MgO > 6 wt % (to avoid effects of fractionation; see Figure 1) and are from combined trace element and isotope data sets. (a) Comparison of data with the single stage ($\mu = 7.91$) depleted mantle Pb isotope evolution model by Chase [1981]. The combined regression line and the model curve intercept give identical dates of 1.7 Ga. (b) Comparison of data with depleted mantle evolution curve (solid line) and “erosion mix” curve (dotted line) by Kramers and Tolstikhin [1997]. No intercept is obtained with the depleted mantle curve. Large open circles show the compositions of depleted mantle and “erosion mix” at 1.7 Ga. The intersection with the tie line (arrows) shows that ~45% of the Pb would have to be derived from a subducted sedimentary source.

of the entire OIB Pb isotope database defines a secondary isochron with a slope equivalent to an age of circa 1.7 Ga. This is identical to the single stage μ (7.91) MORB source mantle intercept.

Two aspects of Chase's [1981] model have become paradigms to explain the geochemistry of oceanic basalts: (1) the view that linear arrays of OIB Pb isotopes have age significance (i.e., dating the time of melt separation) and (2) that the ultimate source for incompatible trace element enriched OIBs with radiogenic Pb (so-called HIMU = high μ)

magmas are derived from ancient, recycled oceanic crust [e.g., Hofmann, 1997]. However, this interpretation depends a priori on the assumption that the Pb isotope evolution of the MORB source mantle can be modeled with a single-stage μ .

4. Pb Isotope Evolution of the MORB Source Upper Mantle

Models of the Pb isotope evolution of Earth's geochemical reservoirs must explain both terrestrial Pb paradoxes: (1) the fact that modern MORB samples plot to the right of the meteoritic isochron, and (2) the discrepancy that exists between the modern MORB source mantle Th/U ratio of 2.6 compared to a time-integrated ratio of ~3.8 from the Pb isotope compositions (see Kramers and Tolstikhin [1997] for a detailed review). The MORB source mantle Pb evolution scenario of Chase [1981] clearly offers no explanation for either of these paradoxes. All but the most simplistic Pb isotope evolutionary models predict that the U/Th/Pb ratios of the MORB source mantle must have changed through geological history. Some models, which try to solve the first terrestrial Pb paradox, proposed that the MORB source mantle μ increased with time due to Pb depletion [e.g., Cumming and Richards, 1975; Chauvel *et al.*, 1995]. However, these models fail to explain the second terrestrial Pb paradox. Chauvel *et al.* [1995] developed a model to explain the present-day Pb isotope composition of MORB but did not solve its temporal evolution. Their model can thus not be used to test the validity of Chase's [1981] assumptions. Models which solve both paradoxes have in common that MORB source mantle μ decreased from ~8.5 after accretion to ~6 in late Archaean times and increased again to ~11 at the present day [e.g., Zartman and Haines, 1988; Kramers and Tolstikhin, 1997; Collerson and Kamber, 1999]. The postcore formation temporal topology of MORB source mantle μ is influenced mainly by the amount of continental crust present at any given time, the amount of continental recycling, and the timing of establishment of a pandemic oxidizing atmosphere (in which U becomes mobile during weathering). The crust volume versus time curve predicted by Pb isotopic constraints by Kramers and Tolstikhin [1997] has recently been confirmed by an independent estimate based on the temporal changes in Th/U/Nb systematics of the MORB source mantle [Collerson and Kamber, 1999]. This model is also in excellent agreement with the observed Nd isotope evolution of depleted mantle-derived rocks [Nägler and Kramers, 1998] and geophysical constraints on crustal growth versus destruction [Reymer and Schubert, 1984].

To evaluate whether modern OIB basalts could have been generated from ancient subducted oceanic crust, their Pb isotope ratios must be compared to an appropriate Pb evolution curve for the MORB source mantle (e.g., that proposed by Kramers and Tolstikhin [1997]). Figure 2b compares the OIB Pb isotope regression to the MORB source mantle evolution line of Kramers and Tolstikhin [1997]. This evolution line differs significantly from a single-stage curve (Figure 2a) between circa 3 and 1.5 Ga because the depleted mantle evolved with a strongly reduced μ during that time period. The most important observation in Figure 2b is that the OIB regression line fails to intersect a realistic MORB source mantle evolution curve. Furthermore, regressions through individual OIB data sets either do not intersect the mantle curve or intersect it at locii that correspond to much

younger model ages than those derived from the slope of the regression. These relationships thus demonstrate that OIBs are not derived by melting of ancient subducted oceanic crust.

This finding is in apparent conflict with interpretation of Nb/U, Ta/Th, and Ce/Pb ratios of basalts. The similarity of the average of these ratios in present-day MORB and OIB has been used to suggest that most OIBs are derived by melting of ancient subducted oceanic crust [Hofmann, 1997]. However, the reason that these ratios (and Ce/Pb) are nonchondritic reflects extraction (and recycling) of continental crust. The similarity of these ratios between present-day MORB and OIBs would therefore suggest that OIBs are derived from young oceanic crust. Ancient (1-2 Ga) oceanic crust has ratios very different from present-day MORB [Collerson and Kamber, 1999]. The fact that averages of these ratios are identical within error must require a different explanation. One important observation is that there is considerably more variation in these ratios in the OIB database than in MORB. Campbell [1998] has suggested that the linear array defined by OIB data in a Nb/U versus Nb/Th diagram is explained by mixing melts derived from chondritic and depleted sources. The similarity of the averages with present-day MORB may therefore be fortuitous. Furthermore, Nb/U, Ta/Th, and Ce/Pb ratios in OIBs are too scattered to warrant using their average values to infer a unique source chemistry.

5. Role of Continental Sediment in OIB Sources

The only scenario in which the OIB Pb isotope regression could have circa 1.7 Ga age significance would have to involve melting of a source which represents a mixture of 1.7 Ga oceanic crust and a component that had evolved with a substantially higher μ . In the framework of current OIB models, the only plausible high- μ component is sediment derived from continental crust. Figure 2b illustrates that ~45% of the original Pb would have to be derived from sediment (approximated by the "erosion mix" in the model of Kramers and Tolstikhin [1997]). The flux of sediment would depend on how much Pb from the original sediment eventually reached the mantle (i.e., was not lost by metasomatic transfer during dehydration in the subducting slab [cf. Chauvel *et al.*, 1995]).

There is, however, strong trace element evidence that continental contamination of the source of OIBs is not permissible [e.g., Hofmann, 1997]. This is illustrated (Figure 1b) on a plot of the Nb/Yb ratio versus the Th/Yb ratio [Ewart *et al.*, 1998]. With the exception of four analyses (out of 257), all non-SCLM-contaminated OIBs have relatively low Th/Yb ratios at a given Nb/Yb ratio. This indicates insignificant contribution of continent-derived material (for comparison, see the locus of global subducting sediment (GLOSS) [Plank and Langmuir, 1998]) in the OIBs selected for the database. Combined Pb isotope and trace element data thus show that the slopes of the OIB Pb isotope arrays have no age significance.

6. A New Model for OIB Pb Isotope Systematics

The linear Pb isotope arrays displayed by individual OIBs must therefore reflect binary mixing. This conclusion is strongly supported by the recent discovery of direct evidence for binary mixing in HIMU islands [Saal *et al.*, 1998]. Saal *et al.* [1998] found that the range of Pb isotope compositions recorded by individual melt inclusions in isotopically homogenous lavas spans 50% of that of the worldwide OIB data. A very strong linear correlation exists between

$^{208}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios of these melt inclusions which Saal *et al.* [1998] interpreted to reflect binary mixing. At first glance, such mixing models would have to involve a number of end-members (because the slopes of individual OIB archipelagos can vary substantially [cf. Chase, 1981]).

However, in the following, we show that it is not necessary to postulate a number of end-members and that the entire variation in Pb isotope compositions can be explained by mixing between only two long-lived end-member reservoirs with substantially different $^{207}\text{Pb}/^{204}\text{Pb}$ ratios. The wide variation in the $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ (but not in $^{207}\text{Pb}/^{204}\text{Pb}$) ratios can be created by short-term isolation of high (Th + U)/Pb reservoirs [e.g., McKenzie and O'Nions, 1998].

The two long-lived end-members in our model are MORB (i.e., depleted mantle) and a source associated with DupAl. The composition of the MORB end-member is similar to that defined by Kramers and Tolstikhin [1997], although it is important to note that it differs between individual ocean basins. The composition of the DupAl source is more difficult to constrain. The DupAl anomaly has been defined as an array of Pb isotope compositions that have high $^{207}\text{Pb}/^{204}\text{Pb}$ for a given $^{206}\text{Pb}/^{204}\text{Pb}$ ratio [after Dupré and Allègre, 1983]. It is typical of Indian MORB and Southern Hemisphere OIBs [Castillo, 1988]. In our model, however, we postulate a putative end-member source for the DupAl anomaly which we call DupAl source that represents a single Pb isotope composition rather than an array of compositions. The Pb isotope composition of the DupAl source is approximated by the composition of the Discovery Tablemount OIB which exhibits the strongest DupAl anomaly at the lowest $^{206}\text{Pb}/^{204}\text{Pb}$ [Sun, 1980]. It is, however, important to keep in mind that the Discovery Tablemount itself may also have a MORB contribution and the true DupAl source may have an even higher $^{207}\text{Pb}/^{206}\text{Pb}$ ratio. Nevertheless, the main feature of our model is that both end-members have a similar $^{206}\text{Pb}/^{204}\text{Pb}$ ratio, but the DupAl source has a significantly elevated $^{207}\text{Pb}/^{206}\text{Pb}$ ratio (Figure 3). Mixing between these two sources alone can therefore explain almost the entire range of $^{207}\text{Pb}/^{204}\text{Pb}$ ratios of global OIBs. The tie line between present-day MORB and DupAl defines the unradiogenic limit of the global OIB data array shown in Figure 2a.

In contrast to the variation in $^{207}\text{Pb}/^{204}\text{Pb}$, the entire spectrum of compositions of OIBs toward more radiogenic $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios could have evolved over geologically short timescales (e.g., 100-200 Myr) in an environment with elevated U/Pb and Th/Pb. On this basis we propose a two-stage evolution for OIB Pb isotope systematics.

In this model, portions of the depleted mantle or oceanic lithospheric mantle (that later become OIB sources) are metasomatized by a melt or fluid with DupAl Pb isotope composition (we use the term metasomatism in its widest possible sense, describing a process in which depleted upper mantle is refertilized in highly incompatible elements by addition of melts or fluids derived from the DupAl source). In addition to inheriting the DupAl source Pb isotope composition we also propose that the metasomatized depleted mantle becomes variably enriched in U and Th relative to Pb. Over the time that elapses between metasomatism and melting of OIB parental magma the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios will increase strongly as a function of the μ and Th/U ratio of the metasomatized depleted mantle. The $^{207}\text{Pb}/^{204}\text{Pb}$ ratio, however, will only increase slightly. The uncertainty in the composition of the true DupAl source Pb isotope composition

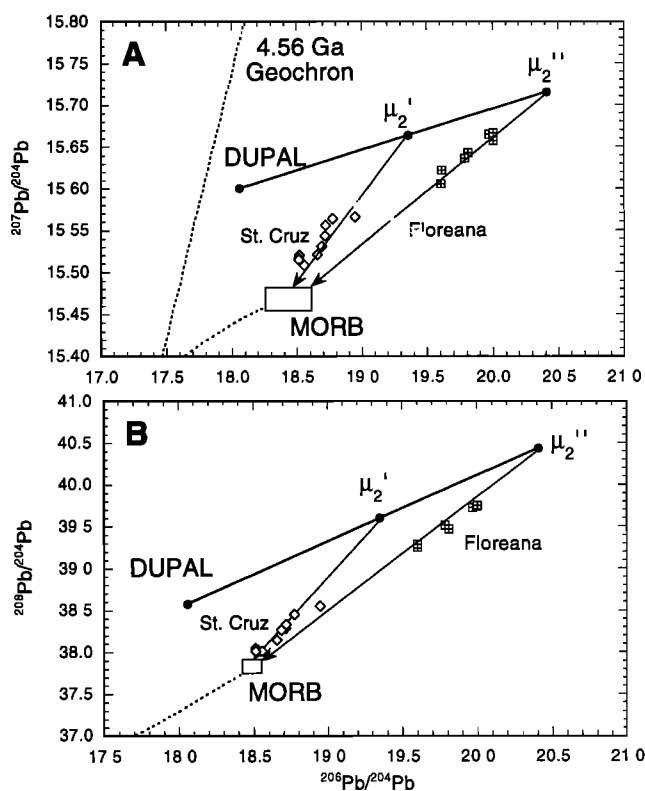


Figure 3. Two-stage Pb evolution mixing model shows that the entire OIB Pb isotope array ($^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ on Figure 3a, $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ on Figure 3b) can be generated by mantle metasomatism 150 Myr prior to melt generation. The metasomatizing melt (labeled DupAl source) has a composition with a higher time-integrated μ than mid-ocean ridge basalt (MORB) and is approximated by the Discovery Tablemount ocean island basalt back-calculated to 150 Ma (using $\mu = 8.7$ and $\text{Th}/\text{U} = 2.7$). The vector connecting the DupAl source with μ_2' ($= 55$) and μ_2'' ($= 100$) is (a) an isochron of 150 Ma (b) calculated with a Th/U ratio of 2.5. Mixing between a 150 Ma metasomatized mantle with variable μ_2 (lines connecting DupAl source to μ_2) and present-day MORB can generate the entire triangle defined by the global ocean island basalts, shown in Figure 2. For reasons of clarity, only data from two Galapagos islands (Santa Cruz and Floreana [White *et al.*, 1993]) are shown for comparison. Mixing lines between μ_2' and μ_2'' with MORB successfully predict the arrays displayed by Santa Cruz (open diamonds) and Floreana (cross-hatched squares), respectively. The slopes of these mixing lines correspond to apparent reservoir ages of circa 2.0 and circa 2.3 Ga, respectively.

precludes dating of the time of evolution in the metasomatized environment. In our model this metasomatic stage lasts 150 Myr which is similar to the age of the oceanic lithosphere underlying many ocean islands. We derive the Pb isotope composition of the metasomatizing DupAl melt by back-correcting the Discovery Tablemount OIB Pb to 150 Ma, using $\mu = 8$ and $\text{Th}/\text{U} = 2.7$. The following calculations are not sensitive to the exact choice of these parameters. Figure 3a shows the compositions of such metasomatized parts of the mantle after 150 Myr using μ of 50 and 100.

Melting of mixtures involving normal MORB source mantle and metasomatized mantle yields linear arrays in Pb isotope diagrams with slopes corresponding to apparent ages in the order of 1 to 2 Gyr (Figure 3a). A similar result is obtained in

$^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ space (Figure 3b), but the slope defined by the metasomatized source is sensitive to the choice of the Th/U ratio.

This model can be tested by comparison with Pb isotope compositions of OIBs. For example, using Pb isotope data from two of the Galapagos islands (Floreana and St. Cruz; data from White *et al.* [1993]) which define distinctive and different linear arrays (Figures 3a and 3b) in common Pb space. The slope of the St. Cruz data in the uranogenic diagram (Figure 3a) corresponds to an apparent age of circa 2.3 Ga, whereas Floreana data yield a slope equivalent to an apparent age of circa 2.0 Ga. These regression lines intersect present-day MORB (Figure 3a) and the 150 Ma metasomatized-DupAl isochron at μ corresponding to 55 and 100. The thorogenic Pb can be modeled to produce a good linear correlation if the metasomatized mantle evolved with a Th/U ratio of ~ 2.5 .

This calculation clearly shows that the entire OIB Pb isotope array can be generated by the envisaged two-stage evolution. This model can be used to constrain the nature of the DupAl source, and its validity can be assessed using combined He and Pb isotope systematics from Hawaii.

7. He Isotope Constraints on the Source of DupAl

The significance of the DupAl isotopic signature is enigmatic. The key question is whether DupAl has a well-defined Pb isotope composition or whether it represents an array sub-parallel to Northern Hemisphere MORB Pb. In the first case, DupAl isotope composition could reflect that of the lower (primitive) mantle. In the latter case, DupAl could be interpreted as long-lived (~ 1 -2 Gyr) isotopically distinct reservoirs in the upper mantle probably subducted oceanic lithosphere and/or sediment as suggested by Rehkämper and Hofmann [1997]. It is significant that many OIBs that plot above the Northern Hemisphere Pb isotope reference line (and hence carry a so-called DupAl anomaly) have elevated $^3\text{He}/^4\text{He}$ ratios. As practically no ^3He is produced in the mantle [Tolstikhin, 1975], elevated $^3\text{He}/^4\text{He}$ ratios are universally interpreted to reflect incorporation of primordial He in a source with ordinary upper mantle He [e.g., Farley and Neroda, 1998]. The unavoidable implication for conventional geochemical mantle models is that Pb and He isotopes in OIBs would have to be at least partly decoupled, with Pb derived from a recycled source and He being plume-derived [cf. Hanyu and Kaneoka, 1998] or degassed at shallow mantle levels [Hilton *et al.*, 1995].

However, Eiler *et al.* [1998] have recently reported an intriguing correlation between He and Pb isotopes in Hawaiian lavas which can be used to test our OIB Pb isotope model. Assuming that DupAl is the lower mantle and has relatively constant Pb and He isotope compositions, a qualitative prediction of the evolution of He isotope systematics of our model is illustrated in Figure 4a. The DupAl component initially has a primordial $^3\text{He}/^4\text{He}$ ratio. The $^3\text{He}/^4\text{He}$ ratio will decrease and the $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios will increase as a function of time and the ambient $(\text{U}+\text{Th})/\text{He}$ and $(\text{U}+\text{Th})/\text{Pb}$ ratios. Following melting of the metasomatized source, the $^3\text{He}/^4\text{He}$ ratio will be further changed by mixing with a MORB melt (see Figures 4a and 4b for full discussion). According to our model, positive correlations between Pb isotope ratios and $^3\text{He}/^4\text{He}$ ratios should result if linear arrays exist in Pb isotope diagrams. Furthermore, our model predicts that steep Pb isotope regression lines should be associated

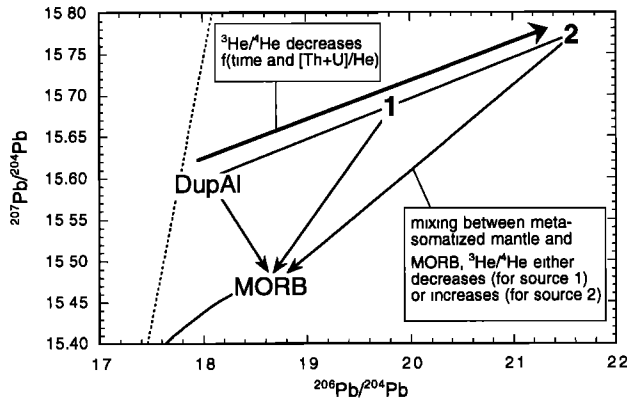


Figure 4a. Qualitative prediction of He isotope evolution based on Pb isotope model (Figure 3). The primordial, high $^3\text{He}/^4\text{He}$ ratio of the DupAl source decreases in the metasomatized mantle as a function of time and $(\text{U}+\text{Th})/\text{He}$. In the most extreme cases (high- μ ocean island basalts), the ratio will approximate 0. Mixing with MORB will further lower the $^3\text{He}/^4\text{He}$ ratio for the less radiogenic metasomatized mantle (source 1) or increase the ratio for those metasomatized mantle domains which evolved to the most radiogenic Pb compositions (source 2). The prediction of this qualitative model is that if a linear array in a Pb isotope exists for a set of OIBs, linear arrays should also be obtained for plots of Pb isotope ratios versus the $^3\text{He}/^4\text{He}$ ratio.

with the primordial He isotope signatures (unless He was degassed during metasomatism cf. [Hilton *et al.*, 1995]).

Unfortunately, a comprehensive OIB Pb and He isotope database only exists for Hawaii [Eiler *et al.*, 1998]. Koolau,

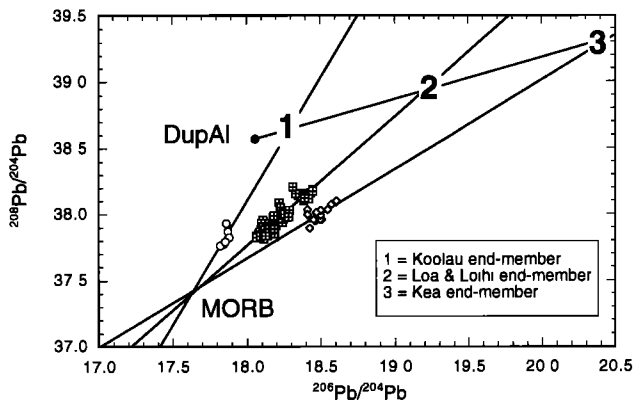


Figure 4b. Thorogenic Pb isotope diagram showing compositions of basalts from Koolau (open circles), Loa and Loihi (cross-hatched squares) and Kea (solid circles). Data for Koolau are from Roden *et al.* [1994] and Bennett *et al.* [1996] and for Loihi, Loa, and Kea are from compilation by Eiler *et al.* [1998]. Note that the three groups define significantly different trends as shown by linear regressions. The regressions intersect narrowly at a composition corresponding to the least radiogenic Pacific MORB samples [Castillo *et al.*, 1998] except for the anomalous unradiogenic Garrett Transform basalts [J. I. Wendt *et al.*, manuscript in preparation, 1999]. A mantle model was calculated to predict the compositions of the metasomatized (150 Ma) mantle sources with the same parameters as in Figure 3b, except that a Th/U ratio of 1 was found to best fit the data. These end-member compositions for (1) Koolau, (2) Loa and Loihi, and (3) Kea were obtained with μ of 10, 50, and 100, respectively.

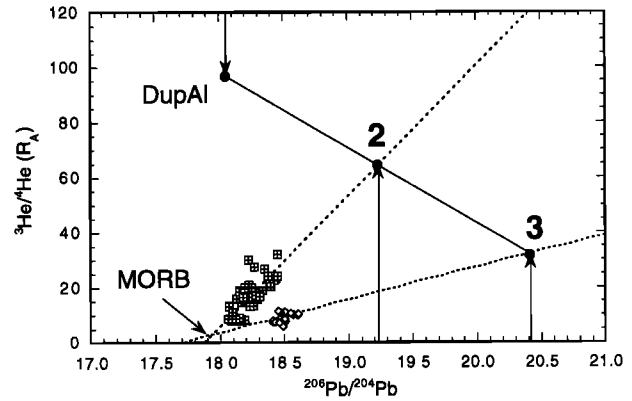


Figure 4c. $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^3\text{He}/^4\text{He}$ (R_A) ratios of Loa and Loihi and Kea basalts (no combined He-Pb data available for Koolau). As predicted by the qualitative model (Figure 4a), both groups define linear trends. There is significant scatter which could partly be due to poorer reproducibility of He isotope measurements and due to the fact that He isotopes are usually measured on phenocrysts, whereas Pb isotopes are measured on rock powders. Nevertheless, the linear regressions intersect at a composition not dissimilar to Pacific MORB. The important observation is that the Kea samples define a much shallower trend in accordance with the model predictions (the Kea source (3) in Figure 4b) evolved with a higher $(\text{Th}+\text{U})/\text{He}$ ratio than the Loa and Loihi source (2 in Figure 4b)). The He isotope composition of the metasomatized mantle sources can be estimated by extrapolating the regression lines to the Pb isotope composition determined in the model (Figure 4b). Note, however, that in reality, these mixing lines would probably be curves because of differences in He and Pb concentrations between MORB and metasomatized mantle. Nevertheless, to a first approximation, the Kea metasomatized mantle (3) is estimated to have had a $^3\text{He}/^4\text{He}$ (R_A) ratio of ~ 35 while the Loa and Loihi mantle (2) was distinctly more primordial with a $^3\text{He}/^4\text{He}$ (R_A) ratio of ~ 60 . Simple lever rule allows to extrapolate to the original He isotope composition of DupAl. The $^3\text{He}/^4\text{He}$ (R_A) ratio of ~ 90 obtained by this method is significantly higher than the commonly assumed lower mantle ratio of ~ 35 [Porcelli and Wasserburg, 1995].

Mauna Loa (plus Loihi) and Mauna Kea yield well-defined but different arrays in thorogenic Pb space (Figure 4b). Also shown in Figure 4b is a vector showing the effects of DupAl metasomatism (150 Ma) which satisfies the data (same parameters as for the Galapagos islands except for a Th/U ratio of 1.0). Figure 4c shows that positive correlations are found between the He and Pb isotope compositions and that Mauna Loa displays a distinctively steeper array. The topology of these mixing lines is likely to be nonlinear due to differences in Pb and He concentrations in the end-members. Linear regressions were calculated (Figure 4c) as the data have insufficient spread to constrain a mixing hyperbola. End-member $^3\text{He}/^4\text{He}$ ratios for Mauna Loa and Mauna Kea can be calculated from the 150 Ma Pb isotope DupAl isochron (Figure 4b). This extrapolation to metasomatized mantle before mixing with MORB-like mantle shows (in agreement with the prediction of the model) that the $^3\text{He}/^4\text{He}$ ratio of the Mauna Kea source had been reduced to $^3\text{He}/^4\text{He}$ (R_A) of ~ 35 , whereas that of the Mauna Loa source was still ~ 65 $^3\text{He}/^4\text{He}$ (R_A). Furthermore, these values can be used to constrain the $^3\text{He}/^4\text{He}$ ratio of the original DupAl source (prior to in situ U and Th

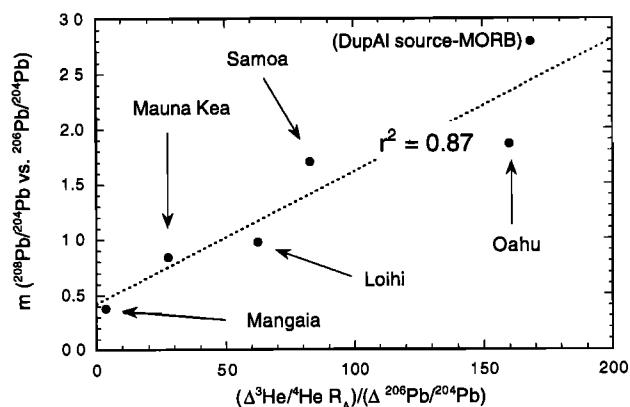


Figure 4d. Plot of the slope (m) defined in thorogenic Pb space versus the total range in He isotope composition divided by the total range in $^{206}\text{Pb}/^{204}\text{Pb}$ composition for several OIB data sets (Loa and Loihi and Kea from *Eiler et al.* [1998]; Oahu from *Roden et al.* [1994] and *Bennett et al.* [1996]; Samoa from *Farely et al.* [1992]; Mangaia from *Woodhead* [1996] and *Hanyu and Kaneoka* [1997]). The graph shows that the various OIBs define a wide range in their $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ slopes, with Mangaia (HIMU) characterized by the shallowest slope. The total range in He isotope compositions ($\Delta ^3\text{He}/^4\text{He} (R_A) = ^3\text{He}/^4\text{He} (R_A) \text{ maximum} - ^3\text{He}/^4\text{He} (R_A) \text{ minimum}$) divided by the total range in Pb isotope compositions ($\Delta ^{206}\text{Pb}/^{204}\text{Pb} = ^{206}\text{Pb}/^{204}\text{Pb} \text{ maximum} - ^{206}\text{Pb}/^{204}\text{Pb} \text{ minimum}$) increases systematically with increasing $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ slope. In other words, HIMU islands show very little variation in their He isotope compositions for a given variation in Pb isotope composition. This is predicted by the qualitative model (Figure 4a). The shallowest slopes in Pb isotope diagrams thus correspond to metasomatized mantle in which the $^3\text{He}/^4\text{He} (R_A)$ ratio is much reduced, thereby strongly limiting the possible range of $^3\text{He}/^4\text{He} (R_A)$ between 0 (HIMU) and ~ 8.5 (MORB). The strongest variations in He isotope compositions are expected for mixtures between pure DupAl source and MORB (shown for comparison).

decay) by the simple lever rule. Using this analysis we obtain a value of ca. $90 ^3\text{He}/^4\text{He} (R_A)$.

This self-consistent model for Pb and He isotope systematics constrains the source of the DupAl component to be the undegassed (primitive) portion of the lower mantle. An important feature of our model is the inference that all OIBs (except for those with a SCLM component) carry a primordial He isotope signature. However, in the radiogenic OIBs (HIMU) the originally high $^3\text{He}/^4\text{He}$ ratio is reduced to a value less than MORB due to U and Th decay (possibly also by degassing). As a result, HIMU OIBs are characterized by low ($\sim 6 ^3\text{He}/^4\text{He} (R_A)$) but relatively uniform He isotope ratios in spite of a wide range in Pb isotope ratios. This relationship is illustrated on Figure 4d in which the slope (m) defined in thorogenic Pb space versus the total range in He isotope composition divided by the total range in $^{206}\text{Pb}/^{204}\text{Pb}$ composition for Koolau, Kea, Loihi, Samoa, and Mangaia is plotted. The total range in He isotope compositions ($\Delta ^3\text{He}/^4\text{He} (R_A) = ^3\text{He}/^4\text{He} (R_A) \text{ maximum} - ^3\text{He}/^4\text{He} (R_A) \text{ minimum}$) divided by the total range in Pb isotope compositions ($\Delta ^{206}\text{Pb}/^{204}\text{Pb} = ^{206}\text{Pb}/^{204}\text{Pb} \text{ maximum} - ^{206}\text{Pb}/^{204}\text{Pb} \text{ minimum}$) increases systematically with increasing $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ slope. If the Th/U ratios of natural metasomatized OIB sources is between

~ 1 and 4, the observed linear relationship of these data ($r^2 = 0.87$) is predicted by our model. In other words, it must be expected that HIMU islands show very little variation in their He isotope compositions with variation in their Pb isotope compositions. Our combined Pb-He model explains both MORB and OIB trends and avoids the involvement of up to five mantle end-members proposed by other authors [e.g., *Hanan and Graham*, 1996].

8. Geological Test of the Mantle Mixing Model

Two features of our model break with conventional geochemical views of OIB genesis and therefore must be discussed in more detail. The first is our interpretation that the enriched reservoir (DupAl) is the undegassed lower mantle, the second concerns the inferred moderately high- μ metasomatism in the OIB melt source region.

According to our model, OIBs are binary mixtures between MORB source upper mantle and undegassed lower mantle. This is in effect a "rediscovery" of the model first proposed by *Morgan* [1971] and *Schilling* [1973] but later rejected on the grounds that it did not account for the highly variable geochemical and isotopic composition of OIBs [see, e.g., *Hofmann*, 1997]. However, there is growing geophysical and geochemical evidence in support of this original "standard" model. Improved resolution of seismic tomography has shown that mantle plumes beneath hotspots previously interpreted to be sampling upper mantle heterogeneities, in fact originate from the core-mantle boundary and not from the 670-km discontinuity (e.g., Hawaii [*Ji and Nataf*, 1998] and Iceland [*Shen et al.*, 1998]). While the tomographic data in themselves do not necessitate the involvement of lowermost mantle in the source of erupted OIBs, important recent Os isotope data for basalts from Hawaii and the Azores show involvement of a core or lower mantle-derived component [*Walker et al.*, 1995; *Widom and Shirey*, 1996; *Brandon et al.*, 1998]. Furthermore, the magnitude of the decrease in both P and S wave velocities in the lowermost portion of the mantle is interpreted to reflect partial melting in the vicinity of the D'' layer [*Mori and Helmberger*, 1995; *Williams and Garnero*, 1996; *Revenaugh and Meyer*, 1997; *Vidale and Hedlin*, 1998; *Lay et al.*, 1998]. It is significant that these ultralow-velocity zones appear to be spatially correlated with present-day hotspots [*Williams et al.*, 1998]. This provides further evidence that plumes emanating from the core-mantle boundary could provide melts (with DupAl isotope composition) that metasomatize the asthenosphere or the oceanic lithospheric mantle.

These discoveries necessitate deep boundary layer processes to be reevaluated, in particular, the effects of volatiles on the solidus of the deep mantle [cf. *Zerr et al.*, 1998]. It is clear from the thermal structure of Earth that lower mantle plumes can only originate from the base of the lower mantle. Geochemical evidence presented in this paper thus requires that only lowermost lower mantle is undegassed and is characterized by near-bulk silicate earth isotope evolution. It places no constraints on the degree of depletion of the lower mantle above the low-velocity boundary layer. The rapidly improving picture of lower mantle dynamics and structure thus fully supports our conclusion that the DupAl Pb, He (and, as we will show later, Sr and Nd) isotope ratios characterize a region in the lowermost mantle rather than ancient recycled oceanic lithosphere [*Kellogg et al.*, 1999]. This confirms *Castillo's* [1988] suggestion regarding the geographical extent of the

DupAl signature in OIBs and Indian MORB which is closely associated with large-scale regions of low seismic velocity in the lower mantle and that the DupAl anomaly traces regions of upwelling lower mantle.

The second feature of our model that needs geological confirmation is the inferred moderately high- μ DupAl-induced metasomatism in the OIB melt source region. Liquid immiscibility of carbonate-silicate melts stands out among intramantle processes that are able to strongly fractionate between different incompatible elements [e.g., *Veksler et al.*, 1998]. Carbonatite metasomatism in oceanic upper mantle has been documented [*Hauri et al.*, 1993; *Schiano et al.*, 1994; *Johnson et al.*, 1996; *Baker et al.*, 1998]. It is also a common feature in continental lithospheric mantle [*Green and Wallace*, 1988; *Yaxley et al.*, 1991; *Bell and Simonetti*, 1996; *Xu et al.*, 1996; *Ionov et al.*, 1997; *Wiechert et al.*, 1997; *Witt-Eickchen et al.*, 1998]. In some cases (e.g., Cape Verde and Canary Islands), carbonatites are directly associated with OIBs [*Kokfelt et al.*, 1997; *Kogarko et al.*, 1995]. The origin of carbonatite melts themselves is controversial. Until recently, it was believed (on isotope-geochemical grounds [e.g., *Hauri et al.*, 1993]) that carbonatites could originate from carbon which was recycled into the upper mantle with subducted slabs. *Sasada et al.* [1997] refuted this view based on the presence of excess ^{129}Xe in carbonatites that must be derived from a reservoir which is less degassed than MORB source mantle. More recently, *Marty et al.* [1998] reported important, irrefutable evidence that a 380 Ma carbonatite complex from the Kola Peninsula contains contribution from primordial He ($^3\text{He}/^4\text{He}$ (R_A) up to 19.1) and Ne sources. In our view it is significant that carbonatites and metasomatized mantle commonly occur in regions associated with DupAl isotope characteristics [e.g., *Toyoda et al.*, 1994]. Metasomatic melts derived from undegassed mantle therefore exist in nature. In this respect, it has been suggested that carbonatitic metasomatism is caused by volatile flux associated with mantle plumes thereby fertilizing the upper mantle [*Baker et al.*, 1998].

The remaining question is whether the μ of metasomatized mantle is high enough to account for the observed increase in the $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios over a time period of 100–200 Myr. To date, there exist no measurements of U/Pb and Th/Pb ratios of metasomatizing melt inclusions, but there is strong circumstantial evidence that the envisaged upper limit for μ (between 50 and 100) is a realistic estimate for metasomatized mantle. Evidence for this is as follows:

1. Clinopyroxenes from metasomatized mantle xenoliths have μ ranging from 12.5 to 162 and Th/U ratios between 1.4 and 5.5 [*Hauri et al.*, 1993; *Baker et al.*, 1998]. Silicates from Brazilian carbonatites associated with the Parana basaltic province have an average μ of 158 ± 66 and an average Th/U ratio of 2.1 ± 0.8 [*Toyoda et al.*, 1994]. These carbonatites are from 80 and 130 Ma, and their silicates show the increase in $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios predicted by our model.

2. The He and Xe isotope composition of these Brazilian carbonatites [*Sasada et al.*, 1997] show strong effects of alpha decay of U and Th and ^{238}U -fission, respectively. This underscores the validity of our combined Pb and He isotope model.

3. Ca-rich melt-inclusions with high U and Th concentrations have recently been reported from 43°N on the

Mid-Atlantic Ridge which is associated with DupAl Pb isotope systematics [*Kamenetsky et al.*, 1998].

4. High U/Pb OIB archipelagos show relatively high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios for a given $^{207}\text{Pb}/^{204}\text{Pb}$ value. *Halliday et al.* [1995 p.133] concluded that this "feature is most easily explained by enrichment of U relative to Pb about 100 Ma prior to melting, a time similar to the age of the lithosphere".

5. *McKenzie and O'Nions* [1998] have suggested that the trace element geochemistry of many OIBs requires fertilization of "typical" upper mantle prior to OIB melting and that subducted oceanic crust and/or sediment are insufficiently enriched in the most incompatible elements to account for concentrations typically found in OIBs with $\text{MgO} > 6$ wt %.

Clearly, more research is needed to better characterize the combined U/Th/Pb systematics of metasomatized mantle (and oceanic lithosphere). On the basis of current data it is likely that two processes have the potential to strongly fractionate U and Th from Pb: first, as mentioned above, separation of a carbonate melt from a silicate melt, and second, exhaustion of Ca-perovskite in lower mantle melting. Trace element distribution between lower mantle phases Mg-wüstite, Mg-perovskite, and CaSi-perovskite [*Kesson et al.*, 1998] is probably very extreme, with concentrations of most trace elements in CaSiO_3 being 3 orders of magnitude higher than in the other minerals [*Kato et al.*, 1988; *Harte et al.*, 1994]. If U, Th, and Pb distribution in CaSi-perovskite is similar to that of CaTi-perovskite (as indicated by similar rare earth element (REE) and high-field-strength-element distribution), there is a possibility that melts from the lower mantle may have highly variable U/Pb and Th/Pb ratios, depending on the residual mineralogy.

9. Implications for Sr and Nd Isotope Systematics of OIBs

Combined Sr and Nd isotope systematics of OIBs are less complicated than those of Pb and He. The negative correlation trend between global isotope ratios, originally termed "mantle trend", was interpreted to reflect mixing between depleted and undepleted magma sources. As isotopic data for more OIBs were obtained, it became clear that a significant number plotted substantially away from the "mantle trend" (Figure 5a). It is important to note that those OIBs that were omitted from our database on the grounds of SCLM contamination generally plot farthest away from a linear mixing trend [*Hofmann*, 1997 Figure 3]. It is necessary to consider whether the deviations found in the remaining OIBs could be produced by mixing of only two end-members.

Using the mixing equations by *DePaolo and Wasserburg* [1979] a mixing envelope was calculated that encompassed the entire OIB $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ isotope array. The end-members used were a typical MORB melt and an enriched melt with slightly subchondritic $^{143}\text{Nd}/^{144}\text{Nd}$ and slightly superchondritic $^{87}\text{Sr}/^{86}\text{Sr}$. In order to encompass all the OIB data $(\text{Sr}/\text{Nd})_{\text{MORB}}/(\text{Sr}/\text{Nd})_{\text{enriched}}$ (K) has to range from 0.2 (upper mixing curve on Figure 5a) to 5.0 (lower mixing curve). This predicts a wide range of ~ 7 to ~ 40 in Sr/Nd ratios in OIBs. Figure 5b is a histogram of OIB Sr/Nd ratios and clearly shows that the observed Sr/Nd variability permits significant deviations from the "mantle trend". This range in the Sr/Nd ratio in global OIBs is rather unexpected since Sr and Nd have

near identical bulk distribution coefficients in MORB-style melting [e.g., Hofmann, 1997]. These data indicate that our binary mixing model is not in conflict with Sr and Nd isotope constraints.

10. Significance of the New Model for Mantle Isotope Taxonomy

Conventional mantle isotope taxonomy uses plots of Pb isotope ratios versus Sr and Nd isotope ratios. It implicitly follows from our model that the use of such plots is questionable and may lead to erroneous conclusions. This is because the Pb isotope systematics reflect two evolutionary stages. First, the long timescale separation of upper and lower mantle which leads to a pronounced difference in $^{207}\text{Pb}/^{204}\text{Pb}$ ratios. Second, a short timescale evolution in an environment with highly variable U/Pb and Th/Pb. This leads to pronounced differences in $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios. Sr and Nd isotope systematics, however, mainly reflect the long-term separation. Sm/Nd fractionation in particular is limited by the similarity in chemical behavior of these elements. There is potential for some modification of the Sr isotope signature during the short-time evolution if metasomatism were to lead to extreme Rb/Sr fractionation. However, as shown above, mixing calculations demonstrate that such a process is not required to explain the Sr-Nd isotope array.

Nevertheless, our model allows us to reinterpret the nature of previously postulated mantle end-members:

The enriched mantle 1 (EM1) end-member is characterized by high $^{207}\text{Pb}/^{204}\text{Pb}$ and relatively low $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios and shows a strong affinity with primordial noble gases. Nd and Sr isotopes plot close to chondritic values. Therefore we postulate that the EM1 end-member represents lower mantle with no significant effects of short timescale metasomatism. This could either be due to a lack of significant U/Pb and Th/Pb fractionation of the metasomatising melt or could indicate that the metasomatic stage was very short. Mixing between lower mantle and depleted mantle results in the characteristically steep Pb isotope slopes, strongly variable He isotope ratios, and a narrow range in $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios.

The HIMU end-member is characterized by very radiogenic $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios and is associated with He isotopes that are significantly more evolved than MORB. Nd isotope ratios are typically midway between chondrite and depleted mantle, and Sr isotope ratios are typically quite primitive. We postulate that the HIMU end-member represents metasomatized upper mantle (or even oceanic lithospheric mantle) that inherited the isotope composition of lower mantle (i.e., EM1). However, in contrast to EM1, the metasomatic stage of HIMU lasted some 100-200 Myr and was characterized by high U/Pb and Th/Pb ratios. Mixing between HIMU and depleted mantle results in the characteristically shallower (than EM1) Pb isotope slopes and the typically low $^3\text{He}/^4\text{He}$ ratios. The rather primitive Sr isotope composition of HIMU could reflect involvement of a metasomatic melt/fluid with strongly fractionated incompatible elements (i.e., low Sr concentration, high U and Th concentrations). Obviously, EM1 and HIMU are genetically related in that they both start off with lower mantle isotope compositions. There is thus no sharp dividing boundary between these two end-members.

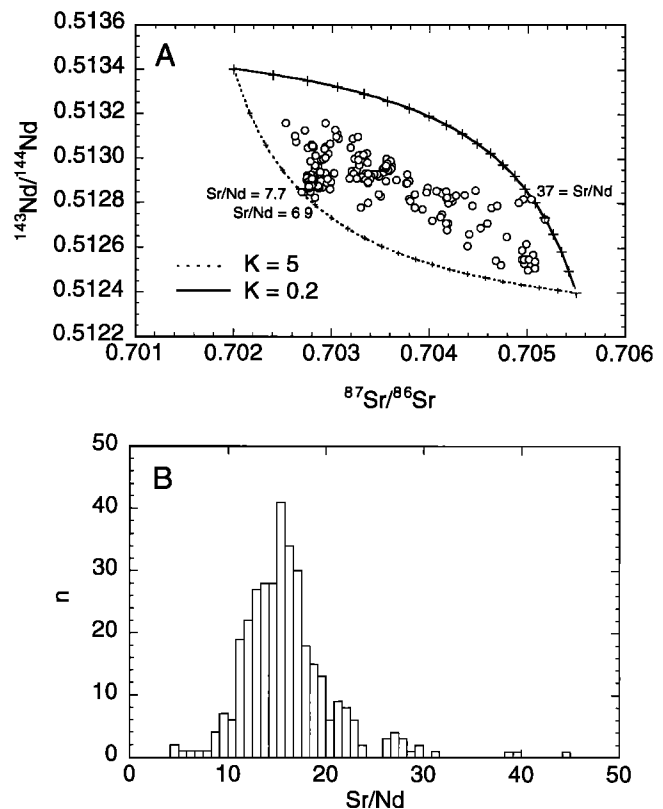


Figure 5. Sr-Nd isotopic and elemental systematics in global OIBs excluding those with a SCLM component (data sources as in Figures 1 and 2). (a) The $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ isotope plot highlights the scatter of OIB data around a linear negative slope (the “mantle array”). A mixing envelope was calculated to encompass all the data. The primitive end-member was chosen to have $^{143}\text{Nd}/^{144}\text{Nd} = 0.5134$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.702$, 11.18 ppm Nd, and 135 ppm Sr (typical depleted MORB). The enriched end-member has slightly subchondritic $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.5124 and slightly superchondritic $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7055. For the upper mixing curve, Nd and Sr concentrations in the enriched end-member were set to 5.5 ppm and 330 ppm, respectively. This corresponds to a K value of 0.2; where K is $(\text{Sr}/\text{Nd})_{\text{MORB}}/(\text{Sr}/\text{Nd})_{\text{enriched}}$. For the lower mixing curve, Nd and Sr concentrations in the enriched end-member were assumed to be 52 ppm and 125 ppm, respectively. This corresponds to a K value of 5.0. The predicted Sr/Nd ratios of the relevant mixtures are also plotted and range between 6.9 and 37. (b) Histogram of Sr/Nd ratios in global OIBs. Note that the range is significantly greater than that reported by *DePaolo and Wasserburg* [1979] and exceeds that required by the mixing calculations (6.9 to 37). It is therefore possible that the entire $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ array of OIBs could be generated by mixing of only two end-members.

In our revised nomenclature EM2 is not an end-member but represents SCLM that contaminates oceanic mantle derived melts. Because of the heterogeneity of SCLM (in terms of composition and age) no unique isotope composition can be defined for EM2. Since SCLM-contaminated OIBs were omitted from the database, our combined Pb-He model cannot be applied to EM2 melts.

The last end-member we require is depleted MORB source mantle and we believe that all OIBs entrained some depleted mantle component. All other putative “end-members” are not required and can be explained as mixtures of the above four components.

11. Implications for the Dynamics of Mantle Convection and the Chemical Evolution of the Mantle

Our reinterpretation of OIB geochemistry places new constraints on the chemical structure of the mantle and the dynamics of mantle convection. The most important conclusions are as follow:

1. Apart from SCLM, there is no evidence for long-lived geochemical reservoirs in the oceanic upper mantle. This finding is supported by consideration of the long-term isotope and geochemical history of this reservoir. In particular, the temporal evolutions of Pb and Nd isotopes and U/Nb and Th/U ratios require that continental material has been recycled back into the upper mantle, especially after 2.0 Gyr [Kramers and Tolstikhin, 1997; Kramers et al., 1998; Nägler and Kramers, 1998; Collerson and Kamber, 1999; Elliott et al., 1999]. Yet recycled continental material appears to be well dispersed by vigorous convection in the MORB source mantle as evidenced, for example, by the constant MORB Nb/U ratio (44.5 ± 2.5). The most anomalous MORB isotope compositions are found in Indian MORB. On the basis of our model we conclude that these isotope anomalies reflect stronger leaking of lower mantle material into the asthenosphere under the Indian ocean (see Figure 6a).

2. Our model requires lowermost mantle to be undegassed, relatively undepleted in incompatible elements and to have evolved to yield near-bulk-silicate-earth isotope ratios. Seismic velocity studies indicate that deeply subducted oceanic lithosphere appears to disseminate at a depth of ~ 1500 km [van der Hilst et al., 1997; Kellogg et al., 1999]. From these observations it is unlikely that the D" layer which is sampled by OIBs is the repository for subducted oceanic slabs [Kellogg et al., 1999].

3. If our model is correct, the Pb isotope composition of the Discovery Tablemount OIB can be used to estimate the composition of lowermost undegassed mantle. On Figure 6b we show that the present-day lowermost mantle Pb isotope composition can be modeled by a single-stage μ (closed system) of 8.9 and a Th/U ratio of 4.21, starting with an initial composition of $^{206}\text{Pb}/^{204}\text{Pb} = 9.818$; $^{207}\text{Pb}/^{204}\text{Pb} = 11.201$; and $^{208}\text{Pb}/^{204}\text{Pb} = 29.839$ at 4.3 Ga ([Kramers and Tolstikhin 1997] taking effects of core formation into account). If the Discovery Tablemount OIB contains a (small) MORB component (as has to be suspected), the μ of lowermost mantle may be slightly higher, but the Th/U ratio is well within error of chondritic estimates (see Table 1 of Kramers and Tolstikhin [1997] for a compilation of estimates).

4. Our results also have implications for the initial He isotope composition of Earth. The pertinent question is whether Earth's initial He isotope composition was solar ($^{280}\text{He}/^{4}\text{He}$ (R_A)) or “planetary” (~ 100 $^{3}\text{He}/^{4}\text{He}$ (R_A)). It has been argued that a “planetary” composition is more appropriate [Ozima and Podosek, 1983], and models attempting to constrain mass transfer between lower and upper mantle reservoirs have used this value as a starting point [e.g.,

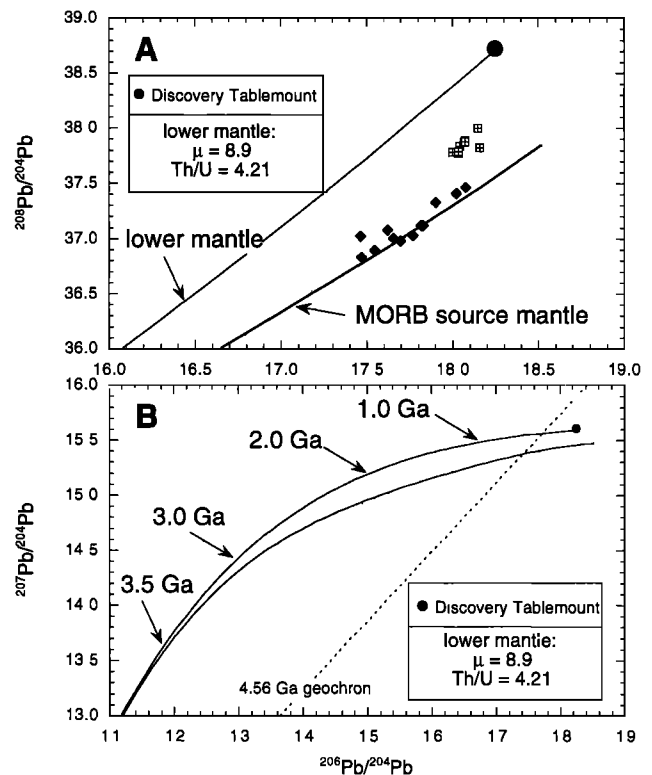


Figure 6. (a) Thorogenic Pb isotope evolution of lowermost mantle modeled to predict present-day isotope composition of Discovery Tablemount ocean island basalt. Model parameters are initial Pb at 4.3 Ga (taking effects of core formation into account); $^{206}\text{Pb}/^{204}\text{Pb} = 9.818$ and $^{208}\text{Pb}/^{204}\text{Pb} = 29.839$ [Kramers and Tolstikhin, 1997]; $\mu = 8.9$; $\text{Th/U} = 4.21$; and a time of 4.3 Gyr. Also shown are most depleted MORB samples from Garrett transform (solid diamonds; data from J. I. Wendt et al., manuscript in preparation, 1999) to illustrate the observed range in MORB Pb isotope composition. The anomalous isotope composition of Indian MORB (cross-hatched squares; data from Rehkämper and Hofmann [1997]) is explained by admixture of lowermost mantle material to normal MORB. This would indicate mass transfer between deepest and shallowest mantle in an ocean basin that has evolved during the last ~ 100 Myr. (b) Uranogenic Pb isotope evolution of lowermost mantle modeled to predict present-day isotope composition of Discovery Tablemount ocean island basalt. Model parameters are initial Pb at 4.3 Ga (taking effects of core formation into account); $^{206}\text{Pb}/^{204}\text{Pb} = 9.818$ and $^{207}\text{Pb}/^{204}\text{Pb} = 11.201$ [Kramers and Tolstikhin, 1997]; $\mu = 8.9$; and a time of 4.3 Gyr. MORB source mantle and Geochron are shown for comparison. Note that the MORB source mantle starts to deviate significantly from the lowermost mantle after ~ 3 Gyr due to crust extraction (which lowered μ) and plots farther to the right of the Geochron due to preferential recycling of U after ~ 2.0 Ga [Collerson and Kamber, 1999].

Porcelli and Wasserburg, 1995; O’Nions and Tolstikhin, 1996]. However, terrestrial Ne and Ar isotope systematics have recently been interpreted in terms of a solar initial rare gas isotope composition of Earth [Honda et al., 1993; Pepin, 1998]. Our model shows that the He isotope ratios measured in OIBs are lowered by admixture of MORB-type He and by U and Th decay during a metasomatic stage (Figure 4c). Taking these effects into account, we calculate a present-day lowermost

mantle ratio of ~ 90 $^3\text{He}/^4\text{He}$ (R_A). This is almost as high as the "planetary" value and given >4 Ga nucleogenic ^4He production in a near-chondritic lowermost mantle, the initial ratio of Earth must have been significantly higher than the "planetary" value, possibly as high as the solar wind value (280 $^3\text{He}/^4\text{He}$ (R_A)).

12. Summary

A comparison of OIB Pb isotope systematics with the temporal Pb isotope evolution of the depleted mantle demonstrates that linear arrays defined by the global OIB database and by individual archipelagos have no age significance. They must therefore be mixing lines. The range in $^{207}\text{Pb}/^{204}\text{Pb}$ in OIBs is the result of mixing between only two reservoirs: the upper mantle and a near-bulk-silicate-earth μ reservoir, which we propose to be the lowermost mantle. The wide spread in $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ of OIBs, however, is the result of short timescale evolution in localized environments with highly variable $(\text{Th}+\text{U})/\text{Pb}$. The so-called EM1 end-member lacks effects of the short timescale modification which is most pronounced in the HIMU end-member. The two-stage evolution proposed for OIB Pb (and He) isotope systematics explains why there is no correlation between Pb isotopes with other radiogenic tracers and thereby provides an explanation for the HIMU isotope paradox [Ballentine *et al.*, 1997]. A two-stage evolution model also obviates the need for decoupling of He and Pb in the interpretation of OIB genesis [Hanyu and Kaneoka, 1998].

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References

- Albarède, F., B. Luais, G. Fitton, M. Semet, E. Kaminski, B. G. J. Upton, P. Bachèlery, and J.-L. Cheminée, The geochemical regimes of Piton de la Fournaise volcano (Réunion) during the last 530,000 years, *J. Petrol.*, **38**, 171-201, 1997.
- Baker, J., G. Chazot, M. Menzies, and M. Thirlwall, Metasomatism of the shallow mantle beneath Yemen by the Afar plume—Implications for mantle plumes, flood volcanism, and intraplate volcanism, *Geology*, **26**, 431-434, 1998.
- Ballentine, C. J., D.-C. Lee, and A. N. Halliday, Hafnium isotopic studies of the Cameroon line and new HIMU paradoxes, *Chem. Geol.*, **139**, 111-124, 1997.
- Barling, J., S. L. Goldstein, and I. A. Nicholls, Geochemistry of Heard Island (southern Indian Ocean): Characterization of an enriched mantle component and implications for enrichment of the sub-Indian Ocean mantle, *J. Petrol.*, **35**, 1017-1053, 1994.
- Bell, K., and A. Simonetti, Carbonatite magmatism and plume activity: Implications for the Nd, Pb and Sr isotope systematics of Oldinyo Lengai, *J. Petrol.*, **37**, 1321-1339, 1996.
- Bennett, V. C., T. M. East, and M. D. Norman, Two mantle-plume components in Hawaiian picrites inferred from correlated Os-Pb isotopes, *Nature*, **381**, 221-224, 1996.
- Brandon, A. D., R. J. Walker, J. W. Morgan, M. D. Norman, and H. M. Pritchard, Coupled Os-186 and Os-187 evidence for core-mantle interaction, *Science*, **280**, 1570-1573, 1998.
- Campbell, I. H., The mantle's chemical structure: Insights from the melting of products of mantle plumes, in *The Earth's Mantle: Composition, Structure, and Evolution*, edited by I. Jackson, pp. 259-301, Cambridge Univ. Press, New York, 1998.
- Castillo, P., The Dupal anomaly as a trace of the upwelling lower mantle, *Nature*, **336**, 667-670, 1988.
- Castillo, P. R., J. H. Natland, Y. Niu, and P. F. Lonsdale, Sr, Nd and Pb isotopic variation along the Pacific-Antarctic rise crest, 53-57°S: Implications for the composition and dynamics of the South Pacific upper mantle, *Earth Planet. Sci. Lett.*, **154**, 109-125, 1998.
- Chaffey, D. J., R. A. Cliff, and B. M. Wilson, Characterisation of the St. Helena magma source, in *Magmatism in the Ocean Basins*, edited by A. D. Saunders and M. J. Norry, *Geol. Soc. Spec. Publ.*, **42**, 257-276, 1989.
- Chase, C. G., Oceanic island Pb: Two-stage histories and mantle evolution, *Earth Planet. Sci. Lett.*, **52**, 277-284, 1981.
- Chauvel, C., A. W. Hofmann, and P. Vidal, HIMU-EM: The French Polynesian connection, *Earth Planet. Sci. Lett.*, **110**, 99-119, 1992.
- Chauvel, C., S. L. Goldstein, and A. W. Hofmann, Hydration and dehydration of oceanic crust controls Pb evolution of the mantle, *Chem. Geol.*, **126**, 65-75, 1995.
- Chauvel, C., W. McDonough, G. Guille, R. Maury, and R. Duncan, Contrasting old and young volcanism in Rurutu Island, Austral chain, *Chem. Geol.*, **139**, 125-144, 1997.
- Chen, C.-Y., F. A. Frey, J. M. Rhodes, and R. M. Easton, Temporal geochemical evolution of Kilauea volcano: Comparison of Hilina and Puna basalt, in *Earth Processes: Reading the Isotopic Code*, *Geophys. Monogr. Ser.*, vol. 91 edited by A. Basu and S. Hart, pp. 161-181, AGU, Washington, D.C., 1996.
- Cliff, R. A., P. E. Baker, and N. J. Mateer, Geochemistry of Inaccessible island volcanics, *Chem. Geol.*, **92**, 251-260, 1991.
- Collerson, K. D., and B. S. Kamber, Evolution of the continents and the atmosphere inferred from Th-U-Nb systematics of the depleted mantle, *Science*, **283**, 1519-1522, 1999.
- Cumming, G. L., and J. R. Richards, Ore lead isotope ratios in a continuously changing Earth, *Earth Planet. Sci. Lett.*, **28**, 155-171, 1975.
- DePaolo, D. J., and G. J. Wasserburg, Petrogenetic mixing models and Nd-Sr isotopic patterns, *Geochim. Cosmochim. Acta*, **43**, 615-627, 1979.
- Dupré, B., and C. J. Allègre, Pb-Sr isotope variations in Indian Ocean basalts and mixing phenomena, *Nature*, **303**, 142-146, 1983.
- Eiler, J. M., K. A. Farley, and E. M. Stolper, Correlated helium and lead isotope variations in Hawaiian lavas, *Geochim. Cosmochim. Acta*, **62**, 1977-1984, 1998.
- Elliott, T., Element fractionation in the petrogenesis of ocean island basalts, Ph.D. thesis, Open Univ., Milton Keynes, England, 1991.
- Elliott, T., A. Zindler, and B. Bourdon, Exploring the kappa conundrum: The role of recycling in the lead isotope evolution of the mantle, *Earth Planet. Sci. Lett.*, **169**, 129-145, 1999.
- Ewart, A., K. D. Collerson, M. Regelous, J. I. Wendt, and Y. Niu, Geochemical evolution within the Tonga-Kermadec-Lau arc-back-arc systems: The role of varying mantle wedge composition in space and time, *J. Petrol.*, **39**, 331-368, 1998.
- Farley, K. A., and E. Neroda, Noble gases in the Earth's mantle, *Annu. Rev. Earth Planet. Sci.*, **26**, 189-218, 1998.
- Farley, K. A., J. H. Natland, and H. Craig, Binary mixing of enriched and undegassed (primitive?) mantle components (He, Sr, Nd, Pb) in Samoan lavas, *Earth Planet. Sci. Lett.*, **111**, 183-199, 1992.
- Fisk, M. R., B. G. J. Upton, C. E. Ford, and W. M. White, Geochemical and experimental study of the genesis of Reunion Island, Indian Ocean, *J. Geophys. Res.*, **93**, 4933-4950, 1988.
- Fodor, R. V., F. A. Frey, G. R. Bauer, and D. A. Clague, Ages, rare-earth-element enrichment and petrogenesis of tholeiitic and alkalic basalts from Kahoolawe Island, Hawaii, *Contrib. Mineral. Petrol.*, **110**, 442-462, 1992.
- Frey, F. A., M. O. Garcia, and M. F. Roden, Geochemical characteristics of Koolau Volcano: Implications of intershield geochemical differences among Hawaiian volcanoes, *Geochim. Cosmochim. Acta*, **58**, 1441-1462, 1994.
- Garcia, M. O., J. M. Rhodes, F. A. Trusdell, and A. J. Pietruszka, Petrology of lavas from the Puu Oo eruption of Kilauea volcano, III, The Kupaianaha episode (1986-1992), *Bull. Volcanol.*, **58**, 359-379, 1996.
- Green, D. H., and M. E. Wallace, Mantle metasomatism by ephemeral carbonatite melts, *Nature*, **336**, 459-462, 1988.
- Haase, K. M., P. Stoffers, and C. D. Garbe-Schönberg, The petrogenetic evolution of lavas from Easter Island and neighbouring seamounts, near-ridge hotspot volcanoes in the SE Pacific, *J. Petrol.*, **38**, 785-813, 1997.
- Halliday, A. N., D.-C. Lee, S. Tommasini, G. R. Davies, C. R. Paslick, J. G. Fitton, and D. E. James, Incompatible trace elements in OIB and

- MORB source enrichment in the sub-oceanic mantle, *Earth Planet. Sci. Lett.*, **133**, 379-395, 1995.
- Hanan, B. B., and D. W. Graham, Lead and helium isotope evidence from oceanic basalts for a common deep source of mantle plumes, *Science*, **272**, 991-995, 1996.
- Hanyu, T., and I. Kaneoka, The uniform and low $^3\text{He}/^4\text{He}$ ratios of HIMU basalts as evidence for their origin as recycled materials, *Nature*, **390**, 273-276, 1997.
- Hanyu, T., and I. Kaneoka, Open system behaviour of helium in case of the HIMU source area, *Geophys. Res. Lett.*, **25**, 687-690, 1998.
- Hards, V. L., P. D. Kempton, and R. N. Thompson, The heterogeneous Iceland plume: new insights from the alkaline basalts of the Snaefell volcanic centre, *J. Geol. Soc. London*, **152**, 1003-1009, 1995.
- Harte, B., M. T. Hutchinson, and J. W. Harris, Trace element characteristics of the lower mantle: an ion probe study of inclusions in diamond from São Luiz, Brazil, *Mineral. Mag.*, **58A**, 386-387, 1994.
- Hassler, D. R., and N. Shimizu, Osmium isotopic evidence for ancient subcontinental lithospheric mantle beneath the Kerguelen Islands, southern Indian Ocean, *Science*, **280**, 418-421, 1998.
- Hauri, E. H., N. Shimizu, J. J. Dieu, and S. R. Hart, Evidence for hotspot-related carbonatite metasomatism in the oceanic upper mantle, *Nature*, **365**, 221-227, 1993.
- Hémond, C., C. W. Devey, and C. Chauvel, Source composition and melting processes in the Society and Austral plumes (South Pacific Ocean): Element and isotope (Sr, Nd, Pb, Th) geochemistry, *Chem. Geol.*, **115**, 7-45, 1994.
- Hilton, D. R., J. Barling, and G. E. Wheller, Effect of shallow-level contamination on the helium isotope systematics of ocean-island lavas, *Nature*, **373**, 330-333, 1995.
- Hoernle, K., and H.U. Schmincke, The role of partial melting in the 15-Ma geochemical evolution of Gran Canaria: A blob model for the Canary hotspot, *J. Petrol.*, **34**, 599-626, 1993.
- Hofmann, A. W., Mantle geochemistry: the message from oceanic volcanism, *Nature*, **385**, 219-229, 1997.
- Honda, M., I. McDougall, and D. Patterson, Solar noble gases in the Earth: The systematics of helium-neon isotopes in mantle derived samples, *Lithos*, **30**, 257-265, 1993.
- Humphris, S. E., and G. Thompson, Geochemistry of rare earth elements in basalts from the Walvis Ridge; implications for its origin and evolution, *Earth Planet. Sci. Lett.*, **66**, 223-242, 1983.
- Ionov, D. A., W. L. Griffin, and S. Y. O'Reilly, Volatile-bearing minerals and lithophile trace elements in the upper mantle, *Chem. Geol.*, **141**, 153-184, 1997.
- Ji, Y., and H.-C. Nataf, Detection of mantle plumes in the lower mantle by diffraction tomography: Hawaii, *Earth Planet. Sci. Lett.*, **159**, 99-115, 1998.
- Johnson, K. E., A. M. Davis, and L. T. Bryndzia, Contrasting styles of hydrous metasomatism in the upper mantle: An ion microprobe investigation, *Geochim. Cosmochim. Acta*, **60**, 1367-1385, 1996.
- Kamenetsky, V. S., S. M. Eggins, A. J. Crawford, D. H. Green, M. Gasparon, and T. J. Falloon, Calcic melt inclusions in primitive olivine at 43°N MAR: Evidence for melt-rock reaction/melting involving clinopyroxene-rich lithologies during melt generation, *Earth Planet. Sci. Lett.*, **160**, 115-132, 1998.
- Kato, T., A. E. Ringwood, and T. Irifune, Experimental determination of element partitioning between silicate perovskites, garnets and liquids: Constraints on early differentiation of the mantle, *Earth Planet. Sci. Lett.*, **89**, 123-145, 1988.
- Kellogg, L. H., B.H. Hager, and R. D. van der Hilst, Compositional stratification in the deep mantle, *Science*, **283**, 1881-1884, 1999.
- Kesson, S. E., J. D. Fitz Gerald, and J. M. Shelley, Mineralogy and dynamics of a pyrolite lower mantle, *Nature*, **393**, 252-255, 1998.
- Kogarko, L. N., C. M. B. Henderson, and H. Pacheco, Primary Ca-rich carbonatite magma and carbonate-silicate-sulphide liquid immiscibility in the upper mantle, *Contrib. Mineral. Petrol.*, **121**, 267-274, 1995.
- Kogiso, T., Y. Tatsumi, G. Shumoda, and H. G. Barschus, High μ (HIMU) ocean island basalts in southern Polynesia: New evidence for whole mantle scale recycling of subducted oceanic crust, *J. Geophys. Res.*, **102**, 8085-8103, 1997.
- Kokfelt, T., P. M. Holm, C. J. Hawkesworth, D. W. Peate, and C. Hémond, OIB source regions stabilised at the time of continental break-up: HIMU basalts from the Cape Verde Islands *Eos Trans. AGU*, **78** (46), Fall Meet. Supp., F814, 1997.
- Kramers, J. D., and I. N. Tolstikhin, Two terrestrial lead isotope paradoxes, forward transport modelling, core formation and the history of the continental crust, *Chem. Geol.*, **139**, 75-110, 1997.
- Kramers, J. D., T. F. Nägler, and I. N. Tolstikhin, Perspectives from global modeling of terrestrial Pb and Nd isotopes on the history of the continental crust, *Schweiz. Mineral. Petrogr. Mitt.*, **78**, 169-174, 1998.
- Lay, T., Q. Williams, and E. J. Garnero, The core-mantle boundary layer and deep Earth dynamics, *Nature*, **392**, 461-468, 1998.
- le Roex, A. P., R. A. Cliff, and B. J. I. Adair, Tristan da Cunha, South Atlantic: Geochemistry and petrogenesis of a basanite-phonolite lava series, *J. Petrol.*, **31**, 779-812, 1990.
- Lee, D.-C., A. N. Halliday, J. G. Fitton, and G. Poli, Isotopic variation with distance and time in the oceanic sector of the Cameroon line: Evidence for a mantle plume origin and rejuvenation of magma transport paths, *Earth Planet. Sci. Lett.*, **123**, 119-138, 1994.
- Marty, B., I. Tolstikhin, I. L. Kamensky, V. Nivin, E. Balaganskaya, and J. L. Zimmermann, Plume-derived rare gases in 380 Ma carbonatites from the Kola region (Russia) and the argon isotopic composition in the deep mantle, *Earth Planet. Sci. Lett.*, **164**, 179-192, 1998.
- McKenzie, D., and R. K. O'Nions, Melt production beneath oceanic islands, *Phys. Earth Planet. Inter.*, **107**, 143-182, 1998.
- Morgan, W. J., Convection plumes in the lower mantle, *Nature*, **230**, 42-43, 1971.
- Mori, J., and D. V. Helmberger, Localized boundary layer below the mid-Pacific velocity anomaly identified from a PcP precursor, *J. Geophys. Res.*, **100**, 20,359-20,365, 1995.
- Nägler, T. F., and J. D. Kramers, Nd isotopic evolution of the upper mantle during the Precambrian: Models, data and the uncertainty of both, *Precambrian Res.*, **91**, 233-252, 1998.
- O'Nions, R. K., and I. N. Tolstikhin, Limits on the mass flux between lower and upper mantle and stability of layering, *Earth Planet. Sci. Lett.*, **139**, 213-222, 1995.
- Ozima, M., and F. A. Podosek, *Noble Gas Geochemistry*, Cambridge Univ. Press, New York, 1983.
- Palacz, Z. A., and A. D. Saunders, Coupled trace element and isotope enrichment in the Cook-Austral-Samoa islands, southwest Pacific, *Earth Planet. Sci. Lett.*, **79**, 270-280, 1986.
- Pepin, R. O., Isotopic evidence for a solar argon component in the Earth's mantle, *Nature*, **394**, 664-667, 1998.
- Plank, T., and C. H. Langmuir, The chemical composition of subducting sediment and its consequences for the crust and mantle, *Chem. Geol.*, **145**, 325-394, 1998.
- Porcelli, D., and G. J. Wasserburg, Mass transfer of helium, neon, argon, and xenon through a steady-state upper mantle, *Geochim. Cosmochim. Acta*, **59**, 4921-4937, 1995.
- Rehkämper, M., and A. W. Hofmann, Recycled ocean crust and sediment in Indian Ocean MORB, *Earth Planet. Sci. Lett.*, **147**, 93-106, 1997.
- Revenaugh, J., and R. Meyer, Seismic evidence of partial melt within a possibly ubiquitous low-velocity layer at the base of the mantle, *Science*, **277**, 670-673, 1997.
- Reymer, A., and G. Schubert, Phanerozoic addition rates to the continental crust and crustal growth, *Tectonics*, **3**, 63-77, 1984.
- Reynolds, R. W., and D. J. Geist, Petrology of lavas from Sierra Negra volcano, Isabela Island, Galápagos archipelago, *J. Geophys. Res.*, **100**, 24,537-24,553, 1995.
- Roden, M. F., T. Trull, S. R. Hart, and F. A. Frey, New He, Nd, Pb, and Sr isotopic constraints on the constitution of the Hawaiian plume: Results from Koolau Volcano, Oahu, Hawaii, USA, *Geochim. Cosmochim. Acta*, **58**, 1431-1440, 1994.
- Saal, A. E., S. R. Hart, N. Shimizu, E. H. Hauri, and G.D. Layne, Pb isotopic variability in melt inclusions from oceanic island basalts, Polynesia, *Science*, **282**, 1481-1484, 1998.
- Sasada, T., H. Hiyagon, K. Bell, and M. Ebihara, Mantle-derived noble gases in carbonatites, *Geochim. Cosmochim. Acta*, **61**, 4219-4228, 1997.
- Schiano, P., R. Clocchiatti, N. Shimizu, D. Weis, and N. Mattinelli, Cogenetic silica-rich and carbonate-rich melts trapped in mantle minerals in Kerguelen ultramafic xenoliths: Implications for metasomatism in the oceanic upper mantle, *Earth Planet. Sci. Lett.*, **123**, 167-178, 1994.
- Schilling, J. G., Iceland mantle plume Geochemical study of Reykjanes Ridge, *Nature*, **242**, 565-571, 1973.
- Shen, Y., S. C. Solomon, I. T. Bjarnason, and C. J. Wolfe, Seismic evidence for a lower-mantle origin of the Iceland plume, *Nature*, **395**, 62-65, 1998.
- Späth, A., A. Le Roex, and R. A. Duncan, The geochemistry of lavas

- from the Comores Archipelago, western Indian Ocean: Petrogenesis and mantle source region characteristics, *J. Petrol.*, *37*, 961-991, 1996.
- Sun, S.-S., Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs, *Philos. Trans. R. Soc. London*, *297*, 409-445, 1980.
- Tolstikhin, I. N., Helium isotopes in the Earth's interior and in the atmosphere: A degassing model for the Earth, *Earth Planet. Sci. Lett.*, *26*, 88-96, 1975.
- Toyoda, K., H. Horiuchi, and M. Tokonami, Dupal anomaly of Brazilian carbonatites: Geochemical correlations with hotspots in the South Atlantic and implications for the mantle source, *Earth Planet. Sci. Lett.*, *126*, 315-331, 1994.
- Turner, S., C. Hawkesworth, N. Rogers, and P. King, U-Th isotope disequilibria and ocean island basalt generation in the Azores, *Chem. Geol.*, *139*, 145-164, 1997.
- van der Hilst, R. D., S. Widiyantoro, and E. R. Engdahl, Evidence for deep mantle circulation from global tomography, *Nature*, *386*, 578-584, 1997.
- Veksler, I. V., C. Petibon, G. A. Jenner, A. M. Dorfman, and D. B. Dingwell, Trace element partitioning in immiscible silicate-carbonate liquid systems: An initial experimental study using a centrifuge autoclave, *J. Petrol.*, *39*, 2095-2104, 1998.
- Vidale, J. E., and M. A. H. Hedlin, Evidence for partial melt at the core-mantle boundary north of Tonga from the strong scattering of seismic waves, *Nature*, *391*, 682-685, 1998.
- Walker, R. J., J. W. Morgan, and M. F. Horan, Osmium-187 enrichment in some plumes: evidence for core-mantle interaction?, *Science*, *269*, 819-822, 1995.
- Weaver, B. L., D. A. Wood, J. Tarney, and J.-L. Joron, Geochemistry of ocean island basalts from the South Atlantic: Ascension, Bouvet, St. Helena, Gough and Tristan da Cunha, in *Alkaline Igneous Rocks*, edited by J. G. Fitton, and B. G. J. Upton, *Geol. Soc. Spec. Publ.*, *30*, 253-267, 1987.
- West, H. B., M. O. Garcia, D. C. Gerlach, and J. Romano, Geochemistry of tholeiites from Lanai, *Contrib. Mineral. Petrol.*, *112*, 520-542, 1992.
- White, W. M., A. R. McBirney, and R. A. Duncan, Petrology and geochemistry of the Galápagos Islands: Portrait of a pathological mantle plume, *J. Geophys. Res.*, *98*, 19533-19563, 1993.
- Widom, E., and S. B. Shirey, Os isotope systematics in the Azores: Implications for mantle plume sources, *Earth Planet. Sci. Lett.*, *142*, 451-465, 1996.
- Widom, E., R. W. Carlson, J. B. Gill, and H.-U. Schmincke, Th-Sr-Nd-Pb isotope and trace element evidence for the origin of the São Miguel, Azores, enriched mantle source, *Chem. Geol.*, *140*, 49-68, 1997.
- Widom, E., K. A. Hoernle, S. B. Shirey, and H. U. Schmincke, Os isotope systematics in the Canary Islands and Madeira: Lithospheric contamination and mantle plume signatures, *J. Petrol.*, *40*, 279-296, 1999.
- Wiechert, U., D. A. Ionov, and K. H. Wedepohl, Spinel peridotite xenoliths from the Atsagin-Dush volcano, Dariganga lava plateau, Mongolia: A record of partial melting and cryptic metasomatism in the upper mantle, *Contrib. Mineral. Petrol.*, *126*, 345-364, 1997.
- Williams, Q., and E. J. Garnero, Seismic evidence for partial melt at the base of Earth's mantle, *Science*, *273*, 1528-1530, 1996.
- Williams, Q., J. Revenaugh, and E. J. Garnero, A correlation between ultralow velocities in the mantle and hotspots, *Science*, *281*, 546-549, 1998.
- Witt-Eickchen, G., W. Kaminsky, U. Kramm, and B. Harte, The nature of young vein metasomatism in the lithosphere of the West Eifel (Germany): Geochemical and isotopic constraints from composite mantle xenoliths from the Meerfelder Maar, *J. Petrol.*, *39*, 155-185, 1998.
- Woodhead, J. D., Extreme HIMU in an oceanic setting: The geochemistry of Mangaia Island (Polynesia), and temporal evolution of the Cook-Austral hotspot, *J. Volcanol. Geotherm. Res.*, *72*, 1-19, 1996.
- Woodhead, J. D., and C. W. Devey, Geochemistry of the Pitcairn seamounts, I, Source character and temporal trends, *Earth Planet. Sci. Lett.*, *116*, 81-99, 1993.
- Woodhead, J. D., and M. T. McCulloch, Ancient seafloor signals in Pitcairn island lavas and evidence for large amplitude, small-scale mantle heterogeneities, *Earth Planet. Sci. Lett.*, *94*, 257-273, 1989.
- Xu, Y., J.-C. C. Mercier, M. A. Menzies, J. V. Ross, B. Harte, C. Lin, and L. Shi, K-rich glass-bearing wherlite xenoliths from Yitong, northeastern China: Petrological and chemical evidence for mantle metasomatism, *Contrib. Mineral. Petrol.*, *125*, 406-420, 1996.
- Yaxley, G. M., A. J. Crawford, and D. H. Green, Evidence for carbonatite metasomatism in spinel peridotite xenoliths from western Victoria, Australia, *Earth Planet. Sci. Lett.*, *107*, 305-317, 1991.
- Zartman, R. E., and S. Haines, The plumbotectonic model for Pb isotopic systematics among major terrestrial reservoirs—A case for bi-directional transport, *Geochim. Cosmochim. Acta*, *52*, 1327-1339, 1988.
- Zerr, A., A. Diegeler, and R. Boehler, Solidus of Earth's deep mantle, *Science*, *281*, 243-246, 1998.
- Zindler, A., and S. Hart, Chemical geodynamics, *Annu. Rev. Earth Planet. Sci.*, *14*, 493-571, 1986.

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