

Some basic concepts and problems on the petrogenesis of intra-plate ocean island basalts

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Basaltic magmatism that builds intra-plate ocean islands is often considered to be genetically associated with “hotspots” or “mantle plumes”. While there have been many discussions on why ocean island basalts (OIB) are geochemically highly enriched as an integral part of the mantle plume hypothesis, our current understanding on the origin of OIB source material remains unsatisfactory, and some prevailing ideas need revision. One of the most popular views states that OIB source material is recycled oceanic crust (ROC). Among many problems with the ROC model, the ocean crust is simply too depleted (e.g., $[La/Sm]_{PM} < 1$) to be source material for highly enriched (e.g., $[La/Sm]_{PM} \gg 1$) OIB. Another popular view states that the enriched component of OIB comes from recycled continental crust (RCC, i.e.; terrigenous sediments). While both CC and OIB are enriched in many incompatible elements (e.g., both have $[La/Sm]_{PM} \gg 1$), the CC has characteristic enrichment in Pb and depletion in Nb, Ta, P and Ti. Such signature is too strong to be eliminated such that CC is unsuitable as source material for OIB. Plate tectonics and mantle circulation permit the presence of ROC and RCC materials in mantle source regions of basalts, but they must be volumetrically insignificant in contributing to basalt magmatism. The observation that OIB are not only enriched in incompatible elements, but also enriched in the progressively more incompatible elements indicates that the enriched component of OIB is of magmatic origin and most likely associated with low-degree melt metasomatism. H_2O and CO_2 rich incipient melt may form in the seismic low velocity zone (LVZ). This melt will rise because of buoyancy and concentrate into a melt rich layer atop the LVZ to metasomatize the growing lithosphere, forming the metasomatic vein lithologies. Erupted OIB melts may have three components: (1) fertile OIB source material from depth that is dominant, (2) the melt layer, and (3) assimilation of the metasomatic vein lithologies formed earlier in the growing/grown lithosphere. It is probable that the fertile source material from depth may be (or contain) recycled ancient metasomatized deep portions of oceanic lithosphere. In any attempt to explain the origin of mantle isotopic end-members as revealed from global OIB data, we must (1) remember our original assumptions that the primitive mantle (PM) soon after the core separation was compositionally uniform/homogeneous with the core playing a limited or no role in causing mantle isotopic heterogeneity; (2) not use OIB isotopes to conclude about the nature and compositions of ultimate source materials without understanding geochemical consequences of subduction zone metamorphism; and (3) ensure that models and hypotheses are consistent with the basic petrology and major/trace element geochemistry.

ocean islands, intra-plate magmatism, mantle source heterogeneity, mantle metasomatism, seismic low velocity zone processes

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If the facts don't fit the theory, change the facts. — Albert Einstein

The above is a widely circulated attribution to Albert Einstein without a known source. The same or similar with known sources are my personal written communications: “‘Facts’ have a half-life; so does the ‘Truth’.” (Michael J. O’Hara); “*The history of petrogenesis has been the history of re-interpretations of origins.*” (Peter J. Wyllie). In my view, these statements are useful reminders to anyone who claims him or her to be a researcher using facts or collecting facts in the process of searching for truth. The essence is that many of the so-called facts are not facts, but interpretations, experiences or perhaps even legends passed on from one (generation) to another over the years. To distinguish interpretations from facts is straightforward in concept, but is not so in practice. For example, observations are not necessarily facts as their meanings are often interpreted by observers. The most common problem that many of us face is the scenario that we may imperceptibly treat some authority interpretations as facts or as being correct without questioning. This is unhealthy and inhibits the advance of our science. What is worse is the situation when we recognize the errors in the authority interpretations, we do not have the courage to challenge, perhaps for complex reasons, including the scenario where we must admit our own mistakes in having previously supported those authority interpretations.

The foregoing is of general significance in our scientific practice, and is particularly pertinent to the theme of this contribution—the history and current views on the origin of intra-plate ocean island basalts (OIB), which is one of the most fundamental problems in modern petrology and geochemistry of the solid Earth, and in which I have been heavily involved. Recognizing that mantle source for oceanic basalts is compositionally heterogeneous and OIB are more enriched in incompatible elements than the more widely distributed mid-ocean ridge basalts (MORB), Hofmann and White^[1] proposed “*Mantle plumes from ancient oceanic crust*”, meaning explicitly that mantle source material for OIB is recycled ocean crust (ROC). This ROC interpretation has been widely accepted as being correct and has influenced many minds over the past 27 years, including, at one stage, myself. I produced the very first high quality trace element data on seafloor basalts. Some aspects of the data set can be explained by the presence of ROC in

the source region of these basalts. This has led to the paper by Niu and Batiza^[2] “*Trace element evidence from seamounts for recycled oceanic crust in the eastern equatorial Pacific mantle*”. However, I soon realized that the data as a whole are inconsistent with this ROC interpretation and ROC cannot be the major source material for OIB in terms of basic petrology, geochemistry and mineral physics^[3–5]. Without directly addressing the criticisms by Niu and O’Hara^[4], Hofmann and co-authors have published a series of papers^[6,7] defending the ROC model.

In this paper, I afford new arguments along with the existing data and known observations to discuss the nature of OIB source materials and their petrogenesis. I do not anticipate every reader to agree with me, but I do make effort such that readers can appreciate that my statements are objective and my conclusions are based on sensible interpretations of the observations with justifications, careful thinking and logical reasoning.

1 Introduction

The primitive mantle (PM) is the silicate portion of the bulk Earth. If we assume the PM to be compositionally uniform, we must explain why the mantle source for mid-ocean ridge basalts (MORB) is more depleted both isotopically and in terms of incompatible elements than the mantle source for OIB. By interpreting MORB mantle depletion as resulting from continental crust extraction in Earth’s early history^[8–10], we could be satisfied with the OIB source being less depleted than the MORB source. However, OIB source is not just less depleted, but enriched in incompatible elements relative to the PM^[4,11–13]. It also varies significantly in inferred abundances and ratios of incompatible elements as well as radiogenic isotopes from one island to another and from one group of islands to another group. Therefore, the mantle source for OIB is heterogeneous on all scales.

By accepting the assumption that the entire mantle is largely in the solid state and that solid-state elemental fractionation is practically unlikely^[14], it is logical to suspect that processes known to occur in the upper mantle and crust (e.g., magmatism, metamorphism, differential weathering, transport and sedimentation) are the likely causes of elemental fractionation. These shallow or near-surface fractionated materials are then introduced into mantle source regions of oceanic basalts through subduction zones. Mantle compositional het-

erogeneity is thus a general consequence of plate tectonics because of crust-mantle recycling. Among many contributions endeavouring to understand the origin of mantle compositional heterogeneity in the context of plate tectonics is the classic ROC model by Hofmann and White^[1]. They proposed that “oceanic crust is returned to the mantle during subduction...”. Eventually, it becomes unstable (at the core-mantle boundary or CMB; see ref. [15]) as a consequence of internal heating, and the resulting diapirs become the source plumes feeding oceanic island basalts and hot spot volcanism.” They also stressed that this recycled ancient oceanic crust, which is the source of OIB, is geochemically more “enriched” in K, Rb, U, Th, and light rare-earth elements relative to the more “depleted” source of MORB. While some details are considered conjectural, the principal idea of the model has, since 1982, been widely accepted by the solid Earth community as being correct, except for those who share the view of Niu and co-authors^[3–5].

Some authors suggest that subducted terrigenous sediments may be responsible for the incompatible element enriched signature of OIB^[16–18]. Others emphasize the importance of mantle metasomatism as an effective cause of enriched geochemical signature of OIB^[3,4,19–28].

2 Recycled oceanic crust is too depleted to be source material for OIB

Niu and O’Hara^[4] demonstrated in terms of straightforward petrology, trace element/isotope geochemistry and mineral physics that ancient recycled oceanic crust cannot be the major source material for OIB. It is noteworthy that we cannot rule out the presence of recycled ocean crust material in OIB source regions however small amount it may be. By assuming that (1) plate tectonics began at ~3.0 Ga (unknown; see ref. [29]), (2) the oldest ocean crust may not be older than 250 Ma before subduction as is the case at present, (3) the average thickness of ocean crust is about 5 km as is at present, then the amount of recycled ocean crust since 3.0 Ga would be ~1.5 wt% of the entire mantle if whole-mantle convection has been the case or ~6 wt% if plate tectonics related mantle convection has been restricted to the upper mantle. So, statistically, ancient subducted oceanic crust material could be present in OIB source regions. However, material with ocean crust composition is very dense under mantle conditions, and it is not straightforward how such dense material can rise in bulk to OIB

source regions^[4].

On the other hand, if we carefully analyze some of the widely accepted interpretations on chemical geodynamics, we can readily see that the ROC interpretation for OIB is flawed. Figure 1 shows this analysis. How can melting of incompatible-element-depleted ROC produce incompatible-element-highly-enriched OIB (process 4 in Figure 1)? Figure 2 compares two independent estimates of average OIB^[19,30] with average N-type MORB^[19] and the mean composition of ocean crust^[4]. It is clear that the ocean crust (or ROC when injected into the mantle) is too depleted in incompatible elements to be possible source material for OIB. In fact, calculations have shown that partial melting of the ROC cannot produce OIB and that partial melting of the PM cannot produce OIB^[12,13,31]. That is, the required source materials for many OIB suites must be even more enriched than the PM^[3,4,12,13,19,20].

Despite the above straightforward analysis and demonstration, Hofmann and co-workers have insisted on the ROC model for OIB^[6,7,32]. Sobolev et al.^[32] interpreted the composition of olivine melt inclusions in some Hawaiian lavas as recording “ghost” plagioclase of ancient recycled gabbros (lower ocean crust). However, as their host olivine is a liquidus phase crystallized from the cooling and evolving melts in crustal magma chambers, the trapped melt cannot be primary melt in equilibrium with mantle minerals^[4]. Hence, caution is necessary when using olivine melt inclusions to infer mantle sources/processes.

Sobolev et al.^[6] argued that the high Ni content in olivine phenocrysts of Hawaiian lavas reflects the presence of volumetrically significant ROC in the mantle source region. The ROC melted first to produce SiO₂-saturated melt, which then reacted with the harzburgite and produced the olivine free pyroxenite in the Hawaiian lava source region. The absence of olivine in the source region then explains the high Ni in the parental melt and hence the high Ni in the olivine phenocrysts crystallized from the Ni-rich melt in a shallow level magma chamber. While this interpretation is interesting, it has been shown in terms of straightforward phase equilibria that Hawaiian basalts require olivine present in the source region^[33]. Furthermore, a robust Ni-olivine Kd and mass balance analysis^[34] pointed out that the calculations and interpretations by Sobolev et al.^[6] on Hawaiian lavas and olivines are flawed. Importantly, the above olivine-free OIB source model cannot in any-

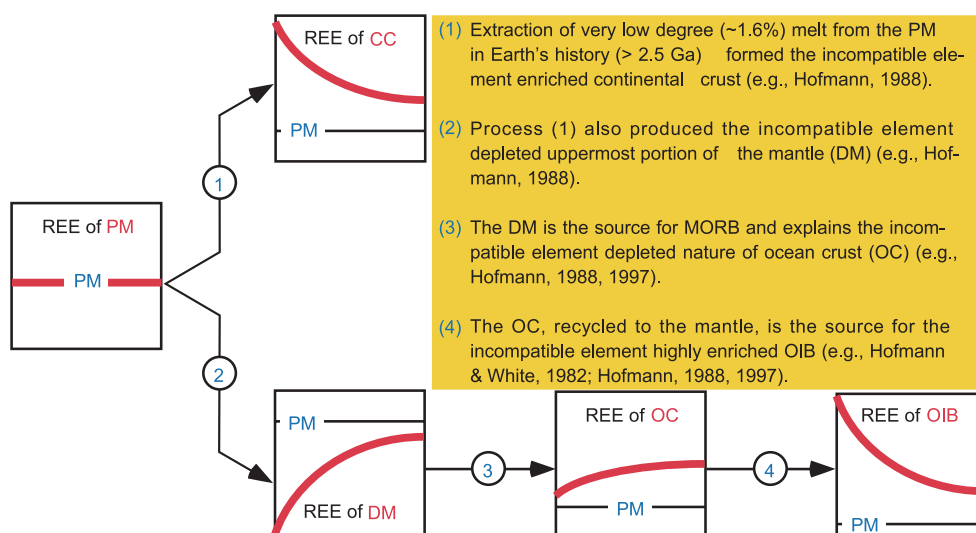


Figure 1 Using schematic rare earth element (REE) patterns to illustrate the general view on the origin of the compositional complementarity between the continental crust (CC) and oceanic crust (OC) following the original work of Hofmann^[10,18]. Note that it is not straightforward how to produce OIB (process 4) that is highly enriched in incompatible elements (e.g., $[\text{La}/\text{Sm}]_{\text{PM}} \gg 1$) by melting the OC that is highly depleted in incompatible elements (e.g., $[\text{La}/\text{Sm}]_{\text{PM}} < 1$), yet “OIB from recycled OC” remains the most popular model on the petrogenesis of OIB since Hofmann and White^[1] despite many difficulties of this model^[4]. PM refers to the primitive mantle.

way at all explain the incompatible-element-enriched Hawaiian OIB geochemistry (see Figure 2).

Sobolev et al.^[7] have gone a step further to argue that Ni content in olivine phenocrysts can be used to estimate the proportions of ROC in mantle source regions of basalts erupted in both ocean basins and on land. Their observation that olivine Ni contents are high in basalts erupted on thick (e.g., >70 km) lithosphere, low in basalts erupted on thin (e.g., <70 km) lithosphere, and lowest in MORB is actually consistent with the lithosphere thickness control on the pressure of melting or the “lid effect”^[35]. That is, the melting pressure or final depth of melt equilibration increases with increasing lithosphere (lid) thickness^[12,31,36], whereas olivine Ni-Kd values decreases with increasing pressure^[37,38]. As a result, parental melts erupted on thick lithosphere are of high-P melting with high Ni, whereas parental melts erupted on thin lithosphere are of low-P melting with low Ni. Consequently, Ni contents in olivines crystallized from all these melts at shallow level magma chambers are proportional to Ni contents in the parental melts, and are high in basalts erupted on thick lithosphere and low in basalts erupted on thin lithosphere. This straightforward phase equilibria control is superior to the interpretation that ROC is necessarily more abundant in OIB source regions beneath thick lithosphere than beneath thin lithosphere^[7], which is coincidentally possible, but lacks physical reasons and scientific

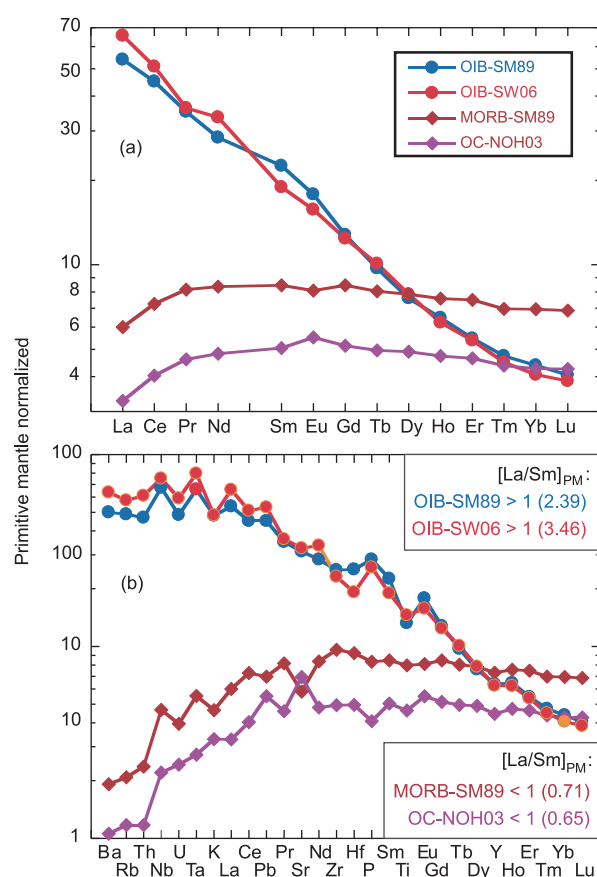


Figure 2 Comparison of average OIB^[19,30] with average N-type MORB^[19] and model ocean crust (OC)^[4] in terms of REE (a) and multiple incompatible element abundances (b) normalized against the primitive mantle (PM^[19]). It is clear that the OC is too depleted in incompatible elements to be source material for OIB.

foundation.

In summary, fragments of ROC material can exist statistically in source regions of oceanic basalts. Therefore, presence of some geochemical signals of ROC in oceanic basalts, if any, is not surprising although how the dense ROC can rise in bulk from the lower mantle (if whole mantle convection is true) or from the transition zone (if plate tectonics-associated mantle convection is restricted to the upper mantle) to source regions of oceanic basalts remains unanswered. However, the ROC model has many more difficulties than certainties as demonstrated by Niu and O'Hara^[4]. Readers are referred to this paper^[4] for all the difficulties, including in particular the lack of signatures of subduction-zone metamorphism/magmatism in the geochemistry of OIB if the latter were indeed from recycled oceanic crust. I emphasize in this current contribution that recycled oceanic crust is too depleted to be source material for OIB (Figure 2). I provocatively present Figure 3 (after ref. [5]) with the hope for a genuine scientific discussion/debate.

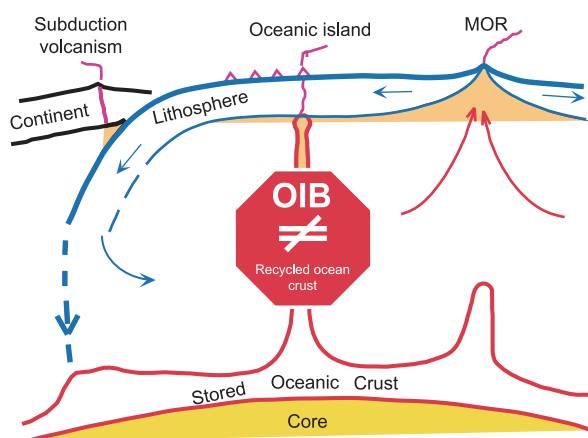


Figure 3 Cartoon (after ref. [5]) modified from Hofmann and White^[1] to emphasize that recycled ocean crust (ROC) is inappropriate as the major source material for OIB (see refs. [4, 5]).

3 Continental sediments are unsuitable as source material for OIB

Many authors suggest that subducted terrigenous sediments are responsible for the incompatible element enriched signature of OIB^[16–18,39–43]. In the context of plate tectonics with mantle circulation and crustal recycling, it is possible and also likely that terrigenous sediments can be transported to source regions of oceanic basalts. The question remains whether these sediments are indeed enriched component seen in OIB. Looking at the REE

patterns (Figure 4(a)), the similarity of average OIB^[19,30] to bulk continental crust (CC^[44]) and global subducting sediments (GLOSS^[45]) is encouraging, but we can readily see the problems with many other elements considered (Figure 4(b)). The CC and GLOSS have characteristic depletion in Nb, Ta, P and Ti and enrichment in Pb—such “CC-like signature” is rather strong and should impart OIB if terrigenous sediments were the enriched component of OIB. In fact, if anything, OIB is relatively enriched, not depleted, in Nb (vs. Th) and Ta (vs. U) (Figure 4(b); also see ref. [2]).

It is noteworthy that Rapp et al.^[46] have recently conducted high pressure (16 to 23 GPa) experiments on terrigenous sediments. They discovered that the stable assemblage has 15% to 30% K-hollandite and “this

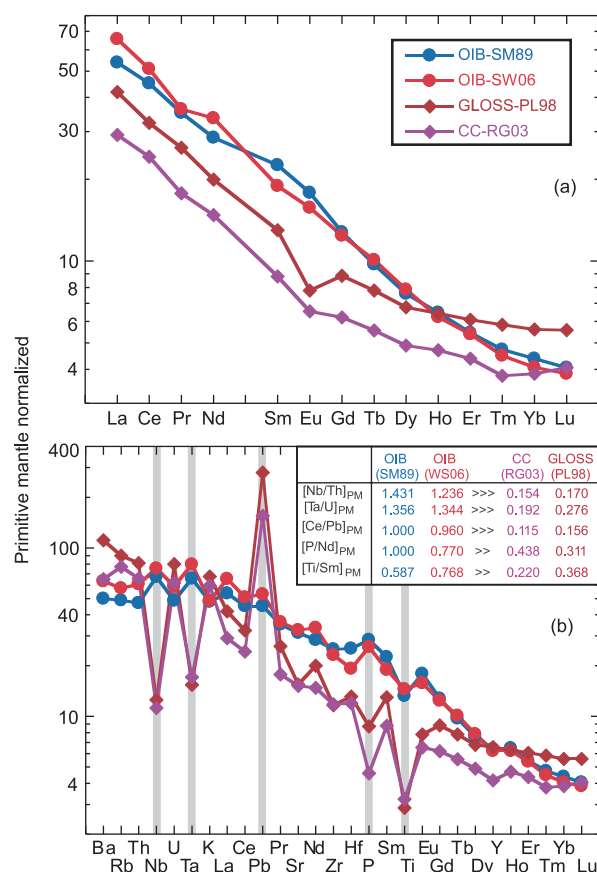


Figure 4 Comparison of average OIB^[19,30] with model bulk continental crust (CC^[44]) and the model global subducting sediments (GLOSS^[45]) in terms of REE (a) and multiple incompatible element (b) abundances normalized against the primitive mantle^[19]. It is clear that the CC (i.e., terrigenous sediments) and GLOSS have the characteristic “continental signature” (i.e., enrichment in Pb and depletion in Nb, Ta, P and Ti) and is thus unsuitable as source material for OIB. If anything, OIB is enriched, not deleted, in Nb (vs. Th) and Ta (vs. U) in contrast to the CC and GLOSS.

phase controls a significant proportion of the whole-rock budget of incompatible, large-ion lithophile elements (LILE, e.g., Rb, Ba, Sr, K, Pb, La, Ce and Th). They stated further that “comparisons between the abundances and ratios of these elements in K-hollandite with those in EMI type ocean-island basalts from Pitcairn Island and related seamounts, and with the Gaussberg lamproites, indicate the presence of deeply recycled, continent-derived sediments in these lavas’ sources.” They continued “our results suggest that the incompatible trace-element signature of EMI OIB reservoirs in general and of the Gaussberg lamproites in particular can be attributed to recycling of K-hollandite-bearing continental sediments to transition zone depths.” They reached such conclusions without considering Nb, Ta, Zr, Hf and Ti. By considering all these elements in their experimental data, we can readily see that their high-pressure pressed terrigenous sediments with high-P mineral assemblages essentially have the same trace element characteristics as the bulk CC and GLOSS, but differ markedly from average OIB (Figure 5). Willbold and Stracke^[30] have shown that OIB end-members such as EM1, EM2 and HIMU^[47] cannot be uniquely distinguished in terms of incompatible trace elements alone. So, the experimental results by Rapp et al.^[46] do not support their conclusions and continental sediments can retain their trace element characteristics under mantle conditions if the subducted sediments could survive subduction-zone modifications (see below).

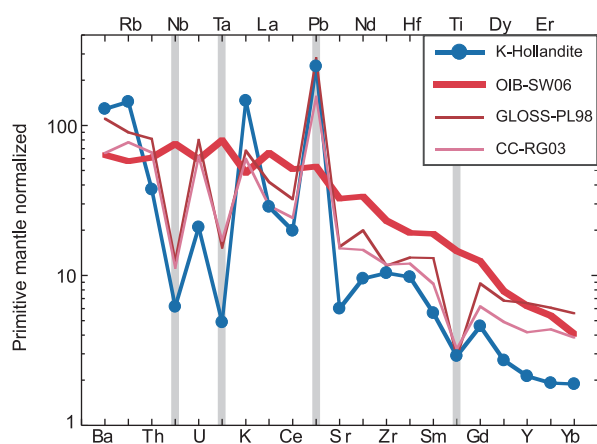


Figure 5 Contrary to the conclusion by Rapp et al.^[46], terrigenous sediments (i.e., CC derived material) under mantle conditions as represented by K-hollandite, the primary host of incompatible elements, retain their trace element signatures and differ markedly from OIB^[30]. Hence, terrigenous sediments (i.e., CC^[44]) cannot be the primary enriched source material for OIB and alkali magmas. GLOSS^[45] is plotted for comparison.

In summary, while it is convenient to invoke continental sediments as an enriched component in OIB source regions, OIB do not actually possess geochemical signatures of the CC or GLOSS. The experimental data by Rapp et al.^[46] do not support their conclusions. In fact, it is not surprising why continental sediments have the same composition whether they are squeezed or not under mantle conditions because the experimental charges are closed systems with no gain or loss of most of these analyzed elements.

4 Mantle metasomatism and the products are best candidates for the enriched characteristics of OIB

The recognition that OIB source materials are more enriched in incompatible elements than the primitive mantle (i.e., $[La/Sm]_{OIB\ Source} > [La/Sm]_{PM}^{[3-5,12,13,19,20]}$) and are more enriched in the progressively more incompatible elements (Figure 6) suggests that OIB sources have undergone a low-degree melt enrichment process or mantle metasomatism. The mantle metasomatism has been described as mantle peridotites (whether primitive mantle or previously depleted melting residues) being infiltrated by a “low-degree” (low-F) melt that is enriched in volatiles (e.g., H₂O and CO₂) and incompatible elements inferred from studies of mantle melts^[19,48,49], from metasomatic minerals (e.g., amphibole, phlogopite) and vein lithologies (e.g., garnet pyroxenite, pyroxenite).

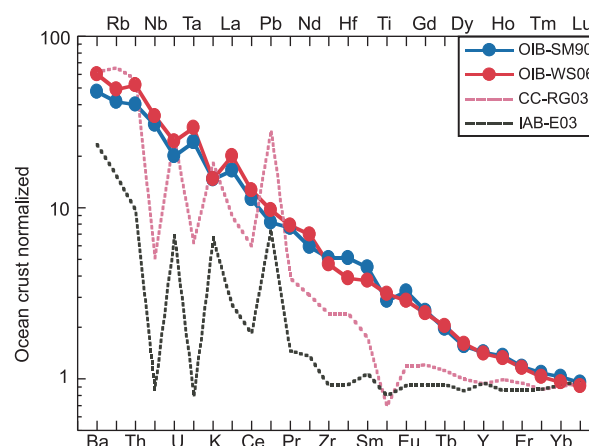


Figure 6 Illustration on ocean crust^[4] normalized multi-element diagram that OIB is enriched in the progressively more incompatible elements, indicating that the enriched component in OIB is of low-degree melt magmatic origin (i.e., mantle metasomatism). Average OIB compositions are as in Figures 2 and 4^[19,30]. For comparison, model compositions of CC^[44] and Island arc basalts (IAB^[81]) are also plotted.

and hornblende) in mantle xenoliths^[50–54] and massif peridotites on land^[26,55,56], and mantle xenoliths from ocean islands^[57,58].

However, where, how and under what conditions such low-F melt metasomatism may take place in the mantle has not been well discussed. Mantle wedge overlying subduction zones is a good candidate (see ref. [24]), but the metasomatic agent there may have an arc-melt signature (i.e., $[\text{Nb}/\text{Th}]_{\text{PM (IAB)}} \ll 1$ and $[\text{Ta}/\text{U}]_{\text{PM (IAB)}} \ll 1$), whereas both MORB and incompatible element-enriched OIB all have $[\text{Nb}/\text{Th}]_{\text{PM (MORB, OIB)}} \geq 1$ and $[\text{Ta}/\text{U}]_{\text{PM (MORB, OIB)}} \geq 1$ ^[2,11,23]. Indeed, the interface between the base of the growing oceanic lithosphere and the seismic low velocity zone (LVZ) atop the asthenosphere is an ideal site for mantle metasomatism^[3,4]. Figure 7 shows that oceanic lithosphere grows with time through basal accretion of the LVZ material (red arrows) before reaching its full thickness (after ~70 million years). The presence of incipient melt is required by and characterizes the LVZ^[4,28,59–62]. This incipient melt would be enriched in volatiles (e.g., H_2O , CO_2) and incompatible elements^[3,4]. As the melt is buoyant at such a depth range, it tends to concentrate into a melt-rich layer

(in green; Figure 7) atop the LVZ. In the process of the lithosphere growth, the uppermost LVZ material forms spinel/garnet lherzolite as newly accreted lithosphere. Trapped low-F melts (from the melt-rich layer) collect and ascend, crystallizing liquidus minerals that add to the ambient peridotite (modal metasomatism)^[54], and leaving behind veins of garnet pyroxenite, hornblende-pyroxenite and hornblende (yellow veins) before being finally absorbed in the ambient minerals (cryptic metasomatism)^[54]. A parcel of mantle (perhaps “plumes”?) ascends and partially melts by decompression when intersecting the solidus. These “plume” melts may gain additional incompatible element enrichments from the melt layer (in green; Figure 7). Continued ascent of the “plume” melts through the lithosphere can assimilate earlier-formed metasomatic veins, leading to further enrichments of ultimately erupted OIB melts^[27,28].

It becomes apparent that the erupted OIB melts may have three components: (a) fertile mantle source materials from depth (plumes?), (b) the melt layer (green), and (c) assimilation of the metasomatic vein lithologies formed earlier (Figure 7). It is also conceptually important to note that the fertile materials from depth (i.e.,

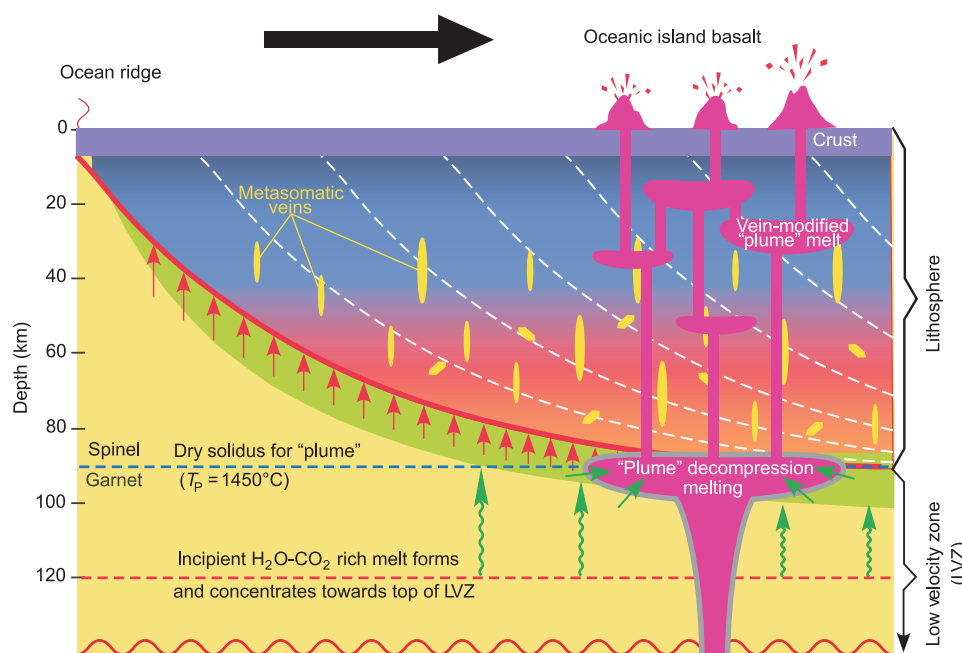


Figure 7 After Humphreys and Niu^[12] to show that mantle metasomatism may take place at the interface between the growing oceanic lithosphere and the top of the seismic low velocity zone (LVZ) where a melt-rich layer (green) may exist^[59–62] and is enriched in volatiles (e.g., H_2O , CO_2) and incompatible elements^[4,11,28]. In the process of the lithosphere growth, this melt will also collect and ascend, crystallizing liquidus minerals added to the ambient peridotite (modal metasomatism), and leaving behind veins of pyroxenite and hornblende^[26,50–54,82] (yellow veins) before being finally absorbed in the ambient minerals (cryptic metasomatism)^[54]. A parcel of mantle material (perhaps “plumes”?) ascends and partially melts by decompression when intersecting the solidus. These “plume” melts may gain additional incompatible element enrichments from the melt layer (green). Continued ascent of the “plume” melts through the lithosphere can assimilate the metasomatic veins formed earlier; leading to further enrichments of ultimately erupted OIB melts^[28].

component “a”) are volumetrically dominant, compositionally peridotitic, and may contain recycled previously metasomatized deep portions of “ancient” oceanic lithosphere that is already enriched in volatiles and incompatible elements for the petrogenesis of the bulk OIB^[4]. Component “a” is required for OIB, explaining the basaltic/picritic composition and the coupling between incompatible elements and radiogenic isotopes in many OIB suites^[4]. Such coupling requires a time interval between formation of metasomatized mantle (see Figure 7 for concept) and the volcanism in excess of 1.0 Gyr, which may represent a minimum period from the time of the subduction of metasomatized oceanic lithosphere into deep mantle to the return of these materials to source regions of basalts^[4].

Components “b” and “c” are not required for contemporaneous OIB volcanism, but their presence and involvement (see Figure 7), if any, can contribute to extremely enriched lavas such as alkali basalts, basanite and nephelinite on many ocean islands and some intra-plate seamounts. In this case, incompatible elements and radiogenic isotopes may be decoupled because of significant parent-daughter element fractionation by the recent metasomatism (Figure 7), yet without having enough time to produce radiogenic isotopes^[4]. For example, the association of incompatible element enrichment with depleted radiogenic isotopic signature is a consequence of the more recent metasomatism^[22,63].

The occurrence of highly alkali basalts at off-ridge seamounts on the young (<3 Ma) seafloor^[64] suggests that the LVZ-related metasomatism is a rapid process. It follows from this and the foregoing discussion that the history of oceanic lithosphere growth through basal accretion in its first ~70 Myrs is the history of the oceanic mantle lithosphere metasomatism^[28] (Figure 7). Hence, mantle lithosphere metasomatism is a widespread phenomenon. The same applies to continental settings if the LVZ is present and if the lithosphere growth through basal accretion occurs. The more recent lithosphere thickening in eastern China, for example, is predictably accompanied by such metasomatism.

5 Continental mantle lithosphere as a potential enriched source for OIB

McKenzie and O’Nions^[20] suggested that subcontinental lithospheric mantle (SCLM) can be important source material for OIB. Because the bulk property of the

SCLM is compositionally depleted (in terms of a basaltic component) and physically buoyant, the geochemically enriched component in the SCLM as a potential OIB source material refers to metasomatic assemblages as evidenced by metasomatic minerals (e.g., amphibole, phlogopite) and vein lithologies (e.g., garnet pyroxenite, pyroxenite and hornblendite) from mantle xenoliths^[50–54] and massif peridotites^[26,55,56]. So, the origin of the metasomatism in the SCLM is the same as that in the growing oceanic lithosphere (see Section 4 above) although the seismic LVZ that is the source of the metasomatic agents (see below) is poorly defined beneath continents except in eastern Australia, eastern China and locations associated with continental rift systems.

The involvement of metasomatized SCLM in intra-plate continental magmatism is physically straightforward, but how metasomatized SCLM materials get involved in OIB source regions is not. This requires that the metasomatized SCLM become part of the convective (asthenospheric) mantle system. SCLM delamination is a widely invoked “process”, but how such process works remains poorly understood because it is physically difficult for the buoyant SCLM to sink into the denser asthenosphere. I maintain the concept of basal hydration-weakening as the most effective mechanism to convert the “lithospheric mantle” into “asthenospheric mantle”^[65,66] in the context of discussing the origin of the lithosphere thinning in eastern China. The paleo-Pacific oceanic lithosphere seismically prominent in the transition-zone beneath eastern China serves as the source of water. Dehydration induced hydrous melt can ascend and effectively weakened the base of the lithosphere and transform the basal lithosphere into asthenosphere. It is important to note that a literature search readily reveals that wherever the idea of “lithosphere delamination” is invoked, oceanic lithosphere subduction was ongoing either simultaneously or shortly beforehand. Other examples include the southern Andes, the western USA, the western Mediterranean and Tibet. On the other hand, mantle plumes have been proposed to have impinged on or to underlie the African lithosphere, yet the lithosphere thinning there has only occurred on limited scales and been associated with active rift zones or ancient sutures. This suggests that thermal erosion, if thermal mantle plumes did indeed exist beneath Africa, is ineffective in thinning the lithosphere, and the role of water or hydration-weakening is indeed the key mechanism^[65,66]—no

oceanic lithosphere subduction is currently ongoing or occurred in the recent past beneath the African plate, i.e., no source of water introduction into the sub-African lithosphere. The closest plate boundaries to the African plate are ocean ridges, the south Mid-Atlantic Ridge, the Southwest Indian Ridge, the Central Indian Ridge and the Red sea spreading centers (see ref. [66]).

It is also noteworthy that regardless of the history and actual mechanism of lithosphere thinning in eastern China and eastern Australia, their present-day lithosphere-asthenosphere structure resembles that beneath ocean basins^[67–69], which, in my view, results from the presence of well-developed seismic LVZ as a result of the presence of water and hydrous melt.

6 The nature of metasomatic agents

The observation that metasomatic vein lithologies (pyroxenite, hornblende, other amphibole and phlogopite bearing assemblages as well as grain-boundary enrichments etc.) are common in deep portions of both oceanic and continental lithosphere requires that the metasomatic agents originate from the seismic LVZ. The observation that OIB are more enriched in the progressively more incompatible elements (Figure 6) requires that the metasomatic agents are incipient H₂O- and CO₂-rich silicate melts. It is important to note that carbonatite melt as a metasomatic agent has become popular in the last few years^[70–72], but carbonatite melts have variably different trace element systematics from OIB^[73,74] and would be compositionally unsuitable as metasomatic agents for OIB.

Having established that the metasomatic agent is likely to be H₂O- and CO₂-rich incipient melt in the LVZ, it is necessary to discuss briefly the origin of H₂O and CO₂ (or other reduced forms such as CH₄). Many lines of direct and indirect evidence indicate that volatiles are abundant in the earth's mantle^[75], some of which are likely to be primordial and some may be recycled through plate tectonics. For example, subduction-dehydration is necessarily incomplete^[65,76], and the paleo-Pacific oceanic lithosphere in the transition-zone beneath eastern China is probably an effective source of water that is undergoing isobaric heating and dehydration. The latter may be the very cause of the LVZ beneath eastern China (as is eastern Australia), resembling the upper mantle structure beneath ocean basins. Under great mantle depths, volatiles likely reside in the other-

wise stable nominally anhydrous phases, but can exist as a free vapour phase (or phases) in the sub-lithospheric upper mantle, inducing incipient melting and the LVZ.

7 A radiogenic isotope perspective

I have not yet touched on radiogenic isotopes not because they are unimportant, but because much of the discussion on mantle source heterogeneity in general and OIB source variability in particular over the past ~ 25 years has concentrated on radiogenic isotopes without much success^[18,47,77]. In my view, the validity of any model used to explain OIB source isotopic heterogeneity must pass basic tests in terms of straightforward petrology and major/trace element geochemistry as discussed above and elaborated in detail by Niu and O'Hara^[4]. If a model fails the test of basic petrology and geochemistry, its implications for isotopic heterogeneity become insignificant. If a model fails to explain simple isotopic systems such as Rb-Sr, Sm-Nd and Lu-Hf, then its implications for the more complex isotope systems such as U-Pb and Th-Pb cannot be very useful.

The global MORB and OIB data define first-order linear mantle arrays in Sr-Nd, Sr-Hf and Nd-Hf spaces, which could be explained by mixing between enriched (radiogenic Sr and unradiogenic Nd and Hf) and depleted (unradiogenic Sr and radiogenic Nd and Hf) source materials in terms of magmatic processes with complex histories. However, it is the consideration of Pb isotopes in OIB that has led to the general perception that several isotopically distinct mantle source end-members (e.g., DM, EM1, EM2, HUMU) are required to explain the global mantle isotopic variability^[18,47,77] (Figure 8). The depleted MORB mantle (DM) is thought to result from continental crust extraction in Earth's early history, but the origin of OIB end-members is enigmatic. The isotopic ratio differences among these endmembers reflect the differences of the radioactive parent/radiogenic daughter (P/D) ratios (e.g., Rb/Sr, Sm/Nd, U/Pb and Th/Pb) in their ultimate mantle sources, which with time evolve to distinctive fields in isotope ratio spaces. By assuming (1) the earth's core has played little role in causing mantle isotopic heterogeneity, (2) the PM was compositionally uniform/homogeneous soon after the core separation, and (3) significant P-D element fractionation in the solid state is unlikely in the deep mantle due to extremely slow diffusion^[14], then processes known to occur in the upper mantle and crust (e.g., par-

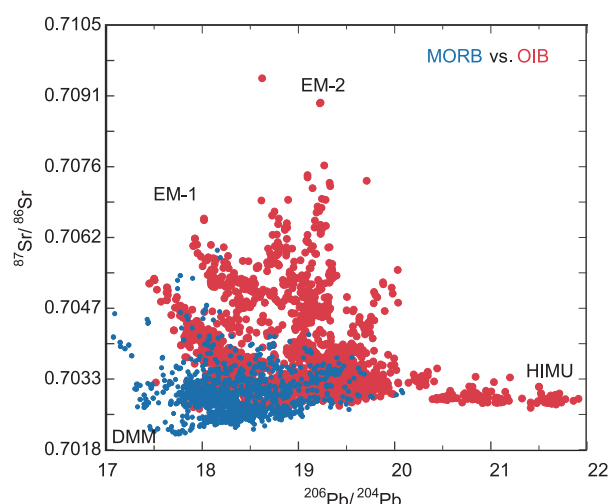


Figure 8 Mantle isotopic end-members defined by the global OIB and MORB data in $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ space. The data are from the compilation of Stracke et al.^[83] plus those reported by Regelous et al.^[84,85], Wendt et al.^[86] and Niu et al.^[23].

tial melting, magma differentiation, metamorphism, differential weathering, transport and sedimentation) are the likely causes of any P/D fractionation. Subduction of these *shallow and surface processed materials (SSPM)* must be volumetrically the major agent that causes mantle compositional heterogeneity. The latter has led to the contention that such heterogeneities can be related to specific subducted components, namely:

(1) Subduction of land-derived sediments with high Rb/Sr and low Sm/Nd of upper continental crust contributes to EM2 type lavas; (2) subduction of pelagic sediments, depleted oceanic lithosphere, and metasomatized continental lithosphere are likely candidates for EM1 type lavas; and (3) subducted altered oceanic crust with high U/Pb ratio and appropriate values for other P/D ratios produces mantle sources with HIMU type characteristics^[18,30,39,40,47,78–80]. While these interpretations are apparently reasonable, they encounter the problems elaborated in Sections 3 and 4 above. Furthermore, these interpretations cannot be in anyway validated without a critical assessment of the geochemical consequences of subduction-zone metamorphism. Figure 9 shows that subducted *SSPM* can be modified as they pass through the subduction factory and this process needs to be accounted for in any realistic mass balance models. In other words, we cannot simply use OIB isotopes to infer the compositions of subducted “sediment” (of various types) or “altered oceanic crust”. We must assess and characterize the modified equivalents of these components that have passed through the subduc-

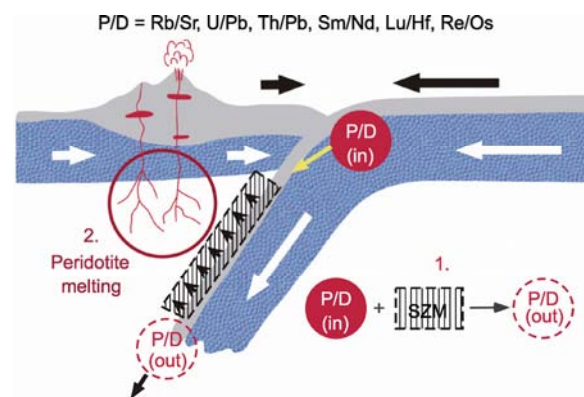


Figure 9 Cartoon showing that P/D (radioactive parent/radiogenic daughter elements) ratios of materials entering the “subduction factory” will change because of subduction-zone (dehydration) metamorphism (SZM) (1), which is required to cause mantle wedge melting for arc magmatism (2). Hence, $P/D(\text{in}) \neq P/D(\text{out})$, and it is P/D ratios of materials out of the subduction factory, i.e., “P/D (out)”, that determine mantle source isotopic compositions that could be recognized in OIB. That is, in an attempt to explain mantle isotopic variations in the context of plate tectonics (i.e., crust-mantle recycling), it is necessary to understand the geochemical consequences of subduction-zone metamorphism^[4] before using OIB isotopes to infer P/D ratios in ultimate source materials processed at shallow levels (magmatism and metamorphism) or at the surface (weathering on land and on the seafloor).

tion factory. Hence, understanding the geochemical consequences of subduction-zone metamorphism is key towards understanding mantle isotopic heterogeneity, while keeping in mind the common assumptions in testing these various hypotheses.

8 Summary

(1) One of the fundamental advances in modern geochemistry of the solid Earth is the recognition of chemical and isotopic heterogeneities in the Earth’s mantle through studies of oceanic basalts, in particular OIB. A large Sr-Nd-Hf isotopic variability is conspicuous on a global scale and can be interpreted to a first-order (not in detail) as resulting from mixing between depleted MORB source and an enriched component. However, consideration of Pb isotopes has led to several distinct mantle source end-members (e.g., DMM, EM1, EM2 and HIMU). Despite much effort, our current understanding on the origin of these mantle isotopic end-members remains unsatisfactory for several reasons.

(2) One reason is that we have concentrated our effort in terms of plate tectonic processes by assuming that (a) the primitive mantle (PM, after the core separation) is compositionally homogeneous/uniform throughout, and

(b) the core has played little role in causing mantle isotopic heterogeneity. These working assumptions are necessary, but may not be correct at least for U-Pb and Th-Pb isotopic systems.

(3) Another obvious reason is that we have imperceptibly treated *SSPM* with a particular set of P/D ratios entering subduction zones as ultimate source material of a particular isotopic end-member by assuming such P/D ratios do not change during subduction-zone metamorphism. This is unlikely to be correct given the “known” slab dehydration metamorphism and the induced subduction-zone magmatism. Hence, to understand the geochemical consequences of subduction metamorphism is essential towards an improved understanding of mantle isotopic heterogeneity.

(4) The most important reason is that all the existing efforts in explaining the mantle isotopic heterogeneity is essentially based on isotopic studies only without considering basic petrologic and geochemical feasibility. For example, altered ocean crust with possibly high U/Pb is thought to be the origin of HIMU lavas and subducted terrigenous sediments with high Rb/Sr is thought to be the source of EM2 lavas. However, in terms of incompatible trace elements, EM1, EM2 and HIMU lavas are essentially indistinguishable, but all differ distinctively from the ocean crust and continental crust.

(5) Recycled ocean crust (MORB lavas, sheeted dikes and deep crustal gabbros individually or taken together) are too depleted (e.g., $[La/Sm]_{PM} < 1$) to be source material for incompatible element enriched ($[La/Sm]_{PM} \gg 1$) OIB.

(6) While recycled terrigenous (continental) sediments are enriched in incompatible elements with $[La/Sm]_{PM} \gg 1$ resembling that of OIB, they have characteristic “CC-like signature” (i.e., Pb enrichment and Nb, Ta, P and Ti depletion) and are thus unsuitable as a major source material for OIB.

(7) OIB melts may have three components: (a) fertile OIB source material from depth, (b) a melt layer that may develop at the interface between the growing oceanic lithosphere and the seismic LVZ accumulated from incipient melt within the LVZ, and (c) the metasomatic vein lithologies by the melt layer formed earlier in the lithosphere. Component “a” is compositionally peridotitic, volumetrically dominant, and may contain or come from recycled ancient metasomatized deep portions of oceanic lithosphere.

(8) Many of the issues/problems discussed here also apply to basaltic volcanism in continental settings away from plate boundaries with at least three differences: (a) uniquely stronger lithospheric lid-effect on melt compositions, especially for those erupted on thickened lithosphere, (b) the assimilated metasomatic vein lithologies are likely older with associated isotopic imprint, and (c) inevitable and varying extent of crustal contamination.

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