The Earth's Central Part: Its Structure and Dynamics, edited by T. Yukutake, pp. 357–367.
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Polynesian Super Plume: A Window down to the Core/Mantle Boundary

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(Received July 29, 1994; Revised December 12, 1994; Accepted December 13, 1994)

Characteristics of five proposed geochemical reservoirs in the Earth's mantle has been discussed based mainly on isotope compositions of basalt lavas in the oceanic regions. Among these, the HIMU source with higher Pb isotope ratios is characteristically documented in the two regions, S. Pacific and W. Africa, where the low-velocity mantle column down to the base of the lower mantle has been observed by seismic tomography. It is thus possible to consider that the HIMU source is located near the core/mantle boundary and that the HIMU magmas are produced by the upwelling of a super plume from the deep mantle. The isotopic and trace element signature for the HIMU source could be best explained by the selective extraction of Pb into the core from the subducted ancient oceanic crust stored at the base of the mantle through the interaction between silicate mantle and metallic core. The HIMU lavas are also distinct in their higher Nb/Zr ratios; analyses of such ratios for green rocks in accretionary prisms, that are fragments of oceanic plateaus, may be useful in identifying the activity of ancient super plumes.

1. Introduction

Hotspot magmas have been believed to be originated in the deeper part of the mantle and tap the geochemical reservoirs situated in that region. Among various kinds of hotspot rocks, have been devoted considerable attention to investigating ocean island basalts (OIBs), as they are believed to have little interaction with the continental crust having quite distinct geochemical characteristics from the mantle. Isotope geochemistry for OIB have revealed that the compositions of most OIB seem to be explicable in terms of multi-component mixing between at least five distinct end members within the Earth's mantle (Allègre and Turcotte, 1985; White, 1985; Woodhead *et al.*, 1993). One of those end members is 'primitive mantle', the existence of which is largely conjectural. Other four components can be defined from extrapolation of existing isotopic data for OIB in a series of two-dimensional variation diagrams (Fig. 1). These are the 'depleted' MORB source (MS in Fig. 1), two types of 'enriched' mantle components, EM1 and EM2, and HIMU characterized by very radiogenic Pb isotope compositions (Zindler and Hart, 1986). Consideration both of the origin and the mechanism of emplacement of those end member components should provide key constraints on better understandings of the dynamic processes occurring in the Earth's interior.

This paper reviews briefly the geochemical characteristics of the end member geochemical components in the mantle, emphasizes the importance of the Polynesian super plume in documenting the evolution of the whole mantle, discusses a possible mechanism for producing an end member geochemical component, HIMU, typically observed in the Polynesian OIB, and advocates a new insight for documenting the ancient activity of super plumes.

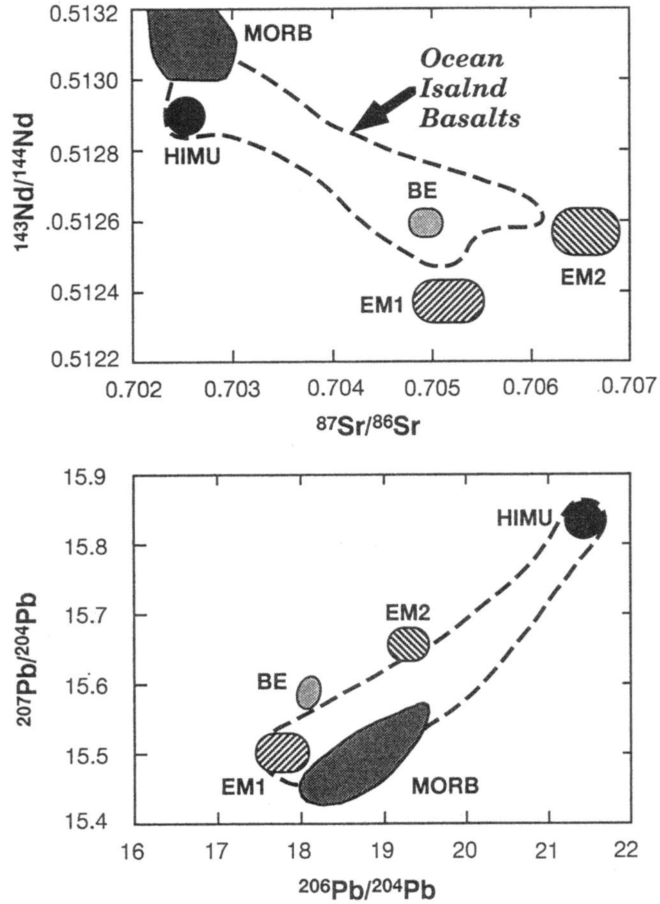

Fig. 1. Schematic isotopic signatures for five geochemical reservoirs in the mantle, which have been proposed for explaining the variation of ocean island basalt compositions (broken lines). BE; bulk silicate earth reservoir from Zindler and Hart, (1986).

2. Geochemical Reservoirs in the Earth's Mantle

MORB source (MS)

The 'depleted' isotopic characteristics of N-type MORB (high $^{143}Nd/^{144}Nd$, low $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$) require the presence of a depleted end member component. It has been well demonstrated that N-MORB is clearly removed from OIB based both on isotopic and trace element compositions. The above isotopic characteristics of N-MORB show that MS was depleted by extraction of partial melts that could solidify to form the continental crust more than 10^9 years ago, although there is growing evidence that the continental crust is not the only complement to MS and that there are ancient enriched geochemical reservoirs in the mantle (Anderson, 1983; McCulloch *et al.*, 1983; Menzies and Murthy, 1980). With regard to the location of the depleted MS, has been accepted the idea that the reservoir is present beneath all active ridges; that the reservoir may be also required in the upper mantle beneath the continent and the arc. It may be thus suggested that the depleted MS would be widely distributed in the upper mantle.

MS is generally believed to be located at the shallower part of the upper mantle, although it is little constrained. The depth of MORB separation from MS is about 30 km based on results of melting experiments both on natural MORB and peridotites (e.g., Fujii and Scarfe, 1985; Hirose and Kushiro, 1993). However, this depth means the upper limit of MS and does not provide any evidence for the base of MS in the upper mantle. In order to produce MORB magmas with a temperature of about 1300°C at a 30 km depth, the depth of commencement of partial melting during the adiabatic ascent of mantle materials may be estimated to be 70–100 km, which would be the minimum depth to the base of MS. A different line of evidence for the depth of MS can be given from isotopic compositions of intraoceanic arc lavas. The magma source in the mantle wedge in most arc-trench systems should change from its original composition during the formation of backarc basins. A rare opportunity for estimating the original mantle wedge composition is provided from lavas from the Sangihe arc that is an oceanic arc not associated with a backarc basin. Sr-Nd isotopic compositions for those lavas led Tatsumi *et al.* (1991) to the conclusion that a rather enriched source is originally located even beneath the volcanic front where the depth to the slab surface is about 110 km. It is thus suggested that MS is limited, if present, to the uppermost mantle shallower than 110 km. This is consistent with the suggestion from the seismic tomography data by Zhang and Tanimoto (1992).

Enriched mantle (EM1 and EM2)

Isotopic trends for some OIBs such as Walvis Ridges, Kerguelen, and Samoa require the presence of enriched mantle components (Fig. 1). EM components are characterized by low $^{143}Nd/^{144}Nd$, variable $^{87}Sr/^{86}Sr$, and high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$. Zindler and Hart (1986) referred the low and high $^{87}Sr/^{86}Sr$ components as EM1 and EM2. The Sr-Nd isotope compositions both of ultramafic nodules containing hydrous phases and from the continent areas and lower continental crustal materials are largely identical to those of EM1 (e.g., McKenzie and O'Nions, 1983; Menzies, 1983), suggesting the involvement of those lithospheric materials in producing the EM1 character, although continental crust-derived sediments play an additional role in forming EM1 signatures (Weaver *et al.*, 1986; Woodhead *et al.*, 1993).

Two different categories of interpretation have been advocated for the origin of the EM2-type component. Several workers (Carlson, 1984; Hawkesworth and Vollmer, 1979; Wörner *et al.*, 1986) emphasized a similarity between EM2 and upper continental crust or continentally derived sediments and suggested the involvement of such sediment components in EM2. On the other hand, EM2 is also considered to be produced in the mantle wedge by the migration of aqueous fluids (Menzies, 1983; White, 1985; Zindler and Hart, 1986). However, the latter process is limited to arc-trench systems where effective sediment subduction can take place, because the Sr-Nd isotopic compositions of slab-derived fluids have characteristics with higher $^{143}Nd/^{144}Nd$ ratios at least in Izu-Mariana and Sangihe arcs presumably with little sediment subduction (Tatsumi *et al.*, 1991, 1992).

High U/Pb mantle (HIMU)

HIMU, an acronym for high U/Pb ratio, is characterized by very radiogenic Pb isotope compositions (Fig. 1). The HIMU signature is observed for OIB only from French Polynesia (Tubuai) in the South Pacific and St. Helena to the east of the Mid-Atlantic Ridge (e.g., Zindler and Hart, 1986). The extreme enrichments of radiogenic Pb suggest an enrichment in both U and Th relative to Pb on the order of 10^9 years ago (Hauri and Hart, 1993; Tatsumoto, 1978).

It should be stressed that the above enrichment was not associated with the increase in Rb/Sr ratio, because HIMU is characterized by relatively low $^{87}Sr/^{86}Sr$ ratio.

Three different processes have been proposed for understanding the high U/Pb ratio in the HIMU reservoir. First, selective extraction of Pb that has a chalcophile character from some portion of the silicate mantle to the metallic core resulting in the increase of U/Pb ratio in the mantle (Allègre, 1982; Allègre *et al.*, 1980; Vidal and Dosso, 1978; Vollmer, 1977). The counterargument for this mechanism by Newsom *et al.* (1986) is the constant ratio between sidero/chalcophile and incompatible lithophile elements such as Pb/Ce among most OIBs including HIMU lavas. However, partitioning of siderophile elements between basaltic melts and mantle/phenocryst minerals has not been well understood. Second, the HIMU character could form from subduction of the ancient altered oceanic crust significantly enriched in U by interaction with seawater (Chase, 1981; Chauvel *et al.*, 1992; Hofmann and White, 1982). However, Zindler and Hart (1986) precluded this mechanism; the fractionation of U from Th in such alteration cycle cannot explain higher $^{208}Pb/^{204}Pb$ ratios in HIMU basalts. It has been alternatively suggested that Pb might be selectively extracted from the subducted ancient oceanic crust during its dehydration process in a subduction zone (Weaver, 1991; Zindler *et al.*, 1982). This mechanism have been widely accepted, as the arc lavas complementary show a low-U/Pb character. However, there has not been any experimental support on higher degree of transportation of Pb during dehydration processes. In conclusion, there has been no agreement on the origin of HIMU, although no one doubts the presence of HIMU in the Earth's mantle.

3. Polynesian Hotspots: A Present Super Plume

A significant class of volcanism, typically basaltic in compositions, occurs within plates and is characterized by linear chains of volcanoes. These volcanic provinces are believed to result from focused deep mantle zones of melting called hotspots that remain stationary based on their systematic geometry and age distributions (Wilson, 1963, 1965). Hotspots are not evenly distributed, but may be concentrated in zones where high geoid residuals are also observed; two centres of high geoid residuals are documented, W. Africa to S. Atlantic and S. Pacific (Crough and Jurdy, 1980).

In the S. Pacific, more than ten hotspots are concentrated forming a superswell at the ocean bottom with the maximum geoid anomaly of higher than 60 meters (Fig. 2). It should be also stressed in the region that a number of voluminous oceanic plateaus, collectively called Darwin Rise, are located in the NE Pacific (Fig. 2). These plateaus are considered to have been built in the mid-Cretaceous (ca. 100 Ma) at the position of the present Polynesian super swell (McNutt and Fischer, 1987; Sager and Han, 1993; Nakanishi *et al.*, 1992). The estimated volume for those oceanic plateaus is more than 250 $\times$ 10^6 km^3 in total; that of Ontong Java (ca. 120 Ma), Manihiki (ca. 120 Ma), Shatsky Rise (ca. 140 Ma), Magellan Rise (140–150 Ma), and Hess Rise (ca. 110 Ma) is 50, 25, 25, 20, and 20 $\times$ 10^6 km^3, respectively. These plateaus are very voluminous among so-called large igneous provinces (LIPs), one of which, the Deccan Trap, is estimated to be 2–3 $\times$ 10^6 km^3 in volume. It may be thus suggested that the S. Pacific has been a location where super plumes have been actively formed and the activity has continued at least since mid-Cretaceous, although the activity has been intermittent not continuous.

It has been also suggested that the positions of the present super plume in the S. Pacific may correlate with regions of slow Vp in the lower mantle (Morelli and Dziewonski, 1987). Recent results of the whole mantle P-wave tomography (Fukao *et al.*, 1992; Inoue *et al.*, 1990) further demonstrated that characteristic large-scale columnar zones of slow velocity anomaly are located immediately beneath the S. Pacific and W. Africa, whereas the low-V column is limited to the mantle shallower than ca. 1000 km beneath other hotspots such as Hawaii. It is thus possible

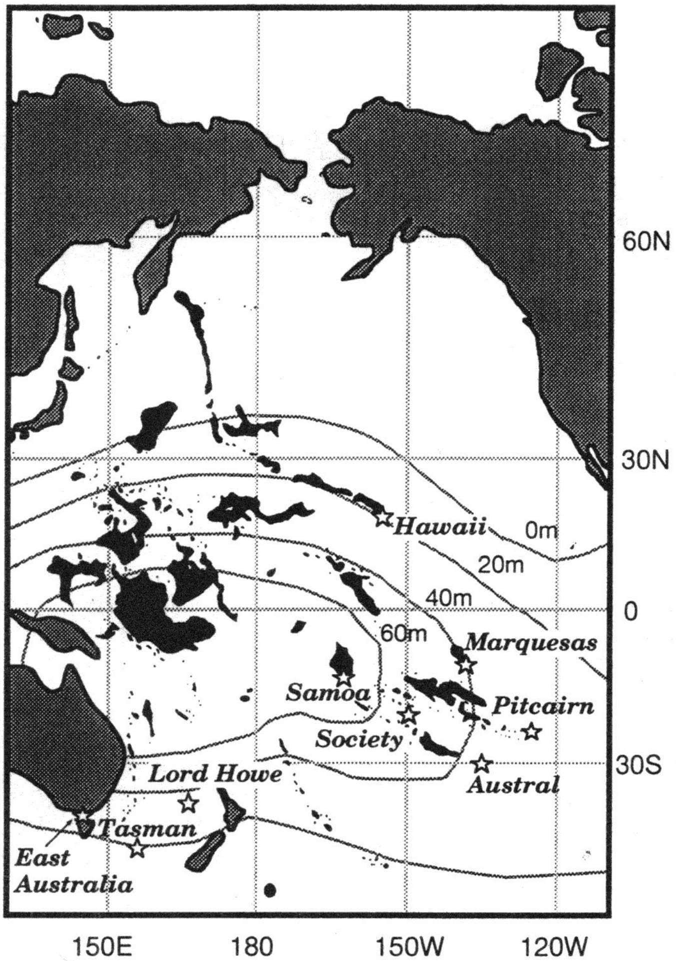

Fig. 2. Oceanic Plateaus (solid areas) and present hotspots (stars) in the Pacific. Hotspots are concentrated in zones of high geoid residuals (contours from Crough and Jurdy, 1980).

to speculate that the super plume in the above two regions originates at the base of the lower mantle. If so, then lavas from those two region are only candidates for the geochemical probing on the lower mantle.

It may be interesting to emphasize the possible correlation between the presence of superswell at the ocean bottom, the presence of the low-V column in the mantle down to the core/mantle boundary and the occurrence of HIMU lavas in the S. Pacific (French Polynesia) and the W. Afr'ica (St. Helena). It is thus likely that the HIMU geochemical reservoir is situated and/or formed in the deeper part of the mantle, probably at the core/mantle boundary. Seismic tomography (Fukao *et al.*, 1992; Inoue *et al.*, 1990) and numerical simulation (e.g., Machetel and Weber, 1991; Honda *et al.*, 1993; Liu, 1994) have demonstrated the possible downwelling of the cold oceanic crust or the megalith (Ringwood and Irifune, 1988) towards the base of the lower mantle. Therefore, the mechanism of formation of the HIMU reservoir including the involvement of subducted MORB would be valid.

In order to clarify the geochemical, especially trace element, characteristics of the HIMU

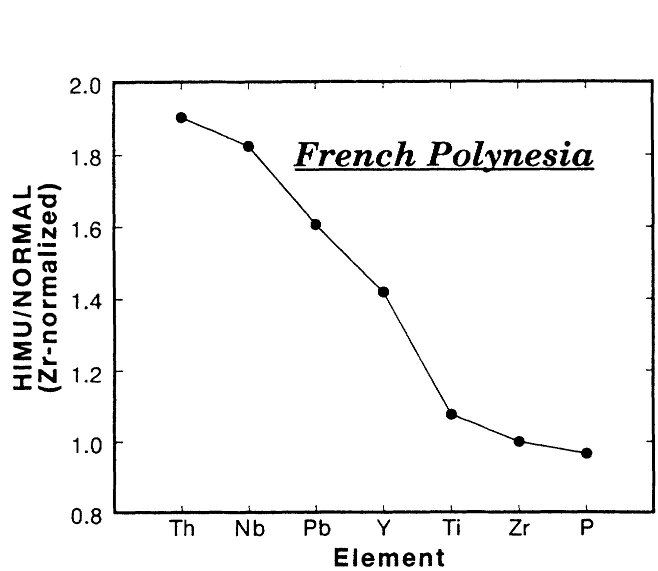

Fig. 3. Trace element characteristics of HIMU lavas relative to normal (non-HIMU, i.e., EM1 and EM2) basalts in French Polynesia (Kogiso and Tatsumi, unpublished data). The order of elements in the horizontal axis is that of degree of enrichment.

component, and furthermore to probe the processes occurring in the deeper mantle, we have collected more than 200 basalt samples from French Polynesia. We may tentatively draw a diagram showing the trace element characteristics of the HIMU reservoir (Fig. 3).

4. Origin of HIMU: Mantle-Core Interaction?

The origin of HIMU may be a key to understanding both of the dynamic processes and the evolution of the deeper mantle. It may be likely that the subducted ancient (~1–2 Ga) oceanic crust is one of essential components comprising the HIMU reservoir, based on mixing calculation using both Pb and Os isotope systematics (e.g., Chauvel *et al.*, 1992; Hauri and Hart, 1993). These authors prefer a mechanism of producing high U/Pb ratios in the source including the selective extraction of Pb during the dehydration processes in subduction zones. In order to examine this mechanism, we have conducted dehydration experiments and demonstrated the mobility of U and Pb during that process (Kogiso *et al.*, 1995).

Serpentinite was used as the source of H_2O, simply because of its higher amount of H_2O. Although amphibolite with oceanic crustal basalt compositions instead of serpentinite should be used for this type of approach, the residual minerals after dehydration (garnet, clinopyroxene and coesite for amphibolite and olivine and orthopyroxene for serpentinite) may be rather incompatible with both U and Pb. It may be thus possible to assume that the partitioning of those elements between such solid phases and an aqueous fluid is governed by solubility of elements in a fluid phase. If so, then the present experiments using serpentinite may provide an analogue to processes occurring in the subducting oceanic crust, at least in terms of transportation of U and Pb.

The comparison between compositions of the starting serpentinite and the anhydrous residue after dehydration under mantle P/T conditions may provide an estimate for the degree of transportation of elements with an aqueous fluid phase (Tatsumi *et al.*, 1986). Natural serpentinite from Cyprus was used as a starting material, set in a perforated platinum capsule, and run at 1.0 GPa and 800°C for 6 hrs, well above the stability limit of serpentine. Both the run products and a starting materials were analyzed with an ICP-MS. The mobility of measured elements, the amount lost during the dehydration divided by the amount originally present, is shown in Fig. 4. The results largely confirm the early suggestion (Tatsumi *et al.*, 1986) that an element with a larger ionic radius would be more readily transported with an aqueous fluid when comparing elements with an identical charge. However, a clear exception is Pb that is almost immobile during the dehydration process, whereas U may be a bit mobile. This is quite a reverse tendency that most workers have expected. One of possible explanations for such unusual behavior of Pb would be the presence of sulfide minerals in the dehydration product, although we have found only one tiny (a few micron meter) sulfide grain in the experimental charge. Further systematic experimental works should be required in order to evaluate the role of sulfide minerals and examine the fractionation of U/Pb ratio during the slab dehydration.

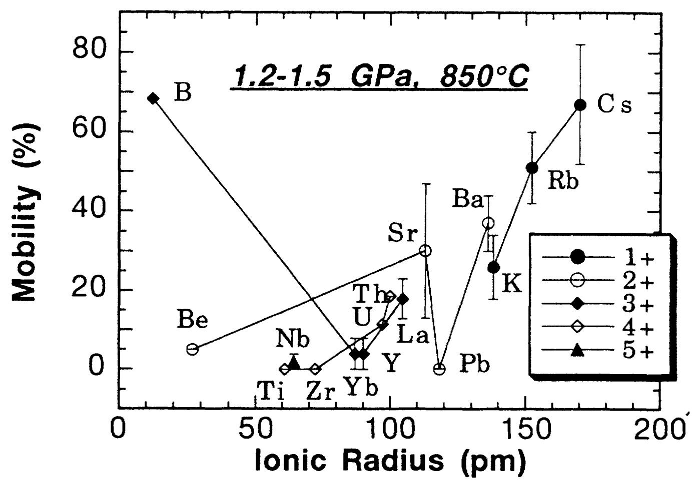

Fig. 4. Mobility of elements during the dehydration process of serpentinite. It should be stressed that Pb is almost immobile, suggesting the difficulty of selective extraction of Pb during the dehydration process in subduction zones (data from Kogiso *et al.*, 1995).

Alternatively, Pb should be highly partitioned into metallic core during the interaction between the silicate mantle and the core, probably at the base of the mantle. Although further experimental work examining this possibility must be required at ultrahigh-pressure conditions, it may be tentatively concluded based on the the present experimental results that the HIMU character could be formed originally from the ancient subducted MORB by the process including the selective extraction of Pb into the Earth's core at the core/mantle boundary not effectively caused by dehydration processes.

5. Identification of Ancient Super Plumes

The occurrence of HIMU rocks only in two regions, French Polynesia and St. Helena, where super plumes may be located, may lead to the suggestion that one of the possible and effective tool for identifying the activity of super plumes in the Earth's history is to document the HIMU character from basaltic rocks. In order to avoid the complex and unknown interaction between the continental components typically observed in the continental crust and the subcontinental upper mantle, efforts should be focused on lavas from the oceanic region. However, two major problems arise. First, most basalts in the oceanic region, especially those forming the oceanic plateaus, are severely altered and do not largely keep their original compositions. Several authors have attempted to identify the HIMU character based on trace element compositions including LILE/HFS ratios such as Ba/Nb. However, concentrations of LILEs are believed to change significantly during the alteration processes and may not be used for the present purpose. Among elements probably immobile during the alteration, Nb and Zr have small partition coefficients for major peridotitic and basaltic phases and behave as incompatible elements during the magmatic processes especially for rather undifferentiated OIBs. Figure 5 demonstrates that the HIMU lavas have clearly higher Nb/Zr ratios than other basaltic rocks including other types of OIBs and MORBs. It may be thus suggested that the Nb/Zr ratio can be a useful parameter identifying the ancient HIMU rocks and further documenting the ancient activity of the super plume.

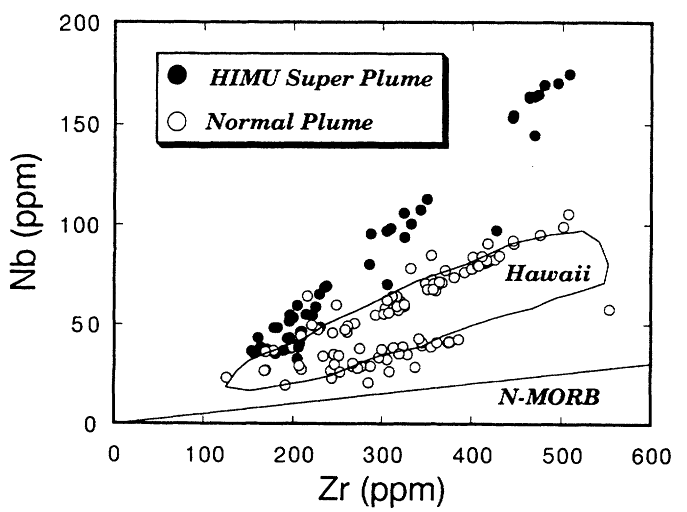

Fig. 5. Nb/Zr ratios for basalt lavas in the French Polynesia, Hawaii and N-MORB. HIMU rocks are characterized by their higher Nb/Zr ratios.

Second, plate tectonics has revealed that the present ocean floor was produced later than 200 Ma; there is no record of plume activity older than that age on the present ocean floor. However, the fragment of oceanic plateaus may be stored at the ancient convergent plate boundaries as a mélange within the accretionary prism. These accreted oceanic rocks are metamorphosed and called ‘green rocks’. During such high-T type metamorphism, dehydration processes may largely govern the migration of elements, suggesting that concentrations of HFS elements such as Nb and Zr have not changed by that process. We thus advocate that the identification of high Nb/Zr rocks from the accretionary prism in the circum-Pacific region should provide the only estimate for the ancient activity of the super plume situated in the present S. Pacific.

6. Conclusions

1) Among five distinct geochemical reservoirs in the Earth's mantle, HIMU is probably located in the deeper mantle, because HIMU lavas are documented only from the S. Pacific and W. Africa where the low-V column are observed in the mantle down to the core/mantle boundary, providing that the low-V column corresponds to the presence of a super plume upwelling from the base of the mantle.

2) The selective extraction of Pb from the ancient subducted oceanic crust (MORB) into the Earth's core, as well as Pb migration during the subduction processes, would contribute to forming the HIMU character.

3) HIMU lavas have systematically higher Nb/Zr ratios than other oceanic rocks. The ratio may not change during alteration and magmatic processes and provide an estimate for the source characteristics from the analyses of even differentiated, altered, and metamorphosed oceanic rocks.

4) The activity of ancient super plume may be documented by analyzing Nb/Zr ratios of green rocks in the accretionary prism both in the circum-Pacific and other regions.

We wish to acknowledge two anonymous reviewers for their important comments. Positive reviews by two anonymous referees and Y. Honkura should be appreciated. This work was partly supported by grants-in-aid for a special research project from the Ministry of Education, Science, and Culture.

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