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Evidence for recycled plate material in Pacific upper mantle unrelated to plumes

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Abstract

We report Sr, Nd, and Pb isotopic data of young alkaline basalt lava from a new type of volcano (petit-spot) on the northwestern Pacific Plate. Petit-spot lavas show Dupal, or extremely EM-1-like, Sr–Nd–Pb isotopic compositions. The data cannot be explained by contamination of pelagic sediment, in spite of the prediction on the basis of geological observation. We thus consider that the geochemistry of petit-spot lava indicates the existence of recycled fertile plate materials, not only the Dupal isotopic signature, in the northern hemisphere Pacific upper mantle unrelated to one or more active plumes. In consideration of published experimental results for fertile plate materials, selective melting of recycled material is a process critical in generating petit-spot lava. Moreover, the small volume of the volcano and low degree of melting in the mantle source needed to form strongly alkalic lavas suggest that petit-spot volcanism is originated from small-scale heterogeneities of recycled material. This idea consistently explains the geochemistry and noble gas isotopic composition of petit-spot lava, and also suggests small-scale heterogeneity widespread in the upper mantle of the Pacific Ocean. Together with a revised view of upper mantle heterogeneity, we propose that gross upper mantle composition is controlled by abundances and scales of regions of recycled material that correspond to differences in the relative position to the Pangea supercontinent, suggesting the link to the tectonic origin of the global scale heterogeneity.

1. INTRODUCTION

The chemical structure of the mantle reflects evolutionary processes within the solid Earth, which are controlled by the formation and recycling of oceanic and continental lithosphere over the past 4.6 billion years. Various enriched mantle sources (EM-1 and 2: enriched mantle 1 and 2), and HIMU (high-U/Pb (high-μ) mantle: Zindler and Hart, 1986; Hofmann, 1997) have been identified, on the basis of isotopic variations in ocean island basalt (OIB). Even if these mantle components are based only on the Sr, Nd, and Pb isotope perspective (Armienti and Gasperini, 2007; Iwamori and Albarède, 2008), we have a consensus on the existence of various recycled plate materials in Earth's interior. The upper mantle is classically believed to consist largely of incompatible-element-depleted mantle peridotite (DMM: Depleted Mid-ocean ridge basalt (MORB) Mantle) (Zindler and Hart, 1986; Salters and Stracke, 2004; Workman and Hart, 2005) produced by the formation of oceanic and continental crust (Hofmann, 1997), on the basis of its depleted and similar geochemistry and isotopic composition of MORB throughout the global mid-ocean ridge system. However, trends for isotopic compositions for Pacific, Atlantic, and Indian MORB converge on an isotopic composition within a tetrahedron defined by the DMM, EM-1, EM-2, and HIMU endmembers. This

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common component, referred to as "FOZO" (Hart et al., 1992; Stracke et al., 2005) or "C" (Hanan and Graham, 1996), is thought to represent pollution of the upper mantle by recycled oceanic crust.

MORB and OIB in the Indian Ocean and the southern Atlantic Ocean show coherent and characteristic Sr–Nd–Pb isotopic signatures (Dupré and Allègre, 1983), that are termed the Dupal anomaly (Hart, 1984). It was assumed that the Dupal anomaly implies hemispheric-scale fertile geochemical heterogeneity in southern hemisphere upper mantle, because these enriched basalts comprises a globe-encircling belt centered on 30°S including the South Pacific Isotopic and Thermal Anomaly (SOPITA) (Hart, 1984; Smith et al., 1989; Staudigel et al., 1991). The fertile and depleted mantle domains are termed the Indian Ocean and Pacific Ocean mantle domains, respectively (e.g., Dupré and Allègre, 1983; Hamelin and Allègre, 1985; Klein et al., 1988; Mahoney et al., 1992; Meyzen et al., 2005; Iwamori and Albarède, 2008). However, the Dupal or EM-1 signature observed along mid-ocean ridges in the northern Atlantic (Schilling et al., 1999; Hanan et al., 2000; Blichert-Toft et al., 2005), Arctic (Goldstein et al., 2008; Liu et al., 2008), and Pacific (Pacific–Antarctic ridge: Vlastélic et al., 1999, Chile ridge: Klein and Karsten, 1995; Sturm et al., 1999), and observed on off-ridge or isolated seamounts in Atlantic (Castillo and Batiza, 1989; Shirey et al., 1987; Geldmacher et al., 2008) and Pacific (Vlastélic et al., 1998) (see also Electronic Annex for detailed review). The Dupal signature is also reported from western pacific marginal basins (Hickey-Vergas, 1998; Shinjo et al., 2000; Flower et al., 2001; Hoang and Uto, 2006; Pearce et al., 2007; Hickey-Vargas et al., 2008), Ontong Java Plateau (Ishikawa et al., 2007), Shiberian Traps (Ivanov, 2007), Tuva–Mongolian massif (Rasskazov et al., 2002), and Columbia River (Chesley and Ruiz, 1998). These observations highlight the heterogeneous nature of the upper mantle, not only southern hemisphere, but also in the Indian and Pacific mantle domains.

Recently, small young volcanoes (petit-spots) have been discovered on the old (Early Cretaceous: ~135 Ma) northwestern Pacific Plate (Hirano et al., 2006, 2001). Hirano et al. (2006) showed that petit-spot lava: (1) originates from the shallow mantle on the basis of noble gas isotopic compositions, (2) formed diminutive volcanoes compared to hotspots and large igneous provinces, and (3) were erupted at different times over an area exceeding 400 km wide. As these observations cannot be explained by a mantle plume model. Hirano et al. (2006) proposed that petit-spots originate from melting in the uppermost mantle asthenosphere, and that the magma exudes where the Pacific plate flexes and fractures before subducting. An important aspect of petit-spots is that this provides a unique window for inaccessible mantle source material beneath the oldest Pacific plate. To investigate the geochemical features of the upper mantle unrelated to plumes in northern hemisphere Pacific, we have determined Sr, Nd, and Pb isotopic compositions of basalts collected from petit-spot volcanoes. Here we describe geochemical details of the petit-spot lavas that indicate a strong EM-1 signature existing in the interior of the depleted Pacific upper mantle unrelated to active plumes. We further discuss the importance of this small-scale mantle melt as an indicator of small-scale mantle heterogeneities existing in the Pacific upper mantle. This point of view, together with previous observations for upper mantle heterogeneity, leads us to reconsideration the nature of mantle domains.

2. SAMPLES AND METHODS

Petit-spot volcanoes are located on the seaward slope of the northern Japan Trench, approximately 600 km ESE of the Japan Trench (Hirano et al., 2006). On the basis of magma eruption ages and the Pacific Plate motion, each eruption appears to have occurred over an area 600 km wide (Hirano et al., 2008). We analyzed fresh alkaline basalt lava dredged from a knoll and exposed normal fault walls in the Japan Trench, and also from a young volcano 600 km from the Japan Trench. Lava forms knolls in both regions and includes highly vesicular samples. Sheet flow lavas from the fault walls include a few vesicular samples as well.

Strontium and Niobium isotope analyses were acquired by thermal ionization mass spectrometry (TIMS) using the VG Sector 54 with three Faraday collectors at RIKEN. Approximately 0.4–0.5 g powdered rock samples were digested completely with 2 mL HNO_3, 5 mL $HClO_4$, and 5 mL HF in tightly sealed 30 mL Teflon PFA screw-cap beakers, heated for 18 h on a hot plate at 180 °C, then evaporated for more than 5 h at 110 °C and finally nearly to dryness at 180 °C. Residues were dissolved with 10 mL 2% HNO_3 by heating. Strontium and rare earth element (REE) were separated using column separation with a cation exchange resin (Bio-Rad Laboratories, AG50W-8X), and Nd was further isolated from the REE using Ln resin (Eichrom Technologies). The measured isotopic ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$. The average value for the NIST SRM-987 Sr standard was 0.710266 ± 0.000016, and JNdi-1 Nd standard of GSJ (Geological Survey of Japan) was 0.512102 ± 0.000008. The analytical procedures follow Chang et al. (2000) and Shimizu et al. (2000). Lead isotope analyses employed multiple collector inductively coupled plasma source mass spectrometry (MC-ICP-MS) at Shimane University using a VG Plasma 54. Powdered rock samples were digested in mixed acid (1:4 mixture of 15.4 N HNO_3 and 20.4 N HF). Lead in a 0.1-g sample powder was separated using anion exchange resin in a mini-column (1 mL). An external Tl mass bias correction and standard bracketing method improved analytical precision. The analytical procedure follows Kimura and Nakano (2004). Average values for the NIST SRM-981 standard were $^{206}Pb/^{204}Pb = 16.9346 \pm 0.0027$, $^{207}Pb/^{204}Pb = 15.4914 \pm 0.0025$, and $^{208}Pb/^{204}Pb = 36.6940 \pm 0.0074$, respectively, and is traceable to the recommendation value of SRM-981 of Todt et al. (1996).

3. RESULTS AND DISCUSSION

3.1. Isotopic compositions of basalts from petit-spot

Alkaline basalts from petit-spot volcanoes have almost identical Sr and Nd isotopic compositions, and Pb isotopic compositions vary only slightly (Fig. 1 and Table 1), despite having been erupted over a 400-km area. The isotopic compositions of the petit-spot lavas fall very close to the EM-1 isotopic endmember composition in terms of Sr–Nd–Pb plots (Fig. 1).

Petit-spot lava was either injected into or erupted on pelagic sediment, and lava assimilates sediments at its contacts with the sediment (Machida et al., 2005; Hirano et al., 2006; Fujiwara et al., 2007). Therefore, we should examine the possibility of contamination of the lava by pelagic sediment. We assume an average composition of the Pacific pelagic sediment, and examine whether or not mixing of DMM-derived melt and sediment reproduces the isotopic compositions of the lava (see Annex for details). Our binary mixing calculation (Fig. 1) clearly shows that such mixing cannot account for the isotopic composition, especially the low $^{206}Pb/^{204}Pb$, of lava from petit-spot. Therefore, EM-1 signature of the petit-spot lavas are probably inherited from the mantle source. Instead, relatively large Pb isotopic variation of the petit-spot lavas can be explained by mixing between magmas from EM-1 source and pelagic sediments as the data scatter between EM-1 and pelagic sediment with near EM-2 compositions.

All the petit-spot alkali basalt lavas has high concentrations of incompatible trace elements indicating extreme enrichment in highly incompatible elements, (e.g., Rb, Ba, U, Th, and Nb) and light rare earth elements (REE), and depletion in heavy REE, which is typical of oceanic island alkalic basalts (Hirano et al., 2006). These suggest that the petit-spot magmas formed by small degrees of partial melting of a fertile mantle source, leaving garnet as a residue (e.g., Kimura et al., 2006; Willbold and Stracke, 2006), rather than from a depleted mantle source such as DMM (Salters and Stracke, 2004; Workman and Hart, 2005). Combined with its EM-1 isotopic signature, the petit-spot lava reflects an enriched component in the Pacific upper mantle domain.

The isotope compositions of petit-spot lava fall within the range of compositional variations of global MORB (Fig. 1). However, the lavas are higher in $^{87}Sr/^{86}Sr$, lower in $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$, and higher in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$ than those of Pacific

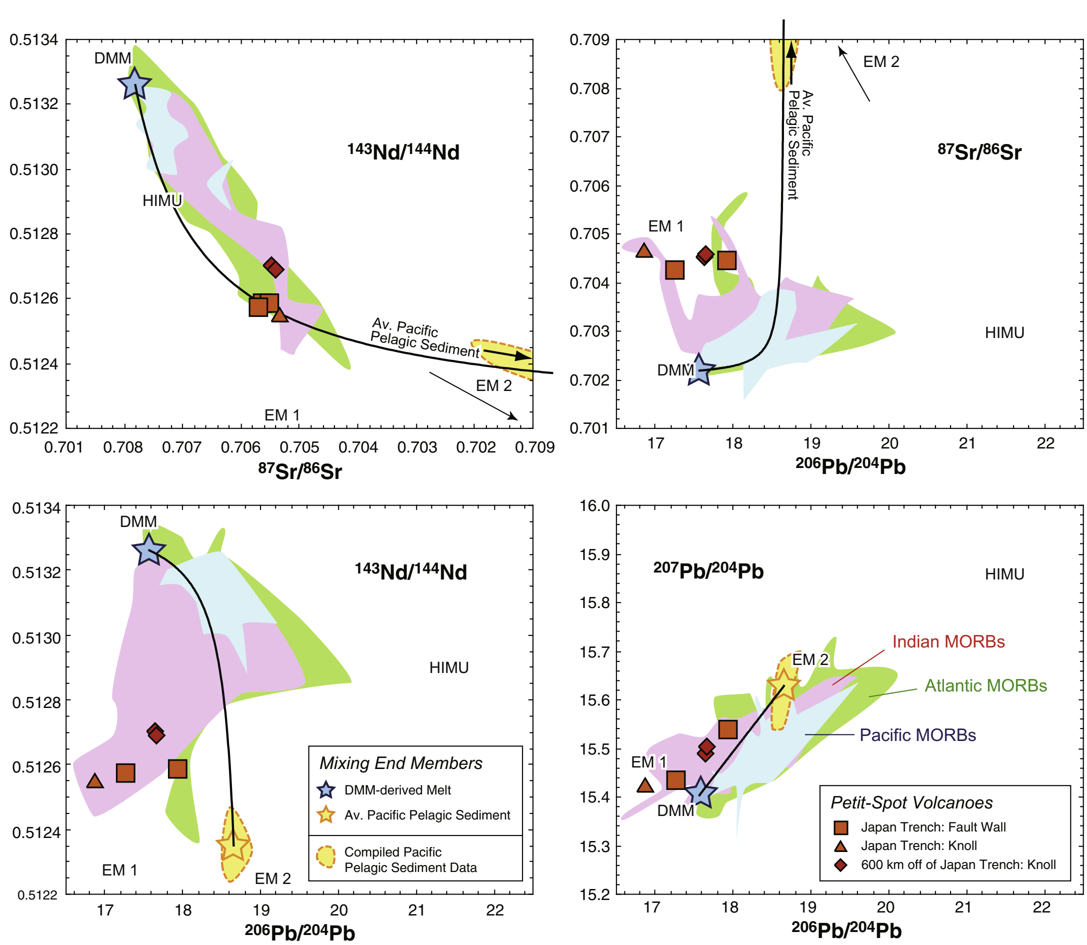

Fig. 1. Sr–Nd–Pb isotopic variations of basalts from petit-spot volcanoes. Black curves represent binary mixing between DMM-derived melt and pelagic sediment of the Pacific Ocean seafloor. Estimated compositions of DMM-derived melt and pelagic sediment are listed in Annex. MORB data are compiled from PetDB database (http://www.petdb.org/pg1.jsp) together with Meyzen et al. (2005) for the southwest Indian ridge. HIMU (high-U/Pb mantle), EM-1 and EM-2 (enriched mantle 1 and 2) are mantle endmembers predicted by isotopic variations in ocean island basalt (OIB) (Zindler and Hart, 1986).

Table 1
Sr, Nd, and Pb isotopic compositions of basalts from the petit-spot area.

Site	Locality	Sample name	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Japan Trench	Fault Wall	KR03-07 D1-002	0.704361 (24)	0.512589 (07)	—	—	—
Japan Trench	Fault Wall	KR03-07 D1-004	0.704472 (20)	0.512591 (07)	17.9242 (21)	15.5423 (28)	38.0864 (33)
Japan Trench	Fault Wall	KR04-08 D02-009	0.704280 (18)	0.512576 (09)	17.2659 (26)	15.4372 (22)	37.3876 (29)
Japan Trench	Knoll	KR03-07 D2-414	0.704662 (20)	0.512550 (09)	16.8745 (27)	15.4260 (27)	37.0918 (34)
600 km off of Japan Trench	Knoll	KR04-08 D07-001	0.704519 (23)	0.512694 (09)	17.6363 (22)	15.4891 (25)	37.7796 (30)
600 km off of Japan Trench	Knoll	KR04-08 D08-002	0.704590 (18)	0.512691 (07)	17.6691 (57)	15.5045 (57)	37.8471 (59)

Errors shown in parentheses represent 2σ and apply to the last two digits.

MORB or DMM. Remarkably, the isotopic compositions are equivalent to Indian and southern Atlantic MORB with Dupal signatures (Dupré and Allègre, 1983; Hart, 1984), and are almost identical to the composition of EM-1 end-member (Zindler and Hart, 1986) (Fig. 1 and EA-1). The Pacific plate in this region is supposed to be unaffected by any mantle plume as there are no hotspot tracks nearby (Koppers et al., 2003; Hirano et al., 2006). The low velocity anomaly near the 410-km discontinuity under the ocean-ward side of the Japan trench (Obayashi et al., 2006) was reconstructed by a mathematical model assuming that the Pacific superplume dragged down by the plate subduction (Honda et al., 2007). However, we cannot observe any connections between this low velocity anomaly and the shallower mantle (Hirano et al., 2006). Thus, the isotopic compositions of the petit-spot lavas provide strong evidence for an EM-1 mantle component or Dupal signature in the Pacific upper mantle unrelated to plumes.

3.2. Size of recycled material: considerations in petit-spot and other igneous provinces

Radiogenic Sr–Nd–Pb isotopic compositions of EM-1 require time-integrated growth of fertile source material following recycling (Hofmann, 1997), whatever the EM-1 source material. Given this constraint, explaining the presence of the EM-1 (Indian Ocean mantle domain-like) component in the DMM-dominated Pacific mantle domain is a major issue. As a preliminary approach, we first consider the volume of recycled material for volcanism at petit-spots, spreading ridges, and oceanic islands.

3.2.1. Small-scale recycled materials for origin of petit-spot lava

The basalt geochemistry of petit-spot volcanoes suggests that magma was produced by low degrees of partial melting at high pressure (Hirano et al., 2006). Under such conditions, fertile material, such as carbonated peridotite, pyroxene-rich eclogite, pyroxenite, and hornblend pyroxenite or hornblendite as recycled crust or metasomatized lithospheric mantle, melts relatively easily compared to surrounding depleted (and refractory) peridotite, because the melting point of the fertile material is lower than that of depleted peridotite (e.g., Olafsson and Eggler, 1983; Falloon and Green, 1990; Takahashi et al., 1998; Sobolev et al., 2007; Pilet et al., 2008). Therefore, recycled material blobs in the DMM source melt preferentially, and EM-1 components are entrained selectively by the magma. Because of the small volume of petit-spot volcanoes, large-scale source material should not be required even in the case of small degrees of melting.

The petit-spot lavas have high Ar isotope ratios ($^{40}Ar/^{36}Ar > 10{,}000$), which obviously differ from OIBs ($^{40}Ar/^{36}Ar < 3000$). The isotopic ratio is well within the range of typical DMM value ($^{40}Ar/^{36}Ar = 4000–30{,}000$) (Hirano et al., 2006). Noble gases have higher diffusion rates than most other elements (e.g., Sr, Nd, and Pb), because of their chemical inertness (e.g., Sneeringer et al., 1984; Trull and Kurz, 1993; Cherniak, 1998; Van Orman et al., 2001). Even if the petit-spot EM-1 source was entrained into the upper mantle by an ancient plume or convection, the memory of the pristine noble gas for small blob of EM-1 had already been lost due to diffusion and homogenization with the ambient DMM. This mechanism explains well the apparent discrepancy between solid earth element and noble gas isotopes of the petit-spot lavas. The discussion also suggests that small amount of enriched material are widespread in the upper mantle of the Pacific Ocean.

3.2.2. EM-1–DMM geochemical connection: scales of mantle heterogeneity between hotspot and petit-spot

Isotopically heterogeneous local melt from different mantle domains mix imperfectly in a magma plumbing system, as indicated by olivine-hosted melt inclusions in some OIBs such as Pitcairn and Hawaii (Saal et al., 2005). The heterogeneity in hotspot EM-1 has been interpreted as mixing between melts from EM-1 material and DMM mantle lithosphere during EM-1 melt migration in the lithosphere (e.g., Eisele et al., 2002; Saal et al., 2005; Ito and Mahoney, 2005). EM-1 and DMM are the two common components in both those OIBs and petit-spot basalt. However, the dominant component that determines bulk rock isotope chemistry is EM-1 in both cases. The major difference between the petit-spot volcanoes and most EM-1-type OIB suites (such as Pitcairn and part of Hawaii) is that the latter's magmatic volume of EM-1 differs by several orders of magnitude.

Saal et al. (2005) argued that melt from various enriched sources is diluted by a DMM-derived melt. However, DMM-derived melt does not strongly affect bulk rock chemistry of OIB, because the dilution is limited to the contact between the melt channel and the ambient mantle. Therefore, if petit-spot basalt and OIB are derived from similar degrees of melting, the magmatic volume may be a proxy for the scale of the source material. In the case of Hawaii, apart from tholeiitic Koolau basalts, most of lavas enriched in the EM-1 component occur in the post shield stage and thus are alkalic, therefore, the degree of melting of the mantle source is likely to be low (0.5–5%; e.g., Kimura et al., 2006; Willbold and Stracke, 2006), similar to petit-spot. Thus, voluminous alkalic volcanism of OIB indicates large-scale heterogeneity in the source mantle.

3.2.3. EM-1–DMM geochemical connection: are mid-ocean ridges and petit-spot generated from a common heterogeneous mantle?

An outstanding question is why we rarely detect the EM-1 isotopic signature in the Pacific MORB. Recent proposals for MORB genesis suggests that MORB also originates from heterogeneous shallow upper mantle consisting of refractory peridotite and a pyroxene-rich fertile mantle source. Fertile source-derived melt contributes 10–30% of magma as estimated by olivine phenocryst chemistry (Sobolev et al., 2007). This view was challenged by work on experimental petrology that reduced the necessary amount of pyroxene-rich mantle (Wang and Gaetani, 2008). However, the role of pyroxene-rich mantle for the oceanic basalts source should not be underestimated, as high Ni olivine is potentially the product from pyroxinite or eclogite melting in the upper mantle (Sobolev et al., 2005).

Upper mantle beneath the Pacific plate does not have to contain large amounts of recycled material, as shown by the petit-spot lavas (see discussions in the previous section). This was envisaged due to the low volcano volume and the small degree of melting in the mantle source needed to form strongly alkalic lavas. At the mid-ocean ridges, ambient DMM, along with EM-1 (and/or other) recycled material, must melt at a higher melting degrees of the mantle (~8–20%; Klein and Langmuir, 1987). Therefore, we can consider that the influence of minor components (EM-1 or pyroxene-rich source) is diluted and therefore invisible in the bulk geochemistry of MORB (e.g., Morgan, 2001). The above concept is consistent with the statistical upper mantle assemblage model (SUMA; Meibom and Anderson, 2003) assuming sampling upon mantle melting and averaging of small-scale heterogeneities in the mantle, ultimately providing relatively depleted MORB.

3.3. Features of global upper mantle heterogeneity

Given the three extreme cases (petit-spot, spreading ridge, and oceanic island), we explore the scale of heterogeneity in the Pacific and Indian Ocean mantle domains in the following section.

Oceanic island basalts in several regions in the Pacific (Fig. 2), such as SOPITA (e.g., Cheng et al., 1999; Eisele et al., 2002; Stracke et al., 2003), Hawaii hotspot track (e.g., Roden et al., 1994), and Galapagos hotspot (e.g., White et al., 1993), show enriched isotopic compositions. These observations suggest that fertile recycled material is present beneath these regions. However, if selective sampling due to low degree partial melting causes the observed various enriched mantle signatures, the overall mantle could not be very fertile. In contrast to those particular locations, it is clear that the extent of EM-1 isotopic enrichment of the Pacific MORB is low (Fig. 1). However, a few exceptions are observed on MORB from the Chile Ridge and the Pacific–Antarctic Ridge (PAR) which have EM-1-like signatures (Fig. 2). These appear to be related to a relatively large-scale EM-1 mantle blob embedded in DMM, because this EM-1 signature is diluted by the large extents of partial melting within the melting zone of the spreading ridge. With the presence of the EM-1 component in the source mantle of the petit-spot area, it is possible that enriched components in the Pacific MORB mantle domain are widespread. The scale may be very small (petit-spot), larger (Pitcairn), or possibly larger (Chile Ridge and PAR). In the view of frequency of sampling and volume of EM-1 lavas, the physiographic distribution of the EM-1 component appears to be dense in the southern Pacific (SOPITA or Chile and PAR), and sparse in the northern Pacific (petit-spot or Juan de Fuca Ridge) (Fig. 2).

Indian and southern Atlantic Ocean MORB sources (the Dupal mantle) would include considerable amounts of various enriched components such as EM-1, EM-2, and HIMU, judging from large variations in bulk rock chemistry (Fig. 1). Basalts from the Godzilla seamount in the northern Atlantic (Fig. 2) have a strong EM-1 signature, similar to petit-spot basalts, although the volcanism appears unrelated to the neighboring hotspot (Geldmacher et al., 2008). Notwithstanding similar trace element geochemistry to that of the petit-spot basalt suggesting low degrees of partial melting, the volume of the Godzilla seamount is larger than that of the petit-spot volcano (height ~1 km for the Godzilla Seamount (Geldmacher et al., 2008) in contrast to ~200 m for petit-spot volcano (Machida et al., 2005; Hirano et al., 2006), and diameter of volcano is widely different). Therefore, large amounts of fertile source material in northern Atlantic upper mantle is suggested. In addition, the upper mantle beneath the Arctic Ocean is highly heterogeneous (Liu et al., 2008). The EM-1 or Dupal-like signature is also observed (Fig. 2) in the northern Atlantic Ocean (Shirey et al., 1987; Schilling et al., 1999; Hanan et al., 2000; Blichert-Toft et al., 2005) and in back-arc and marginal basins east of the Eurasian continent (Hickey-Vergas, 1998; Shinjo et al., 2000; Flower et al., 2001; Hoang and Uto, 2006; Pearce et al., 2007; Hickey-Vargas et al., 2008). Although the scale of heterogeneity is not identified, the upper mantle in these regions probably includes considerable amount of recycled material.

More heterogeneous mantle is located beneath the region once occupied by the Pangea Supercontinent (e.g., Indian, Atlantic, and Arctic Oceans), or near its periphery (e.g., Philippine Sea plate) (Fig. 2). In these regions, recycled materials could have been injected into both the lower and upper mantle via subduction of oceanic plates (e.g., Fukao et al., 2001). Furthermore, delamination and thermal erosion of the continental plate likely occurred during breakup with upwelling of a super plume (e.g., Hawkesworth et al., 1986; Class and le Roex, 2006), during crustal thickening or thinning by continental collision or underplating of hot mantle (e.g., England and Houseman, 1989; Kay and Kay, 1993; Zhai et al., 2007), and/or during crustal growth by arc volcanism (e.g., Jull and Kelemen, 2001; Tatsumi et al., 2008). These processes also insert large amounts of recycled material into the upper mantle. We thus consider the Indian Ocean mantle domain to be

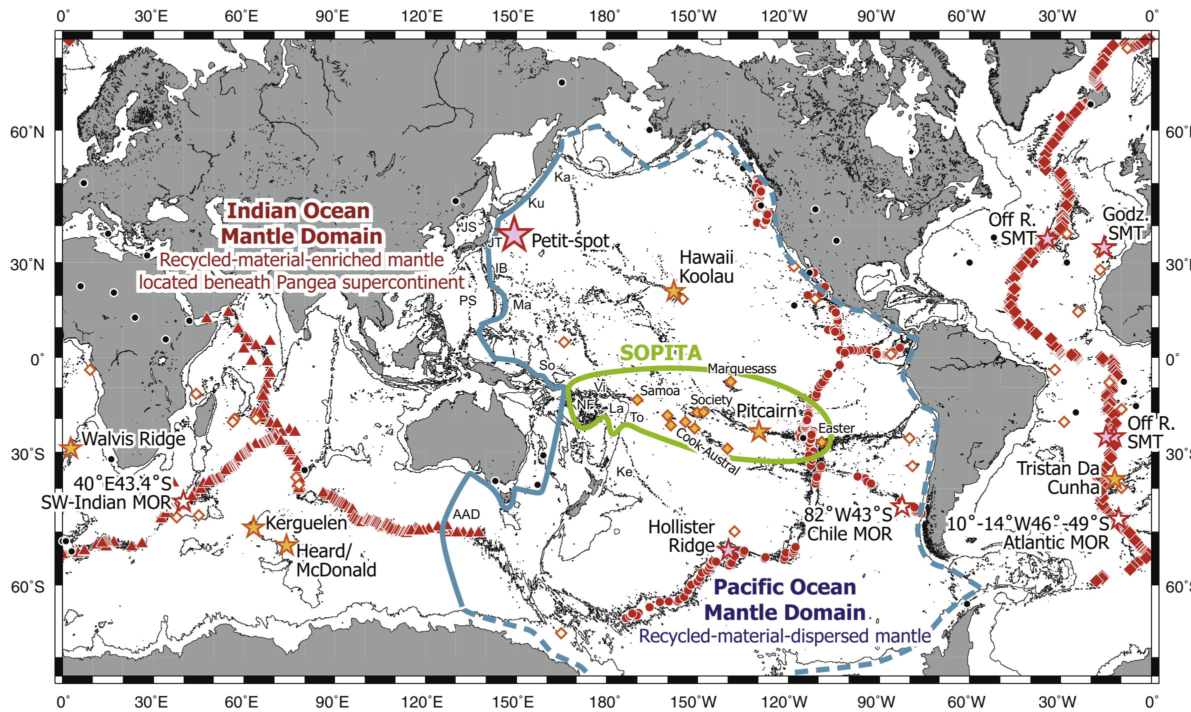

Fig. 2. Distribution of the Pacific and Indian Ocean mantle domains. The Pacific Ocean upper mantle includes various amount of isolated recycled material of various scales and we term this Pacific Ocean mantle domain ‘recycled-material-dispersed mantle’. In contrast, the upper mantle lying beneath the Pangea supercontinent (e.g., the Indian, Atlantic, and Arctic oceans) or on its periphery (i.e., the Philippine Sea plate) includes abundant and perhaps large-scale recycled material, and we term this Indian Ocean mantle domain ‘recycled-material-enriched mantle’. The filled red stars indicate the locations of EM-1 at intra-plate seamounts: the petit spot in the northwestern Pacific (this study), the Hollister Ridge in the southern Pacific (Vlastélic et al., 1998), the Godzilla Seamount (Godz. SMT) in the northern Atlantic (Geldmacher et al., 2008), and off-ridge seamounts (Off R. SMT) near the Oceanographer Fracture Zone of the northern Atlantic Ridge (Shirey et al., 1987) and near the southern Atlantic Ridge at 26°S (Castillo and Batiza, 1989). The open red stars indicate the locations of EM-1 along mid-ocean ridges (MOR): the southwest Indian ridge at 40°E, 43.4°S, the southern mid-Atlantic ridge at 10–14°W, 46–49°S, and the Chile ridge at 82°W, 43°S. Other red symbols indicate locations of compiled mid-ocean ridge basalt (MORB) for comparisons in Fig. 1 and EA-1 as follows: circles, Pacific MORB; diamonds, Atlantic MORB; triangles, Indian MORB. Yellow and black symbols indicate the locations of most hotspots as compiled by Anderson and Schramm (2005): yellow stars, EM-1 OIB; yellow diamonds, EM-2 (Society, Marquesass, and Samoa) and HIMU (Cook-Austral and Ester) OIB situated in the middle of the Pacific Ocean (see text); yellow open diamonds, other OIB for comparison in Fig. EA-2; black dots, other hotspots. The light blue solid line depicts the boundary between Indian and Pacific Ocean mantle domains postulated in Nebel et al. (2007), modified east of the Australian continent and near the Australian–Antarctic discordance (AAD) on the basis of Pearce et al. (2007) and Hanan et al. (2004), respectively. Dashed light blue lines depict the eastern boundary between the Indian and Pacific Ocean mantle domains (correlating to the periphery of the Pangea supercontinent) proposed in this study. Light green line indicates region of the South Pacific Isotopic and Thermal Anomaly (SOPITA) proposed by Staudigel et al. (1991), modified around the Tonga-Lau and Vanuatu-North Fiji arc-basin systems on the basis of Pearce et al. (2007). Trenches along the western margin of the Pacific plate are: Ka, Kamchatka; Ku, Kurile; JT, Japan; IB, Izu-Bonin; Ma, Mariana, So, Solomon; Vi, Vitiaz; To, Tonga; Ke, Kermadec. Back-arc and marginal basins are: JS, Japan Sea; PS, Philippine Sea; NF, North Fiji basin; La, Lau basin. Contours indicate 3000 m isobath.

defined as ‘recycled-material-enriched mantle’ created during evolution of the Pangea Supercontinent. In contrast, recycled material in the Pacific Ocean, especially in the northern part, might have been dispersed by mantle convection while isolated from the region of continental evolution. We thus propose that the Pacific Ocean mantle domain is defined as ‘recycled-material-dispersed mantle’, that is, the domain is dominated by DMM with various amount of isolated recycled materials of different scale.

How the Pacific upper mantle structuralizes small-scale recycled material prior to petit-spot volcanism is an important issue for fundamental and comprehensive understanding of Earth’s recycling. To do this, determination of the origins of the recycled material is important. However, several hypothetical sources have been proposed for the origin of EM-1: recycling of (1) subcontinental lithospheric mantle (e.g., Shirey et al., 1987; Mahoney et al., 1992; Geldmacher et al., 2008; Liu et al., 2008; Goldstein et al., 2008), (2) continental lower crust (e.g., Escrig et al., 2004; Hanan et al., 2004), (3) subducted oceanic crust and/or sediment (e.g., Dupré and Allègre, 1983; Rehkämper and Hofmann, 1997; Eisele et al., 2002), and (4) metasomatized mantle by fluid and/or silicate melt released from a subducting slab in supra-subduction zone (e.g., Kempton et al., 2002). Metasomatized oceanic lithosphere mantle is also a possible source for alkaline lavas (Pilet et al, 2008). Moreover, for recycling of these materials, delivery to upper mantle may not only be via injection from the deep mantle (e.g., Courtillot et al., 2003; Gibson et al., 2005; Zhao, 2007) such as an ancient plume. Several geophysical observations indicate that hotspots are not necessarily deep in origin (Anderson, 2005). Furthermore, some hotspot volcanism such as Iceland and the SOPITA region can be explained by shallow tectonic processes without plumes (McNutt et al., 1997; McNutt, 1998; Foulger et al., 2005; Natland and Winterer, 2005). These discussions suggest that shallow recycling, such as delamination, is also an important process. Independent component analysis (Iwamori and Albarède, 2008) suggests that Sr–Nd–Pb isotopic space may be simply explained by two independent vectors indicating melting on mid-ocean ridges or interaction with aqueous fluid in subduction zones. We obviously need further considerations on the above mentioned problems; however, this is beyond the scope of this paper. Understanding the nature of a mantle with heterogeneities ranging from small-scale to hemispheric-scale should contribute to constraining the various hypotheses. The study of the petit-spot volcanism may further our understanding of the origin and distribution of recycled material in the depleted upper mantle by providing an alternative mode of mantle examination.

4. CONCLUSIONS

Young alkaline basalt lavas from a new type of volcano, petit-spot, on the northwestern Pacific Plate have Dupal, or extreme EM-1-like, Sr–Nd–Pb isotopic compositions. This indicates that Pacific upper mantle that is far from active plumes has small-scale heterogeneities of recycled material embedded. Our results from the petit-spot, together with previous studies, suggest that the Earth's upper mantle is heterogeneous due to the existence of enriched materials of various scales and abundances. They are more abundant beneath hotspots or hotspot–ridge interaction regions. The region in the Pacific Ocean mantle contains only sparsely distributed enriched materials whereas the Indian Ocean mantle domain appears to be richer in them. Physiographical differences between the Pacific and Indian Ocean mantle domains suggest that the abundance and scale of these blobs of recycled material corresponds to the evolution of the Pangea Supercontinent.

Even in the upper mantle with a primarily DMM composition, enriched materials are present. Enriched materials are occasionally sampled effectively by small-scale, low degree melting to generate isolated alkali basalt volcanoes. The mantle heterogeneities are, therefore, most effectively explored by examining those small-scale melts. We believe that geochemical mapping of the upper mantle using small-scale volcanism related to plate flexure will provide key constraints on understanding the nature of mantle heterogeneity, including the Dupal signature which is not confined to the southern hemisphere, thereby addressing whole solid Earth recycling.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gca.2009.01.026.

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