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Migrating shoshonitic magmatism tracks Izu–Bonin–Mariana intra-oceanic arc rift propagation

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A B S T R A C T

The southernmost Izu–Bonin arc and northernmost Mariana arc are characterized by K-rich and shoshonitic lavas, referred to as the alkalic volcano province (AVP). These compositions are unusual for intra-oceanic arcs and the interpretation of the AVP is controversial. Rifting to form the Mariana Trough back-arc basin occurs just south of the AVP although back-arc seafloor spreading has not begun. Here we report the results of dredge sampling of the West Mariana Ridge (WMR) in the region of rift propagation; this recovered exclusively medium K to shoshonitic basalts that show clear arc-like geochemical signatures.

Ar–Ar ages of WMR shoshonitics systematically young northward. Age of c. 6 Ma was obtained at 21.5°N, c. 3 Ma at 23–23.5°N, and zero-age shoshonites occur on Io-to Island (formerly Iwo Jima) at 24.8°N. Shoshonitic magmatism migrated northward at 4.3 cm/year, in advance of northward-propagating Mariana Trough rifting. This implies that AVP shoshonitic magmatism manifests processes and sources that are uniquely associated with earliest back-arc basin rifting.

High-precision Pb isotopic analyses reveal that WMR lavas form a single trend between 2 components, one with lower $^{206}Pb/^{204}Pb$ and high $\Delta 7/4$ (arc-like), and another with high $^{206}Pb/^{204}Pb$ as well as low Δ 7/4 and 8/4 (HIMU-like). These components could correspond respectively to subducted pelagic sediment and subducted seamounts and volcaniclastics with HIMU isotopic signature. These slab-derived components alone, however, cannot fully explain chemical characteristics of WMR shoshonitic lavas. These lavas require a component with high $\Delta 7/4$ and high Ce/Pb, which is not likely to be either pelagic sediment or seamount volcanics. This component is only expressed when rifting begins, suggesting that it resides in enriched lithosphere or uppermost asthenosphere, which is easily melted due to decompression caused by rifting, when the lithosphere is first ruptured. This component might be linked to slow Vs anomalies in the mantle wedge beneath the AVP.

1. Introduction

Intra-oceanic arcs erupt magmas with different compositions that reflect position above the subduction zone, for example, along and behind the volcanic front (Kimura and Stern 2008). Different magmatic compositions also reflect different upper plate strain regimes, for example MORB-like lavas erupt at sites of back-arc spreading (Taylor and Martinez 2003). Transitional strain regimes – for example, evolution of an arc lacking a back-arc basin (BAB) to a system with back-arc spreading – may also be accompanied by distinctive magmas that reflect enriched material in the lithosphere that is tapped when back-arc rifting begins. It is widely recognized that alkaline magmatism occurs associated with intra-oceanic or continental rifting (e.g., Gill and Whelan, 1989; Gibson et al., 1993; Luhr, 1997). Extreme enrichment provided by subducting slab (Gill and Whelan, 1989) or enriched mantle (phlogopite-bearing pyroxenite) sources affected by ancient metasomatic events (Luhr, 1997) combined with low degree of partial melting were proposed as causes of alkaline magma formation. Extension associated with rifting could facilitate extrusion of small amount of these alkaline melts to the surface. Hence, understanding the origin of earliest BAB rift-related melts and the temporal variation of this volcanism provides valuable insights for elucidating lithospheric processes at the initiation of rifting, and also sheds light on the compositional structure of the uppermost mantle.

The southern Izu–Bonin arc and northernmost Mariana arc (Fig. 1) erupt unusually alkaline shoshonitic lavas, and referred to as the alkalic volcano province (AVP; Bloomer et al., 1989a; Sun and Stern, 2001; Ishizuka et al., 2007). This area lies immediately north of where the Mariana Trough BAB terminates. Back-arc rifting is propagating

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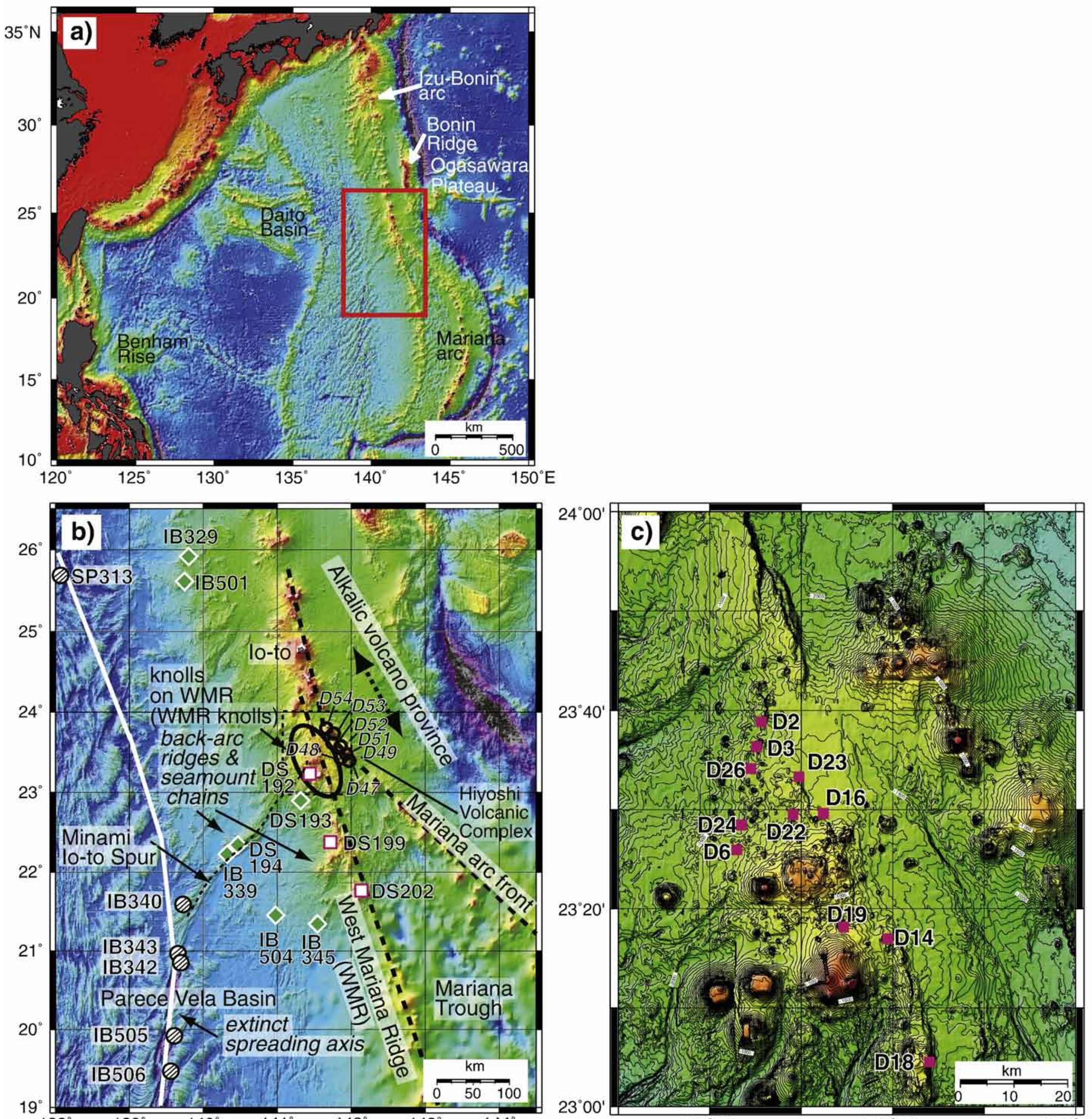

Fig. 1. a) Location of the studied area in the Izu–Bonin–Mariana arc. Area for (b) is shown as a red box. b) Bathymetric feature of the studied area. Bathymetric data are from the Japanese Coast Guard. Dredge and drilling stations where the samples used in this study were collected were also shown. Symbols indicating the locations of sampling stations are the same as used in subsequent geochemical and age data figures. Area for (c) is shown in a black dashed box. c) Dredge sampling locations for the knolls on the West Mariana Ridge (WMR knolls). Bathymetric data was obtained by this study.

northward through this region, but spreading and creation of oceanic crust has not begun. Large variations in magma chemistry and age, coupled with recent efforts to resolve the underlying seismic velocity structure (e.g., Miura et al., 2007; Isse et al., 2009) make this area appropriate for studying how arc lava ages and compositions reflect the onset of rifting and what this tells us about the nature and location of enriched mantle sources.

In this paper we present new $^{40}Ar/^{39}Ar$ ages, whole rock chemistry and high-precision isotopic data for AVP rear-arc volcanoes; these have never been studied before. These data illuminate the spatial and temporal variabilities of magmatism associated with initial back-arc rifting and what might control these variations.

2. Geological background

The studied area is in the northernmost Mariana and southernmost Bonin arc around the northern termination of the Mariana Trough BAB (Fig. 1). The Mariana arc volcanic front follows the easternmost (NW-SE trending) ridge shown in Fig. 1b. The northernmost bathymetric expression of the Mariana Trough is at 23.5°N, although the neovolcanic extensional zone terminates at Nikko volcano at 23.1°N (Gribble et al., 1998). The West Mariana Ridge (WMR) is a remnant arc (Karig, 1972) that separated from the magmatic arc by opening of the Mariana Trough.

The submarine volcanoes of interest here occur as knolls and volcanic cross-chains behind the AVP magmatic front. There are many small knolls on the northernmost WMR (23.1–23.7°N; Fig. 1c), possibly monogenetic volcanoes (WMR knolls, hereafter). These volcanoes are generally less than 1.5 km in basal diameter and rise less than 200 m above the surrounding seafloor. West of the WMR lies the Parece Vela Basin, a back-arc basin that was active between 25 and 15 Ma (Okino et al., 1999) and is now extinct. Some seamount chains and volcanic ridges extend SW from the WMR into the Parece Vela Basin (Fig. 1b). The most prominent volcanic ridge is Minami Io-to Spur (Fig. 1b), which extends more than 250 km into the extinct Parece Vela Basin spreading axis.

The magmatic front in the studied area is the 150-km-long AVP, which erupts high K and shoshonitic lavas. This province extends from Io-to Island in the north to Hiyoshi Volcanic Complex in the south. The AVP shows distinct enrichments in major elements, trace elements, and isotopic composition. There are no radiometric ages from AVP lavas, but southern volcanoes seem extinct and northern volcanoes (Io-to and Fukutoku–Oka-no-Ba) are active (Stern et al., 1984, Bloomer et al. 1989b, Otani et al., 2004).

3. Samples studied

Samples were collected by dredging during R/V Natsushima, NT06-08 cruise and also by drilling conducted as a part of the Japanese Law of the Sea Project. Brief descriptions of the studied samples are listed in Supplementary data (Table S1). Samples mainly come from the WMR, WMR knolls, Minami Io-to Spur, other back-arc seamounts in the eastern Parece Vela Basin, and the extinct Parece Vela Basin spreading ridge (Fig. 1b and c). We also reanalyzed isotopic compositions of samples from AVP frontal arc volcanoes studied by Sun and Stern (2001) using the more precise Pb double spike technique (Ishizuka et al., 2003).

Samples are lava blocks or clasts of monolithic volcanic breccia. WMR volcanic rocks (apart from those of WMR knolls) are sparsely-plagioclase-phyric andesite (IB199) with groundmass showing variolitic texture made of plagioclase and cpx (clinopyroxene), and cpx-olivne basaltic andesite with intersertal texture (IB192 and IB202). Samples drilled from Minami Io-to Spur are basalt to basaltic andesite with generally hyalopilitic groundmass and phenocrysts of plagioclase, olivine, ±cpx, and occasionally opx (orthopyroxene). Core samples taken from the extinct Parece Vela Basin spreading center are basalt with variolitic groundmass and phenocrysts of plagioclase, cpx and minor olivine. Dredged samples from WMR knolls are generally vesicular basalts. Western knolls have more plagioclase phenocrysts (>10%) than olivine and cpx (e.g., NT06-08 D3, D5, D6), whereas eastern knolls have more olivine phenocrysts than plagioclase, if any. Dredged samples from WMR knolls have Mn-oxides coating normally less than 5 mm, but in some cases as thick as 1 cm.

Studied samples are generally very fresh apart from some alteration of olivine to iddingsite (Table S1).

4. Geochronology and geochemistry

4.1. Analytical techniques

Detailed description of analytical procedures is included in Supplementary data.

4.2. Age of back-arc volcanism

Basaltic lavas from back-arc ridges and seamounts in the eastern Parece Vela Basin gave Late Miocene ages, between 10–12.5 Ma (Fig. 2, Table 1), while a basalt lava (IB343BMS03CA01) from the extinct Parece Vela Basin spreading center gave an age of 15.0 Ma. These data are consistent with the idea that Parece Vela Basin back-arc spreading ceased (~15 Ma), well before the northern Mariana Trough began spreading (c. 2.5 Ma: Yamazaki et al., 2003). Basalts from West Mariana Ridge seamounts gave much younger ages of 4–6 Ma (Fig. 2, Table 1). This volcanism predates rifting or spreading of the Mariana Trough in this region. WMR knolls gave ages between 2.6 and 4.3 Ma (Fig. 2, Table 1).

4.3. Geochemistry of back-arc and AVP lavas

Basalts from the extinct Parece Vela Basin spreading center are low K tholeiites. These basalts have 48.4–50.3 wt.% SiO_2, 0.2–0.5% K_2O, Mg# of 47–64, and show LREE-depleted or flat REE patterns ($(La/Yb)_N$ of 0.56–1.4). These basalts are similar to N-MORB except for weak LILE enrichment (K and Ba) in some samples (Fig. 3, Table S2).

Basalts from back-arc ridges and seamounts in the eastern Parece Vela Basin (Table S3, green diamonds in Fig. 3) are generally medium K (Gill, 1981), and can be either tholeiitic or calc-alkaline based on FeO*/MgO vs. SiO_2 plot (Miyashiro, 1974). These basalts mostly have 47–52 wt.% SiO_2, 0.55–1.65% K_2O, and Mg# of 47–71, and show LREE-enriched patterns ($(La/Yb)_N$ of 1.2–5). These rocks are distinctly more enriched in LILE and depleted in high-field-strength elements (HFSE) relative to Parece Vela Basin "spread" basalts and share chemical characteristics with lavas from Izu–Bonin back-arc seamounts and ridges which had been active between 17 and 3 Ma (Hochstaedter et al., 2000, 2001; Ishizuka et al., 2003, 2006, 2009).

Basaltic lavas from WMR, WMR knolls and AVP magmatic front are distinctly more enriched than those from other parts of the Izu–Bonin–Mariana (IBM) arc and are high K to shoshonitic (Table S4, red squares in Fig. 3). The WMR and WMR knolls basalts mostly have 47–49 wt.% SiO_2, with a wide range of K_2O contents (0.7–2.2 wt.%). WMR knolls generally have higher Mg# (mostly 60–65) than other WMR basalts (Mg# = 42–46), indicating little fractionation. Among these shoshonitc rocks, only those from WMR knolls are nepheline normative. Both WMR and WMR knolls are LREE-enriched, $(La/Yb)_N$ of 7–16.

Shoshonitic basalts from WMR and WMR knolls show trace element patterns that are similar to those from the AVP magmatic front (Sun and Stern, 2001), including strong enrichment of Ba, Pb, and Sr relative to MORB and strong relative depletions in Nb and Ta. WMR shoshonitic lavas show comparable or even higher incompatible element content relative to AVP arc lavas. Both are greatly enriched relative to normal intra-oceanic arc lavas.

Isotopically, basalts from the Parece Vela spreading center overlap the compositional range of Philippine Sea MORB by having relatively high Δ8/4 (Fig. 4b), i.e., showing Indian Ocean MORB character (e.g., Hickey-Vargas, 1991).

AVP and WMR shoshonitic lavas define indistinguishable Pb isotopic trends, especially antivariation of Δ7/4 and Δ8/4 (Hart, 1984) with $^{206}Pb/^{204}Pb$ (Fig. 4a, b, Table S4, S5). Miocene back-arc seamounts and ridges show mostly lower $^{206}Pb/^{204}Pb$ and Δ7/4 and plot much closer to typical IBM arc lavas and Philippine Sea MORB (Fig. 4a, b).

AVP and WMR shoshonitic lavas also show tight linear trends of slightly increasing $^{143}Nd/^{144}Nd$ with $^{206}Pb/^{204}Pb$ (Fig. 4c). This trend is at high angles to that of all other lavas in the region, which show lower $^{143}Nd/^{144}Nd$ with increasing $^{206}Pb/^{204}Pb$. Similarly, AVP and WMR shoshonitic lavas show decreasing $^{87}Sr/^{86}Sr$ with increasing $^{206}Pb/^{204}Pb$, a trend that is again at high angles to other IBM lavas

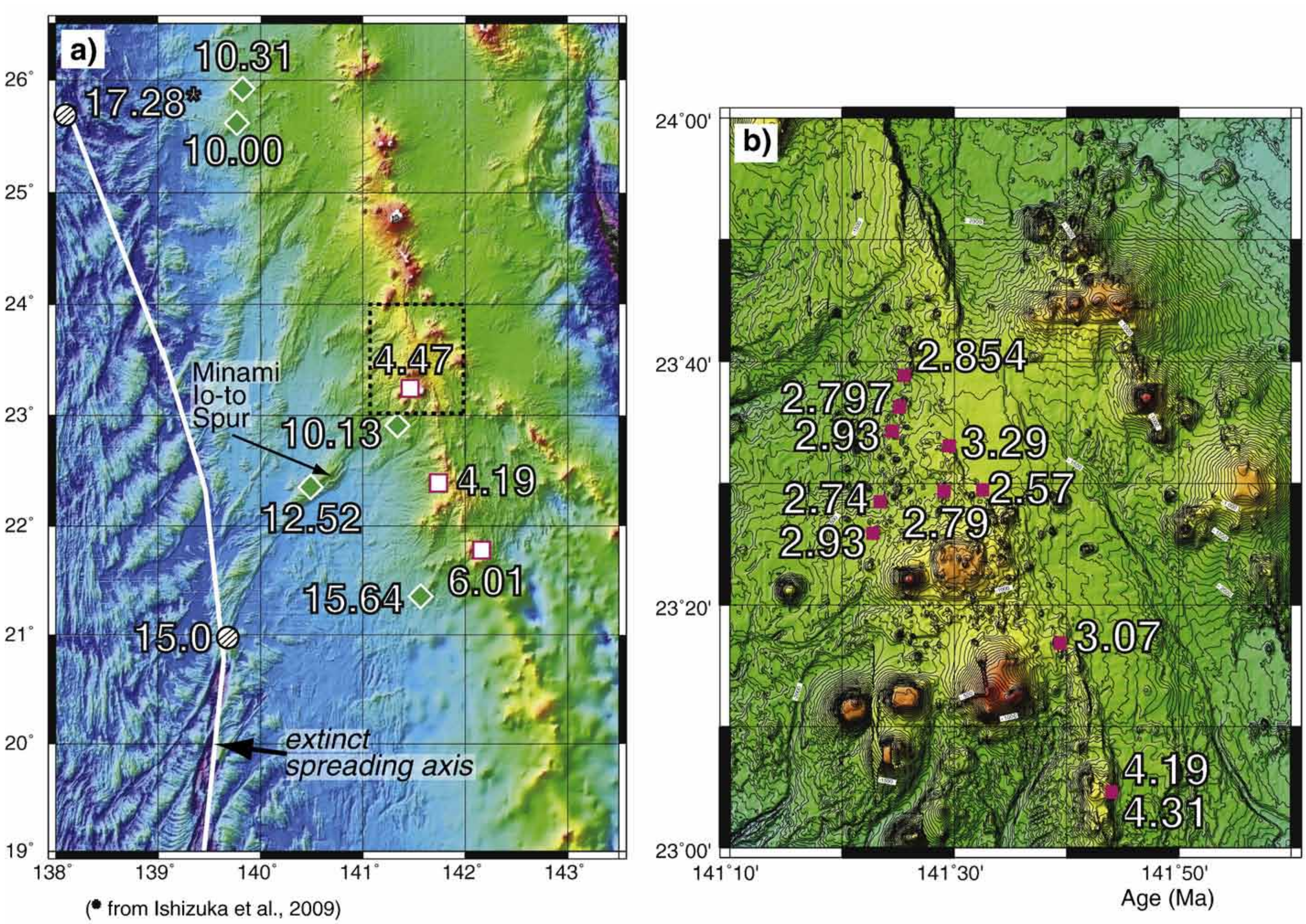

Fig. 2. a) Distribution of ages (in Ma) obtained for volcanic rocks from the Parece Vela Basin, back-arc ridges and seamounts and West Mariana Ridge. Area for (b) is shown in a black dotted line. b) Ages (in Ma) obtained for samples from WMR knolls.

Table 1
Results of stepwise-heating analyses of volcanic rocks from the studied area.

Analysis no.	Station and sample no.	Total age (±1σ)				Plateau age (±1σ)				
		Integrated age (Ma)	Inv. isochron Age (Ma)	$^{40}Ar/^{36}Ar$ intercept	MSWD	Weighted average (Ma)	Inv. isochron Age (Ma)	$^{40}Ar/^{36}Ar$ intercept	MSWD	Fraction of ^{39}Ar (%)
West Mariana Ridge and knolls on the ridge (WMR knolls)										
U05004	IB192BMS04CA01	4.40 ± 0.04	4.28 ± 0.12	842 ± 279	1.14	4.47 ± 0.04	5.4 ± 1.1	−3840 ± 18,900	0.72	51.0
U05002	IB199BMS01CA01	4.10 ± 0.05	3.78 ± 0.18	569 ± 159	1.15	4.19 ± 0.04	3.88 ± 0.16	512 ± 130	1.11	93.1
U05003	IB202BMS01CA01	5.97 ± 0.06	3.3 ± 0.8	365 ± 30	1.03	6.01 ± 0.06	3.3 ± 0.8	365 ± 30	1.03	100.0
U09060	NT0608 D2-102	2.824 ± 0.011	2.77 ± 0.03	311 ± 9	1.73	2.854 ± 0.016	2.84 ± 0.03	302 ± 5	0.79	81.6
U09061	NT0608 D3-1A	2.769 ± 0.022	2.89 ± 0.06	233 ± 31	1.23	2.797 ± 0.024	2.86 ± 0.05	256 ± 31	1.03	95.1
U07194	NT0608 D6-1	2.84 ± 0.08	2.83 ± 0.14	368 ± 27	1.28	2.93 ± 0.09	2.55 ± 0.22	719 ± 241	1.03	93.7
U08001	NT0608 D14-1	2.98 ± 0.16	1.9 ± 0.3	682 ± 269	1.20	3.07 ± 0.14	2.5 ± 0.5	557 ± 316	0.80	72.1
U09062	NT0608 D16-3	2.489 ± 0.023	2.35 ± 0.14	414 ± 124	1.51	2.57 ± 0.03	2.40 ± 0.15	411 ± 103	0.59	86.9
U09059	NT0608 D18-7	4.260 ± 0.022	4.20 ± 0.07	479 ± 124	1.22	4.31 ± 0.03	4.22 ± 0.07	511 ± 136	0.84	90.0
U07188	NT0608 D18-8	4.08 ± 0.11	3.6 ± 0.5	1318 ± 3619	0.82	4.19 ± 0.11	3.6 ± 0.5	291 ± 32	0.82	100.0
U09058	NT0608 D22-1	2.76 ± 0.03	2.59 ± 0.10	521 ± 79	0.72	2.79 ± 0.04	2.57 ± 0.13	559 ± 141	0.75	93.8
U07197	NT0608 D23-1	3.31 ± 0.20	3.0 ± 0.3	361 ± 45	0.68	3.29 ± 0.16	2.55 ± 0.22	361 ± 45	0.68	100.0
U07177	NT0608 D24-2	2.70 ± 0.04	2.82 ± 0.08	249 ± 29	1.45	2.74 ± 0.04	2.77 ± 0.07	279 ± 27	0.98	95.2
U07186	NT0608 D26-1	2.98 ± 0.08	2.73 ± 0.16	348 ± 43	1.20	2.93 ± 0.10	2.99 ± 0.16	257 ± 105	0.42	66.4
Back-arc ridges and seamounts west of the West Mariana Ridge, and Parece Vela Basin										
U04469	IB193BMS03CA01	10.4 ± 0.3	9.9 ± 0.3	329 ± 9	0.68	10.13 ± 0.24	10.0 ± 0.3	319 ± 17	0.68	98.9
U04470	IB194BMS02CA02	11.75 ± 0.10	11.5 ± 0.5	342 ± 24	3.74	12.52 ± 0.10	12.4 ± 0.3	306 ± 24	1.16	71.4
U07179	IB343BMS03CA01	21.3 ± 1.6	13.4 ± 1.2	300.9 ± 1.9	1.22	15.0 ± 0.8	14.2 ± 1.1	297.9 ± 2.0	0.98	76.2
U08208	IB345BMS01CA02	15.67 ± 0.05	14.8 ± 0.3	341 ± 21	9.03	15.64 ± 0.06	15.3 ± 0.3	540 ± 196	2.07	40.7

inv. isochron age: inverse isochron age.
MSWD: mean square of weighted deviates ((SUMS/($n-2$))^0.5) in York (1969).
Integrated ages were calculated using sum of the total gas released.
$\lambda_b = 4.962 \times 10^{-10}\ y^{-1}$, $\lambda_e = 0.581 \times 10^{-10}\ y^{-1}$, $^{40}K/K = 0.01167\%$ (Steiger & Jäger, 1977).

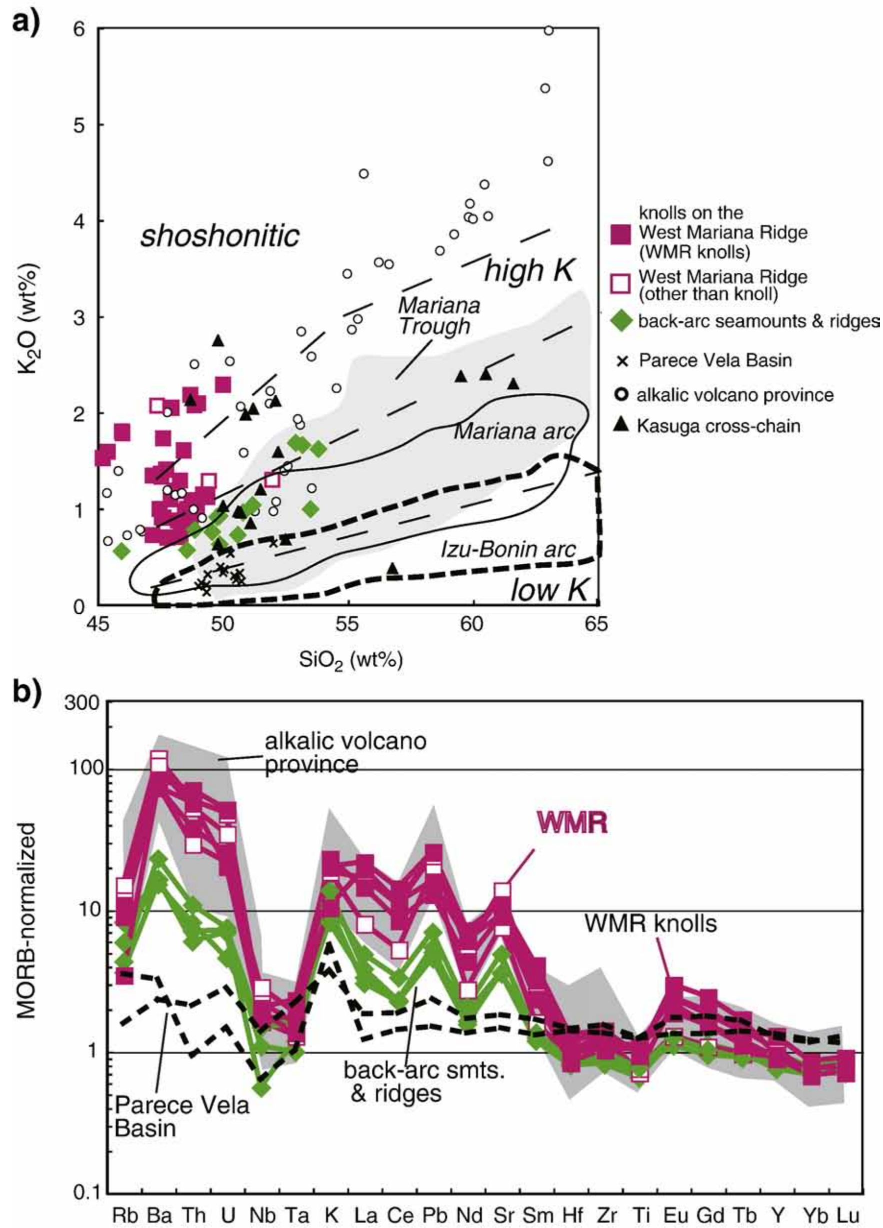

Fig. 3. a) SiO_2–K_2O plot for the volcanic rocks from the studied area. Data source for Quaternary Izu–Bonin volcanic front: Yuasa and Nohara, 1992; Taylor and Nesbitt, 1998; Ishizuka et al., 2003, 2007, 2008; Tamura et al., 2005, 2007, 2009. alkalic volcano province: Bloomer et al., 1989a; Sun and Stern, 2001; Ishizuka et al., 2007. Mariana arc and Mariana Trough; GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/). Kasuga cross-chain: Stern et al., 1993. Rock subdivision is adopted from Le Maitre (1989) and Rickwood (1989). b) Selected MORB-normalized whole rock compositions of volcanics from the studied area (normalized to N-MORB; Sun and McDonough, 1989). Data for alkalic volcano province are from Sun and Stern (2001) and Ishizuka et al. (2007).

(Fig. 4d). The isotopic trends of AVP and WMR lavas are thus very distinct from those defined by all other IBM arc lavas.

5. Discussion

5.1. Temporal migration of shoshonitic magmatism

Shoshonitic magmatism in the IBM arc is limited to north of 23.1°N, i.e., just ahead of northward-propagating Mariana Trough back-arc basin spreading. Except for rear-arc shoshonites of the Kasuga cross-chain (~22°N; Stern et al. 1993) shoshonitic igneous rocks are not found anywhere else in the IBM arc system. This implies a cause-and-effect relationship between rifting and shoshonitic magmatism.

Currently, shoshonitic volcanism only occurs in the northernmost Io-to volcano at 24.8°N and Fukutoku–Oka-no-Ba volcano at 24.2°N. Io-to volcano has been active since at least 2000 years ago and has numerous active fumaroles (Stern et al., 1984), and Fukutoku– Oka-no-Ba erupts frequently (Otani et al., 2004). Linear regression on the relation between age and location of shoshonitic magmatism implies that shoshonitic magmatism migrated north at an average rate of 4.3 cm/year (Fig. 5a).

Based on magnetic, gravity and seafloor fabric data in the northern Mariana Trough, Yamazaki et al. (2003) concluded that back-arc spreading occurs as far north as 22°N, whereas only rifting occurs north of this. Yamazaki et al. (2003) used magnetic anomaly patterns to infer that Mariana Trough spreading propagated northward with time (Fig. 5b). This northward propagation of spreading is more rapid

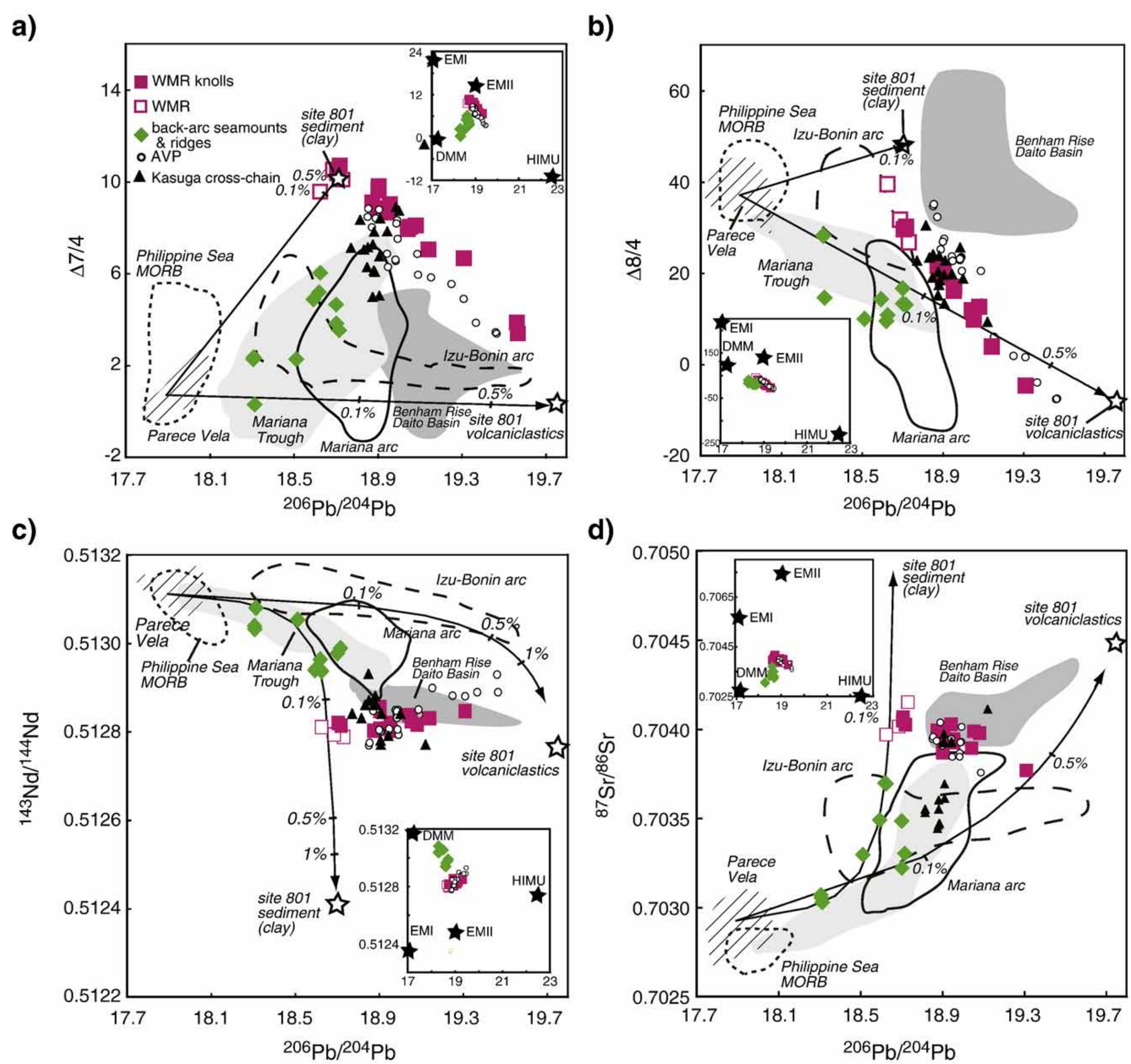

Fig. 4. a–c) Pb and Nd isotope variation and d) Pb-Sr isotope variation for the Izu-Bonin backarc area. Data source for Philippine Sea MORB: Hickey-Vargas, 1991, 1998a; Savov et al., 2006; Ishizuka et al., 2009. Izu-Bonin arc: Taylor and Nesbitt, 1998; Ishizuka et al., 2003, 2006, 2008; Tamura et al., 2005, 2007, 2009; Yokoyama et al., 2003, 2006. Mariana Trough: Stern et al., 1990; Gribble et al., 1998. Mariana arc: GEOROC database. Benham Rise and Daito Basin: Hickey-Vargas (1998a). ODP Site 801 volcaniclastics and sediment (clay): Plank and Langmuir, 1998. Schematic mixing lines on plots a–d) are drawn between assumed Philippine Sea MORB mantle source and melt of subducted volcaniclastics and pelagic sediment. Composition of these melts are estimated by assuming 3% degree of partial melting and adopting partition coefficient of Kessel et al. (2005).

than the migration of shoshonitic volcanism inferred from our dating (14.7 vs. 4.3 cm/year) but still consistent with northward propagation of BAB rifting and spreading.

The age difference between initiation of rifting and spreading in the northern Mariana Trough is estimated to be 2–3 m.y. (Yamazaki et al., 2003), implying that it takes this much time from when arc crust initially is stretched to the start of seafloor spreading, and is consistent with the fact that no spreading occurs where shoshonitic magmatism is younger than 3 Ma.

We do not have enough data to ascertain whether there was shoshonitic (or alkaline) magmatism along the length of the Mariana arc associated with rifting. It will be difficult to confirm this by surveying frontal arc because of the later overprinting of magmatism at the arc front. Unfortunately there is almost no geochemical data available for the WMR south of our survey area. It is known that shoshonitic magmatism does not always occur when rifting begins in the IBM arc. For example no shoshonitic rocks associated with rifting have been reported from the Izu–Bonin sector of the IBM arc (e.g., Ishizuka et al., 2002). It is not clear yet what causes difference in type of magmatism at the initial stage of rifting. We speculate that composition of lithospheric mantle (or uppermost mantle) affected by previous episode of enrichment (e.g., slab input), rate of extension at the rifting, etc. might control the composition of rifting-related magmatism.

5.2. Source of enrichment: subducted sediments and OIB?

Isotopic trends for shoshonitic lavas are distinct from those of other IBM arc lavas and imply that different sources contributed to WMR and AVP magmatism. Fig. 4 shows possible endmember components involved in AVP and WMR shoshonitic magma sources. Overlapping trends for AVP frontal arc lavas and WMR shoshonites don't point to Philippine Sea MORB-type asthenosphere, which usefully approximates the composition of the mantle wedge prior to subduction-related

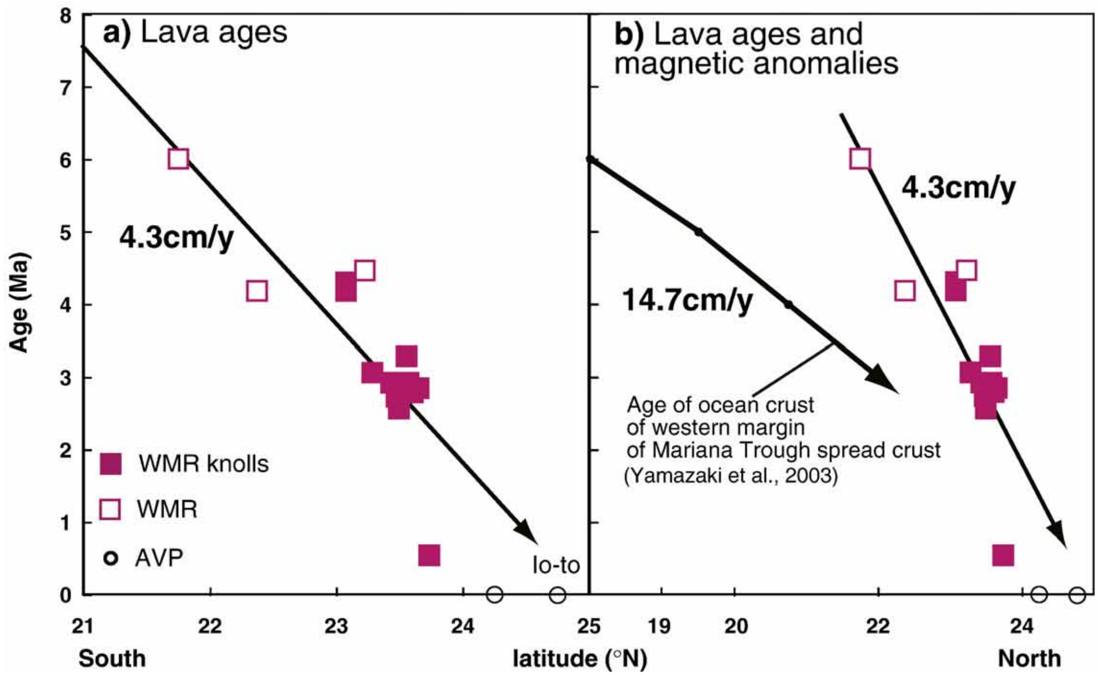

Fig. 5. Temporal migration of shoshonitic magmatism. a) This plot shows that $^{40}Ar/^{39}Ar$ age of basalts and shoshonitic rocks from WMR and WMR knolls becomes younger northwards. Average rate of northward migration of shoshonitic magmatism is estimated to be 4.3 cm/year by linear fitting of the age data on this plot. Location of currently active shoshonitic volcanoes of Io-to and Fukutoku–Oka-no-Ba is also shown. b) Comparison between the northward propagation of spreading of Mariana Trough (Yamazaki et al., 2003) and migration of shoshonitic magmatism. Propagation of spreading appears to be delayed by 2–3 m.y. compared to rifting.

metasomatism for other IBM arc and back-arc basin magmas, including the Late Miocene back-arc seamounts and ridges and Parece Vela Basin spread basalts. The AVP–WMR trend could reflect mixing between two subduction-related endmembers, one with high $^{206}Pb/^{204}Pb$ and low Δ7/4 and the other with low $^{206}Pb/^{204}Pb$ and high Δ7/4 (Fig. 4a). The high $^{206}Pb/^{204}Pb$ endmember could be subducted seamounts with HIMU isotopic signature, known to exist on the Pacific Plate (Southern Wake seamount trail: Koppers et al., 2003). These seamounts are being subducted beneath the southern Izu–Bonin arc and northernmost Mariana arc. Isotopic signatures similar to these seamounts have previously been recognized in arc lavas from the southernmost Izu–Bonin arc (Ishizuka et al., 2007).

The low $^{206}Pb/^{204}Pb$ endmember could be subducted pelagic clay (Plank and Langmuir, 1998). This sediment has higher Δ7/4 and Δ8/4 and lower $^{143}Nd/^{144}Nd$ relative to the HIMU seamounts. Thus, variable contributions of these 2 endmembers could cause the linear trends on Pb–Nd, Pb–Sr and Pb–Pb isotopic plots seen for the shoshonitic basalt (Fig. 4a–d). Since the AVP–WMR isotopic trend is well-defined, this scenario requires remarkably homogeneous endmembers which swamp contributions from all other sources, including Philippine Sea MORB-type asthenosphere. In contrast, the isotopic composition of Miocene back-arc seamounts and ridges can be explained by relatively small contributions of subducted seamounts and pelagic sediment components to the MORB-type mantle source, similar to the behavior of most other IBM lavas.

The estimated significant variations in the proportion of subducted sediment and volcaniclastic material involved in shoshonitic magmas is consistent with observation made on subducting seamounts on the Pacific Plate (e.g., Pautot et al., 1987; Nishimura et al., 2007). For seamounts on the Pacific Plate that are approaching the Izu–Ogasawara Trench, effectively no pelagic sediment was observed on the seamount slopes, which indicates that subducted component should be almost exclusively volcanogenic material when seamounts and surrounding areas are subducted (Nishimura et al., 2007).

The contribution of subducted pelagic sediment is slightly larger than other parts of the Mariana arc (Fig. 4). Larger contributions of sediment component compared to other parts of the Mariana arc might be explained by (at least) one (or more) of three ways.

1) "Sediment component" is not pure subduction component, but is a combination of just-subducted material and pre-existing enriched mantle (i.e., Endmember X). Because Endmember X has similar isotopic composition to inferred subducted component, it is difficult to estimate the proportion of enrichment caused by currently subducted material. So the contribution of subduction component shown in Fig. 4 should be considered as a maximum estimate.
2) Sediment component from currently subducting material may be larger in the studied area. The much larger input of subducted sediment might be due to asthenospheric upwelling which would affect the mantle wedge and might increase slab surface temperature to melt more subducted sediments.
3) Shoshonitic rocks from the AVP and WMR could have formed by lower degrees of partial melting based on their high incompatible element concentrations. If so, the relative contribution of subducted sediments could be higher even if the amount of sediment component added to the source is similar.

Contribution of these subducted components is consistent with observed Ba and Th enrichment of the studied lavas (Fig. 6). AVP and WMR shoshonitic lavas show similar degrees of Ba and Th enrichment relative to the MORB-OIB array, compatible with overwhelming contributions from the subducted slab. On the other hand, Miocene back-arc seamounts and ridges show much less enrichment in these elements.

WMR and AVP shoshonitic rocks are more enriched in Th than other IBM arc lavas, and this is accompanied by high Nb/Yb (Fig. 6), indicating smaller degrees of partial melting and/or derivation from more fertile mantle relative to the mantle feeding the rest of the arc. This Th enrichment is compatible with contributions from melts of subducting pelagic sediment and volcanics of subducting seamounts.

Another constraint on slab-derived components comes from O isotope studies of AVP lavas (Ito and Stern, 1986; Eiler et al., 2000; Ito

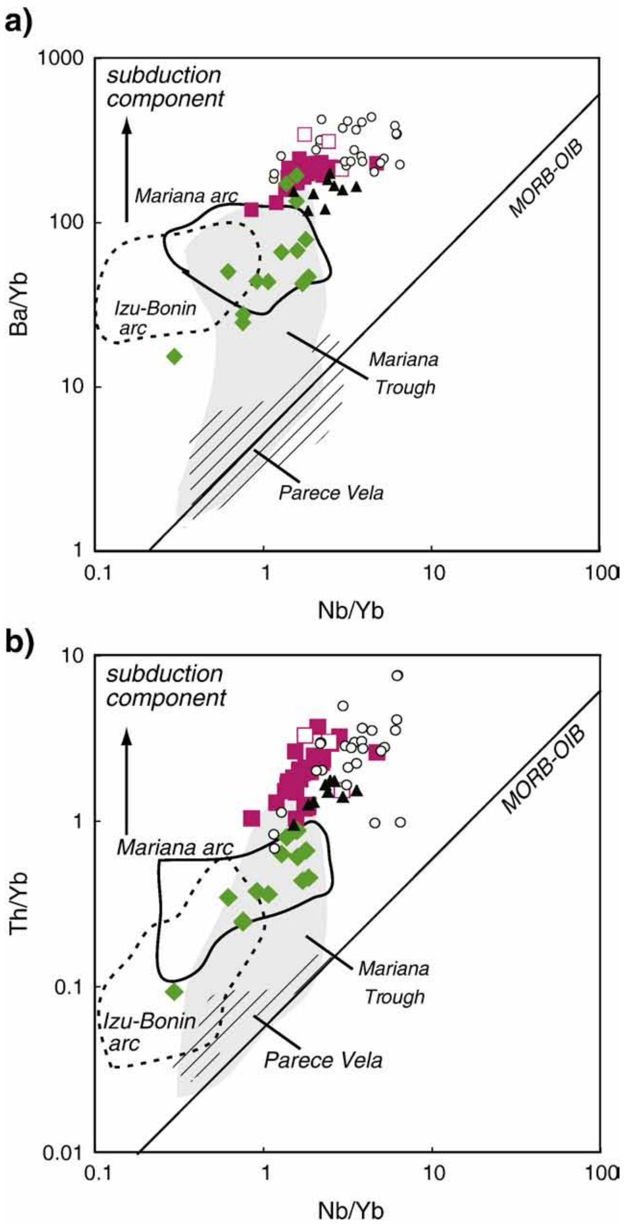

Fig. 6. a) Ba/Yb–Nb/Yb and b) Th/Yb–Nb/Yb plots to identify Ba and Th enrichment in the studied volcanics. Line representing the array of global MORB-OIB composition is from Pearce et al. (2005). Deviation from MORB array on both plots implies an enrichment of Ba and Th by the addition of a subduction component (arrowed). Data source are the same as for Fig. 3.

et al., 2003). Oxygen isotopic compositions of AVP magmas are similar to or slightly higher than MORB values, permitting <4% of high $\delta^{18}O$ pelagic sediment contribution. This is consistent with our estimate – based on radiogenic isotopes – that pelagic sediment contributions to the shoshonitic magmas are generally less than 1% (Fig. 4).

5.3. Source of enrichment: enriched mantle tapped during rifting?

Subducted seamounts and pelagic sediment added into a MORB-type mantle wedge explain many aspects of WMR and AVP shoshonitic trace element and isotopic characteristics. However, these slab-derived sources alone cannot fully explain the chemical characteristics of AVP shoshonitic lavas, and it is possible that enriched mantle sources are at least partly responsible. Furthermore, it seems unlikely that a unique mixture of subducted HIMU OIB and pelagic sediments should dominate magma sources only when BAB rifting begins. The fact that these unusual lavas appear only in advance of rifting compels examination of potential enriched sources in the shallow mantle. Fig. 7 shows relationships between Pb and Nd isotopes and Ce/Pb, which should discriminate slab-derived components (normally with low Ce/Pb) and mantle components (with high Ce/Pb (20–25)). These plots indicate contributions from sources with mantle-like Ce/Pb. We call this component "Endmember X", indicating that we do not know how it formed or where it resides. Endmember X has high, mantle-like Ce/Pb along with high $\Delta 7/4$, $^{206}Pb/^{204}Pb$ (19.0), and $^{87}Sr/^{86}Sr$ (0.7040) as well as low $^{143}Nd/^{144}Nd$ compared to Philippine Sea MORB-type mantle source (Fig. 7: e.g., Hickey-Vargas, 1991, 1998a; Savov et al., 2006; Ishizuka et al., 2009).

Based on the published sedimentary sections sampled by ODP drilling outboard of the Mariana arc (Plank and Langmuir, 1998), other significant sediment lithologies besides subducted HIMU OIB and pelagic clays are chert and radiolarite. Both lithologies have much lower Ce and Pb contents compared to pelagic clays and have low Ce/Pb (c. 3). This implies that subducting pelagic sediments are not likely candidates for Endmember X.

Another subducting component is altered oceanic crust. It has 8–11 ppm Ce, 0.3–0.5 ppm Pb, and Ce/Pb ~ 25 (Kelley et al., 2003), but with much higher $^{143}Nd/^{144}Nd$ (c. 0.51313; Hauff et al., 2003) than required for Endmember X. ODP Site 801 contains alkali basalt in the uppermost igneous section. This basalt fulfills some aspects of Endmember X such as high Ce/Pb (>20), $^{87}Sr/^{86}Sr$ (0.7042), $^{143}Nd/^{144}Nd$ (0.51294) and $^{206}Pb/^{204}Pb$ (19.36). However this basalt has significantly lower $\Delta 7/4$ (-4) and $\Delta 8/4$ (-41) than required for Endmember X.

The above lines of evidences indicate that currently subducting components do not satisfy requirement for Endmember X. This interpretation is consistent with inferred low Ba/La and Th/Ce for this endmember (Figs. 7d, S1b). At the same time, the isotopic composition of this component lies between the two above-mentioned slab-derived endmembers (Fig. 7). Endmember X only appears in AVP and WMR shoshonitic lavas, i.e., emerges only when rifting begins. An enriched mantle component with isotopic compositions that are similar to Endmember X is recognized in the Philippine Sea region, i.e., Benham Rise and Daito Basin area (Fig. 1a; Hickey-Vargas, 1991, 1998a). Basalts from these areas show OIB-like trace element characteristics. The isotopic fields for Benham–Daito lavas lie very close to those defined by AVP–WMR lavas, and like these, point towards HIMU (Fig. 4 insets). The inferred isotopic composition of Endmember X is similar to the source of lavas from the Benham Rise and Daito Basin (Figs. 4 and 7; Hickey-Vargas, 1998a,b) apart from the observation that the latter source has slightly lower $\Delta 7/4$ (Fig. 4a) and slightly higher $\Delta 8/4$.

If this EMII-like component existed in the lithosphere or uppermost asthenosphere, it would be first to melt when decompression associated with rifting began (Fig. 8). We have already established that only magmas produced at the earliest stages of rifting possess this endmember component, and that this unique mantle source is tapped when rifting begins. These enriched magmas probably reflect the presence of an easily mobilized relatively LILE- and LREE-rich region in the lithosphere or uppermost asthenosphere, a region that is progressively tapped as rifting migrates (Fig. 8) and that is quickly exhausted. Higher $\Delta 7/4$ for this endmember relative to Philippine Sea EMII-like source could be due to overprinting of enriched shallow mantle by a slab component with elevated $\Delta 7/4$, perhaps due to fluids released from subducted pelagic sediments. As rifting evolves to spreading, upwelling asthenospheric MORB-type mantle melts to produce back-arc basin basalt. These interpretations are supported by geophysical evidence that the upper mantle beneath the region of rift propagation has anomalously slow seismic velocities (Isse et al., 2009). This suggests that the presence of anomalous mantle underlies the region of rift propagation. Additional detailed

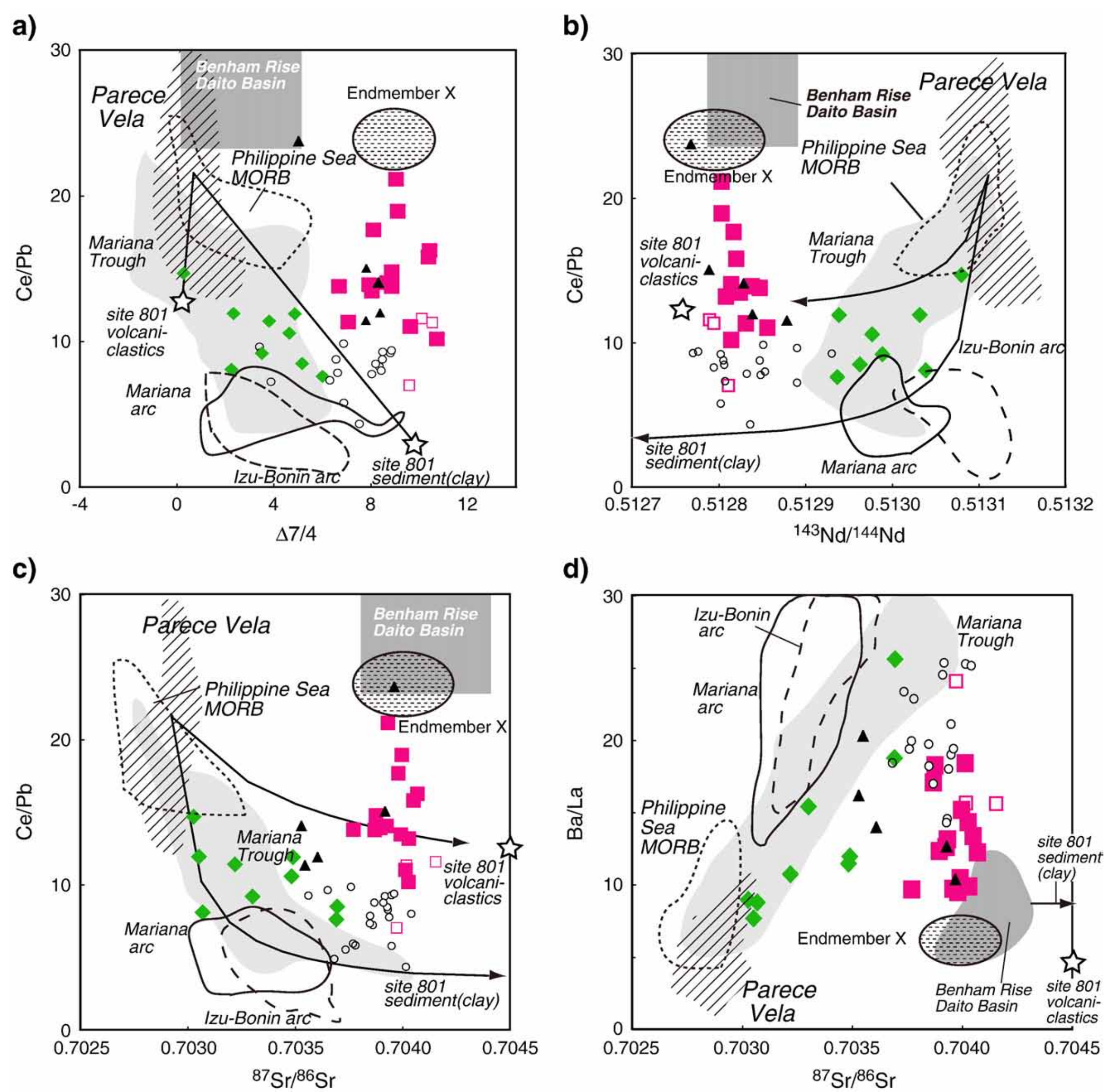

Fig. 7. a–d) Isotope vs. trace element ratio plots to show inferred endmember components to the studied volcanics. Endmember X is recognized as an endmember having mantle-like trace element ratios (i.e., high Ce/Pb, low Ba/La), but distinct isotopic composition from Philippine Sea MORB. Compositional range of OIB in Philippine Sea region (Benham Rise and Daito Basin) is also shown. Data for Benham Rise and Daito Basin are from Hickey-Vargas (1998a, b).

seismic tomographic study may provide further constraints on the relationship between magma compositions and BAB rift initiation.

5.4. Origin of enriched Endmember X

The enriched Endmember X has significantly lower LILE/LREE than expected for slab-derived fluid/melt. Nevertheless, this endmember is estimated to have more enriched isotopic composition relative to Philippine Sea MORB-type asthenospheric mantle, i.e., isotopic character similar to an EMII–HIMU mixture. A candidate for this enriched component is ancient subducted material stored in the mantle. This kind of material could have lost most of its LILE during dehydration upon subduction, but still possess relatively enriched isotopic composition. A related scenario assumes that this is an ancient component that existed in the shallow mantle in the region long before modern IBM subduction began (e.g., Hickey-Vargas, 1992). Benham Rise and Daito Basin OIB approximate the composition of Endmember X and erupted in Eocene to early Oligocene time (c. 37 and 45 Ma: Hickey-Vargas, 1998a). This implies that the enriched component in Philippine Sea OIB-like lavas existed before modern IBM subduction was established. Such a component is likely to be easily melted upon first rupture of lithosphere during rifting.

Another possible source for Endmember X is the material subducted after the IBM arc began (as discussed in 5.2). Enriched isotopic compositions associated with moderately LILE-enriched Endmember X might be explained by a two-stage process. Mantle beneath the studied area is supposed to have been metasomatized by material released during previous and/or on-going subduction of the Pacific Plate. Also melt produced by slab fluxing might have accumulated and affected the composition of upper part of asthenosphere or lower part of lithosphere without erupting to the surface (Pearce et al., 2005). This metasomatized (enriched) mantle could have experienced melt extraction once as a part of arc magmatism, and then could have been involved in production of shoshonitic

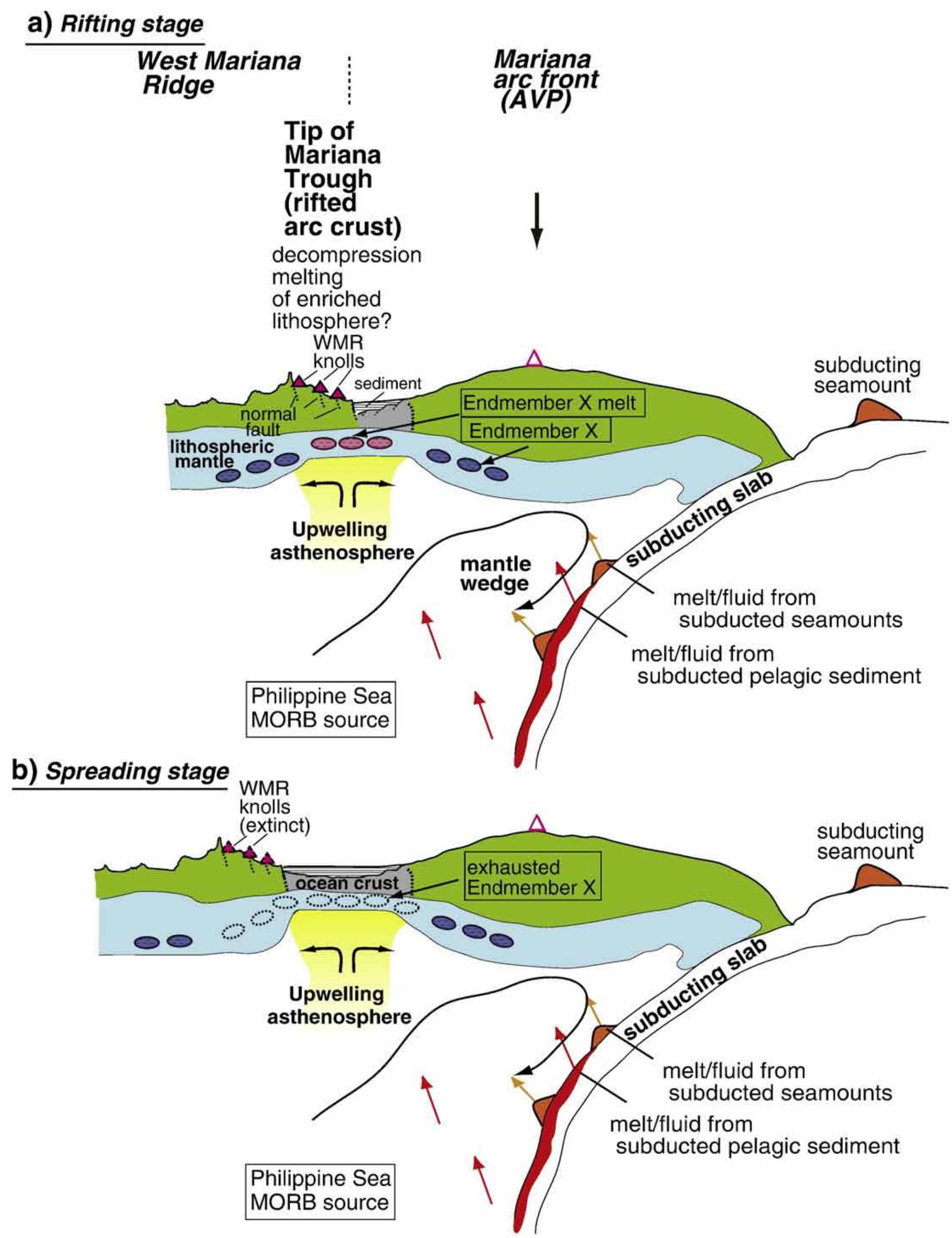

Fig. 8. Schematic cartoon for the magmatic process of northern Mariana Trough area. a: Rifting stage. Shoshonitic magmatisms in AVP and WMR are both affected by melt of subducted sediment and volcanicastics of subducted seamounts. In addition, shoshonitic magma from WMR and WMR knolls associated with initiation of rifting has contribution of enriched endmember, shown as Endmember X, which could reside in lithospheric mantle. This component might be melted only upon decompression cause by rifting and associated upwelling of asthenospheric mantle. b: Spreading stage. By the time back-arc spreading commenced, Endmember X has been exhausted, and basalts erupted in Mariana Trough are mainly fed by asthenospheric mantle (Philippine Sea MORB source).

magma due to decompression melting upon initiation of rifting. This type of process has been proposed to explain enriched magmatism at early stage of continental rifting (e.g., Chazot et al., 2005; Grange et al., 2008). Our results demonstrate that enriched lithospheric mantle could also exist in an oceanic island arc setting and similarly become evident only at the earliest stage of arc rifting.

Further studies of the spatial and temporal variations of enriched mantle components in the Philippine Sea region might give insight into the origin of this enriched endmember and make it easier to choose between the two possibilities discussed above.

6. Summary

This study for the first time demonstrates that unusually enriched magmas have been migrating northward just in front of propagating

Mariana Trough rifting, at 4.3 cm/year for the last 6 m.y. Other conclusions result from this study:

1) Shoshonitic magmatism on the WMR and AVP has well-defined isotopic trends that are distinct from those of other parts of the IBM arc.
2) Shoshonitic magmatism shows mixing between two endmembers that are distinct from the subduction-modified Philippine Sea MORB-type asthenospheric mantle source characteristic of most IBM arc melts. One component appears to be a mixture of fluids and/or partial melt of pelagic sediment (clay) and volcanics from subducting intraplate seamounts.
3) The other endmember (Endmember X) for WMR and AVP shoshonitic rocks appears to be enriched mantle. Endmember X is distinct from Philippine Sea MORB-type source by having high Δ7/4, $^{206}Pb/^{204}Pb$, and $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$. This isotopic character is similar to other Philippine Sea OIB.
4) Endmember X only appears at when BAB rifting begins. This indicates that Endmember X probably resides in the lithosphere or uppermost asthenosphere or lowermost lithosphere, which is easily melted and quickly exhausted due to decompression caused by rifting.

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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.epsl.2010.03.016.

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