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Research Article

Pb, Nd, and Sr isotopic constraints on the origin of Miocene basaltic rocks from northeast Hokkaido, Japan: Implications for opening of the Kurile back-arc basin

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Abstract Late Miocene (7–9 Ma) basaltic rocks from the Monbetsu-Kamishihoro graben in northeast Hokkaido have chemical affinities to certain back-arc basin basalts (referred to herein as Hokkaido BABB). Pb-, Nd- and Sr-isotopic compositions of the Hokkaido BABB and arc-type volcanic rocks (11–13 Ma and 4–4.5 Ma) from the nearby region indicate mixing between the depleted mantle and an EM II-like enriched component (e.g. subducted pelagic sediment) in the magma generation. At a given $^{87}Sr/^{86}Sr$, Hokkaido BABB have slightly lower $^{143}Nd/^{144}Nd$ and slightly less radiogenic $^{206}Pb/^{204}Pb$ compared with associated arc-type lavas, but both these suites are difficult to distinguish solely on the basis of isotopic compositions. These isotopic data indicate that while generation of the Hokkaido BABB involves smaller amounts of the EM II-like enriched component than do associated arc lavas, Hokkaido BABB are isotopically distinct from basalts produced at normal back-arc basin spreading centers. Instead, northeast Hokkaido BABB are more similar to basalts erupted during the initial rifting stage of back-arc basins. The Monbetsu-Kamishihoro graben may have developed in association with extension that formed the Kurile Basin, suggesting that opening of the basin continued until late Miocene (7–9 Ma).

Key words: Kurile back-arc basin, Miocene, northeast Hokkaido, Pb-, Nd- and Sr-isotopic compositions, rift.

INTRODUCTION

Opening of the Japan Sea and Kurile back-arc basins is pivotal in the tectonic evolution of northeastern Asia. It has been widely accepted that development of the Japan Sea back-arc basin occurred from 28 Ma to 18 Ma (Otofuji *et al.* 1985; Nohda *et al.* 1988; Kaneoka *et al.* 1992; Tamaki 1995). However, various tectonic models have been proposed for the formation of the Kurile Basin but no consensus has been obtained. Kimura & Tamaki (1985) argued that the Kurile Basin spreading originated from the clockwise rotation of the Okhotsk Terrane since about 30 Ma that resulted from the north-eastward migration of the East Asian Terranes of the Eurasian Plate due to the Indo-Eurasia Collision. Kimura & Kusunoki (1997) revised the model and proposed that the opening of the Kurile Basin that formed during Oligocene to middle Miocene time was due to dextral strike-slip fault after collision between the Eurasian plate and the Okhotsk plate. Maeda (1986), however, inferred that spreading in the Kurile Basin is younger than 17 Ma based on the cessation age of the Hidaka magmatism in central Hokkaido. Combining bathymetric, structural and geophysical evidence, Gnibidenko *et al.* (1995) concluded that the Kurile back-arc basin may have formed either as young as Miocene time or as old as late Cretaceous. Takeuchi (1997) inferred on the basis of K-Ar ages of South Sakhalin volcanic rocks that back-arc spreading of the Kurile Basin ceased during the late Miocene (*ca* 9 Ma).

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To elucidate the origin of the Kurile Basin, the most direct approach is to study volcanic rocks that form in the back-arc basin. Recently, Ikeda (1998) and Yamashita *et al.* (1999) showed that the geochemical characteristics of some basaltic rocks of 7–9 Ma from northeast Hokkaido are similar to those of back-arc basin basalts. The present study, following Ikeda (1998), reports new Pb, Nd, and Sr isotopic data for the basaltic rocks with purpose of constraining the mantle source characteristics and tectonic evolution along the southern margin of the Kurile back-arc basin.

GEOLOGIC AND GEOCHEMICAL BACKGROUND

Northeast Hokkaido is situated along the southwest flank of the Kurile back-arc basin and between the Kurile and Japan Sea basins (Fig. 1). Neogene volcanic rocks (4–14 Ma) are widely distributed in this area, generally trending north-south (Watanabe *et al.* 1991; Goto *et al.* 1995; Okamura *et al.* 1995). The volcanic rocks are mainly calc–alkaline in nature and are associated with icelandites and high-Ti andesites (Kokubu *et al.* 1994; Goto *et al.* 1995; Okamura *et al.* 1995).

The geology of the study area is characterized by the north-south Monbetsu-Kamishihoro graben (Yahata & Nishido 1995; Yahata 1997). It is ~10 km wide and extends for ~60 km in the north-south direction (Okamura *et al.* 1995; Watanabe 1995; Yahata & Nishido 1995; Yahata 1997) (Fig. 1). The offshore extension of the graben is inferred from seismic profiling (Tamaki *et al.* 1978) to continue at least 40 km into the Sea of Okhotsk (Watanabe 1994). The graben formed since about 11.5 Ma

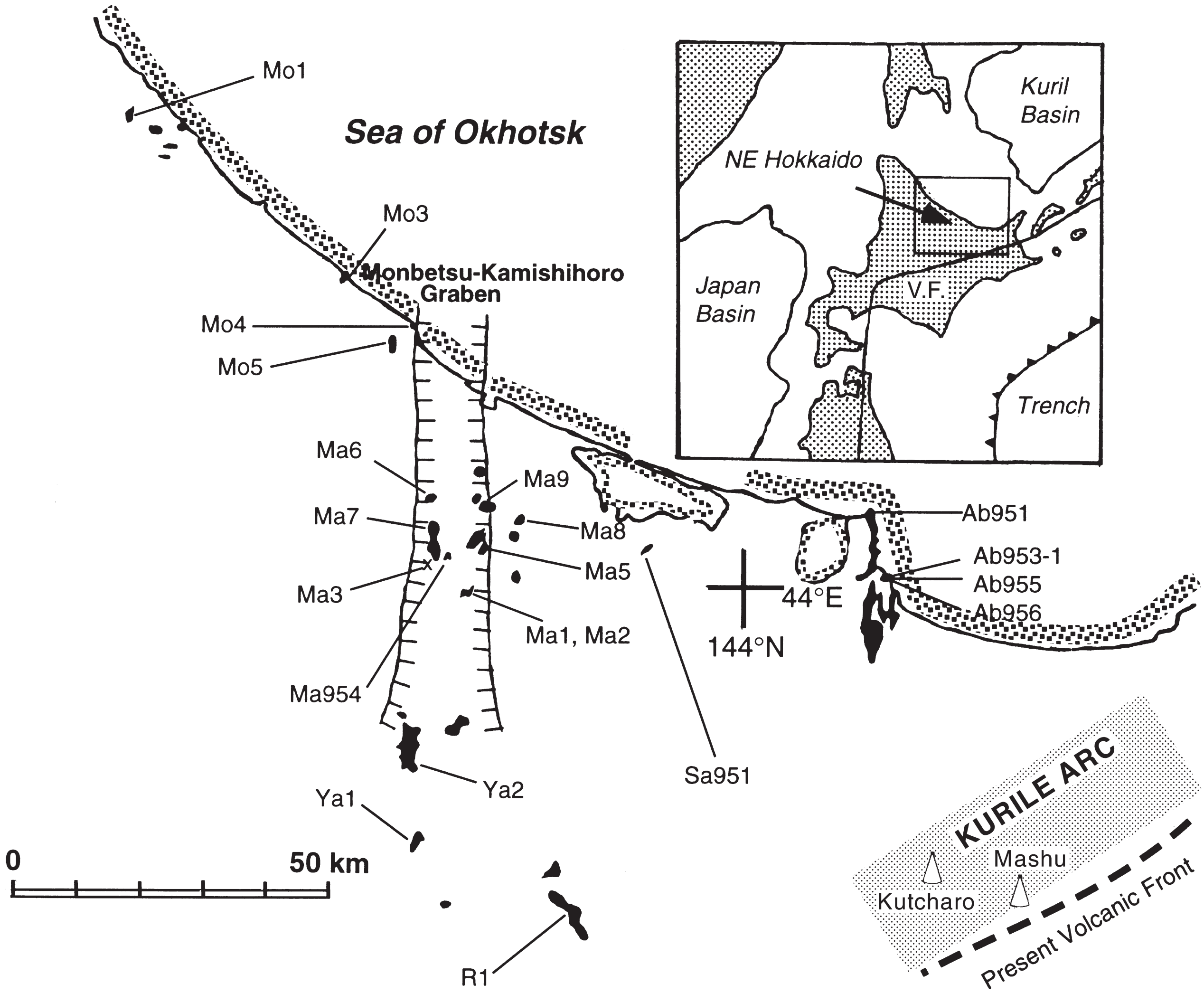

Fig. 1 Distribution of Neogene basaltic rocks in northeast Hokkaido, showing locations of analyzed samples and Quaternary volcanoes of the Kurile Arc. The 3000 m bathymetric contour is used to outline the Japan Basin and Kurile Basin in the inset map. VF, volcanic front.

(Yahata 1997) and is revealed by drilling to be deeper than 700 m (Ministry of International Trade and Industry, Japan 1991). Volcanic activity in the graben and adjacent areas is characterized by eruption of rhyolite-dominant bimodal suites (Oba 1975; Goto *et al.* 1995; Okamura *et al.* 1995). Mafic rocks (basalt and basaltic andesite) of 7–9 Ma age in the area have geochemical characteristics of back-arc basin basalt (BABB) and are compositionally distinct from other Neogene basaltic rocks in northeast Hokkaido, which generally plot on discrimination diagrams in fields for arc lavas (Ikeda 1998; Yamashita *et al.* 1999). In particular, relatively high TiO_2 contents (1–1.5%) of the 7–9 Ma mafic rocks suggest that these rocks are derived from a mantle source whose composition is comparable to the sources of MORB and BABB.

Discrimination diagrams of Saunders & Tarney (1991) applied to northeast Hokkaido lavas (Figs. 2, 3; data source, Ikeda 1998) confirm that the 7–9 Ma suite has BABB affinities whereas the other Neogene lavas have strong arc affinities. These BABB-type lavas are compositionally similar to basaltic rocks from Ocean Drilling Program (ODP) Legs 127 and 128 in the Japan Sea, interpreted as sills and lava flows erupted or shallowly intruded in a marine environment during back-arc extension and spreading in the middle Miocene (Allan & Gorton 1992). All of the Hokkaido samples plot along a similar medium-K trend in the K_2O-SiO_2 diagram, although the 7–9 Ma lavas generally have less silica than do the arc-related suites (Ikeda 1998). This is consistent with different phenocryst assemblages observed in the suites (Ikeda 1998): the 7–9 Ma BABB lavas contain abundant plagioclase and olivine, whereas the arc-like suite is dominated by plagioclase and clinopyroxene, with subordinate olivine, orthopyroxene and hornblende. Petrographic and chemical variations correspond to geographic variations, with arc-like suites distributed widely across northeast Hokkaido, whereas 7–9 Ma BABB are concentrated in and on the periphery of the Monbetsu-Kamishihoro graben. Because of the geochemical similarities of the 7–9 Ma Monbetsu-Kamishihoro basalts to back-arc basin basalts, we will refer to these basalts as 'Hokkaido BABB'.

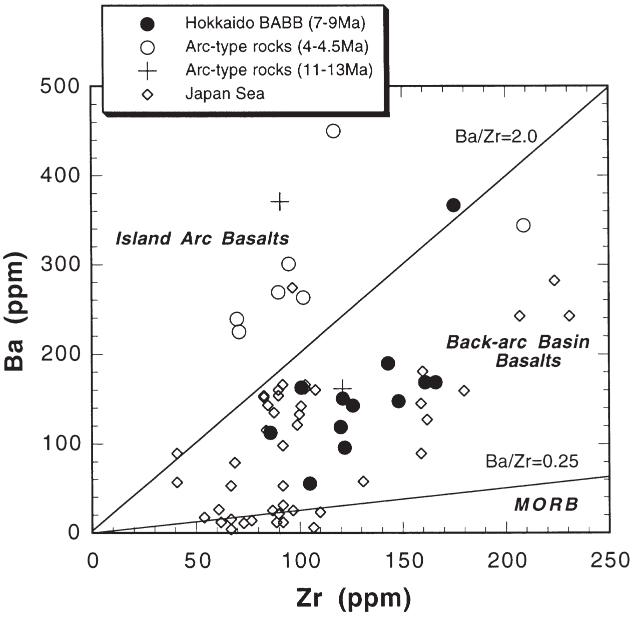

Fig. 2 Ba versus Zr diagram (Saunders & Tarney 1991) for Neogene volcanic rocks from northeast Hokkaido and Japan Sea (ODP Legs 127 and 128). Data source, Ikeda (1998) and Allan & Gorton (1992).

At ~6 Ma, the locus of volcanism shifted from a graben-parallel trend to a northwest–southwest direction that corresponds to the direction of present day Kurile arc due to a clockwise rotation of the Pacific plate (Watanabe 1995).

SAMPLES AND ANALYTICAL METHODS

Samples studied here are the same as those analyzed for major and trace elements by Ikeda (1998) and are quite fresh. Mineral assemblages of the samples are listed in Ikeda (1998).

Sr and Nd isotope analyzes were performed using an automated Finnigan MAT 261 (USA),

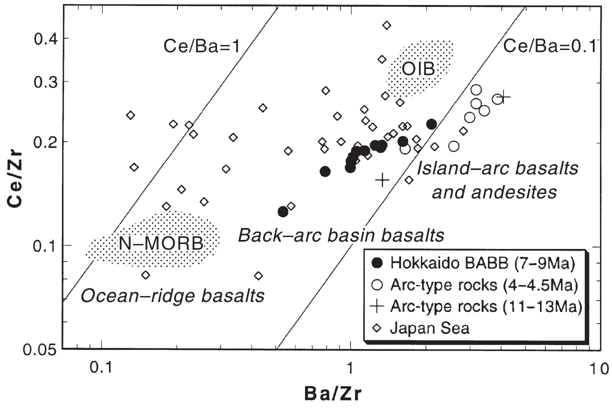

Fig. 3 Ce/Zr versus Ba/Zr diagram for Neogene volcanic rocks from northeast Hokkaido and Japan Sea (ODP Legs 127 and 128), with graphical range of mid-ocean ridge basalts, back-arc basin basalts and island-arc basalts and andesites, and fields of N-MORB and oceanic island basalt of Saunders and Tarney (1991). Plot data are from Ikeda (1998) and Allan and Gorton (1992). N-MORB, normal-type mid-ocean ridge basalt; OIB, oceanic island basalt; BABB, back-arc basin basalts.

Model MAT mass spectrometer with five collectors at the Institute for Study of the Earth's Interior, Okayama University following the method of Kagami *et al.* (1992). $^{87}Sr/^{86}Sr$ were fractionation-corrected to $^{86}Sr/^{88}Sr = 0.1194$. $^{143}Nd/^{144}Nd$ were fractionation-corrected to $^{146}Nd/^{144}Nd = 0.7219$ and adjusted to BCR-1 = 0.512640. Standard values (±2 SD) over the period of data collection are: National Bureau of Standards (NBS) 987 $^{87}Sr/^{86}Sr = 0.710231 \pm 0.000012$, 0.710232 ± 0.000012 and 0.710239 ± 0.000011; and BCR-1 $^{143}Nd/^{144}Nd = 0.512680 \pm 0.000013$, 0.512697 ± 0.000012 and 0.512698 ± 0.000013.

Lead isotope compositions were determined with a Finnigan MAT 261 multicollector in the static multicollector mode at the University of Texas at Dallas (UTD). The Pb separation procedures follow the method of Manton (1988). Lead isotopic compositions were corrected for fractionation by 0.15%/amu. NBS 981 after fractionation corrections over the period of data collection yielded $^{206}Pb/^{204}Pb = 16.944 \pm 0.017$, $^{207}Pb/^{204}Pb = 15.501 \pm 0.022$ and $^{208}Pb/^{204}Pb = 36.764 \pm 0.066$ (±2 SD, $n = 10$). Analytical uncertainties were controlled by fractionation in these samples and were estimated to be no greater than ±0.15%/amu (±0.051 for $^{206}Pb/^{204}Pb$; ±0.069 for $^{207}Pb/^{204}Pb$; ±0.22 for $^{208}Pb/^{204}Pb$). Because analytical uncertainties for Pb isotopic compositions are controlled by fractionation uncertainties, these are highly correlated on Pb–Pb isotope diagrams.

Sr, Rb, Nd and Sm concentrations were determined with Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at Activation Laboratories Ltd, Canada. Lead concentrations were determined by isotope dilution using an automated Finnigan MAT 261 at UTD. Other major and trace element data for the samples studied here are listed in Ikeda (1998).

RESULTS

The isotopic data along with silica concentrations and trace element content are listed (Tables 1, 2).

The range of initial $^{87}Sr/^{86}Sr$ for Hokkaido BABB is generally less radiogenic than the associated arc lavas (0.70317–0.70364 versus 0.70323–0.70411). Comparison with Japan Sea BABB is precluded by the pervasive effects of seawater alteration on the former basalts. Hokkaido BABB generally have higher initial $^{87}Sr/^{86}Sr$ (0.70317–0.70364) than those of Mariana Trough BABB (mean $^{87}Sr/^{86}Sr = 0.7029$, Volpe *et al.* 1987) and N-MORB (0.7025, Sun & McDonough 1989) but overlap with ranges of other BABB, such as those from the East Scotia Sea (0.7029–0.7034) and Lau Basin (0.7030–0.7042) (Saunders & Tarney 1979; Volpe *et al.* 1988).

The Sr and Nd isotopic compositions from this study and Okamura *et al.* (1995) are shown (Fig. 4). The data of Okamura *et al.* (1995) are for Miocene lavas of northern Hokkaido which include part of the present study area. Arc-type lavas from northeast Hokkaido span a wide range, from more

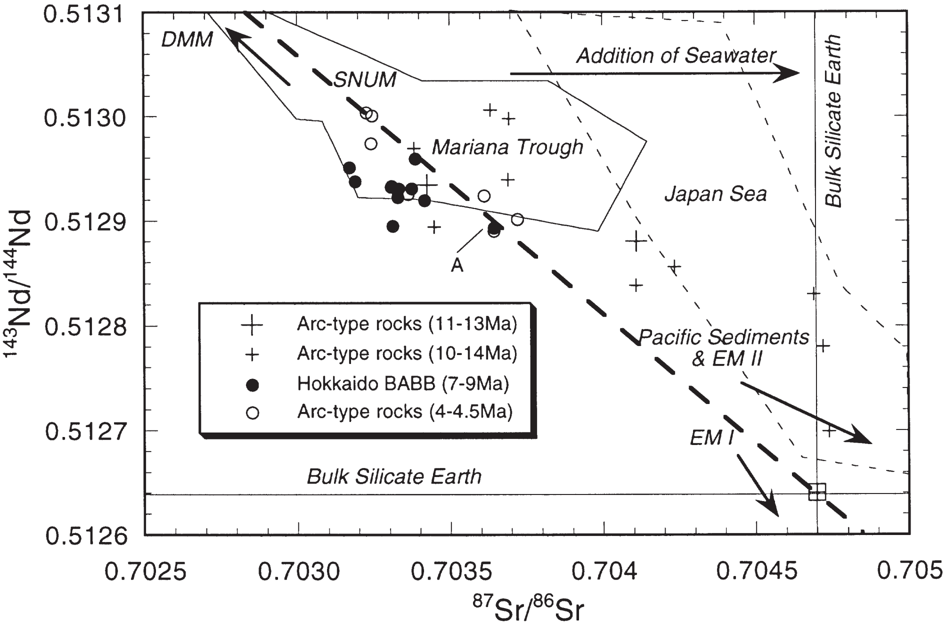

Fig. 4 Initial Sr–Nd isotopic compositions of Neogene volcanic rocks from northeast Hokkaido. Data sources: Sr–Nd correlation line for the upper mantle (O'Nions *et al.* 1979); depleted MORB mantle, enriched mantle, Pacific sediment components, Japan Sea basalts and Mariana Trough basalts (Zindler and Hart (1986); Cousens *et al.* (1994) and Gribble *et al.* (1998)). Hokkaido BABB includes andesite (Ma3: A). +, 10–14 Ma arc-type lavas include data of Okamura *et al.* (1995). Note that Japan Sea basalts show the effects of pervasive sea water alteration in their Sr isotopic compositions. BABB, back-arc basin basalts; SNUM, Sr–Nd correlation line for the upper mantle; DMM, depleted MORB mantle; EM, enriched mantle.

Table 1 Sr and Nd isotopic compositions with SiO_2 and trace element data for the volcanic rocks from Northeast Hokkaido

Sample	SiO_2 (wt%)	$^{87}Sr/^{86}Sr$	Sr (p.p.m.)	Rb (p.p.m.)	Rb/Sr	$(^{87}Sr/^{86}Sr)_i$	$^{143}Nd/^{144}Nd$	Sm (p.p.m.)	Nd (p.p.m.)	Sm/Nd	$(^{143}Nd/^{144}Nd)_i$	Nor. age (Ma)
Island-arc type volcanic rocks (11–13 Ma)												
Mo1	55.23	0.704199 (12)	198.0	32.5	0.16	0.704111	0.512894 (9)	12.5	3.4	0.27	0.512880	13
Ab951	51.92	0.703459 (11)	397.7	30.0	0.08	0.703425	0.512945 (12)	16.3	4.1	0.25	0.512934	11
Back-arc basin basalts including andesite (7–9 Ma)												
Ma1	49.63	0.703215 (12)										
Ma2	49.80	0.703348 (11)	333.8	18.9	0.06	0.703329	0.512930 (9)	16.1	4.0	0.25	0.512922	8
Ma3*	63.19	0.703700 (10)	277.6	47.3	0.17	0.703644	0.512901 (17)	24.9	6.2	0.25	0.512893	8
Ma954	51.88	0.703398 (9)	292.2	23.5	0.08	0.703375	0.512938 (12)	14.5	3.7	0.26	0.512931	7
Ma5	51.88	0.703353 (12)	353.5	18.8	0.05	0.703333	0.512939 (11)	19.7	4.7	0.24	0.512931	9
Ma6	49.57	0.703319 (14)	333.7	5.9	0.02	0.703313	0.512904 (14)	14.6	4.1	0.28	0.512895	8
Ma7	49.77	0.703197 (8)	366.3	7.2	0.02	0.703191	0.512946 (12)	13.7	3.7	0.27	0.512937	8
Ma8	49.20	0.703317 (10)	318.1	9.5	0.03	0.703307	0.512940 (5)	11.1	2.8	0.25	0.512932	8
Ma9	49.41	0.703179 (11)	305.0	6.5	0.02	0.703172	0.512960 (13)	11.2	3.2	0.29	0.512951	8
Mo3	53.12	0.703407 (11)	323.8	18.7	0.06	0.703386	0.512968 (11)	16.4	4.0	0.24	0.512959	9
Mo4	52.22	0.703441 (12)	327.2	21.3	0.07	0.703417	0.512928 (12)	16.2	3.9	0.24	0.512919	9
Mo5	52.06	0.703333 (11)	354.6	23.3	0.07	0.703309	0.512942 (12)	22.8	5.8	0.25	0.512933	9
Island-arc type volcanic rocks (4–4.5 Ma)												
R1	57.07	0.703666 (11)	288.2	40.0	0.14	0.703643	0.512894 (12)	26.6	6.8	0.26	0.512890	4
Ya1	52.04	0.703621 (11)	325.1	18.9	0.06	0.703611	0.512928 (8)	14.5	3.7	0.26	0.512924	4
Ya2	56.97	0.703741 (14)	283.5	36.2	0.13	0.703720	0.512905 (12)	25.2	6.0	0.24	0.512901	4
Sa951	56.39	0.703385 (12)	244.7	33.2	0.14	0.703363	0.512929 (11)	13.0	3.2	0.25	0.512925	4
Ab953-1	51.50	0.703253 (10)	380.9	21.7	0.06	0.703242	0.512978 (10)	12.4	3.0	0.24	0.512974	4.5
Ab955	58.01	0.703240 (11)	403.1	29.8	0.07	0.703226	0.513008 (11)	14.6	3.4	0.23	0.513004	4.5
Ab956	52.11	0.703255 (10)	376.3	19.2	0.05	0.703246	0.513005 (8)	11.9	2.9	0.24	0.513001	4.5

* Andesite, $(ratio)_i$ initial isotope ratio.

SiO_2 concentrations listed by Ikeda (1998). Two standard deviation uncertainty (parentheses) corresponds to the last two digits. Normalized ages for the calculation of the initial isotope ratios are estimated from compiled data set in Ikeda (1998).

Table 2 Isotopic composition of lead and concentrations of Ce and Pb for the volcanic rocks from NE Hokkaido

Sample	Ce	Pb	Ce/Pb	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	Δ7/4[†]	Δ8/4[†]
Island-arc type volcanic rocks (11–13 Ma)								
Mo1	18.75	5.5	3.41	18.339	15.524	38.313	4.5	51.4
Ab951	24.80	5.3	4.68	18.362	15.498	38.242	1.7	41.6
Back-arc basin basalts including andesite (7–9 Ma)								
Ma1	23.90	2.8	8.54	18.274	15.488	38.175	1.6	45.5
Ma2	20.37	2.1	9.70	18.352	15.563	38.429	8.2	61.3
Ma3*	39.81	8.9	4.47	18.335	15.507	38.244	2.8	45.0
Ma954	23.80	3.6	6.61	18.333	15.542	38.352	6.4	56.0
Ma5	30.42	3.6	8.45	18.254	15.473	38.134	0.3	43.8
Ma6	20.26	4.3	4.71	18.296	15.517	38.243	4.3	49.6
Ma7	20.09	2.4	8.37	18.235	15.518	38.185	5.0	51.2
Ma8	16.74	2.5	6.70	18.411	15.599	38.530	11.2	64.4
Ma9	13.17	2.0	6.59	18.248	15.508	38.159	3.9	47.0
Mo3	26.07	3.2	8.15	18.255	15.524	38.206	5.4	50.9
Mo4	28.21	3.3	8.55	18.273	15.499	38.177	2.7	45.8
Mo5	30.17	3.5	8.62	18.292	15.524	38.259	5.0	51.7
Island-arc type volcanic rocks (4–4.5 Ma)								
R1	31.38	8.1	3.87	18.429	15.517	38.350	2.8	44.2
Ya1	19.96	4.5	4.44	18.407	15.546	38.396	5.9	51.5
Ya2	40.15	7.0	5.74	18.391	15.561	38.439	7.7	57.7
Sa951	21.40	5.4	3.96	18.338	15.536	38.355	5.8	55.7
Ab953-1	18.54	4.4	4.21	18.384	15.549	38.302	6.5	44.9
Ab955	27.22	4.1	6.64	18.371	15.557	38.343	7.4	50.5
Ab956	17.40	3.1	5.61	18.321	15.503	38.161	2.6	38.4

* Andesite.

[†] Deviation from Northern Hemisphere Reference Lines (NHRL, Hart 1984). Ce data from Ikeda (1998).

depleted than Hokkaido BABB to near bulk earth compositions. However, Hokkaido BABB show a restricted range of relatively depleted compositions (initial ^{143}Nd/^{144}Nd = 0.51289–0.51296, corresponding to εNd values of +3.9 to +5.3) and generally plot in or near the field of Marina Trough BABB and slightly to the left of the Hokkaido arc-type lavas on a plot of ^{143}Nd/^{144}Nd versus ^{87}Sr/^{86}Sr (Fig. 4). Hokkaido BABB thus approximate the 'Rear-Arc Trend' of Stern *et al.* (1993), whereas the arc-type lavas approximate the 'Front-Arc Trend'. This relationship is typical of modern arc and BABB couples.

Most of the arc-type lavas from northeast Hokkaido plot on or above the upper mantle Sr–Nd correlation line (SNUM in Fig. 4, O'Nions *et al.* 1979) extending in the direction of EM II (enriched mantle II, Zindler & Hart 1986) and Pacific sediments. This characteristic is common in island-arc volcanic rocks (Gill 1981). The Hokkaido BABBs plot under the SNUM line and the field of the Japan Sea basalts (Fig. 4). Note that the Japan Sea basalts have elevated Sr isotopic compositions due to seawater alteration (Cousens *et al.* 1994). The Sr–Nd isotopic characteristic of the Hokkaido BABB suggest that mantle source compositions are not simply combinations of depleted MORB-type mantle and a high ^{87}Sr/^{86}Sr subduction component such as seawater.

Lead isotopic compositions of northeast Hokkaido lavas (Table 2) are shown on ^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb and ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb diagrams (Fig. 5). These are the first Pb isotope data for volcanic rocks from Hokkaido. Note that all Hokkaido lavas are easily distinguished from the Japan Sea lavas but are difficult to distinguish from each other or from arc lavas elsewhere in Japan. Both the arc-type lavas and Hokkaido BABB are characterized by a restricted range of ^{206}Pb/^{204}Pb (18.24–18.41) with large ranges in ^{207}Pb/^{204}Pb (15.47–15.60) and ^{208}Pb/^{204}Pb (38.13–38.53). Back-arc basins where true sea floor spreading such as the Mariana Trough occur are characterized by large variations in ^{206}Pb/^{204}Pb (Fig. 5), a feature not seen in Hokkaido BABB. Instead, Hokkaido BABB have the restricted range in ^{206}Pb/^{204}Pb that do Japan Arc lavas. Hokkaido BABB have slightly less radiogenic ^{206}Pb/^{204}Pb relative to the arc-type lavas. Both Hokkaido suites and Japan Arc samples plot in a field that is distinct from Pacific MORB and oceanic basalts from the northern hemisphere

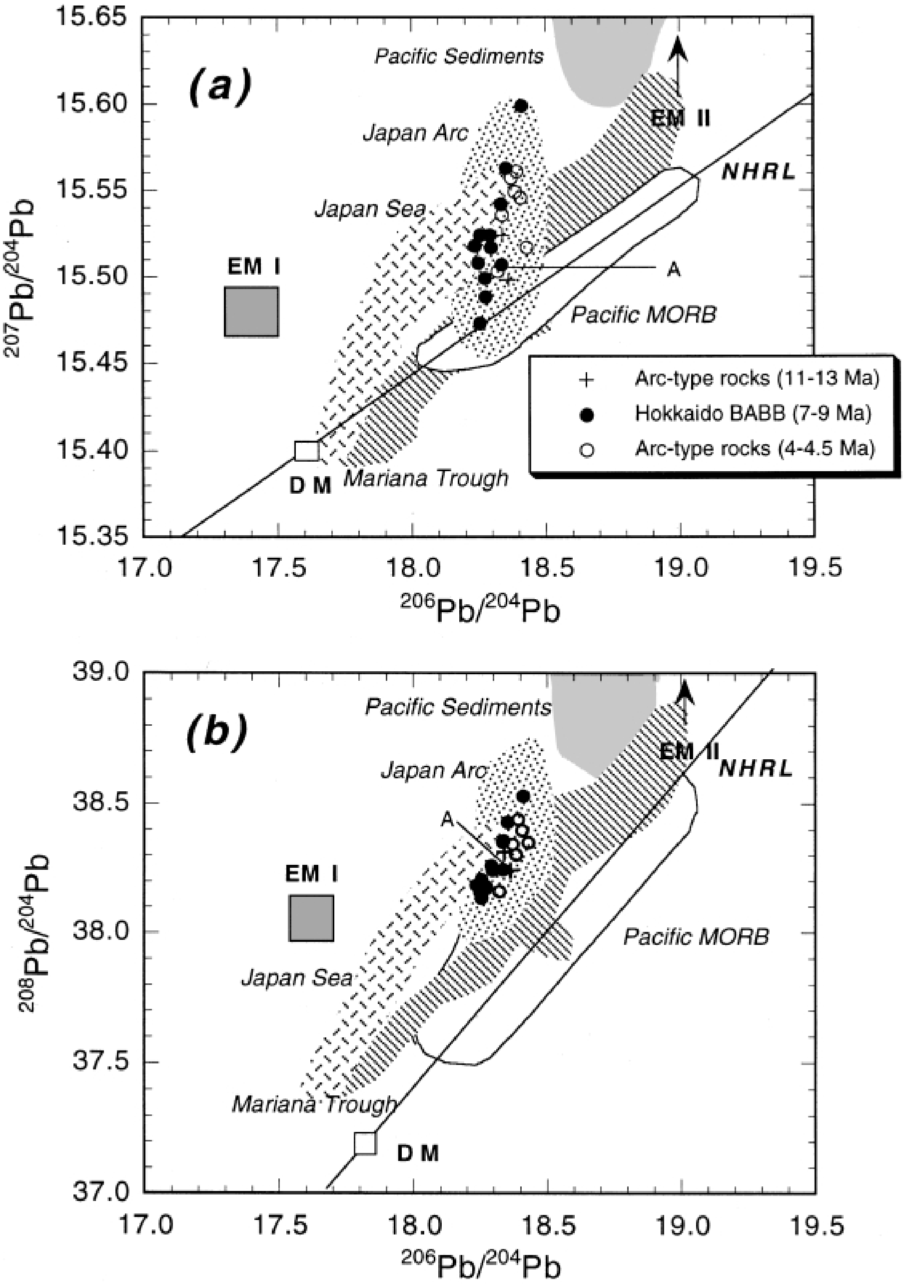

Fig. 5 (a) $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and (b) $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagrams for Neogene volcanic rocks from northeast Hokkaido, compared with other lavas from the Japan Arc (after Tatsumoto, 1969; Tatsumoto and Knight, 1969; Kersting *et al.* 1996) and back-arc basin lavas from the Mariana Trough (after Volpe *et al.* 1990; Gribble *et al.* 1998) and Japan Sea (after Cousens *et al.* 1994). Pacific mid-ocean ridge basalt and Pacific sediments are compiled from Zindler and Hart (1986), and Cousens *et al.* (1994). Hokkaido BABB includes one andesite sample (Ma3, labelled A).BABB, back-arc basin basalts; MORB, mid-ocean ridge basalt; NHRL, Northern Hemisphere Reference Line (Hart, 1984); DM, depleted mantle; EM I and EM II, enriched mantle.

(Northern Hemisphere Reference Line, Hart 1984) and trend toward EM II and Pacific sediment. These features reinforce the idea that Hokkaido BABB are derived from sources that are much more similar to those that generate arc lavas than to those that yield spread basalts in back-arc basins.

DISCUSSION

Pb–Nd–Sr isotopic data for the Neogene volcanic rocks of northeast Hokkaido partially allow Hokkaido BABB and arc lavas to be discriminated, but there is still a large amount of overlap between these two groups, and they share more isotopic similarities than differences when Hokkaido lavas are compared to BABB suites from around the globe. This implies that the two Hokkaido suites were derived from similar sources. Nevertheless, the major and trace element compositions of 7–9 Ma lavas are similar to typical BABB suites and their concentration around the Monbetsu-Kamishihoro graben implies structural control and localization of melt generation along zones of extension, possibly related to back-arc basin extension to form the Kurile Basin. The major problem we now address is how extension inferred to have occurred in the Kurile Basin may have affected the genesis of the back-arc basin basalts from northeast Hokkaido, particularly with respect to the mantle source involved the tectonic evolution of this area.

MANTLE SOURCE OF HOKKAIDO BABB

Although the Pb–Nd–Sr data for Hokkaido BABB and associated arc lavas are similar, the two groups are readily distinguished using major and trace element data (Figs. 2,3, Ikeda 1998). The ^{206}Pb/^{204}Pb for northeast Hokkaido BABB are slightly lower than those of the arc-type volcanics (Fig. 5). The Pb–Nd–Sr isotopic compositions of Hokkaido BABB are nevertheless more similar to the associated arc basalts than they are to the isotopic compositions of back-arc basin basalts from Japan Sea, Mariana Trough and East Scotia Sea (Volpe *et al.* 1990; Saunders & Tarney 1991; Cousens *et al.* 1994; Gribble *et al.* 1998) (Figs 4,5). The ^{87}Sr/^{86}Sr versus ^{206}Pb/^{204}Pb and ^{143}Nd/^{144}Nd versus ^{206}Pb/^{204}Pb diagrams (Fig. 6) more clearly demonstrate the distinct systematic differences among the Hokkaido volcanic rocks (BABB and associated arc-type lavas), other volcanic rocks from northeast Japan Arc, Japan Sea and Mariana Trough back-arc basins. For example, the Pb–Nd–Sr isotope ratios for the Hokkaido volcanic rocks plot between those of the Japan Sea and Mariana Trough BABB and are distinct from the isotopic field defined by the northeast Japan Arc volcanics.

It is widely accepted that the mantle source of arc basalts reflects hybridization of oceanic island basalt or MORB-like mantle by subduction-related metasomatic fluids (e.g. Stern *et al.* 1990, 1993). Back-arc basin basalts are interpreted to be derived from a MORB source which has been fluxed with an enriched component (Ikeda & Yuasa 1989; Hochstaeder *et al.* 1990; Stern *et al.* 1990; Volpe *et al.* 1990; Stolper & Newman 1994). Neogene lavas from northeast Hokkaido define a relatively linear array extending from a depleted MORB-type mantle source towards EM II, which is also a direction that corresponds to the field of Pacific pelagic sediments (Figs 4–6). This suggests that an enriched component with the isotopic composition of EM II contributes to the generation of northeast Hokkaido lavas. The EM II-like enriched component could be subducted pelagic sediment, slab-derived fluids, subcontinental lithosphere, continental crust, or a combination of any of these materials (Hofmann & White 1982; Cousens *et al.* 1994). The slab-derived fluids generally have ^{206}Pb/^{204}Pb ($\sim$18.4) and Ba/Th ($>$1000) ratios that are significantly lower and higher, respectively, than those of the subducted sediment (^{206}Pb/^{204}Pb $\approx$ 18.8 and Ba/Th $\approx$ 100) (Turner & Hawkesworth 1997). The volcanic rocks from northeast Hokkaido have relatively low ^{206}Pb/^{204}Pb (18.3–18.4) and low Ba/Th (70–147, recalculation from data of Ikeda 1998). This geochemical sig-

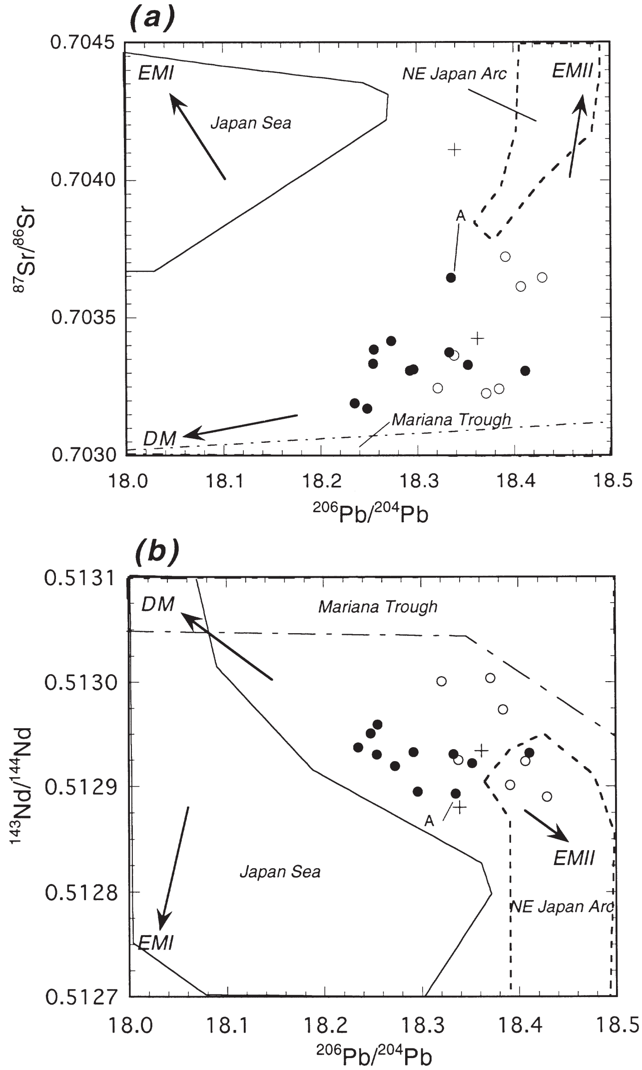

Fig. 6 (a) ^{87}Sr/^{86}Sr (initial ratio) versus ^{206}Pb/^{204}Pb and (b) ^{143}Nd/^{144}Nd (initial ratio) versus ^{206}Pb/^{204}Pb diagrams for volcanic rocks from northeast Hokkaido, compared with the spectrum of volcanics from northeast Japan Arc (after Kersting *et al.* 1996) and back-arc basin lavas from the Mariana Trough (after Gribble *et al.* 1998), and Japan Sea (after Cousens *et al.* 1994). Hokkaido BABB includes one andesite (Ma3, labelled A). Also shown are the directions of the mantle reservoirs identified by Zindler and Hart (1986). +, arc-type rocks (11–13 Ma); ●, Hokkaido BABB (7–9 Ma); ○, arc-type rocks (4–4.5 Ma). BABB, back-arc basin basalts; DM, depleted mantle; EM, enriched mantle.

nature argues against a contribution from the slab-derived fluids for the volcanic rocks from northeast Hokkaido. By contrast, significant subducted sediment contribution to the volcanic rocks from northeast Hokkaido is apparent (Fig. 5). The arc-type volcanics from northeast Hokkaido have low Ce/Pb (Table 2, 3.4–4.7 for the 11–13 Ma rocks and 3.9–6.6 for the 4–4.5 Ma rocks). Ce/Pb for Hokkaido BABB (4.5–9.7) are high relative to the arc-type lavas but are much lower than those of mantle-derived basalts such as ocean island basalt (OIB) and MORB (Ce/Pb = 15–30, Sun & McDonough 1989). This feature of Neogene volcanics from northeast Hokkaido are interpreted as manifesting a sedimentary component (Ce/Pb = 2.4) (Ben Othman *et al.* 1989; Stern *et al.* 1993).

Hokkaido BABB have slightly lower $^{87}Sr/^{86}Sr$ at a given $^{143}Nd/^{144}Nd$ and slightly less radiogenic $^{206}Pb/^{204}Pb$ compared with the arc-type volcanics from the same area (Figs. 4–6). However, there is overlap in the isotopic data between the arc lavas and Hokkaido BABB. The isotopic variations for Hokkaido BABB show that the mantle source is similar to that which generated the arc. The minor isotopic differences between the back-arc basin basalts and the arc-type lavas can be related to less of the arc components, such as sediment flux from the subducted slab for the back-arc basin basalts, along with differences in melt generation styles.

Okamura *et al.* (1998) indicated that the late Miocene to Pliocene (14–5 Ma) basaltic rocks in Sikhote-Alin and Sakhalin, north-eastern Eurasian margin are derived from the asthenospheric mantle (array extending between HIMU and EM I component). The opening Japan Sea was triggered by eastward migration of the hot asthenospheric mantle from beneath northeast China toward the Japan Arc. In contrast, the northeast Hokkaido volcanic rocks define a distinctly different mantle array extending between the depleted mantle (DM) and EM II components (Figs. 4–6). As discussed in Gribble *et al.* (1998), the chemical compositions of lavas erupted during the early (rifting) stages of the Mariana Trough back-arc basin formation are difficult to distinguish from those of arc lavas. Gribble *et al.* (1998) argued that it is impossible to organize the mantle upwelling required to generate MORB-like decompression melts during the early stages of back-arc basin rifting, because induced mantle downwelling persists beneath the extension axis. With continued extension, the rift axis moves away from what should be the arc magmatic front and progressively less of the arc magmatic flux is diverted to the extension axis as the basin widens. As extension continues, finally, the distance between the axis of extension and the zone of sub-arc mantle downwelling is sufficient to allow mantle upwelling to become established and generate a MORB-like decompression melting system (spreading stage). This petrogenetic distinction results in early stage basalts being rift BABB and mature stage basalts being spread BABB. We infer that the tectono-magmatic situation for Hokkaido BABB was similar to that of the rifting stage in the Mariana Trough. We conclude that 7–9 Ma Hokkaido BABB is ‘rift BABB’, not ‘spread BABB’.

RELATIONSHIP TO EXTENSION IN THE KURILE BASIN

Ikeda (1998) proposed that the injection of hot asthenosphere caused Miocene back-arc basin basaltic magmatism associated with the development of the Monbetsu-Kamishihoro graben. Late Miocene bimodal volcanism took place in the graben and the surrounding area (Oba 1975; Kokubu *et al.* 1994). These processes and spatial variations are similar to those of nascent back-arc basins, such as the Sumisu Rift in the Izu-Bonin-Mariana arc (Ikeda & Yuasa 1989) and middle Miocene back-arc rifting in northeast Japan related to Japan Sea opening (Tsuchiya 1990). As mentioned, the geochemical characteristics of Hokkaido BABB are similar to Mariana Trough rift BABB. This is consistent with the abundance of acidic rocks which are never associated with spread BABB but common with rift BABB (Clift 1995; Marsaglia 1995).

On the other hand, Yahata (1997) interpreted that the Monbetsu-Kamishihoro graben formed along a zone of Middle to upper Miocene uplift manifesting east-west compressional stress in central Hokkaido. However, the tectono-magmatic expression of extension along the the Monbetsu-Kamishihoro graben, as indicated in the northeast Hokkaido BABB, is not consistent with a model calling for compression during this time.

Some middle Miocene back-arc rifts in northeast Japan are regarded as failed rifts (Tsuchiya 1990) and these are also recognized in the Japan Sea (Tamaki 1988). The size and geotectonic features of the Monbetsu-Kamishihoro graben are similar to the failed rifts in and around the Japan Sea. Furthermore, lavas associated with its development indicate a back-arc basin setting. The significant difference in age of the rifts indicates that the Monbetsu-Kamishihoro graben cannot be related to Japan Sea opening.

The rift direction or spreading axis of back-arc basins generally is parallel to the direction of arc-trench systems. As indicated, the Monbetsu-Kamishihoro graben trends northerly, which is clearly perpendicular to the northeast-southwest elongation of the Kurile Basin (Fig. 1). The transverse shallow basement ridges strike across the basin. The north-northwest striking basement structures extend between Sakhalin and Hokkaido at the southwest end of the basin. These structures are believed to be shear/lateral fault zones that defined the opening direction (Gnibidenko *et al.* 1995). In this sense, the Monbetsu-Kamishihoro graben, which is located at the southwest end of the Kurile Basin, may represent the shear/lateral fault zones.

There are few constraints on the opening of the Kurile Basin but the fact that the Monbetsu-Kamishihoro graben in northeast Hokkaido lies at the southwest end of the Kurile Basin suggests a genetic relationship. Thus, basaltic magmatism in the Monbetsu-Kamishihoro graben related to back-arc extension in the Kurile Basin continued up to 7–9 Ma. Confirmation of this hypothesis will require ODP drilling in the Kurile Basin.

CONCLUSIONS

The isotopic and trace element features of 4–13 Ma volcanic rocks from northeast Hokkaido mostly result from mixing of depleted mantle and an EM II-like enriched component such as subducted sediments. The Pb–Nd–Sr isotopic and other geochemical data indicate that Hokkaido BABB are rift BABB and reflect lesser involvement of the subducted sediments than do the associated arc-type lavas. This geochemical model is consistent with early stages in the evolution of other back-arc basins, such as the rift stage of the Mariana Trough.

Magmatic and geotectonic features in the Monbetsu-Kamishihoro graben are similar to failed rifts in and around the Japan Sea. The graben may have developed as a failed rift at the southwest end of the Kurile Basin, in which case basaltic magmatism related to back-arc rifting to form the Kurile Basin continued until 7–9 Ma. Future research should focus on development of Kurile Basin, such as establishing the beginning time of volcanism (i.e. the time of Kuril Basin opening), identification of similar failed rifts surrounding the Kurile Basin and identification of magnetic anomalie lineations in the basin.

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