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A new type of intra-plate volcanism; young alkali-basalts discovered from the subducting Pacific Plate, northern Japan Trench

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Abstract. Alkali pillow basalts were collected from the toe of the oceanward slope of the northern Japan Trench. These alkali-basalts formed as a result of a low degree of partial melting of Pacific Ocean mantle and rapid rise of the magma (no fractionation in shallow magma chambers). Reconstructing Pacific Plate motion based on ^{40}Ar-^{39}Ar age dates of 5.95 ± 0.31 Ma for these basalts indicates that they erupted outboard of outer swell or forebulge of the Japan Trench in the NW Pacific. We suggest that these alkali-basalts represent a new form of intra-plate volcanism, whereby magmatic activity occurs off the forebulge of the downgoing Pacific slab, perhaps using conduits related to fracturing of the slab during bending prior to subduction.

1. Introduction

Alkali-basalts occur on various parts on the surface of the earth, most particularly in continental and hotspot areas. These alkali-basalts are products of deep-origin magma from the upper mantle or lower depths. Occurrences of such alkali-basalt are also documented from tectonically unique locations, such as along deep fractures in oceanic crust.

Alkali olivine basalt and trachyandesite representative of the ocean island basalt series have been documented around the Japan Trench on the Joban, Erimo and Takuyo Seamounts [*Kobayashi et al.*, 1987; *Cadet et al.*, 1987]. The ^{40}Ar-^{39}Ar ages of these volcanic rocks range from 120 Ma (Daiichi-Kashima Seamount in the Joban Seamount Chain) to 104 Ma (Erimo Seamount) [*Takigami et al.*, 1989], indicating that these are the products of Cretaceous off-ridge seamount volcanism (Fig. 1A). In contrast, the bathymetry of the study area does not show any evidence for a large volcanic edifice or seamount, but only a small mound (Fig. 1B).

This paper describes an occurrence of young alkali-basalt on the downgoing oceanic slab of a subduction zone. We present the geologic setting, major and trace element compositions, and ^{40}Ar-^{39}Ar age of these basaltic rocks. We then discuss the tectonic and geophysical implications for this first documentation of alkali-basaltic magmatism outboard of outer swell of a subducting oceanic slab.

2. Occurrence and description of samples

Continuous outcrops of pillow basalt were documented and sampled at depths of 7325 to 7360 m on the oceanward slope toe of the northern Japan Trench (39°23' N, 144°16' E) during JAMSTEC (Japan Marine Science and Technology Center) *R/V Kairei/ROV KAIKO* cruise KR97-11. The slope is characterized by trench-parallel (N-S) normal faults with some NNW or NNE faults, due to warping of the downgoing Pacific Plate (the age of the Pacific Plate here is Early Cretaceous [*Kobayashi et al.*, 1998]) (Fig. 1). These normal faults bound horst and graben structures that are approximately 5 km in horizontal extent with 100 to 500 m vertical separations [*Ogawa and Kobayashi*, 1993;

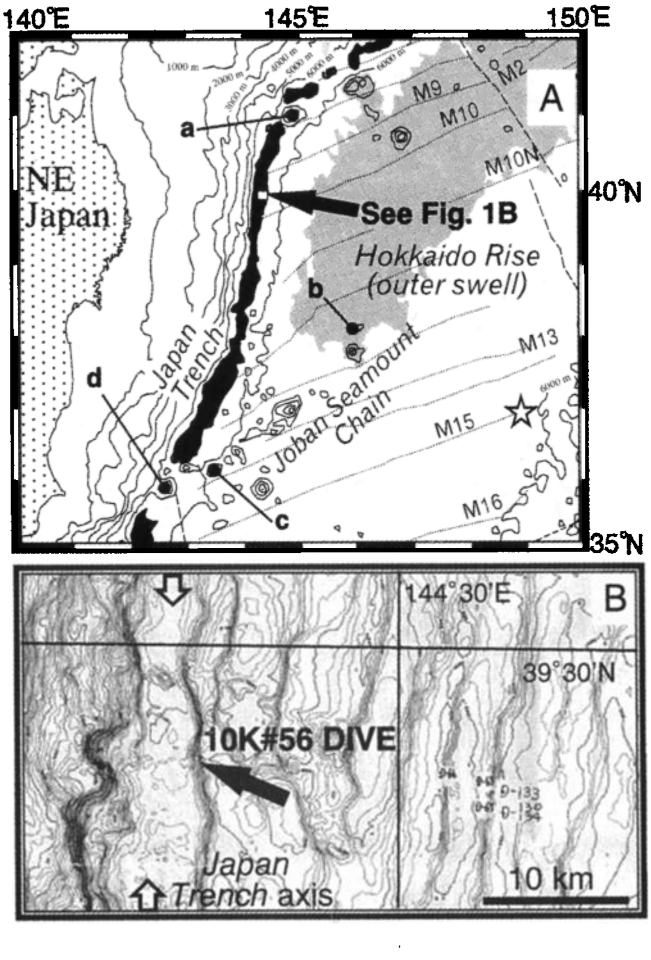

Figure 1. Index maps of the dive site. A: The general bathymetric map of the northwest Pacific ocean floor based on Kobayshi et al. (1998). Black area is trench floor deeper than 7000 m, and grey-shaded area is the outer swell (<5400 m in depth). Radiometric ages of Erimo (a), Ryofu (b), Daini-Kashima (c) and Daiichi-Kashima (d) Seamounts are obtained as follows respectively; (a) 104 Ma and (d) 120 Ma ^{40}Ar-^{39}Ar age [*Takigami et al.*, 1989], (b) 70-72 Ma and (c) 81 Ma K-Ar age [*Ozima et al.*, 1977]. The approximate eruption site is plotted as asterisk. B: Seabeam bathymetric map of the dive site 10K#56 by R/V *KAIREI* at the northern Japan Trench. Contour interval is 250 m. Trench axis is shown by white arrow.

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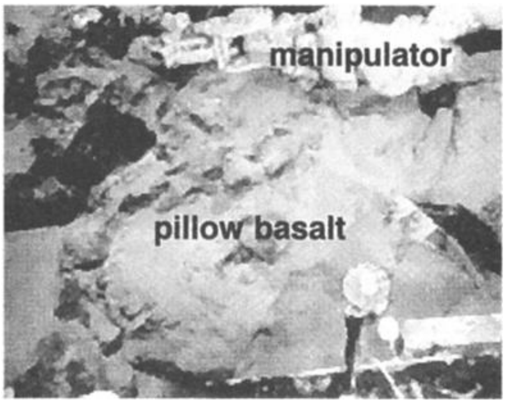

Figure 2. Outcrop photograph of the pillow basalt taken by R/V *KAIREI* video record, indicating a large pillow structure. The field of view is approximately 1 m in length.

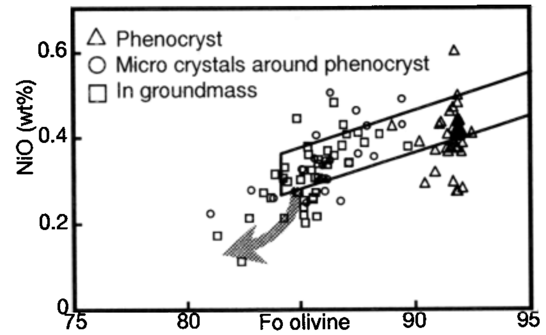

Figure 4. Fo value vs. NiO plot of olivine from 10K#56 R-001 and R-002. Open box zone is mantle olivine array after *Takahashi et al.* (1987). Arrows show trends of olivine fractional crystallization after *Sato* (1977).

Ogawa et al., 1996]. There is no distinct seamount topography associated with the alkali pillow basalt outcrops, however a subdued mound-like feature (100 to 200 m hight, 1 to 2 km in diameter) is recognized using seabeam sonar bathymetric mapping (Fig. 1B).

The ROV *KAIKO* was used to sample rocks from the toe of the oceanward slope (downgoing Pacific Plate) of the subduction zone. The slopes have an average dip of 25° but are locally very steep, forming escarpments along which there are exposures of alkali pillow basalt outcrops at depths of 7325 to 7360 m. The cliffs are covered with thin drapings of soft, black, muddy sediments. The total thickness of the basalt outcrops is more than 35 m. The outcrops are alternations of pillow lava (Fig. 2) and hyaloclastite.

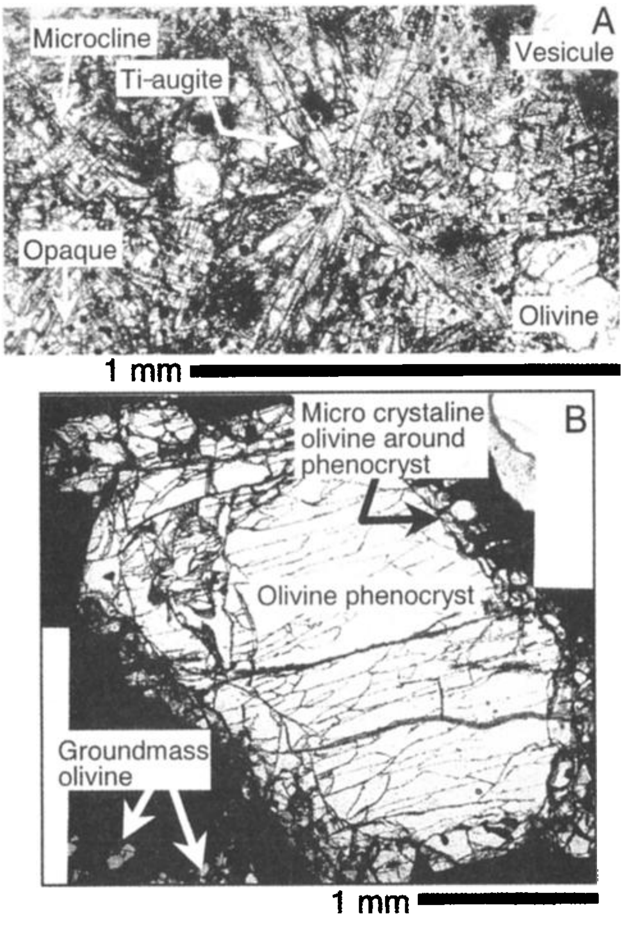

Figure 3. Photomicrographs of thin section of sample (10K#56 R-002). A: groundmass. B: Olivine phenocryst surrounded by micro crystalline olivine.

Two samples, 10K#56 R-001 and R-002, were collected from pillow lava outcrops at around 7360 m depth (Fig. 2). Both samples exhibit curved foliations, representing the surface of a pillow of around 30 cm in diameter. The samples contain a large proportion of vesicles, reaching 10-30 volume percent. The rocks and minerals, which have a dendritic texture, are very fresh, even in vesicles. Large olivine phenocrysts make up from 1.0 % to 2.4 % in volume (R-001 and R-002, respectively), and the groundmass is composed of olivine, Ti-augite, microcline and opaque minerals (Fig. 3A). The olivine phenocrysts (Fo values, 90-93, and NiO contents, 0.3-0.5 wt%) (Fig. 3B) are more primitive in origin than those in the groundmass (Fo values, 80-90, and NiO contents, 0.1-0.5 wt%), and have compositions in equilibrium with the mantle olivine array [*Sato*, 1977; *Takahashi et al.*, 1987] (Fig. 4). Small crystalline olivines around phenocrysts have the same composition as groundmass olivines. Potassium rich contents of microcline, and Ti-augite (TiO_2; 2.0 to 5.0 wt%) characterize the highly alkaline magma. Ilmenite is the most common opaque mineral in the groundmass (Fig.3A). Bulk chemical compositions (Table 1 and 2), trace elements spidergram (Fig. 5A) and REE pattern (Fig. 5B) show that these rocks are enriched in incompatible elements and can be characterized as potassium-rich alkali-basalts, shoshonites.

3. ^{40}Ar-^{39}Ar dating

Sample 10K#56 R-002 was irradiated in the Japan Material Testing Reactor (JMTR) along with three flux monitors (HD-B1 biotite) and synthetic salts to permit the corrections for interfering isotopes. The sample was subjected to eight step-heating intervals by induction heating. The method of Ar isotopic analysis follows *Saito et al.* (1991). Precision limits represent propagated measurement and J-value uncertainties and are reported throughout this paper at the 2 σ level. The detailed data can be obtained through URL [http://www.f2.dion.ne.jp/~ nhirano/JT/].

In order to obtain a plateau age in age-spectrum, we need consistent age over three continuous fractions at 2 σ level. A plateau age of 5.95±0.31 Ma for the sample 10K#56 R-002 was calculated in the age spectrum (Fig. 6a). The J-value error was not used in the age spectrum, and was included at the last stage of age calibration as a plateau age. In addition, we obtained a well-defined isochron using the inverse isochron method (Fig. 6b), and the derived isochron age (5.69±0.43 Ma) is in accord with the plateau age.

Table 1. Bulk compositions of 10K#56 R-001 and R-002 by XRF analysis.

sample		major element (wt%)													
		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O+	H_2O-	Total
R-001	bulk	48.22	2.56	10.30	6.38	4.23	0.14	11.68	7.47	2.95	3.17	0.78	1.76	0.36	100.00
	groundmass[a]	48.84	2.72	11.60	10.44	-	0.13	8.23	7.68	3.04	3.88	0.83	1.23	1.39	100.00
R-002	bulk	48.45	2.84	11.26	6.12	4.36	0.13	7.83	8.14	3 28	3.63	0.84	2.49	0.64	100.00
	groundmass[a]	49.27	2.84	12.18	10.00	-	0.12	6.61	7.61	3.13	4.11	0.87	1.47	1.81	100.00

sample		trace element (ppm)													
		Ba	Ce	Co	Cr	Ga	Nb	Ni	Pb	Rb	Sr	Th	V	Y	Zr
R-001	bulk	1202.3	94.4	56.7	527.8	17.7	36.6	418.1	7.2	47.0	1076.5	2.0	140.1	14.2	243.0
	groundmass[a]	1176.8	-	154.0	424.0	-	37.4	163.1	6.9	56.2	1212.4	4.7	-	18.8	263.8
R-002	bulk	1209.5	108.7	46 7	400.5	20.2	40.3	227.8	7.3	53.1	1092.4	2.0	143.4	15.3	259.9
	groundmass[a]	1191.2	-	129.0	353.0	-	39.4	117.2	7.3	59.0	1140.4	4.9	-	19.7	273.8

[a] Data for the samples separated the olivine phenocryst from the groundmass. In this data[a], Fe_2O_3 show the total Fe-oxide.

Table 2. REE compositions of the bulk samples by the ICP-MS analysis. Analyzed by Dr. M. Komuro and Ms. K. Fujii, Institute of Geoscience, University of Tsukuba (personal communication).

	ppm														
	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
R-001	19.17	54.07	106.95	12.03	49.35	9.41	2.98	7.74	1.00	4.63	0.77	1.83	0.23	1.41	0.19
R-002	20.78	58.69	114.28	12.97	53.61	10.02	3.22	8.38	1.08	4.72	0.88	1.93	0.23	1.46	0.20

4. Tectonic interpretation and geophysical implication

The alkali-basalts documented here are very young, much younger than the ocean floor in this area (identified isochron M9 or M10; around 130 Ma [*Gradstein et al.*, 1994; *Kobayashi et al.*, 1998]). Seamounts in this region are also Cretaceous, with ages ranging from 120-104 Ma. In contrast, the rocks analyzed in this study have ages of 5.95±0.31 Ma (latest Miocene), and are found in small-volumes along seafloor escarpments rather than on seamounts or large volcanic constructions. By performing a plate tectonic reconstruction we have determined that there is no plausible hotspot that could have produced these basalts. We have reconstructed the eruption location of these basalts using the ^{40}Ar-^{39}Ar age of 5.95±0.31 Ma and the present "absolute" motion of the Pacific Plate (10.29 cm/yr to 295.26 degrees [*Gripp and Gordon*, 1990]). Using this method we have derived a position of approximately 612±32 km ESE off the northern Japan Trench, now approximately at 37°N, 149°E. As the volcanic front in the NE Japan Arc has scarcely shifted since the latest Miocene [*Ohki et al.*, 1993], the kinematics of the Pacific slab at 5-6 Ma are the same as at present. According to the bathymetric chart of the northwest Pacific, this area corresponds to a site just oceanward of the current outer swell or forebulge (Hokkaido rise), with an inferred paleo-depth of ~6000 m (asterisk in Fig. 1A).

Enriched incompatible element concentrations and REE pattern indicate that the magma source for these alkali-basalts formed as a result of low degree of partial melting. Disequilibrium between olivine phenocrysts and groundmass olivines suggest that the phenocrysts may be xenocrysts transported from deep in the mantle with rapid rise of the alkali-basaltic magma. If a fracture occurs or is rejuvenated in the

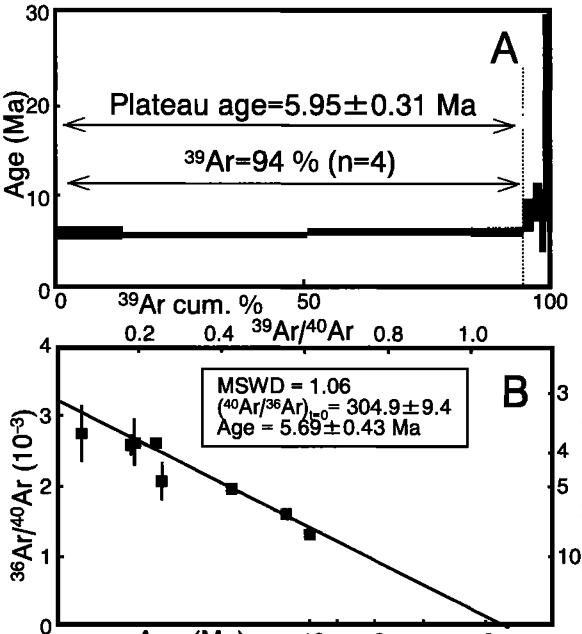

Figure 6. Age determination results by ^{40}Ar-^{39}Ar method of sample 10K#56 R-002. Correction factors and J-value are as follows; $(^{36}Ar/^{37}Ar)_{Ca}$ = (3.744±0.082)×10^{-4}, $(^{39}Ar/^{37}Ar)_{Ca}$ = (9.30±0.44)×10^{-4} and J = (3.412±0.063)×10^{-3}. Calculated using decay constants and potassium isotope ratios from *Steiger and Jager* (1977).

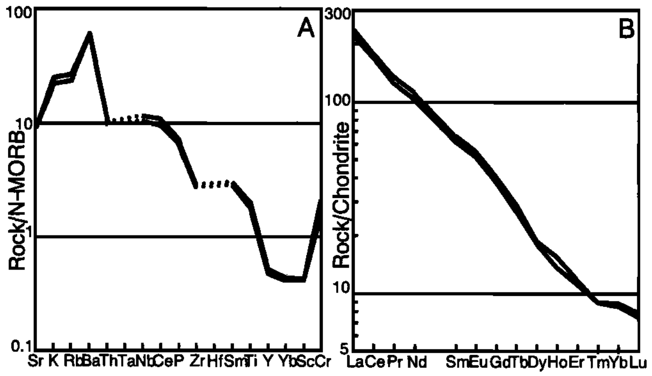

Figure 5. Spidergrams of trace element concentrations in samples 10K#56 R-001 and R-002. A: Normalized by average MORB [*Pearce*, 1982, 1983]. B: Chondrite-normalized REE pattern [*Evensen et al.*, 1978]. U, Ta and Hf were not analyzed.

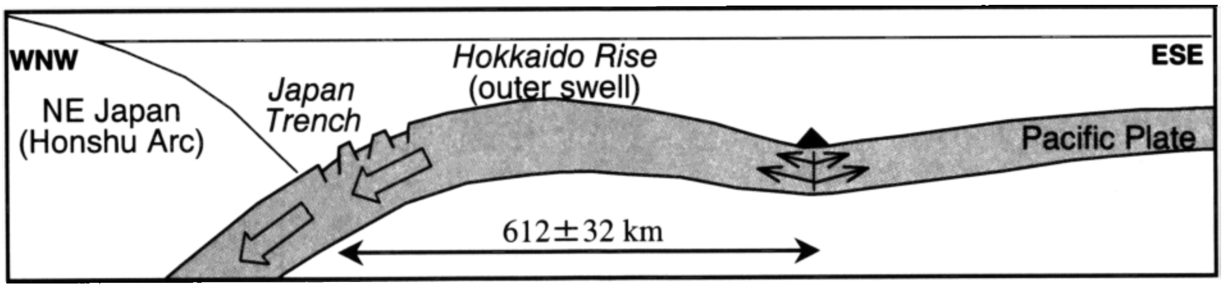

Figure 7. A model of possible alkali-basalt eruption on the old oceanic crust toward the subduction zone. Fracturing of Pacific Plate toward the outer swell may result in the formation of conduits for magma flow to the surface.

oceanic lithosphere, magma from the lowest part where fracture reached may erupt to the seafloor. It can be also assumed that melting was induced by decompression in the upper mantle. The occurrence, mineralogical and chemical characteristics of the basalt samples documented here show that the magma could have ascended toward the surface in this way.

We suggest a possible scenario for the formation and eruption of this new type of intra-plate alkali-basalt (Fig. 7). 1) The oceanic crust undergoes lithosphere scale orthogonal flexure as it begins to enter the outer swell. 2) Extension on the inside of the lithosphere folding on this large-scale causes decompression melting in the upper portions of the lower mantle. 3) Fracturing during folding results in the formation of conduits for magma flow to the surface. If these processes are intrinsic to the subduction of oceanic crust, alkali-basalts should be common in forebuldge regions worldwide.

Geophysical investigations may reveal more about this new type of intra-plate volcanism, specifically about the relationship between subduction and the formation and eruption of alkali-basalts on the outer swell or forebuldge of a subducting slab. If orthogonal flexure, decompression melting, and fracturing occur in the downgoing slab as it enters the subduction zone, they should impart specific physical characteristics (density, velocity, faults and fractures) to the crust and lithospheric mantle. Seismic tomography, seismic reflection/refraction surveys, gravity, and earthquake seismicity should all reflect these changes to the oceanic slab as it moves through the forebulge into the subduction zone.

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