

Review

Chemical geodynamics in the back-arc region of Japan based on the trace element and Sr–Nd isotopic compositions *

EIZO NAKAMURA¹, MALCOLM T. McCULLOCH² and IAN H. CAMPBELL²

¹ *Institute for Study of the Earth's Interior, Okayama University, Misasa, Tottori-ken 682-02 (Japan)*

² *Research School of Earth Sciences, Australian National University, Canberra, ACT 2601 (Australia)*

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Abstract

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¹⁴³Nd/¹⁴⁴Nd, ⁸⁷Sr/⁸⁶Sr, trace and major element results are reported for Cenozoic alkaline basalts and associated tholeiitic basalts from southwestern Japan, and some from Korea and China. Most of the samples plot within the mantle array with ϵ_{Nd} values ranging from +5.0 to –3.2 and ⁸⁷Sr/⁸⁶Sr ratios ranging from 0.7037 to 0.7057.

The isotopic variations observed along traverse sections of alkaline basalts from the trench to the continental sides of southwestern Japan do not suggest a direct relationship between the subduction of the Philippine Sea and Pacific plates, and the generation of alkaline basalt magmas. However, in southwestern Japan the alkaline basalts do show evidence of a subducted component and are more enriched in the mobile incompatible elements, such as Rb, Ba and K, relative to Chinese and Korean basalts.

Negative correlations between ϵ_{Nd} and Sm/Nd and between ϵ_{Nd} and La/Th, as well as a positive correlation between ⁸⁷Sr/⁸⁶Sr and La/Th, are recognized in some of the basalts. These relationships indicate at least two-component magma mixing between (1) magma resulting from a small melting from a depleted mantle and (2) magma resulting from a relatively large amount of melting of an enriched mantle source. It is suggested that the Cenozoic alkaline basalts from southwestern Japan, Korea and China are product of interaction between a MORB-type mantle and a deep mantle plume.

If the mantle plume has ascended from the upper mantle–lower mantle or core–mantle boundary, the subducted Pacific and Philippine Sea plates could not have extended to southwestern Japan. Had they done so they would have arrested, before they reached the melting zone, the ascent of the plumes that produced the alkaline volcanism in southwestern Japan.

Introduction

The alkaline basalts provide information about chemical and physical conditions in the mantle during magma generation, because high pressure experiments (e.g., Green and Ringwood, 1967;

Kushiro, 1973) suggest that they are generated below the base of the lithosphere. However, the genesis of alkaline basalts remains controversial, particularly in view of their high abundance of incompatible elements and their enrichment in the light rare earth elements (LREE). Sr and Nd isotopic studies indicate that the source regions generally have a long-term depletion in Nd/Sm and Rb/Sr ratios relative to chondritic abundance (DePaolo, 1981). This observation is difficult to

* The term “chemical geodynamics” is derived from Allègre (1982).

reconcile with the high Nd/Sm and Rb/Sr ratios that are characteristics of alkaline basalts.

Geochemical data from the back-arc region of island-arcs are sparse, making it difficult to relate the mechanisms responsible for the generation of the basaltic magma to a plate tectonic framework. The chemical and isotopic characteristics of alkaline basalts from a back-arc region can be used to examine the geochemical and isotopic nature of the mantle below island-arc systems, and to assess the physicochemical influences of the subduction zone on the source region in the mantle.

Cenozoic alkaline basalts are widely distributed in northeastern China and around the Sea of Japan, that corresponds to the back-arc region of the Japanese island arc system (Uyeda, 1982). In northeastern Japan, the relationship between subduction of the Pacific plate and magma generation (including calc-alkaline, high alumina, alkaline and tholeiitic basalts) has been clearly established on the basis of trace elements, isotope geochemistry and seismic studies (e.g., Kuno, 1966; Sakuyama, 1979; Ishikawa et al., 1980; Nohda and Wasserburg, 1981; Tatsumi et al., 1983; Tatsumi and

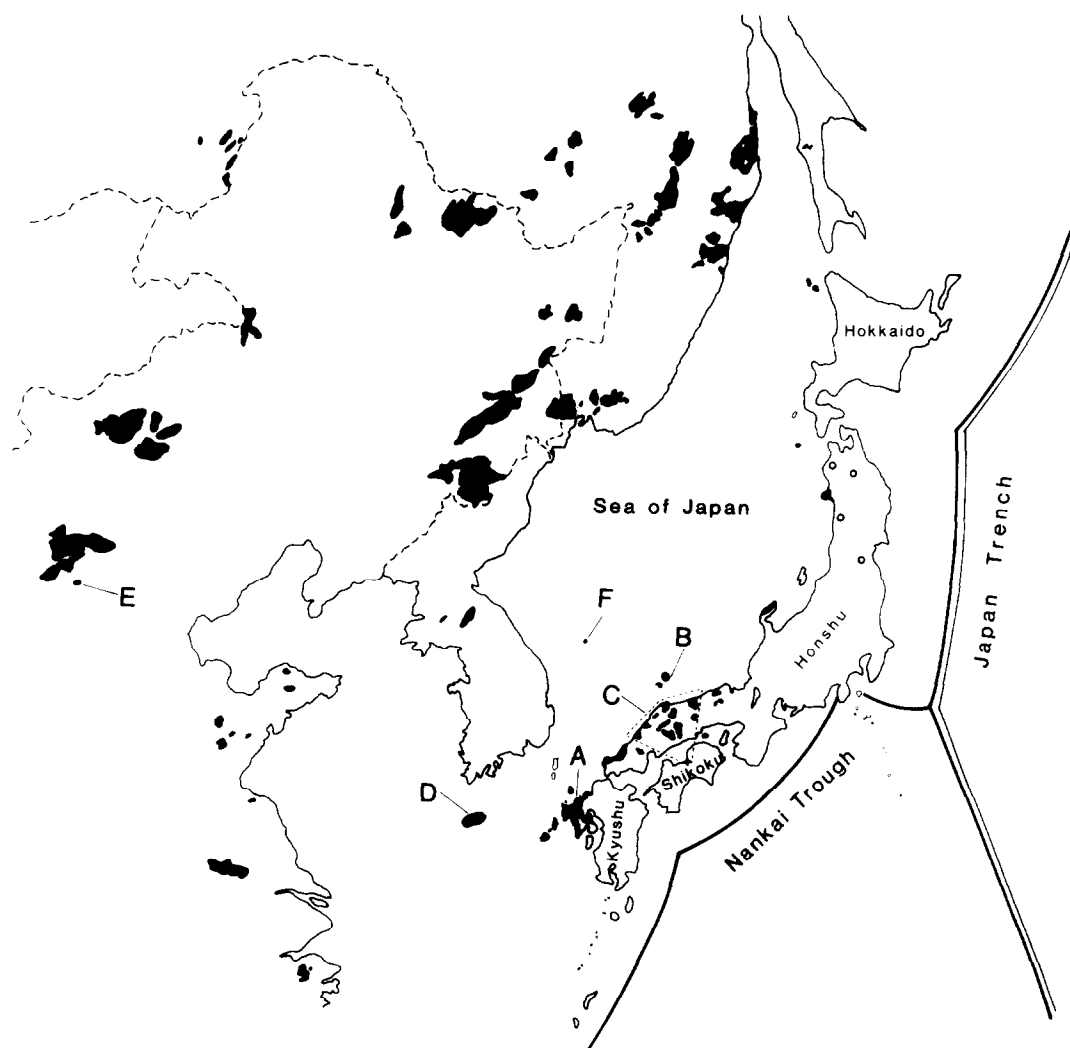


Fig. 1. Distribution of Cenozoic alkaline basalts, associated tholeiitic basalts, and sampling localities. Solid lines represent plate boundaries and/or trench axes. A—northwestern Kyushu; B—Oki-Dogo Island; C—Chugoku district; D—Jejudo Island; E—Datong; F—Ulungdo Island. Data for the basalt distribution are from the Geological Map of China, 1 : 4,000,000 (1976), the Geological Map of Siberia, 1 : 4,000,000 (1973), Aoki (1959), Kurasawa (1967), Takamura (1973) and Lee (1982).

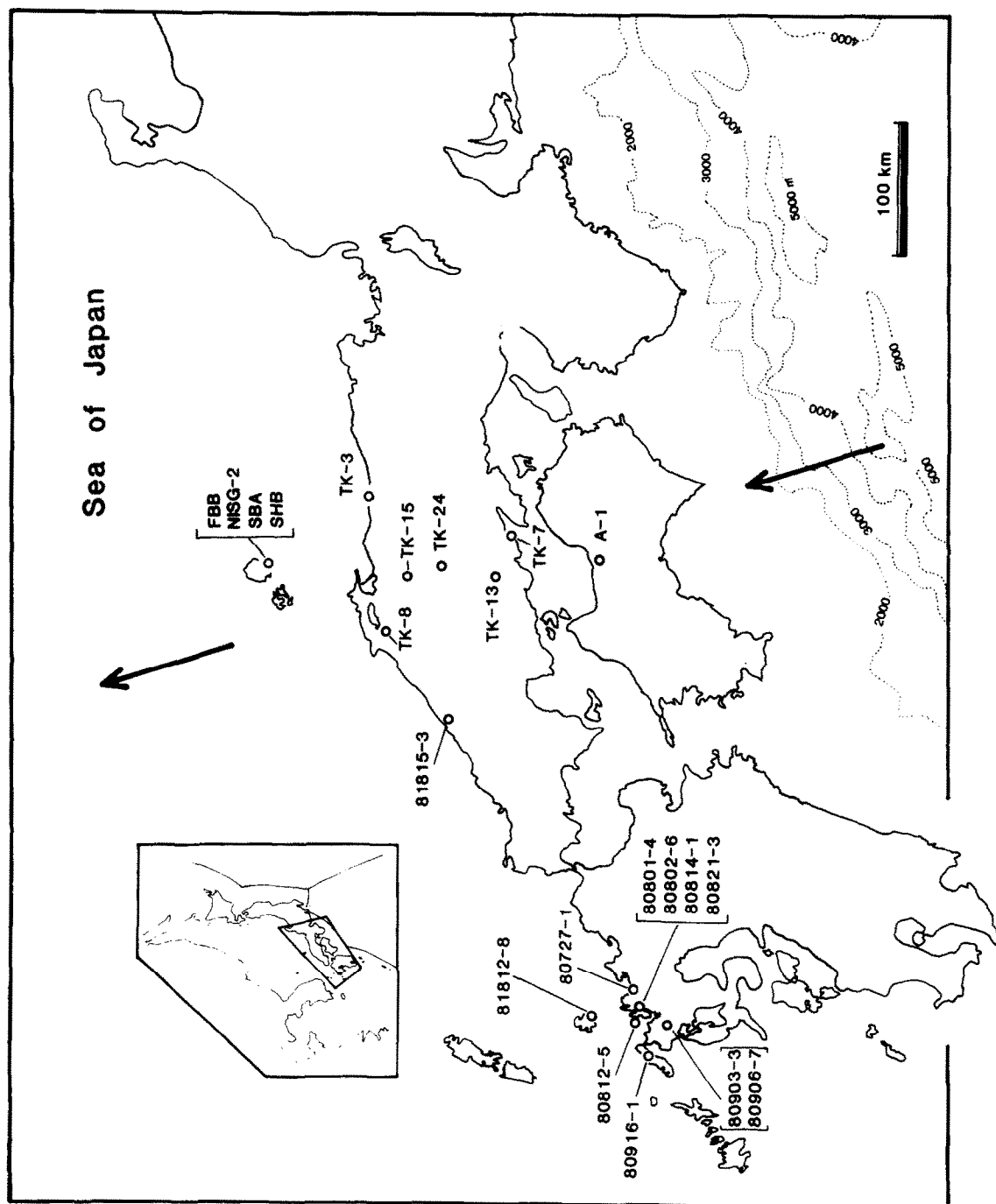


Fig. 2. Map showing sample localities in southwestern Japan. Arrows represent a direction of the traverse for the isotopic variations in Fig. 7.

Nakano, 1984; Sakuyama and Nesbitt, 1986). On the other hand, in southwestern Japan, position of the Wadati-Benioff zones of the subducted Pacific and Philippine Sea plates are uncertain (see Utsu, 1974; Shiono, 1974; Nakanishi, 1980), and available geochemical data on recent volcanic rocks in this region are limited, making it difficult to evaluate the relationship between magma genesis and the subduction of these plates.

In this paper, we present $^{143}\text{Nd}/^{144}\text{Nd}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and major and trace element data for mainly cenozoic alkaline basalts from southwestern Japan, and some from Korea and China, and argue that at least two-component mixing is necessary to produce the alkaline basalts of these areas. We also evaluate the role of subduction of the two plates in the generation of the alkaline basalts in the back-arc region of the Japanese island-arc systems.

Sample collection

The samples used in this study were collected from, Datong, Jejudo Island, northwestern Kyushu (Higashi-Matsuura and Kita-Matsuura districts), Oki-Dogo Island, Chugoku district and Ulungdo Island (Fig. 1). Sample localities in southwestern Japan are shown on Fig. 2. A summary of the geology of the former five areas is given in Nakamura et al. (1989). Ulungdo Island is an additional locality and is situated off the eastern coast of the Korean Peninsula ($37^{\circ}30'\text{N}$, $130^{\circ}50'\text{E}$) and has been studied in detail by Kim (1985). It consists of five stages of alkaline volcanic activity. Sample Nos. 2, 3, 5 and 6 are an accidental fragment of alkaline basalt (2.7 Ma) in the first stage of trachybasaltic pyroclastic rock, a third stage trachyte, a fifth stage leucite-bearing trachyte and a trachybasalt dyke intruding the first stage pyroclastics from Ulungdo Island, respectively.

Analytical methods

Based on petrographic examination, unaltered samples were selected for chemical analyses. Each sample was reduced to a diameter of less than 0.5 cm by jaw crusher and then large megacrystic and/or phenocrystic minerals were removed by

hand-pick prior to crushing to less than 200 microns using an alumina ceramic mill. Samples which contained ultramafic xenoliths were sliced to a thickness of 0.5 cm with a diamond saw; then the xenoliths were removed prior to crushing. This treatment can nearly approach the analyses of solidified liquids.

The powders were then analysed for major and trace elements, and Nd and Sr isotopic compositions. Major and trace element concentrations were determined by a combination of X-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA) at the University of Toronto, using the method described by Barnes and Gorton (1984).

Nd and Sr isotope compositions were determined at the Research School of Earth Sciences at the Australian National University (ANU), using the MSZ mass-spectrometer. Samples of approximate 70 mg were totally spiked with ^{150}Nd and ^{147}Sm tracers and then decomposed in open teflon beakers using HF, HF-HClO₄ solutions, and finally converted into the chloride by 6*N* HCl. The Sr and REE were initially separated from the major elements on 5 g cation exchange columns using 1*N* and 2.5*N* HCl as the elutriants. Sr was purified on 2.5 g column using 1*N* and 2.5*N* HCl. Nd and Sm were separated from each other and the remaining REE in a separate column using 0.2*M* 2-methylactic acid with a *pH* of 4.62. During the analyses of these basalts the blank, using our stock solutions, was 0.5 ng for Nd and 3.5 ng for Sr. No blank corrections were necessary for any of the measured isotope ratios. Nd and Sr isotope ratios were measured as metal using a triple filament in the MSZ mass-spectrometer (McCulloch and Perfit, 1981). Due to the young age of these rocks, the measured ratios are essentially the same as initial ratios.

The results for Nd and Sm concentrations determined by INAA at the University of Toronto agree to within $\pm 10\%$ and $\pm 5\%$, respectively with those determined by isotope dilution on the same samples at ANU (Nakamura, 1986).

Results

Nd and Sr isotopic compositions were determined for 32 samples from southwestern

TABLE 1

Nd and Sr isotopic compositions for the presented samples

Sample No.:	Rb/Sr ^a	⁸⁷ Sr/ ⁸⁶ Sr ^b	Sm/Nd ^c	¹⁴³ Nd/ ¹⁴⁴ Nd ^d	ε _{Nd} ^e	Rock name ^f
<i>Chugoku District</i>						
TK-3	0.0116	0.70432 ± 2	0.150	0.51180 ± 2	-0.7	Ab
TK-15	0.0500	0.70418 ± 3	0.199	0.51193 ± 2	+1.8	Ab
TK-24	0.0635	0.70394 ± 3	0.210	0.51196 ± 2	+2.4	Pb
TK-2	0.0205	0.70537 ± 4	0.211	0.51190 ± 3	+2.3	Th
TK-7	0.0253	0.70499 ± 4	0.246	0.51180 ± 2	-0.7	Th
TK-8	0.0138	0.70466 ± 2	0.255	0.51182 ± 3	-0.3	Th
81815-3	0.0237	0.70381 ± 5	0.163	0.51204 ± 4	+4.0	Ne
A-1	0.0687	0.70434 ± 6	0.198	0.51204 ± 2	+4.0	Ab
<i>Oki-Dogo Island</i>						
SHB	0.0310	0.70491 ± 4	0.195	0.51189 ± 2	+1.1	Hw
MISG-2	0.0763	0.70566 ± 4	0.200	0.51184 ± 2	+0.2	Ab
SBA	0.0949	0.70479 ± 4	0.199	0.51196 ± 2	+2.2	Ab
FBB	0.0594	0.70474 ± 4	0.209	0.51180 ± 1	-0.7	Ab
<i>Northwestern Kyushu</i>						
<i>Higashi-Matsuura District</i>						
80801-4	0.0721	0.70415 ± 4	0.212	0.51195 ± 2	+2.2	Ab
80814-1	0.0492	0.70437 ± 4	0.198	0.51193 ± 2	+1.8	Ab
80802-6	0.0567	0.70421 ± 4	0.291	0.51200 ± 2	+3.2	Ab
80812-5	0.0541	0.70408 ± 4	0.227	0.51203 ± 2	+3.8	Ab
81812-8	0.0206	0.70435 ± 4	0.228	0.51193 ± 2	+1.8	Hw
80727-1	0.0770	0.70426 ± 3	0.210	0.51192 ± 3	+1.6	Ab
80821-3	0.0415	0.70423 ± 2	0.258	0.51196 ± 2	+2.4	Th
<i>Kita-Matsuura District</i>						
80906-7	0.0564	0.70420 ± 4	0.224	0.51196 ± 2	+2.4	Th
80903-3	0.0360	0.70399 ± 5	0.203	0.51203 ± 2	+3.8	Ab
80916-1	0.0639	0.70381 ± 6	0.182	0.51203 ± 2	+3.8	Ab
<i>Ulungdo Island</i>						
No.2	0.0173	0.70487 ± 4	0.178	0.51174 ± 3	-1.9	Tr
No.3	2.333	0.70474 ± 4	0.149	0.51172 ± 3	-2.3	Mu
No.5	0.283	0.70462 ± 5	0.153	0.51178 ± 2	-1.1	Hw
No.6	0.0456	0.70551 ± 4	0.171	0.51167 ± 2	-3.2	Hw
<i>Jejudo Island</i>						
J-1	0.0432	0.70435 ± 3	0.271	0.51198 ± 3	+2.8	Hw
J-4	0.0327	0.70426 ± 3	0.289	0.51200 ± 2	+3.2	Hw
J-5	0.0495	0.70399 ± 3	0.223	0.51200 ± 2	+3.2	Hw
<i>Datong</i>						
Ch-1	0.0437	0.70395 ± 6	0.207	0.51209 ± 2	-5.0	Hw
Ch-12	0.0190	0.70541 ± 3	0.200	0.51176 ± 3	-2.0	Ab
Ch-19	0.0349	0.70370 ± 6	0.208	0.51207 ± 2	+4.6	Ab

^a Rb and Sr were determined by XRF and their precisions were better than 10% and 5%, respectively. Reported errors for isotopic ratios are 2sigma of the mean.

^b Data normalized to ⁸⁶Sr/⁸⁸Sr = 0.1194. The measured ⁸⁷Sr/⁸⁶Sr of standard NBS-987 is 0.71022 ± 1, and the measured ⁸⁷Sr/⁸⁶Sr of BCR-1 is 0.70494 ± 1.

^c Precisions for Sm and Nd concentrations determined by isotope dilution techniques were < 0.2%.

^d Data normalized to ¹⁴⁶Nd/¹⁴²Nd = 0.636151. The measured ¹⁴³Nd/¹⁴⁴Nd of BCR-1 is 0.511833 ± 10.

^e Deviations in parts in 10⁴ from the present-day bulk earth (CHUR) value of ¹⁴³Nd/¹⁴⁴Nd = 0.511836 (Jacobsen and Wasserburg, 1980).

^f Rock name; Ab alkali basalt; Pb picritic basalt; Ne nephelinite; Hw hawaiite; Tr trachyte; Mu mugearite; Th tholeiitic basalt.

TABLE 2

Major and trace element abundances and normative compositions

Sample No.: Locality:	Chugoku District							Okii-Dogo Island						
	TK-3	TK-15	TK-24	TK-2	TK-7	TK-8	A-8	81815-3	SHB	MISG-2	SBA	FBB		
	Sasabatake	Hanada	Aratoyama	Nagawase	Kushiyama	Ejima	Shingu	Hamada	S.Shimasaki	Misaki	Saigo	Fuse		
SiO ₂ (wt.%)	50.2	26.73	45.52	47.66	51.26	50.50	43.76	35.38	45.08	47.43	7.29	47.53		
TiO ₂	1.15	2.59	1.89	1.47	1.24	1.44	2.07	2.68	2.55	1.83	2.72	2.31		
Al ₂ O ₃	16.47	15.65	13.13	18.60	16.99	17.57	14.82	11.08	14.17	14.18	16.36	15.45		
Fe ₂ O ₃	7.78	12.36	11.31	9.40	9.97	11.10	10.53	15.99	10.96	11.12	10.29	10.51		
MnO	0.11	0.16	0.18	0.13	0.15	0.14	0.16	0.33	0.17	0.14	0.18	0.15		
MgO	8.87	8.08	12.18	6.18	6.74	7.03	7.68	9.19	10.54	11.57	7.67	9.88		
CaO	8.93	8.92	11.27	10.47	8.54	9.06	8.95	15.32	9.69	9.52	7.60	7.66		
Na ₂ O	3.64	2.96	2.57	3.02	3.19	2.93	2.47	3.02	4.47	3.50	3.44	3.84		
K ₂ O	1.60	1.82	1.31	0.67	0.99	0.37	1.88	1.63	1.77	1.65	2.77	1.91		
P ₂ O ₅	0.53	0.63	0.53	0.40	0.50	0.20	0.52	2.35	0.74	0.47	0.82	0.51		
Ba (ppm)	870	560	560	340	260	770	1370	930	520	520	970	620		
Rb	19.7	36.5	36.2	15.2	13.4	5.1	46.0	45.5	25.1	45.8	78.8	42.8		
Sr	1700	730	570	740	530	370	670	1920	810	600	830	720		
Th	5.32	4.73	5.10	2.12	2.32	1.27	5.78	19.6	5.08	3.42	6.92	3.66		
Zr	150	250	160	110	220	100	200	350	210	160	280	230		
Y	12.6	23.4	23.5	16.1	31.6	16.9	21.3	51.5	25.0	19.3	28.0	22.9		
Sc	20.4	21.9	33.2	28.1	31.4	20.4	22.0	21.0	25.3	26.4	17.6	18.5		
Cr	260	190	450	100	160	110	210	110	210	650	170	320		
Co	34.3	47.4	49.9	33.7	35.0	46.0	37.8	46.0	58.9	66.2	39.8	51.0		
Ni	190	140	260	45	110	150	130	91	190	280	170	320		
Hf	2.5	5.3	3.6	2.4	4.1	2.3	13.8	6.4	5.3	3.9	6.9	5.8		
Ta	0.5	2.8	2.3	0.8	0.5	0.7	3.0	9.9	3.4	2.4	4.4	3.3		
La	50.4	36.0	34.7	17.5	23.5	10.4	32.1	210	36.4	25.9	44.9	33.7		
Ce	97.7	75.4	71.6	34.2	54.9	23.2	69.5	378	70.9	50.2	88.7	64.7		
Nd	39.6	37.0	32.6	17.8	24.2	14.0	30.39	140.1	38.02	25.73	45.69	33.46		
Sm	5.91	7.38	6.53	3.75	5.95	3.59	6.01	22.84	7.44	5.14	9.09	7.00		
Eu	1.48	2.41	1.97	1.17	1.59	1.29	2.00	6.91	2.50	1.86	2.71	2.48		
Tb	0.39	0.89	0.92	0.53	0.89	0.62	0.80	2.02	1.02	0.77	1.02	0.78		
Yb	1.49	1.91	1.95	1.77	3.46	1.17	1.62	3.43	2.38	2.27	2.25	1.60		
C.I.P.W. norm														
Or	9.59	10.9	7.83	4.07	5.93	2.20	12.1	-	10.6	9.43	16.7	11.4		
Ab	27.7	20.7	9.42	26.3	27.3	25.0	17.9	-	8.17	16.1	20.6	21.1		
An	24.2	24.3	20.7	36.3	29.3	33.9	25.9	12.4	13.5	17.5	21.4	19.5		

Ulungdo Island										Jeddo Island					Datong			
Sample No.:	No. 2	No. 3	No. 5	No. 6						J-1	J-4	J-5	CH-1	CH-12	CH-19			
SiO ₂ (wt.%)	41.7	59.3	56.4	47.3	47.3	20.0	22.4	-	2.62	14.5	16.2	6.77	4.97	6.39				
TiO ₂	3.19	0.26	1.29	2.88	2.88	8.29	8.21	-	-	-	-	-	-	-				
Al ₂ O ₃	14.6	19.1	19.0	17.3	17.3	3.93	3.50	3.50	5.2	-	4.3	20.1	9.36	12.6				
Fe ₂ O ₃	11.7	3.87	5.58	10.21	10.21	1.47	1.62	1.62	11.66	2.43	1.61	1.56	1.52	1.54				
MnO	0.16	0.18	0.14	0.17	0.17	2.39	2.75	2.75	4.28	5.33	4.88	8.87	5.26	4.44				
MgO	7.67	0.31	1.64	3.87	3.87	1.20	0.48	0.48	1.34	5.82	1.77	1.08	1.98	1.22				
CaO	10.1	1.48	3.76	8.47	8.47													
Na ₂ O	2.72	7.36	5.62	3.47	3.47													
K ₂ O	1.27	6.44	5.63	2.73	2.73													
P ₂ O ₅	0.67	0.08	0.32	0.87	0.87													
Ba (ppm)	640	120	870	103	103													
Rb	30	180	160	70	35.0													
Sr	850	70	610	1040	810													
Th	7.43	28.4	19.8	9.47	5.62													
Zr	290	670	480	320	230													
Y	20	40	40	30	20.1													
Sc	22.4	0.79	4.96	12.7	14.9													
Cr	170	10	101	20	11													
Co	45.3	1.88	9.93	27.5	25.4													
Ni	116	97	88	113	13													
Hf	5.47	13.7	9.29	6.19	4.35													
Ta	4.1	10.6	6.8	5.2	3.0													
La	56.3	115	87.5	73.2	39.0													
Ce	106	177	142	141	66.7													
Nd	47.6	54.4	42.9	52.4	24.4													
Sm	8.46	8.12	6.57	8.98	6.63													
Eu	2.56	1.21	2.12	2.97	2.12													
Tb	1.00	1.13	0.81	1.02	0.82													
Yb	2.29	3.83	2.52	2.15	1.45													

TABLE 2 (continued)

Ulungdo Island		Jeju Island					Datong			
Sample No.:	No. 2	No. 3	No. 5	No. 6	J-1	J-4	J-5	CH-1	CH-12	CH-19
C.I.P.norm										
Or	8.09	38.8	33.6	16.8	9.68	3.31	5.17	15.9	4.75	10.5
Ab	13.8	37.2	32.9	24.3	28.7	34.1	32.7	12.4	25.7	26.4
An	25.7	0.06	10.1	24.5	23.6	18.1	16.5	11.1	26.0	14.1
Ne	6.00	14.3	8.20	3.35	8.23	0.82	2.57	14.1	0.42	5.53
Hy	—	—	—	—	—	—	—	—	—	—
Di	19.2	6.03	5.57	11.0	12.8	19.0	20.1	20.5	13.9	16.9
Ol	17.2	2.35	5.47	10.7	9.27	18.1	15.8	16.2	22.0	17.7
Mt	1.83	0.58	0.82	1.51	1.48	1.85	1.91	1.90	1.77	1.92
It	6.53	0.50	2.48	5.69	4.81	3.90	4.35	5.42	3.94	5.19
Ap	1.71	0.91	0.77	2.14	1.33	0.83	0.98	2.48	1.61	1.89
Higashi- and Kita-Matsuura Districts										
Sample No.:	80801-4 Iwano	808014-1 Kirigo	80802-6 Ishimuro	80812-5 Kabeshima	81812-8 Iki	80727-1 Takashima	80821-3 Kirigo	80906-7 Nonogashira	80903-3 Kunimi	80916-1 Hirado
SiO ₂ (wt.%)	48.85	48.39	49.04	49.04	48.65	48.70	48.61	51.00	47.99	48.43
TiO ₂	1.94	1.80	1.82	1.53	2.31	1.80	1.30	1.66	2.42	1.33
Al ₂ O ₃	15.89	17.52	14.80	13.58	16.96	15.52	15.48	15.88	16.10	14.07
Fe ₂ O ₃	12.31	10.97	12.35	12.40	11.07	10.65	12.43	9.98	12.09	10.31
MnO	0.15	0.16	0.17	0.17	0.15	0.14	0.15	0.15	0.16	0.14
MgO	6.99	5.52	9.52	11.56	6.07	7.90	8.04	7.40	6.90	8.29
CaO	8.78	8.21	9.63	9.55	7.49	8.17	8.49	9.10	8.82	8.88
Na ₂ O	3.29	3.68	3.03	2.83	6.25	3.59	3.02	3.50	3.50	3.27
K ₂ O	1.78	1.69	1.07	1.12	2.01	1.89	0.66	1.20	1.51	1.47
P ₂ O ₅	0.53	0.48	0.29	0.28	0.84	0.50	0.20	0.33	0.53	0.41

Ba (ppm)	580	460	490	370	640	550	220	380	540	230
Rb	41.1	30.0	23.8	23.8	13.6	43.9	14.1	26.5	22.3	34.5
Sr	570	610	420	440	660	570	340	47.	620.	540.
Th	4.69	2.88	4.07	2.71	6.33	4.63	1.37	3.68	4.40	7.54
Zr	170	170	140	110	330	180				
Y	23.3	21.6	41.9	19.8	28.2	21.0	21.4	22.2	25.2	20.0
Sc	25.8	20.6	29.5	26.0	17.7	20.1	23.9	27.8	22.6	26.4
Cr	200	48	290	470	94	260	340	250	170	380
Co	49.3	38.3	47.9	57.5	35.3	41.0	20.1	37.6	43.2	100
Ni	160	33	140	270	110	140	132	98.5	62.8	244
Hf	3.8	3.3	2.3	2.4	7.0	4.0	2.41	3.09	4.53	3.51
Ta	2.4	1.3	1.7	1.1	3.8	2.6	0.9	1.1	3.6	2.0
La	31.6	26.7	36.6	19.4	48.8	31.1	12.0	23.0	33.2	40.8
Ce	59.4	50.1	75.0	35.6	90.9	59.0	22.8	45.9	68.5	69.9
Nd	27.03	23.8	24.51	17.75	40.59	26.18	13.4	23.0	32.1	27.5
Sm	5.72	4.71	7.14	4.04	9.00	5.49	3.46	5.16	6.53	5.01
Eu	1.85	1.84	2.60	1.34	2.53	1.71	1.02	1.72	1.95	1.49
Tb	0.68	0.78	1.03	0.80	0.95	0.75	0.67	0.81	1.21	0.50
Yb	2.09	1.73	3.84	1.77	2.53	1.74	2.41	1.09	2.24	1.79
C.I.P.W. norm										
Or	10.6	10.2	6.28	6.62	5.98	11.4	4.01	7.12	9.02	9.08
Ab	25.6	28.6	24.3	20.0	29.5	25.7	26.3	29.8	25.7	27.2
An	23.5	27.0	23.5	21.1	15.3	21.1	27.5	24.2	25.7	27.2
Ne	1.29	1.48	0.61	2.14	12.7	2.89	-	-	2.31	0.92
Hy	-	-	-	-	-	-	11.0	5.11	-	-
Di	13.9	9.57	18.0	19.9	13.5	13.8	-	15.5	13.7	18.7
Ol	18.4	16.5	21.4	24.9	15.0	18.8	14.5	12.8	17.6	18.6
Mt	1.79	1.64	1.79	1.80	1.61	1.59	1.83	1.46	1.77	1.54
Il	3.71	3.51	3.43	2.91	4.39	3.49	2.54	3.17	4.65	2.64
Ap	1.26	1.17	0.68	0.66	1.99	1.21	0.49	0.89	1.27	1.01

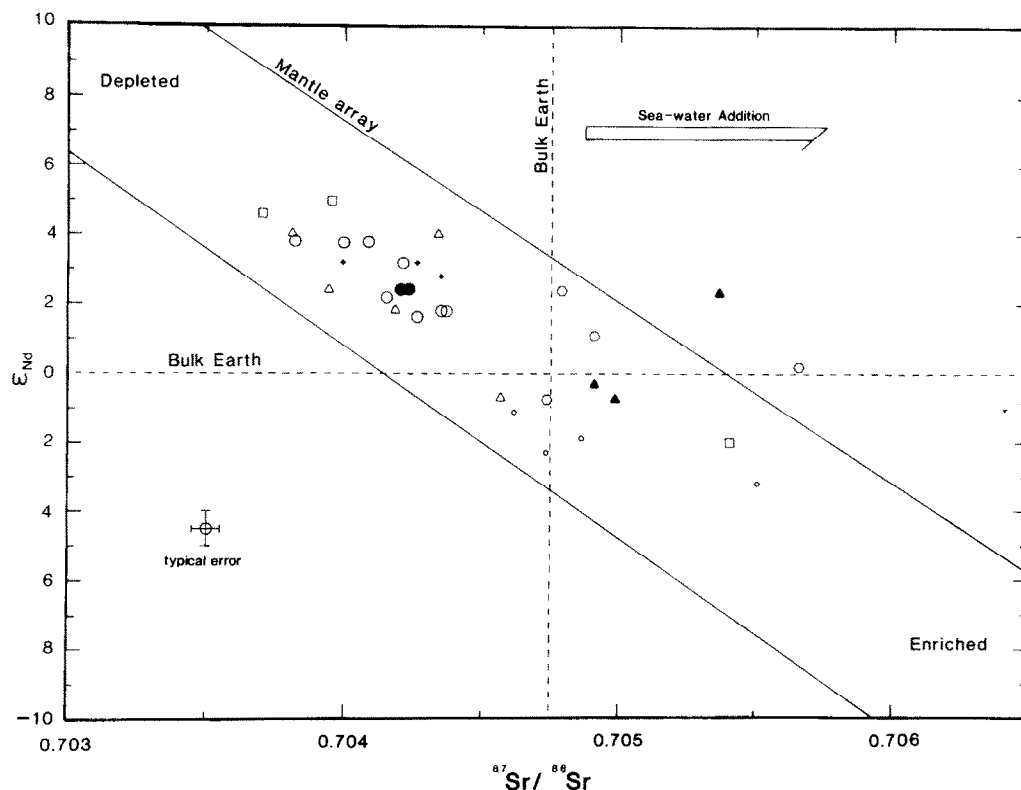


Fig. 3. Nd versus Sr isotopic compositions for studied volcanic rocks from southwestern Japan, Korea and China. Symbols for individual areas are as follows: large circles—northwestern Kyushu; hexagon—Oki-Dogo Island; triangles—Chugoku district; pluses—Jejudo Island; small circles—Ulungdo Island, and squares—Datong. Filled circles and triangles represent tholeiitic basalts from northwestern Kyushu and Chugoku district, respectively. The mantle array is defined by MORB and oceanic island basalts (De Paolo, 1981; O'Nions et al., 1977).

Japan, and some from Korea and China and these data together with major and trace element analyses are given in Tables 1 and 2. The nomenclature for the rocks were determined using normative compositions (Irvine and Baragar, 1971), and Miyashiro's method (1974) was used to classify subalkalic rocks into tholeiitic and calc-alkalic rock series.

The general geochemical and petrological features of the samples are essentially similar to the results given in Nakamura et al. (1989) except for nephelinite and very fractionated trachytic rocks. The geochemical characteristics of the volcanics may be summarized as follows:

(1) There is no significant difference in immobile incompatible element ratios, such as Zr–Y–Ti and Hf–Th–Ta, between samples from China, Korea and southwestern Japan, and their ratios are similar to those of typical continental and

oceanic island alkaline basalts. The Ta content of basalts from southwestern Japan is slightly lower than those from Korea and China.

(2) Some incompatible mobile to immobile element ratios, such as Ba/La, Rb/La and K/La, of basalts from southwestern Japan are higher than the ratios from Korean and Chinese basalts. In particular, average K^* values, $K^* = 2K/(Ta + La)$, when all elements are normalized to primitive mantle values, are less than unity for Korean and Chinese basalts and greater than unity for basalts from southwestern Japan (Nakamura et al., 1985, 1989), and this value decreases with increasing distance away from the Japan trench.

(3) Near constant $(La/Sm)_n$ ratios and cross-over HREE pattern are observed in alkaline basalts in each area (see Nakamura et al., 1989).

(4) Tholeiitic basalts have similar trace elements characteristics, although the highly incom-

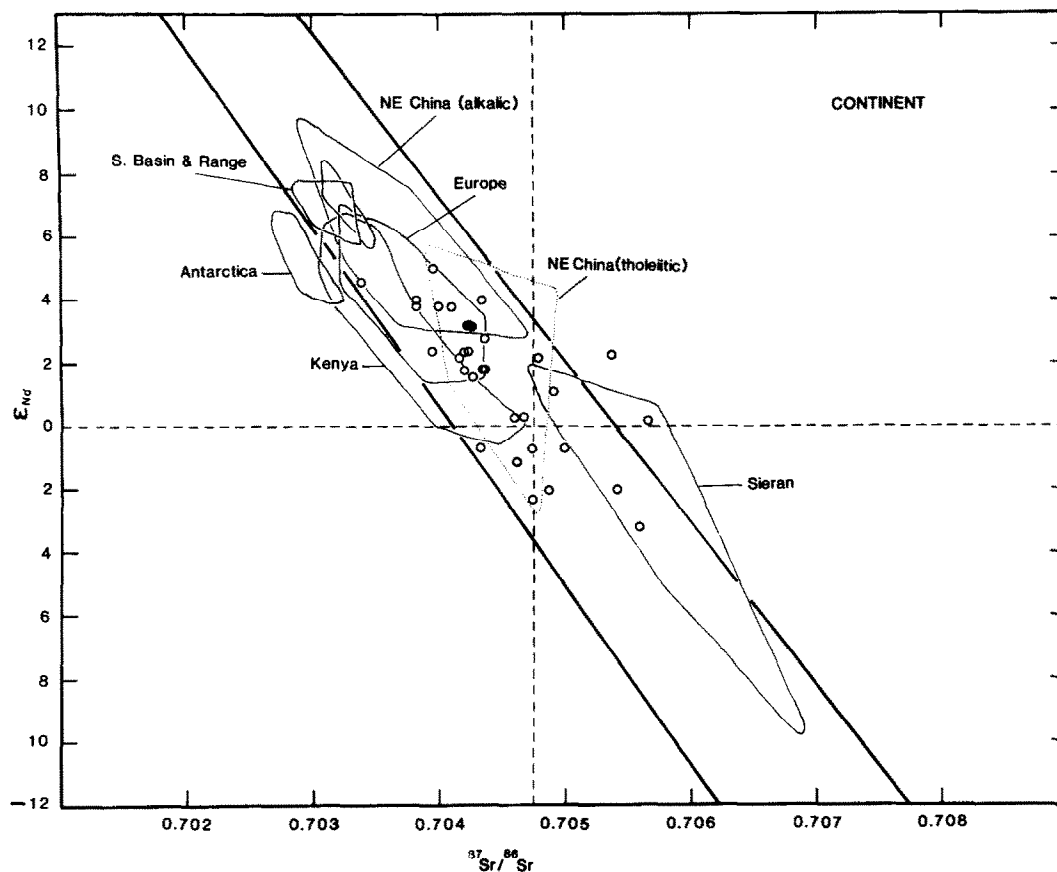


Fig. 4. Comparison of Nd and Sr isotopic compositions between data presented here and published data from typical continental alkaline basalts. Data are from: South Basin and Range Province, Sierran Province, and Snake River Plain–Yellowstone National Park (Menzies, et al., 1983); Antarctica (Futa and Masurier, 1983); Europe (Alibert et al., 1983); Kenya (Norry et al., 1980) and northeastern Chinese alkaline and tholeiitic basalts (Zhou and Carlson, 1983a).

patible element abundances are less than in the alkaline rocks. On the other hand, a nephelinite sample from Hamada, Chugoku district, has a very similar normalized abundance pattern to that of average kimberlites and typical nephelinites (e.g., Kramers et al., 1981).

Nd and Sr isotopic compositions

Nd and Sr isotopic compositions obtained are plotted on the ϵ_{Nd} and $^{87}\text{Sr}/^{86}\text{Sr}$ diagram (Fig. 3). The samples display significant variation in both ϵ_{Nd} and $^{87}\text{Sr}/^{86}\text{Sr}$, and most samples lie within the mantle array.

Basalts from Datong (China) display large variations in both ϵ_{Nd} and $^{87}\text{Sr}/^{86}\text{Sr}$, +5 to -2 and 0.7037 to 0.7054, respectively. These isotopic variations are within the range of results for Cenozoic

basalts from China reported by Zhou and Armstrong (1982) and Zhou and Carlson (1983a, 1983b). According to Zhou and Carlson (1983a, 1983b), the Cenozoic Chinese alkaline basalts have generally higher ϵ_{Nd} (+3 to +9.6) and lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.729–0.7046) than those of tholeiitic and transitional basalts (ϵ_{Nd} = -2.5 to +5.6, $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.7039 to 0.7049).

Alkaline basalts from Jejudo Island (Korea) show little variation in isotopic composition, with ϵ_{Nd} values of from +2.8 to +3.2 and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.7040 to 0.7044. These Sr isotopic compositions are similar to the results presented by Lee (1982). There is no systematic correlation between the Sr isotopic composition and the chemical composition of different type of alkaline volcanics, including alkaline basalts, hawaiite, mugearite and trachyte. Chemical varia-

tions in the volcanics from this island were therefore interpreted by Lee (1982) as reflecting simple crystal fractionation.

Samples which include alkaline basalt, trachybasalt and trachytes from Ulungdo Island, characteristically have low ϵ_{Nd} (-1.1 to -3.2) and high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7046 to 0.7055) relative to the other samples in this study. There is no evidence of a systematic difference in bulk chemistry and isotopic compositions between alkaline basalts and fractionated trachytes. The isotopic compositions of these samples similar to those from Tristan da Cunha and Gough Island (Sun, 1980; White and Hofmann, 1982).

Although most of the alkaline basalt samples from Oki-Dogo Island plot within the field of the mantle array, one sample (MISG-2) shows a high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.7057) relative to ϵ_{Nd} and plots

outside the mantle array. The other samples plot close to the bulk earth as reported by Kagami et al. (1986).

Alkaline and tholeiitic basalt samples including a nephelinite from northwestern Kyushu and Chugoku district show only small variations in Nd and Sr isotopic compositions, in spite of a relatively large number of analyses (Fig. 3). However, two tholeiites (TK-7 and TK-8) and an alkaline basalt (TK-3) are higher in $^{87}\text{Sr}/^{86}\text{Sr}$ and lower in ϵ_{Nd} than other samples from the same areas. Sample No. TK-2 (tholeiite) from the Chugoku district like the alkaline basalt (MISG-2) from the Oki-Dogo Island, plots outside the mantle array. In northwestern Kyushu, there is no significant difference in isotopic compositions between fractionated alkaline basalts, less fractionated alkaline basalts and tholeiitic basalts. Tholeiitic

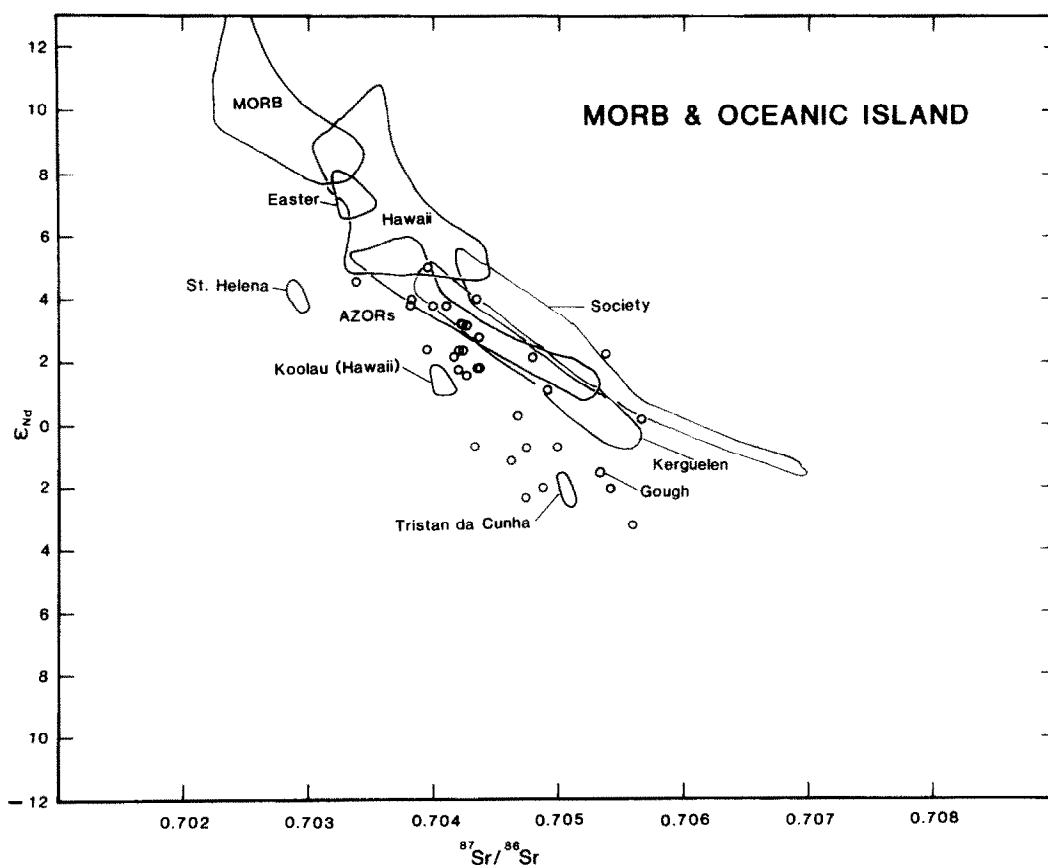


Fig. 5. ϵ_{Nd} versus $^{87}\text{Sr}/^{86}\text{Sr}$ variation diagram for volcanic rocks from mid-ocean ridges and oceanic islands, compared with results in the study. Data source are largely those referenced in White and Hofmann (1982).

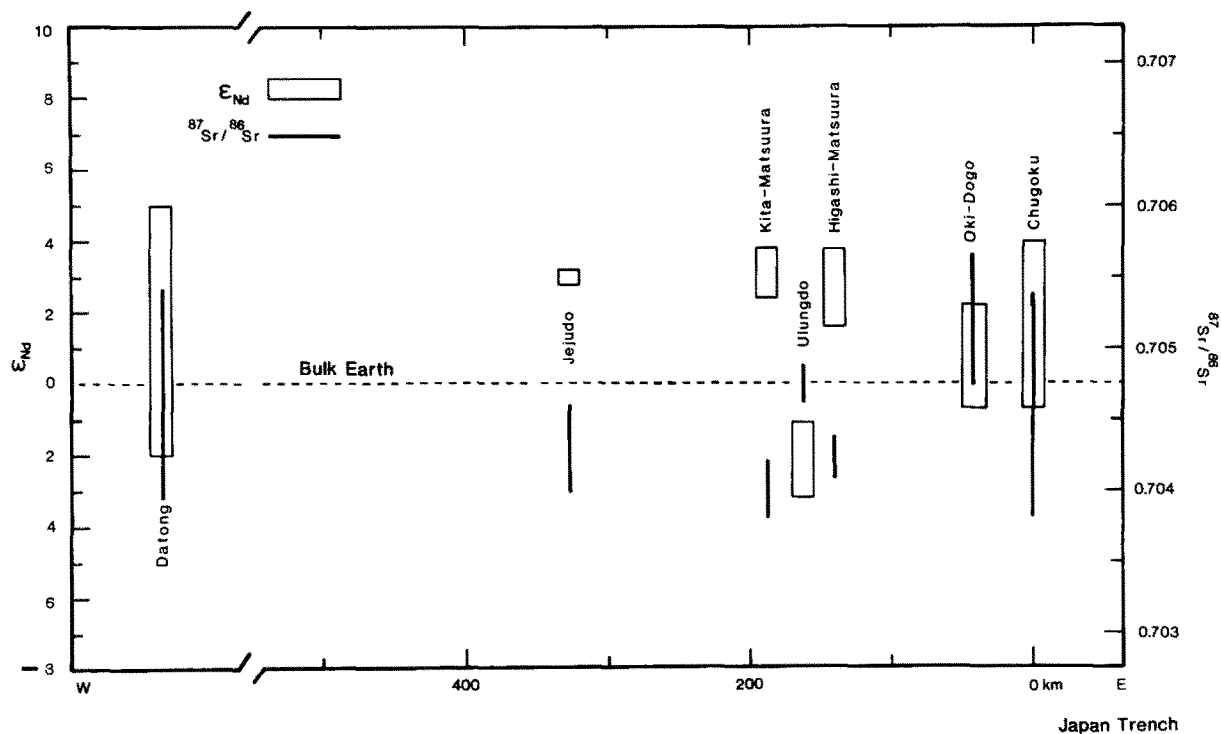


Fig. 6. Variation of Nd and Sr isotopic compositions of alkaline basalts in individual areas along a traverse section from the Japan trench west towards the Chinese craton. The traverse line extends from the nearest location of alkaline basalt in Chugoku district to the Japan Trench. The trend of the traverse section is almost E-W.

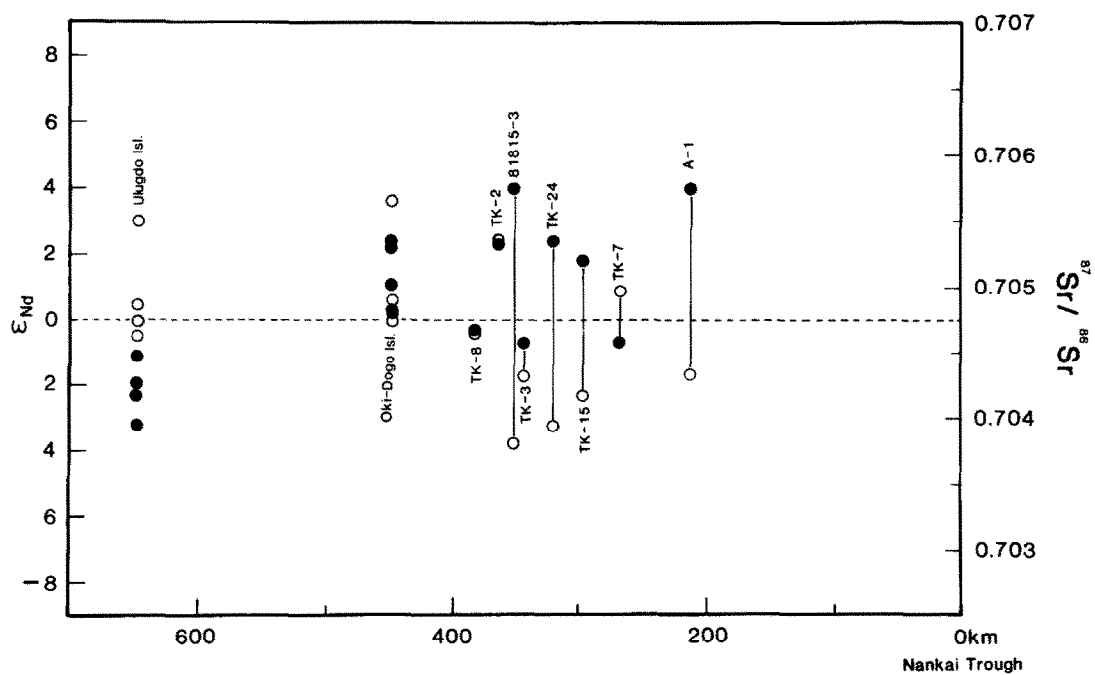


Fig. 7. Variation of Nd and Sr isotopic compositions of Cenozoic basalts along a NW-SE-trending traverse section from the Nankai trough. The distance of each locality from the trough is measured by vertical projection to the traverse section. Solid and open circles represent ϵ_{Nd} and $^{87}Sr/^{86}Sr$, respectively. The direction of traverse section is shown on Fig. 2.

basalts from the Chugoku district tend to have low ϵ_{Nd} and high $^{87}\text{Sr}/^{86}\text{Sr}$ relative to the alkaline basalts.

As shown in Figs. 4 and 5, the isotope analyses generally suggest a long-term depleted source, and overlap with results for continental alkaline basalts from Europe (Alibert et al., 1983), West Antarctica (Futa and Le Masurier, 1983), Kenya (Norry et al., 1980), the Basin and Range, Sierran Province and Colorado Plateau (Menzies et al., 1983) and China (Zhou and Armstrong, 1982; Zhou and Carlson, 1983a; 1983b). Most of these Cenozoic continental intraplate basalt provinces, as well as

the areas studied, have Sr and Nd isotopic compositions that generally plot on the lower left side of the oceanic mantle array, with ϵ_{Nd} values ranging from greater than +8 to lower than -1 (Fig. 5 and see McDonough et al., 1985).

Figure 6 and 7 show the variation of Nd and Sr isotopic compositions of alkaline volcanics in each area plotted against the traverses perpendicular to the Japan trench and the Nankai through. From the trench side to the continental, or Sea of Japan side, there is no evidence of a systematic variation in isotopic compositions with distance from the trench. This suggests that the subduction of the

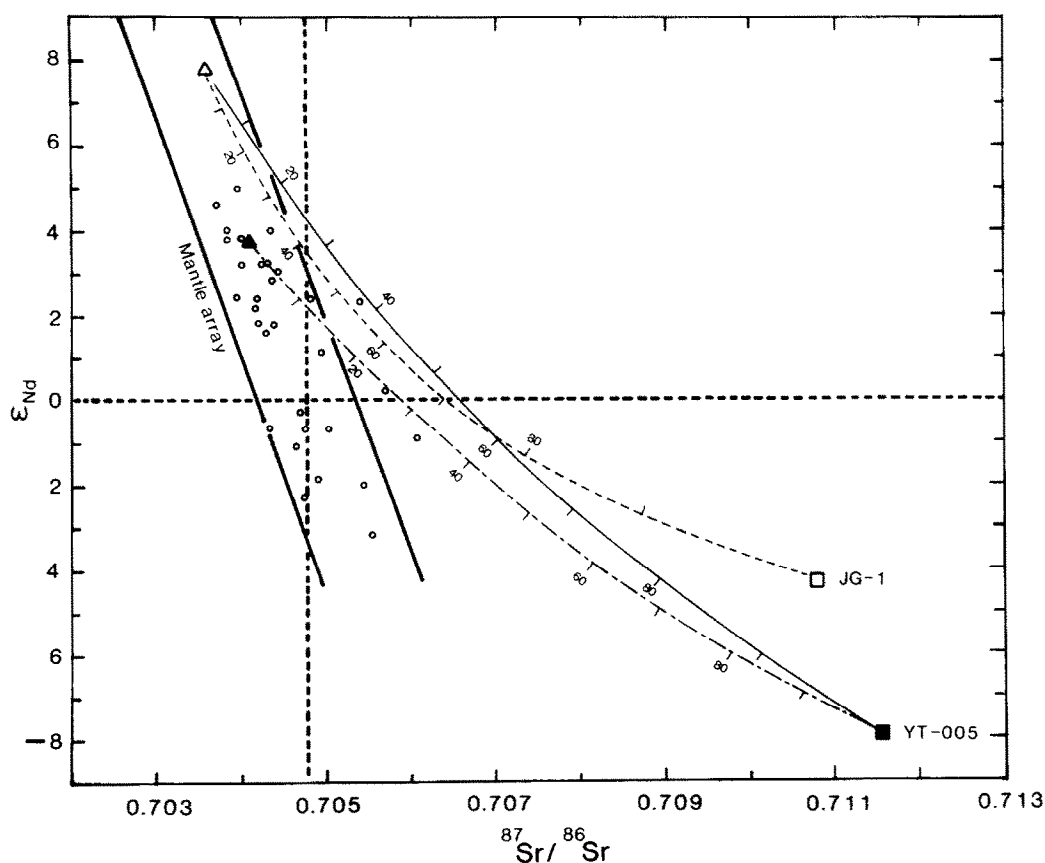


Fig. 8. Bulk mixing relationship between possible alkaline basalt magmas and basement rocks. Solid and open triangles are possible primary alkaline basalts. Samples 80812-5 from northwestern Kyushu (this study) and JY-9 from northeastern China (Zhou and Armstrong, 1982; Zhou and Carlson, 1983a), respectively. Solid and open squares are basement rocks as possible contaminants, Cretaceous Sori granodiorite (JG-1) and Silurian Yatsushiro gneiss (YT-005), respectively (Nohda and Wasserburg, 1981). Open circles represent results obtained in this study. The following parameters, listed in order of the Sr and Nd concentrations (ppm), $^{87}\text{Sr}/^{86}\text{Sr}$, and ϵ_{Nd} were used for each end-member: JY-9: 689, 25.7, 0.70358, +7.8; 80812-5: 440, 17.75, 0.70408, +3.8; JG-1: 186, 19.5, 0.71079, -4.3; YT-005: 347, 21.6, 0.71155, -7.9. Numbers with mixing lines give the weight percent of contaminants mixed with possible primary alkaline basalt magmas.

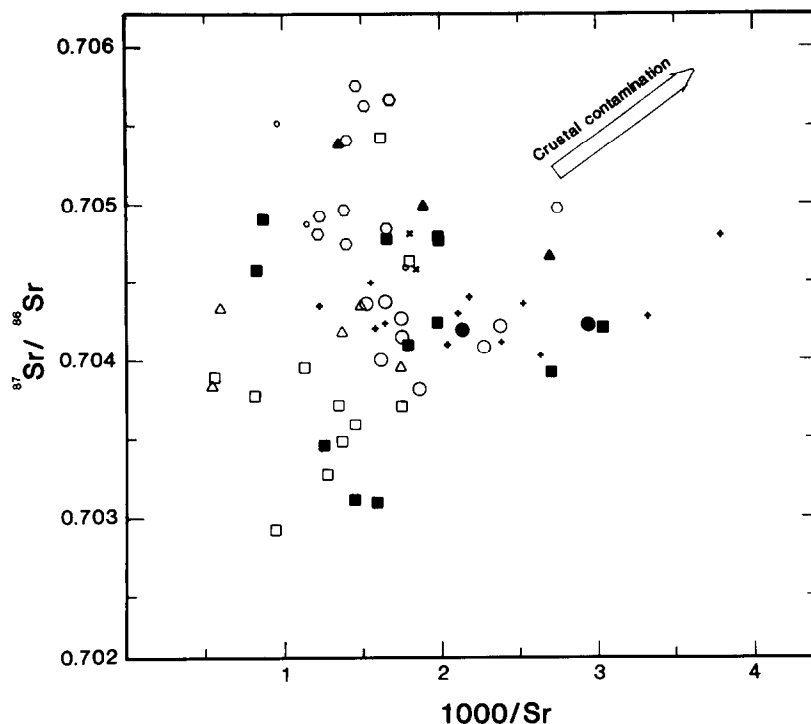


Fig. 9. $^{87}\text{Sr}/^{86}\text{Sr}$ versus $1000/\text{Sr}$ diagram. Symbols are the same as those given in Fig. 3. Published data for Cenozoic basaltic rocks from Oki-Dogo Island (Kurasawa, 1984), Jejudo Island (Lee, 1982) and northeastern China (Zhou and Armstrong, 1982) are also plotted with results of this study. Solid symbols indicate tholeiitic basalts. An arrow shows a crustal contamination trend.

Pacific or the Philippine Sea plate have not influenced the isotopic characteristics of the alkaline basalts.

Crustal contamination

It is possible that the crustal contamination may have produced variations in the chemical and isotope compositions in the samples. However, the Rb and Sr concentrations of the least fractionated samples lie within the range of values expected for a *primary magma* formed by partial melting of the mantle. If the *primitive mantle composition* of Sun (1982) and batch partial melting model (Shaw, 1970) are used, 60–10 ppm Rb and 2100–330 ppm Sr can be obtained by 1 to 7% partial melting of the mantle. Furthermore, there is no significant difference in Nd and Sr isotopic compositions between less fractionated basalts and more fractionated samples from the same areas.

The present-day isotopic composition of the basement samples is characteristic of most con-

tinental crust, showing distinctly negative ϵ_{Nd} and high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio relative to bulk earth. Figure 8 shows mixing lines between probable *primary basalts* from China, JY-9 (Zhou and Armstrong, 1982; Zhou and Carlson, 1983a) and from northwestern Kyushu (80812-5), and *basement* rocks, Silurian Yatsushiro gneiss (YT-005) and Cretaceous Sori granodiorite (JG-1) presented by Nohda and Wasserburg (1981). The mixing lines are shifted to the right of the trend defined by samples, but are parallel to the mantle array. Only two samples, an alkaline basalt from Oki-Dogo Island (MISG-2) and a tholeiitic basalt from Chugoku district (TK-2), plot near the mixing lines. The enriched samples lying within the extension of the mantle array are clearly not related to the mixing lines.

There is no simple relationship between Sr contents and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Fig. 9). Most of the samples studied are SiO_2 -undersaturated and indicate affinity to an alkaline series, which suggests that they have not assimilated an appreciable

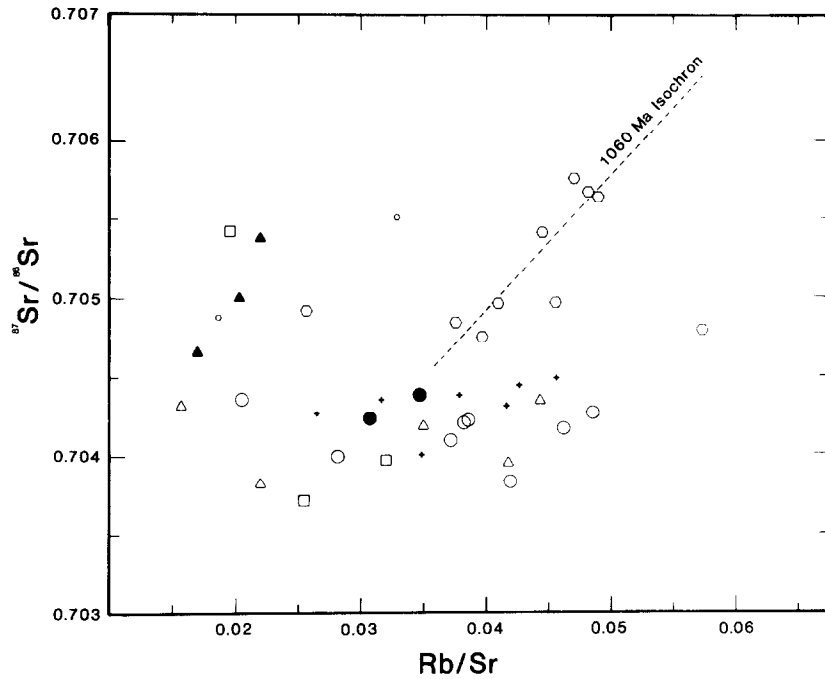


Fig. 10. $^{87}\text{Sr}/^{86}\text{Sr}$ versus Rb/Sr diagram. The results for alkaline basalts, reported by Kurasawa (1984) (Oki-Dogo Island) and Lee (1983) (Jejudo Island) are also given in addition to the results of this study. Symbols are same as those given in Fig. 3.

amount of continental crust (Hawthorn and Volmer, 1979). It should also be noted that there are no differences in normalized incompatible abundance patterns between the samples studied

and typical oceanic and continental alkaline basalts (Nakamura et al., 1989).

These observations suggest that the variations in chemical and isotopic compositions do not re-

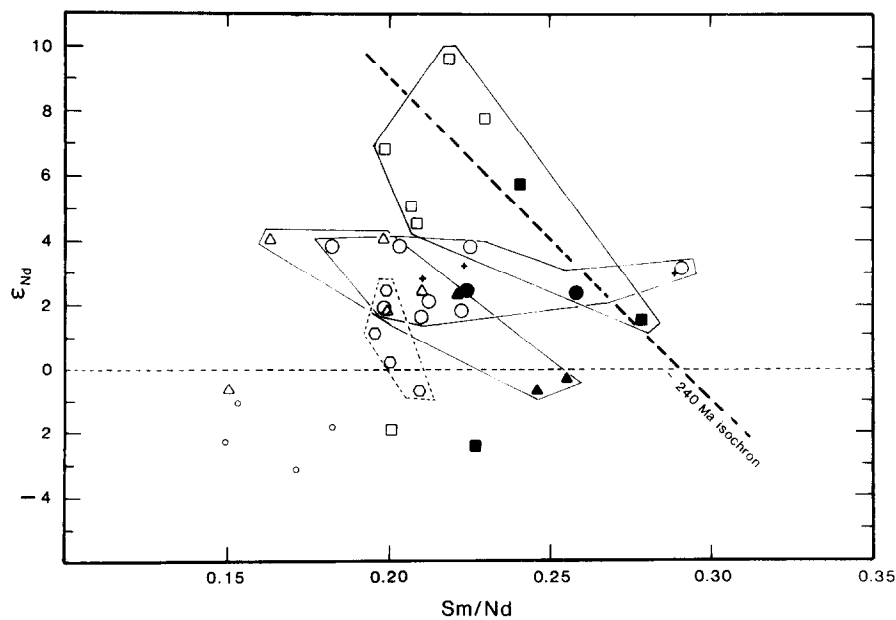


Fig. 11. ϵ_{Nd} versus Sm/Nd diagram. Results for northeastern Chinese basalts done by Zhou and Carlson (1983a), are also shown with the results of this study. Thick broken line is a negative isochron corresponding to -240 Ma. Symbols are the same as in Fig. 3.

sult from crustal contamination, but reflect source characteristics and magmatic processes in the mantle.

Evidence of two-component mixing

Isochron diagram for Rb–Sr and Sm–Nd are depicted in Fig. 10 and 11, with published data on Rb–Sr from Jejudo Island (Lee, 1982) and China (Zhou and Armstrong, 1982), and on Sm–Nd from China (Zhou and Carlson, 1983a). Some extremely fractionated trachytes, from Ulungdo Island, are also plotted on these diagrams.

There is no positive correlation in either case. In Fig. 10, the data are scattered except for samples from Oki-Dogo Island in which published data of Kurasawa (1984) give an isochron age of 1060 Ma, and there is no significant difference in $^{87}\text{Sr}/^{86}\text{Sr}$ and Rb/Sr ratios between alkaline and subalkaline rocks. Neither do available Sr isotopic data on Chinese Cenozoic basalts (Zhou and Armstrong, 1982) show any correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and Rb/Sr ratios.

On the other hand, the Sm–Nd isochron diagram (Fig. 11) indicates a weak negative correlation, especially for the samples from China, Oki-Dogo Island and the Chugoku district, if a

few samples that diverge from the major trends are excluded. This negative correlation might be attributed at least to two-component mixing of sources in the mantle since such a signature cannot be produced by simple partial melting, crystal fractionation or crustal contamination. In the Chugoku district and China, the Sm/Nd ratio and ϵ_{Nd} for tholeiitic basalts tend to be higher and lower, respectively than those of alkaline basalts. These features have also been demonstrated for Hawaiian Island basalts (Zindler et al., 1984), and are consistent with the interpretation of Chen and Frey (1983). They argue that Hawaiian basalts were derived from the mixture of a large proportion of melt derived from enriched mantle plume from the lower mantle and a relatively small degree of partial melt of a depleted MORB-type source. The above observations therefore support the hypothesis that the Sr and Nd isotopic compositions of studied samples plotted within the mantle array have been generated by an interaction between enriched and depleted mantle sources.

Highly incompatible elements, such as Rb, Ba, Th, Ta, Nb, K and LREE, which plot on the left hand side of the normalized abundance pattern diagram (Sun, 1982; Thompson, 1982; Nakamura

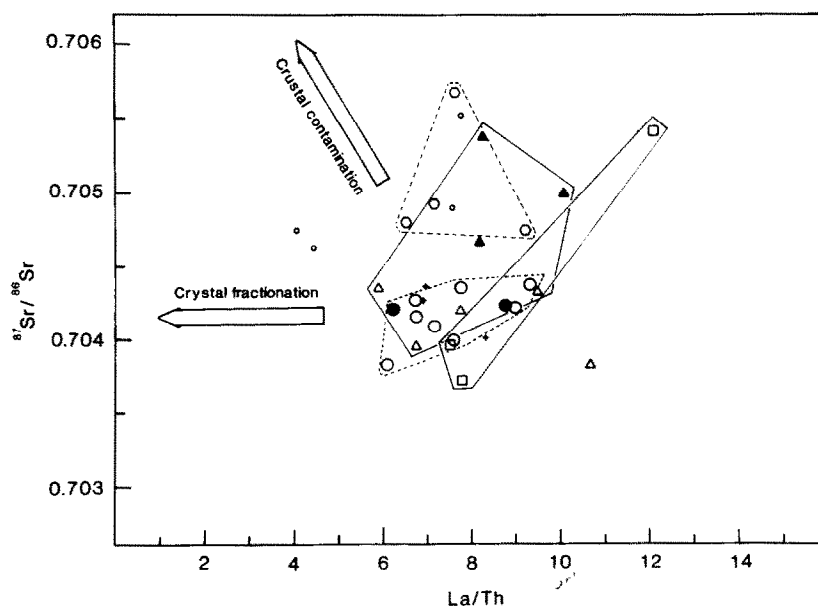


Fig. 12. ϵ_{Nd} versus La/Th diagram. Symbols are the same as those given in Fig. 3. Arrows indicate trends of crustal contamination and crystal fractionation.

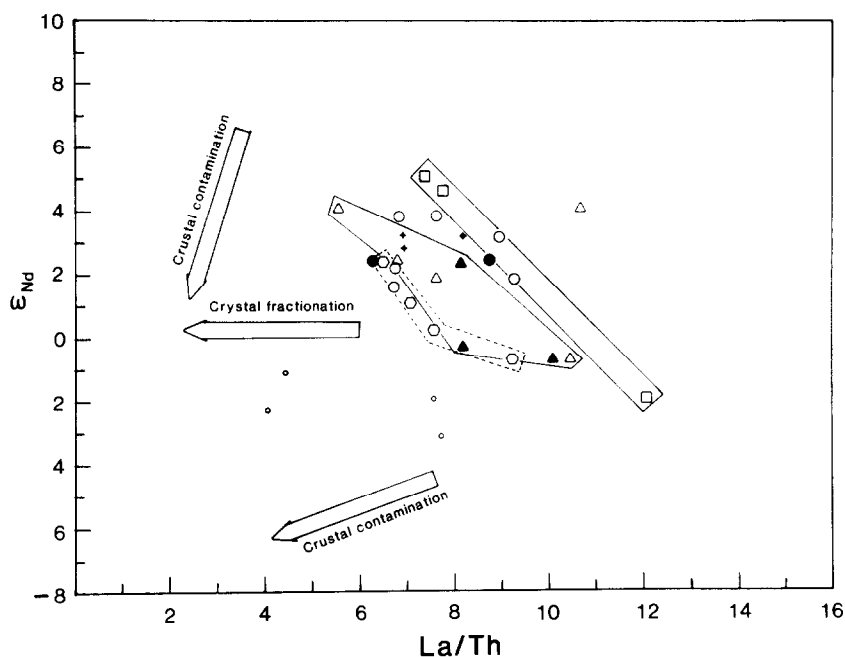


Fig. 13. $^{87}\text{Sr}/^{86}\text{Sr}$ versus La/Th diagram.

et al., 1985), are also useful in evaluating magmatic processes. However, Rb, Ba, Ta, Nb and K have been weakly modified by subduction processes in southwestern Japan (Nakamura et al., 1985, 1989). As a consequence, these elements cannot be used to evaluate processes in the differing tectonic setting of Japan, Korea and China. La and Th are believed to be immobile elements (Pearce, 1983) and are strongly incompatible in basaltic magmatic processes (Frey et al., 1978). La and Th are generally assumed to be almost completely partitioned into the liquid; the bulk distribution coefficient for La being slightly higher than that for Th (Frey et al., 1978). The La/Th ratio should thus decrease with decreasing degree of partial melting.

Figures 12 and 13 show the relationship between ϵ_{Nd} and $^{87}\text{Sr}/^{86}\text{Sr}$ and the La/Th ratio respectively. With the exception of nephelinite from Chugoku district and the samples from Ulungdo Island there is clearly a negative correlation between ϵ_{Nd} and La/Th. There appears a weak positive correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and La/Th ratio in Fig. 12. Variation of the La/Th ratio, as well as variations of Sm/Nd and Rb/Sr ratios are strongly dependent on fractional crys-

tallization and crustal contamination processes. However, these negative and positive correlations cannot be explained by simple fractionation and partial melting models, if isotope equilibration is assumed during magma generation (Hofmann and Hart, 1978). These correlations may indicate mixing between end-member melts formed by a relatively small degree of partial melting of the depleted source and a relatively large degree of partial melting of the enriched source materials. These isotopic and incompatible element signatures are compatible with other geochemical characteristics observed in Nakamura et al. (1989). However the poor correlations obtained may suggest both sources are of variable isotopic compositions.

Nakamura et al. (1989) have also argued that the amount of LREE in the hybrid magma is controlled by the melt component formed by a very small degree of partial melting (less than 0.1% melting) of a depleted source. Further, in order to obtain the observed degree of LREE enrichment, the melt from the depleted source must be an important component in the mixture. If a depleted mantle has an ϵ_{Nd} value of +10 to +12, such as the MORB-type source, then the

enriched component must have a strongly negative ϵ_{Nd} value to produce the alkaline basalts with the ϵ_{Nd} values observed in this study. This means either, that it is strongly LREE enriched, or that it has been enriched for a very long period of time, or both. ϵ_{Nd} and ϵ_{Sr} for alkaline basalts show a wide range of values whereas ϵ_{Nd} and ϵ_{Sr} values in the MORB show little variation. This implies that the degree of enrichment of the enriched source is highly variable, or that the timing of the enrichment is variable or, possibly, a combination of both factors.

Discussion

The trace element and isotopic characteristics presented in the previous section are indicative of mixing of at least two components. The data are not consistent with crustal contamination or crystal fractionation. The incompatible element patterns of alkaline basalts from southwestern Japan, Korea and China are analogous to those of oceanic island alkaline basalts, although alkaline basalts in southwestern Japan are slightly more enriched in the mobile elements, K, Ba and Rb, relative to typical continental and oceanic island basalts. It has been argued in Nakamura et al. (1989) that the alkaline basalts from southwestern Japan are generated by interaction between OIB-type plume and MORB-type upper mantle weakly contaminated by subduction processes. Chinese and Korean basalts, on the other hand, were formed by interaction between the plume and uncontaminated MORB-type upper mantle, since these areas have not been influenced by the subduction of Pacific plate.

It is generally believed that the mantle is chemically and isotopically heterogeneous. Sun (1984) and White (1985) propose six or five components as source material in the mantle for generation of intra-plate basalts. At least two components are necessary to explain the genesis of alkaline basalts and associated tholeiitic basalts in the areas studied. The characteristics of end-members for two-component mixing are as follows:

MORB-type source

MORB-type sources are characterized by the depletion in highly incompatible elements, probably due to the extraction of very small amounts of melts in previous melting events (e.g., Gast, 1968; Armstrong, 1981). Sr, Nd and Pb isotope ratios for *normal* MORB are restricted to the following range of values: $^{87}\text{Sr}/^{86}\text{Sr}$: 0.7022 to 0.7028, ϵ_{Nd} : +9 to +12 and $^{206}\text{Pb}/^{204}\text{Pb}$: 17.6 to 18.6, respectively, indicating long-term depletion of Rb/Sr, Nd/Sm and Pb/U in the MORB-type source (e.g. Dupré and Allègre, 1980; Cohen and O'Nions, 1982).

Based on Nd and Sr studies, Nohda and Wasserburg (1981) suggested that Quaternary volcanic rocks close to the Japan trench in north-eastern Japan contain a component of sediment. Volcanic rocks occurring further from the trench have lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7027) and higher ϵ_{Nd} (+8.3) than those of volcanics occurring closer to the trench. These are similar to the isotopic composition of MORBs (Nohda and Wasserburg, 1981; Notsu, 1983). The Pb isotopic compositions of basalts in northeastern and central Japan clearly show a mixing relationship between oceanic sediments and MORB, becoming less radiogenic with increasing distance from the Japan trench (Hedge and Knight, 1969; Tatsumoto and Knight, 1969; Nakamura et al., 1985). This indicates that a mantle wedge beneath the back-arc side of the arc, to which sedimentary components have not been introduced, should possess an isotopically similar composition to a MORB-type source.

The highest ϵ_{Nd} and lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Cenozoic alkaline basalts from northeastern China are +9.6 and 0.70291 respectively, although isotopic compositions in the basalts are highly variable (Zhou and Armstrong, 1982; Zhou and Carlson, 1983b). Most depleted values approach those of MORBs. We therefore propose that the upper mantle material beneath southwestern Japan, Korea, and China has not been significantly influenced isotopically by the subduction processes and has characteristics basically similar to a MORB-type source.

Plume or OIB-type source

The chemical and isotopic signatures of OIB imply that their source regions have experienced a more complex geochemical evolution than the MORB source region (e.g., Chase, 1981; Allègre, 1982; Hofmann and White, 1982; Thompson et al., 1984). Several types of mantle sources have been proposed, based on different geochemical features of OIB, for example: mantle plume from the lower mantle (Allègre et al., 1983); metasomatized upper mantle (Frey et al., 1978; Clague and Frey, 1982); recycled crust (Armstrong, 1968; 1981); accumulated ancient oceanic crust (Chase, 1981; Hofmann and White, 1982; Ringwood, 1982). The geochemical variations have also been attributed to the interaction between a MORB-type depleted source and a relatively primitive (e.g. DePaolo and Wasserburg, 1976) or enriched source (Chen and Frey, 1983; Zindler et al., 1982).

Most OIB lie on the depleted side of the bulk earth on the Nd–Sr isotope correlation, but some OIB plot in the enriched quadrant; for instance, Gough Island, Tristan da Cunha and some of Kerguelen and Society Islands (Sun, 1980; White and Hofmann, 1982).

Chase (1981), Hofmann and White (1982) and Ringwood (1982) proposed that ancient oceanic crust (0.5 to 2.0 b.y.), accumulated in the mantle via subduction processes, can account for the linear Nd–Sr isotopic correlation observed in OIB. According to model of Hofmann and White (1982), the degree of enrichment (characterized by positive ϵ_{Sr} and negative ϵ_{Nd} values), would depend upon the residence time of accumulated oceanic crust in the mantle. This requires that recycled ancient oceanic crust has a less depleted REE pattern than modern MORB. On the other hand, Ringwood (1982) suggested that the source region for OIB is fertilized by partial melting of the accumulated ancient oceanic crust (*megalith*). These partial melts would have had higher Rb/Sr and Nd/Sm ratios than their sources and hence, given enough time, would evolve to contain more radiogenic Sr and less radiogenic Nd.

The Pb isotopic compositions of alkaline basalts from southwestern Japan and Ulungdo Island are similar to those of basalts from the Gough and

Kerguelen islands (Kurasawa, 1968; Nakamura et al., 1985; Nelson et al., 1986). In spite of having similar $^{206}\text{Pb}/^{204}\text{Pb}$ ratios to present-day MORB, their $^{208}\text{Pb}/^{204}\text{Pb}$ ratios are much higher than MORB, indicating a long-term evolutionary history with a higher Th/U ratio and more primitive. Ancient recycled sediments with high Th/U ratios could have relatively high $^{208}\text{Pb}/^{204}\text{Pb}$ compared to MORB. A small proportion of entrained sediment could significantly modify the composition of subsequent melts. Furthermore, samples from Ulungdo Island, Oki-Dogo Island and Takashima Island fall on a line extending to the MORB field in the $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (see Nakamura et al., 1985). This is also consistent with two-component mixing with the high $^{208}\text{Pb}/^{204}\text{Pb}$ representing the enriched source end-member probably produced by an accumulation of ancient oceanic crust and minor sediment.

Mantle plume and mixing process

As discussed in the previous sections, negative correlations between ϵ_{Nd} and Sm/Nd and fairly constant La/Sm ratios in the alkaline basalts suggest at least two-component mixing; i.e. a mixture of melt formed by a relatively small degree of partial melting of depleted source, and a relatively large degree of partial melting of an enriched source. Furthermore the melt produced by the low degree of partial melting must dominate the resulting mixture to produce the observed degree of LREE enrichment. These depleted and enriched sources correspond to a MORB-type source and an OIB-type source, probably accumulated ancient oceanic crust based on the above assumptions. It has been shown that the ϵ_{Nd} –La/Th diagram is also compatible with two-component mixing (Fig. 12). The La/Th of MORB-type source is expected to be higher than that of the ancient oceanic crust, even though the LREE abundance of former will be smaller. Even so, if the degree of partial melting is very small in the MORB-type source and appreciably larger in the enriched source, then the La/Th ratio of a melt from the MORB-type source could be lower than that from the enriched source because Th is more incompatible than La. The difference in the degree of partial

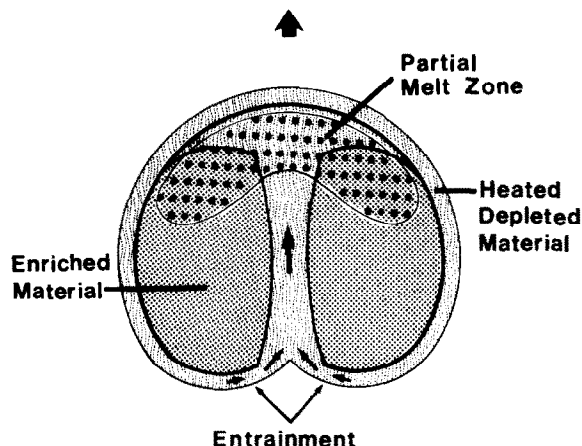


Fig. 14. Diagrammatic structure of an ascending mantle plume in the depleted MORB-type mantle. This diagram is basically originated from Griffiths (1986a, b). Conduction of heat during the rise of the plume causes entrainment of the heated depleted MORB-type mantle material into the enriched plume, and cooling the plume. Although the MORB-type mantle in the plume is slightly cooler than the enriched type, it is much hotter than the adjacent mantle outside the plume. It is also an intimate part of the plume structure and rises because the net density of the mantle in the plume is less than that of the adjacent mantle. If both materials in the plume partially melt, the migrating melts will mix in the partial melt zone.

melting in both sources, based on the variations in La/Th ratio and ϵ_{Nd} , is compatible with other mixing signatures.

Ancient oceanic crust, enriched in incompatible trace elements, that forms a fertile source regions for OIB's sinks back into the mantle because it is cold and dense. However, the buoyancy of these regions gradually increases with time as they acquire heat by conduction from the underlying mantle or core (depending on the level of the interface from which they originate) and by higher internal heat generation by the incompatible elements, such as K, U and Th, relative to the surrounding depleted mantle. Eventually they begin to rise, forming plumes of hot, enriched mantle. Because the ascending plume is now hotter than the overlying MORB-type mantle, it heats the adjacent mantle until its density becomes comparable with that of the mantle in the plume (Griffiths, 1986a, b). As a consequence, the heated boundary layer around the plume effectively becomes part of the plume and is entrained into it as it rises (Fig. 14). The plume therefore becomes

a mixture of mantle from the plume source region which we suggest is the enriched source required for our model and the overlying depleted MORB-type mantle.

When the plume ascends into the upper levels of the mantle, it begins to melt due to decompression. Both types of mantle will melt, but the enriched type would generally undergo a higher degree of melting than the depleted type. There are two reasons for this. First, although the entrained MORB-type mantle gains heat by conduction from the enriched mantle, its temperature will always be significantly less. Second, the depleted mantle has lost much of its low melting point volatile and incompatible elements whereas these elements have been added to the enriched mantle. The depleted mantle will therefore have a solidus temperature appreciably above that of the enriched mantle. Even if both mantle types were heated to the same temperature, the degree of melting would be higher in the enriched mantle. The mechanism for mixing is probably that melt starts in one of the mantle source types in the plume and migrate into another much as envisaged by McKenzie (1984) so that individual eruptions sample a range of mantle depths and therefore a combination of mantle source types.

We suggest that the alkaline basalts of Korea and China have formed by melting a mantle plume that is a mixture of enriched and depleted mantle. The isotopic variation seen in alkaline basalts results, in part, from variations in the contribution of the two end-members to a particular eruptive event and, in part, from variations in the isotopic composition of the two end-members, especially the enriched end-member. However, as noted earlier and elsewhere (Nakamura et al., 1989), the LREE enrichment which is characteristics of alkaline basalts is only possible if the melt formed by the lower degree of partial melting is an important component in the hybrid. This requires that the ascending plume entrains significant amount of MORB-type mantle as it rises, a requirement that is consistent with the work of Griffiths (1986a, b) provided the plume originated sufficiently deep in the mantle.

The geochemistry of the alkaline basalts from southwestern Japan has a weak island-arc sig-

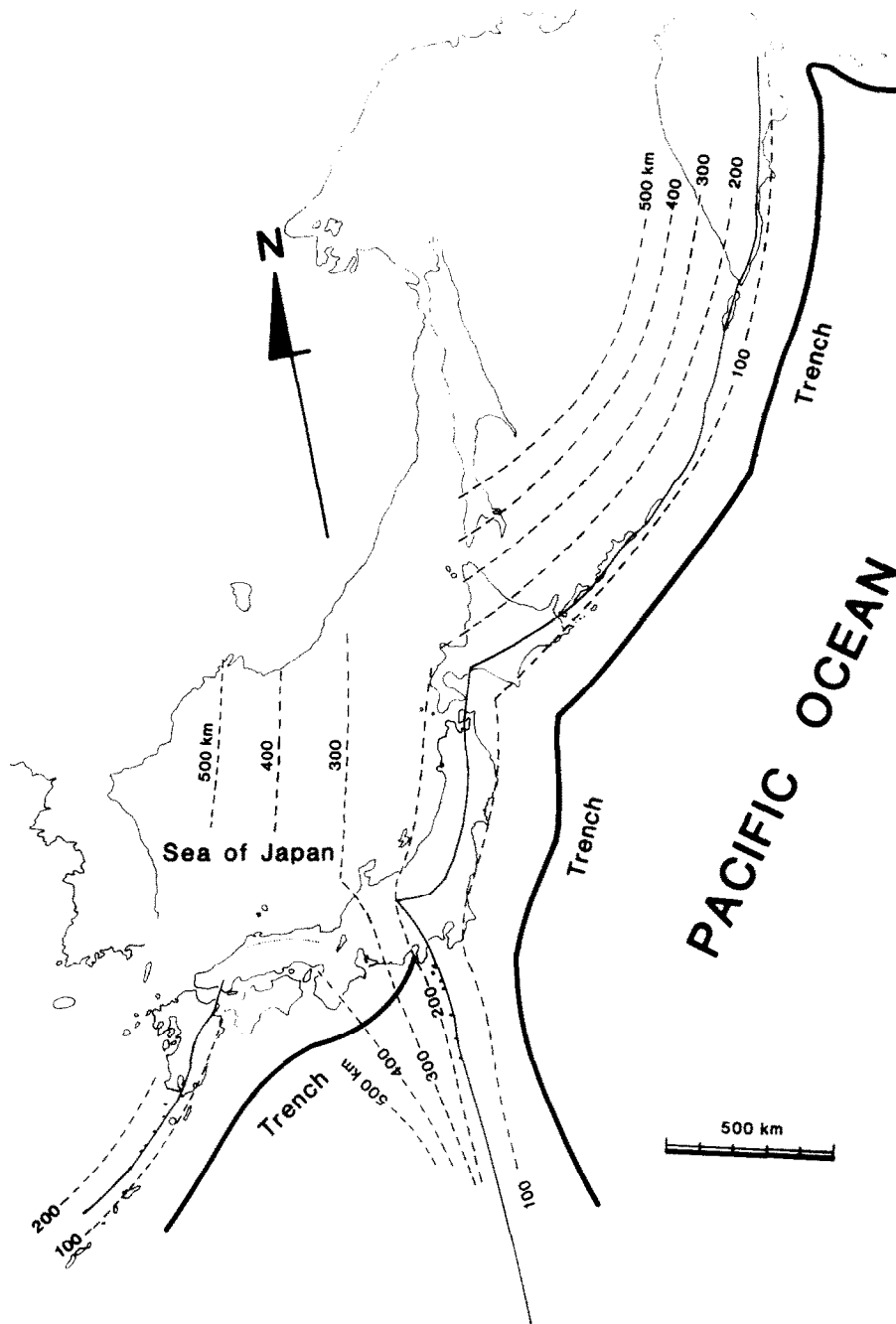


Fig. 15. Contours representing isobaths for the deep seismic zones (Wadati-Benioff zones) beneath the Japanese island-arcs (after Utsu, 1974). Numbers are depths in kilometers as measured at the center of the seismic zone. Thin solid lines and dotted line in the Chugoku district, and thick solid lines show Quaternary volcanic fronts and trench axes, respectively (after Aramaki and Ui, 1982), and they are mutually parallel. The Wadati-Benioff zone corresponding to the subduction of the Pacific plate is not recognized beneath southwestern Japan.

nature which, we suggest, results from a small amount of mantle, contaminated by fluids released from the subducted slab, being heated and melted

by the ascending plume. Since the contaminated mantle comes from the wedge above the subducted slab this process is confined to the upper

half of the upper mantle. The plumes from southwestern Japan are hypothesised to originate deep in the mantle and, during the early stage of their ascent, they entrain MORB-type mantle as they ascend. It is not until they reach the top of the upper mantle that they begin to heat contaminated mantle from the wedge. The plume therefore entrains MORB-type mantle for most of its ascent but can heat and melt the material from the mantle wedge during the final stages, resulting in the basalts derived from the plume having a weak island-arc signature.

Relationship between oceanic crust subduction and hot spot magmatism

The Wadati-Benioff zone corresponding to subduction of the Pacific plate is clearly defined in northeastern Japan, and extends across the Sea of Japan as far as 1200 km from the trench axis and to a depth of more than 600 km (Utsu, 1974). However, the extension of the Pacific plate beneath southwestern Japan is poorly defined (Fig. 15).

Lateral variation in rock series and abundances of incompatible elements in the volcanics in northeastern Japan clearly indicate a relationship between subduction of the Pacific plate and magma generation (e.g., Kuno, 1966; Sakuyama, 1979; Ishikawa et al., 1980; Tatsumi and Nakano, 1984; Nakamura et al., 1985; Sakuyama and Nesbitt, 1986). On the other hand, the Philippine Sea plate is subducting beneath southwestern Japan at a shallower angle (about 15°) than that of the Pacific plate (about 30°) (Shiono, 1974). The leading edge of the Philippine Sea plate, descending from the Nankai trough, has reached the upper mantle only beneath the Chugoku district (Nakanishi, 1980). Lateral variation of Nd and Sr isotopic compositions and trace elements in alkaline basalts and associated tholeiites, similar to produced by the Pacific plate, were not found in the southwestern Japan, and these basalts do not have a strong island-arc geochemical signatures (Nakamura et al., 1985, 1989). These results suggest that the Philippine Sea plate subduction has not contributed to the generation of the basalts of southwestern Japan. Uyeda and

Miyashiro (1974) proposed that the Philippine Sea plate subducted intermittently beneath southwestern Japan and that the last subduction began about 1 to 2 Ma ago. The depth of separation of alkaline basalt magma is generally believed to be more than 75 km (e.g., Green and Ringwood, 1967; Kushiro, 1973). This indicates that the Philippine Sea plate has not attained sufficient depth to influence the geochemistry of the alkaline basalts from southwestern Japan. Although the alkaline basalts and associated tholeiites from southwestern Japan do not show typical island-arc geochemical characteristics, they still show a weak island-arc signature in spite of their having incompatible trace element abundance patterns similar to OIB and continental basalts. Nakamura et al. (1985) proposed that the weak island-arc signature in alkaline basalts from southwestern Japan was due to the transport of metasomatized upper mantle from shallower depths, by mantle wedge convection induced by the subduction of Pacific plate.

The position of the Wadati-Benioff zone resulting from subduction of the Pacific plate is obscure beneath southwestern Japan and, based on seismic studies, it is difficult to define whether or not the subducted plate has extended beneath southwestern Japan where the alkaline basalts occur. Mixing between melts derived from two distinct and isotopically heterogeneous components, a mantle plume and its surrounding MORB-type mantle, has been proposed in the previous sections. The plume must start to ascend from a boundary layer either at 500 to 600 km depth (Ringwood, 1982) or, at the boundary between core and mantle (Hofmann and White, 1982). If either of these models are correct, the Pacific plate could not have extended beneath southwestern Japan during the ascent of the plume because the plume and basalt magma could have had to penetrate the subducting oceanic lithosphere (see Fig. 16). However, the leading edge of the subducted slab must come close to the line of ascent of the alkaline basalt plumes. Otherwise, the MORB-type mantle in the wedge above the slab through which we believe the ascending plumes pass could not have acquired its island-arc-type geochemical signature. As the metasomatized MORB-type upper mantle has not yet extended beneath Korea and north-

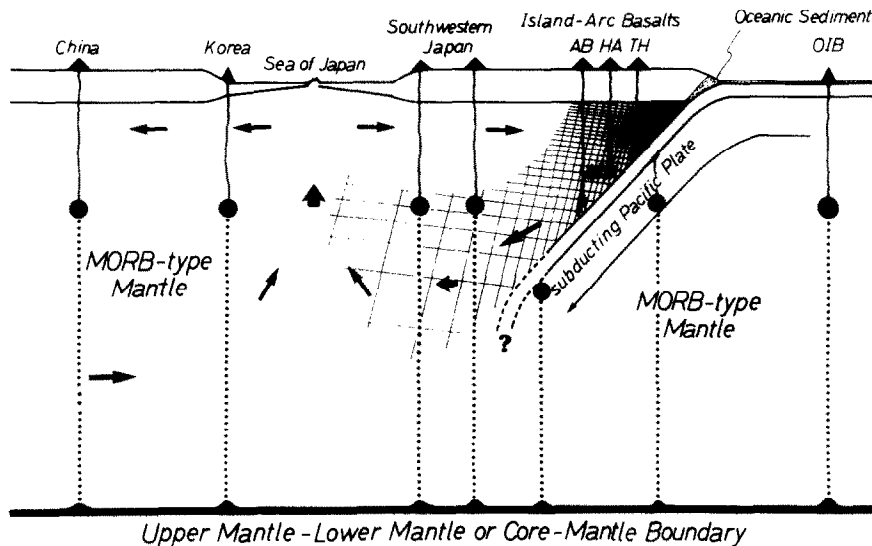


Fig. 16. A diagrammatic model for the chemical geodynamics beneath back-arc region around the Sea of Japan. *AB*, *HA* and *TH* represent typical island-arc basalt types above subducting oceanic crust, alkaline basalt, high alumina basalt and tholeiitic basalt, respectively. They are formed in strongly contaminated MORB-type mantle wedge (cross-hatched zone) caused by dehydration and/or small degree of partial melt of the subducting Pacific plate, at the different depth. The intensity of this contamination decreases with increasing distance from Japan trench. The contaminated zone above the slab is dragged by the induced mantle wedge convection into beneath southwestern Japan. The dragged MORB-type mantle under southwestern Japan is very weakly contaminated relative to source region of the typical island-arc basalts (*AB*, *HA* and *TH*) near Japan trench, because of continuous extraction of mobile incompatible trace elements by production of arc magmas and of the smaller amount of dehydration at greater depths than at the shallower depth. The weakly contaminated mantle is not extended beneath Korea and China. Because the mantle wedge convection cell is different from the cell beneath Korea and China.

The mantle plumes arise from boundary layer, upper mantle–lower mantle boundary or mantle–core boundary, where ancient oceanic crust has been accumulated through subduction process to be enriched sources with variable isotopic composition. The ascending plume heats surrounding mantle. The heated boundary layer around the plume becomes part of plume and is entrained into it until the plume reaches a level from where magma is released to the surface. When the plume ascends into the level of the mantle it begins to melt due to decompression. Both types of mantle in the plume will melt but the enriched type is generally undergoes a higher degree of melting than the depleted type. Then they are mixed together to produce hot spot type magmas. Beneath southwestern Japan, the mantle plume entrained the weakly contaminated MORB-type mantle so that the alkaline basalts have retained weak island-arc characteristics. On the other hand, Chinese and Korean basalts have been produced by similar processes to those from southwestern Japan but have not interacted with a subduction-related contaminated mantle so that they have similar geochemical signature to oceanic island basalt (OIB).

Since enriched mantle plumes arise from the boundary layer, upper mantle–lower mantle or mantle–core boundary, to the upper part of the upper mantle, the leading edges of Pacific plate and Philippine Sea plate had not existed beneath southwestern Japan when hot spot magmatism occurred to form basalts studied. Some plumes had been arrested by the subduction of Philippine Sea and Pacific plates. Therefore, alkaline basalt having OIB-type signature does not occur above the slab at the present time.

eastern China, the Cenozoic basalts from these areas acquire geochemical characteristics similar to OIB and continental basalts, by the interaction between an enriched plume and the depleted MORB-type upper mantle which surrounds it.

Figure 16 summarizes our model for the chemical geodynamics beneath back-arc region around the Sea of Japan.

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