

## The North Fiji Basin basalts and their magma sources: Part II. Sr–Nd isotopic and trace element constraints

M. Nohara<sup>a</sup>, K. Hirose<sup>b</sup>, J.-P. Eissen<sup>c</sup>, T. Urabe<sup>a</sup> and M. Joshima<sup>a</sup>

<sup>a</sup>Geological Survey of Japan, Ibaraki, 305, Japan

<sup>b</sup>University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113, Japan

<sup>c</sup>Centre ORSTOM de Brest, B.P. 70, 29280 Brest Cedex, France

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### ABSTRACT

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Sr–Nd isotope and trace element data are reported for basalts from the North Fiji Basin (NFB). NFB basalts are characterized by extreme variations in isotopic ratios and trace element abundances which are related to mantle heterogeneities. Values of  $^{87}\text{Sr}/^{86}\text{Sr}$  for basalts from the northern segments, N160° and triple junction range from 0.7029 to 0.7041, whereas  $^{143}\text{Nd}/^{144}\text{Nd}$  values vary from 0.51281 to 0.51313. Most of the basalts from these segments are characterized by strong relative enrichments in Rb, Ba, Sr, K, Nb, Ta, La, Ce and Ti that are comparable to OIB components. The central segments, N15° and N–S have  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios between 0.51298 and 0.51363 and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios between 0.7029 and 0.7033, and are depleted in large ion lithophile, light rare-earth and high field strength elements similar to N-MORB. Covariation between trace element and isotopic ratios among NFB basalts supports a model in which melts from the NFB rift system are derived by mixing of OIB-type and depleted N-MORB mantle components. The Sr–Nd isotopic and trace element variability indicates that the NFB basalt source is heterogeneous on the scale of individual melt batches.

### Introduction

The North Fiji Basin (NFB) (Fig. 1) is a back-arc basin which is delimited by the Fiji islands to the east, the Vitiav inactive system to the north, the Vanuatu active island arc to the west and the Hunter Fracture Zone to the south. The SEAPSO 3 and subsequent French–Japan STARMER project clarified that the NFB is an actively spreading back-arc basin (Auzende et al., 1988a,b,c, 1991; Honza et al., 1988, 1989; Ruellan et al., 1989; Urabe et al., 1990). The geological and geophysical results for the NFB are described elsewhere (Falvey, 1978; Malahoff et al., 1982; Auzende et al., 1988a, 1990; Tanahashi et al., 1991). The presently active spreading system can be divided into four segments between 15°S and 22°S, which are from north to south the N160°, N15°, N–S and 174°E segments (Eissen et al., 1991). Most of

the basalts from the N–S segment are depleted in large ion lithophile elements (LILE, Rb, Ba, Sr) and light rare-earth elements (LREE), similar to a depleted mid-oceanic ridge basalt (N-MORB) (Eissen et al., 1990, 1991; Price et al., 1990; Price and Kroenke, 1991). By contrast, basalts from the N160° and South Pandora Ridge are characterized by strong relative enrichment in Rb, Ba, K, Nb, La, Ce, Sr and Ti, even though back-arc basin basalts (BABB) and N-type MORBs also are found (Johnson and Sinton, 1990; Eissen et al., 1991; Price and Kroenke, 1991; Sinton et al., 1991). Isotope data for the NFB basalts are very scarce (Boespflug, 1990; Price et al., 1990; Price and Kroenke, 1991; Sinton et al., 1991). The purpose of this study is to delineate isotopic characteristics of the NFB basalts, and to evaluate the geochemical evolution of the magma sources. The basalts analyzed were recovered by *Kaiyo* and *Yokosuka*

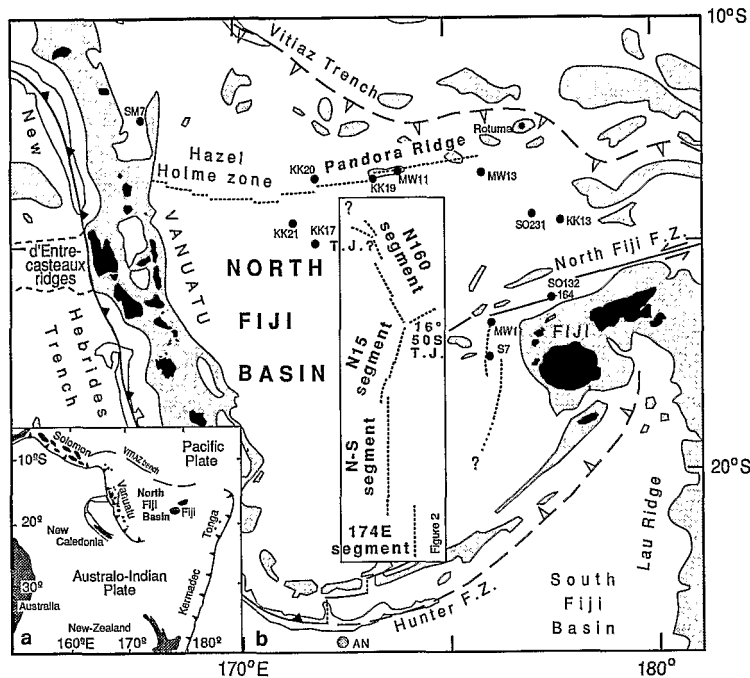


Fig. 1. The North Fiji Basin in the Southwest Pacific (a), and major structures of the North Fiji Basin (b) (Eissen et al., 1994-this volume).

cruises, *Nautilé* and *Shinkai* 6500 dives (Fig. 2). The detailed petrological and geochemical results on these basalts were reported elsewhere (Eissen et al., 1991, 1994-this issue).

### Analytical procedures

The samples were washed ultrasonically in sequential baths of deionized water, rinsing in acetone, deionized water and in ultrasonification in distilled water. The chips were then powdered in an agate mill for trace elements. Trace element concentrations were determined by ICP-MS. Ti, P and K were measured by X-ray fluorescence at UT. Accuracy of analyses of reference materials, JB-1 and JB-2 relative to recommended values and replicate analyses are within 10% and better than 5%, respectively. Samples for Sr and Nd isotope analysis were leached with hot 6 N HCl solution for 12 hours in order to remove the effects of seawater contamination. The determination of Sr and Nd isotopic ratio was done in the static mode on Finnigan MAT 262 mass spectrometer with seven multi-collectors. Isotopic data are

fractionation-corrected to  $^{87}\text{Sr}/^{86}\text{Sr} = 0.11940$  and  $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$ . Measured standard values are:  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710237$  for NBS987 with a total range  $\pm 0.0000011$  and  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511849$  for the La Jolla Nd standard with a total range of  $\pm 0.000003$ .

### Results

#### Trace elements

Trace element data for NFB basalts are listed in Table 1. The representative chondrite-normalized REE patterns for each segment are shown in Fig. 3a-d. Compared with N-S and N15° segment samples, basalts from the N160° segment and triple junction (TJ) are enriched in LILE, LREE and high field strength elements (HFS, Zr, Nb, Ta, Hf and Ti). In particular, 54-1-1 basalt has strong enrichment of LILE, LREE and HFS elements that is comparable to those of South Pandora Ridge and Rotuma samples of Price et al. (1990). Generally, there is a marked enrichment in Rb, K, Sr, Ba, Nb, Hf and Ta from

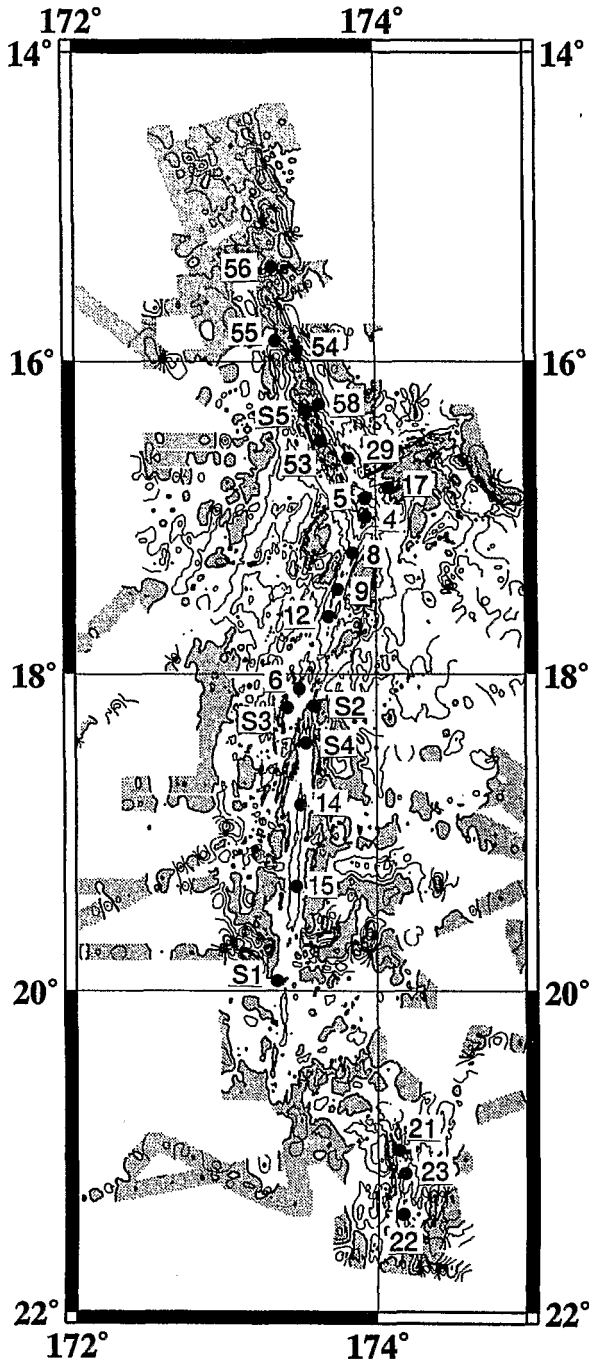


Fig. 2. Sampling sites in the central North Fiji Basin (*S* denotes SEAPSO 3 cruise sample).

the TJ northwestward to the N160° segment, and a corresponding decrease in Ti/K and increase in  $(La/Yb)_n$  (chondrite-normalized) and Ba/Sr in the same direction. Note that the trends indicate an

overall pattern of increasing OIB-like signature to the north, although some samples from the 174°E, N-S, and N15° segments have back-arc basin basalt (BABB) characteristics as pointed out by Eissen et al. (1991). Basalts from Stations 55, 53 and 29 also have high abundances in HFS elements, LREE and LILE relative to those from southern areas, N-S and N15° segments. Its chemical characteristics are intermediate between OIB-like and N-type basalts. In contrast, depleted basalts from the N-S and N15° segments are low in HFS element concentrations (Table 1); Nb 1–4 ppm, Ta < 0.42 ppm, and Hf < 2 ppm. Their trace element and REE abundances are similar to those in depleted N-type MORB already shown by Nohara et al. (1990), Price et al. (1990), Eissen et al. (1991) and Price and Kroenke (1991). The Zr/Nb ratios for N-S and N15° segment basalts are typically near 20, while basalts from the N160° and enriched basalts from the TJ overlap with ratios varying from 4 to 16. Similarly, the La/Ta ratios for basalts from the N-S and N15° segments are about 8–17, whereas the enriched basalts have ratios of 5–7. Basalts from Stations 21 and 23 have relative enrichments in Rb, Ba, Sr and LREE, while Station 23 samples are depleted in LILE, LREE and HFS elements similar to N-MORB. As pointed out by previous workers (Price et al., 1990; Eissen et al., 1991; Price and Kroenke, 1991; Sinton et al., 1991), trace element and REE data show that NFB basalts are generally divided into three types: OIB-like basalts have higher abundances of Rb, Sr, Ba, Nb, Hf, Ta and are characterized by LREE enrichment [ $(La/Yb)_n$ : 3.3–10]. This basalt type has geochemical characteristics of OIB-like rather than N-type MORB or E-type MORBs and has been collected from the South Pandora Ridge and Rotuma (Price et al., 1990; Price and Kroenke et al., 1991). T-type basalts: these basalts are mainly distributed in Stations 21, 22, 29 and 53 which clearly resemble the BABB magma type suggested by Sinton and Fryer (1987) and Eissen et al. (1991). They are geochemically characterized by moderate enrichment in Rb, Ba, Nb, La and Ce relative to N-type MORB, and have moderate enrichment of LREE to heavy REE [ $(La/Yb)_n$ : 1.1–2.7]. This type of basalt has geochemical characteristics that are intermediate between N-MORB

TABLE 1a

Trace element and Sr and Nd isotopic data for NFB basalts (N denotes Nautila dive sample)

(a)	56-12-1	56-12-3	56-12-4	55-11-1-1	55-11-1-3	55-11-1-6	55-11-2-1	55-11-2-5	54-10-1	58-8-9-1
Rb	1.32	1.30	2.38	3.54	5.18	6.83	5.29	3.04	25.32	6.98
Sr		96	147	201	249	209	119	131	381	180
Ba	30	19	34	64	90	81	29	31	408	60
La	3.01	2.74	4.64	5.38	9.06	9.44	4.51	4.57	35.94	5.18
Ce	9.20	8.02	12.12	13.04	21.73	22.18	12.92	13.09	71.86	13.34
Pr	1.26	1.48	2.01	1.74	3.21	3.35	2.20	2.23	9.01	1.64
Nd	7.54	7.22	9.37	857	14.87	15.38	11.41	11.82	35.57	8.18
Sm	2.35	2.58	3.54	2.53	3.85	4.05	3.76	3.75	7.04	2.31
Eu	0.92	1.05	1.17	0.79	1.43	1.53	1.37	1.39	2.25	0.81
Gd	2.98	3.49	4.35	3.08	4.47	4.66	4.43	4.66	6.61	2.62
Tb	0.57	0.76	0.85	0.49	0.88	0.93	0.96	0.98	1.06	0.49
Dy	3.78	5.02	5.85	3.51	5.03	5.16	5.56	5.67	5.03	2.91
Ho	0.75	0.96	1.11	0.69	0.93	1.00	1.05	1.09	0.86	0.56
Er	0.28	3.15	3.61	2.13	3.06	3.19	3.59	3.53	2.64	1.66
Tm	0.33	0.51	0.59	0.23	0.50	0.51	0.58	0.61	0.42	0.21
Yb	2.06	3.11	3.55	1.92	2.86	3.04	3.29	3.57	2.33	1.65
Lu	0.33	0.49	0.54	0.23	0.46	0.47	0.52	0.55	0.35	0.25
Y	22	31	40	19	34	33	35	39	30	19
Zr		80	125	124	138	137	101	114	237	96
Nb	4.47	2.42	7.49	7.28	11.19	11.00	4.04	4.81	62.81	7.52
Hf	2.39	2.22	2.95	2.18	2.82	2.98	2.53	2.36	4.71	2.62
Ta	0.48	0.23	0.58	0.73	0.83	0.88	0.35	0.39	4.53	1.08
Ti				10012					14268	8933
K				2324					11124	3985
P				873					2400	785
$^{87}\text{Sr}/^{86}\text{Sr}$	$0.703023 \pm 12$	$0.703197 \pm 13$	$0.703162 \pm 12$	$0.703012 \pm 10$	$0.703190 \pm 9$	$0.702994 \pm 12$	$0.702934 \pm 9$	$0.702994 \pm 12$	$0.703985 \pm 10$	$0.703175 \pm 9$
$^{143}\text{Nd}/^{144}\text{Nd}$	$0.513049 \pm 9$	$0.513083 \pm 10$	$0.513111 \pm 8$	$0.513053 \pm 12$	$0.513037 \pm 8$	$0.513126 \pm 6$	$0.513126 \pm 6$	$0.513125 \pm 6$	$0.512805 \pm 7$	$0.512991 \pm 10$

(a)	58-8-9-2	58-8-9-3	58-9-9-4	58-8-9-5	58-8-9-6	58-8-9-7	58-1-1	58-1-2	58-2-1	58-2-2
Rb	5.98	4.56	6.59	5.97	6.68	21	22.16	18.3	10.72	10.98
Sr	167		193	180	159	265	368	384	199	190
Ba	50	61	65	62	68	195	226	262	96	96
La	6.13	5.17	6.99	6.3	6.94	14.28	16.24	21.5	7.19	7.90
Ce	14.69	12.47	16.99	15.32	16.72	32.25	33.74	46.25	17.4	17.88
Pr	2.29	1.63	2.60	2.36	2.49	3.86	3.97	5.37	2.21	2.35
Nd	10.64	8.35	11.51	10.92	11.14	17.52	16.43	21.16	10.03	10.53
Sm	3.07	2.49	3.05	3.24	3.07	4.08	3.47	4.54	2.56	2.71
Eu	1.11	0.81	0.89	1.13	1.07	1.34	1.15	1.38	0.94	0.99
Gd	3.32	3.1	2.94	3.42	3.25	4.41	3.31	4.05	2.83	3.21
Tb	0.65	0.50	0.63	0.65	0.63	0.71	0.53	0.64	0.47	0.56
Dy	4.29	3.34	4.38	4.13	4.02	4.13	2.98	3.80	2.86	3.29
Ho	0.79	0.67	0.82	0.78	0.76	0.91	0.56	0.71	0.59	0.71
Er	2.57	2.02	2.62	2.47	2.41	2.08	1.54	2.04	1.72	2.03
Tm	0.4	0.22	0.41	0.38	0.43	0.30	0.22	0.28	0.28	0.30
Yb	2.45	1.80	2.52	2.35	2.30	1.92	1.43	1.83	1.60	1.85
Lu	0.37	0.31	0.38	0.36	0.34	0.28	0.20	0.26	0.22	0.27
Y	27	18	30	27	25	23	26	26	17	21
Zr	102		115	106	95	175	156	174	69	77
Nb	10.89	7.17	11.9	10.87	9.5	22.06	40.61	41.63	10.99	9.86
Hf	2.18	2.1	2.36	2.23	2.16	4.49	2.47	3.03	1.52	1.7
Ta	0.92	0.91	0.97	0.93	0.91	2.8	2.58	2.84	0.92	0.7
Ti						13489				
K						7720				
P						1702				
$^{87}\text{Sr}/^{86}\text{Sr}$	$0.703200 \pm 11$	$0.703175 \pm 7$	$0.70328 \pm 7$	$0.703162 \pm 10$	$0.703174 \pm 6$	$0.703556 \pm 8$	$0.703698 \pm 6$	$0.703694 \pm 7$	$0.703290 \pm 7$	$0.703289 \pm 7$
$^{143}\text{Nd}/^{144}\text{Nd}$	$0.512991 \pm 9$	$0.512972 \pm 8$	$0.512960 \pm 8$	$0.513004 \pm 9$	$0.513001 \pm 6$	$0.512874 \pm 11$	$0.512829 \pm 5$	$0.512785 \pm 8$	$0.512952 \pm 7$	$0.512956 \pm 6$

TABLE 1a (continued)

(a)	53-9-1-4	53-9-1-5	53-9-1-6	53-9-1-7	29-6-1	29-6-3	17-1-1	4-2-1	4-2-5	4-2-6
Rb	7.74	10.16	8.83	5.76	3.06	4.96		1.45	1.26	1.87
Sr	183	190	220	224	158	133		80	116	93
Ba	82	65	87	74	14	31		19	21	25
La	6.82	5.51	8.06	6.59	4.38	5.00	3.69	2.10	2.81	2.98
Ce	15.62	13.39	18.01	15.26	12.61	13.33	10.73	6.47	8.65	8.46
Pr	2.30	2.02	2.55	1.87	1.94	2.06	1.62	1.01	1.43	1.36
Nd	9.74	8.70	11.10	8.93	10.27	10.73	9.04	5.72	7.54	7.56
Sm	2.60	2.68	2.23	2.28	3.40	3.43	2.92	2.01	2.59	2.69
Eu	0.93	1.01	0.96	0.74	1.23	1.18	1.12	0.73	1.03	1.01
Gd	3.02	3.07	2.96	2.75	4.13	4.17	3.93	2.60	3.08	3.37
Tb	0.55	0.59	0.55	0.39	0.80	0.82	0.71	0.45	0.66	0.68
Dy	3.63	3.68	3.15	2.47	4.72	5.03	5.04	3.35	4.32	4.30
Ho	0.67	0.70	0.60	0.54	1.01	1.10	1.05	0.64	0.91	0.98
Er	2.17	2.22	1.93	1.33	2.96	3.07	3.13	2.02	2.80	2.68
Tm	0.35	0.35	0.31	0.18	0.43	0.45	0.44	0.26	0.43	0.42
Yb	2.09	2.34	1.81	1.32	2.69	2.78	2.94	1.95	2.40	2.42
Lu	0.32	0.33	0.27	0.17	0.41	0.43	0.46	0.26	0.41	0.41
Y	23	27	23	13	24	26		16	20	20
Zr	91	96	105	92	99	93		57	75	65
Nb	10.89	9.95	15.38	9.65	3.58	3.25		2.31	2.69	2.73
Hf	1.95	1.81	1.95	2.21	1.89	1.68		1.40	1.71	1.74
Ta	0.96	0.73	1.24	1.16	0.34	0.29		0.23	0.32	0.3
Ti	7434			7973	10851				8873	
K	3155			3570	2158				913	
P	873			960	785				567	
$^{87}\text{Sr}/^{86}\text{Sr}$	$0.703273 \pm 10$	$0.703187 \pm 11$	$0.703383 \pm 10$	$0.703345 \pm 10$	$0.703015 \pm 10$	$0.703126 \pm 9$	$0.702895 \pm 9$	$0.702894 \pm 9$	$0.702824.13$	$0.703081 \pm 11$
$^{143}\text{Nd}/^{144}\text{Nd}$	$0.512947 \pm 7$	$0.512975 \pm 9$	$0.512944 \pm 12$	$0.512892 \pm 10$	$0.513053 \pm 4$	$0.512999 \pm 6$	$0.513123 \pm 5$	$0.513020 \pm 12$	$0.513108 \pm 5$	$0.513084 \pm 6$

(a)	4-2-9-	N4-2-7	N4-2-9	N4-2-21-3	N4-2-21-5	5-3-1	8-5-1	8-5-4-	9-6-2	9-6-3
Rb	1.99	17.00	19.00	2.40	15.25	0.88	2.08	2.55	2.05	1.3
Sr	88	222	255	122	231	110	86	109	105	99
Ba	25	221	169	22	143	9	22	22	20	17
La	3.08	15.31	12.35	2.59	12.70	1.21	3.17	3.46	3.08	2.47
Ce	8.95	32.93	27.00	7.18	27.73	3.56	9.39	9.77	9.02	7.30
Pr	1.48	3.96	3.33	1.16	3.40	0.60	1.49	1.56	1.50	1.19
Nd	7.96	17.14	14.87	5.88	14.91	3.24	8.23	8.61	7.74	6.34
Sm	2.82	4.12	3.58	2.00	3.87	1.29	2.91	3.01	2.86	2.29
Eu	1.05	1.48	1.34	0.82	1.32	0.52	1.15	1.13	1.06	0.85
Gd	3.75	4.46	4.00	2.64	4.31	1.53	3.87	4.17	3.63	2.89
Tb	0.68	0.70	0.65	0.51	0.62	0.29	0.84	0.84	0.75	0.61
Dy	4.56	3.77	3.70	3.20	3.93	2.00	5.11	5.08	4.86	3.93
Ho	1.02	0.74	0.73	0.71	0.76	0.45	1.11	1.15	1.08	0.85
Er	2.83	1.96	2.05	2.09	2.10	1.27	3.29	3.29	3.10	2.44
Tm	0.44	0.28	0.29	0.30	0.25	0.22	0.50	0.50	0.46	0.36
Yb	2.64	1.80	1.88	1.96	1.83	1.17	3.14	3.09	2.96	2.35
Lu	0.46	0.26	0.27	0.29	0.26	0.22	0.51	0.53	0.49	0.39
Y	19	19	25	23	19	10	21	27	26	21
Zr	63	116	139	67	121	27	69	85	78	65
Nb	2.51	22.64	22.64	2.84	22.95	1.2	2.87	3.54	3.75	2.45
Hf	1.87	2.85	2.68	1.86	2.7	0.64	1.79	1.72	1.75	1.6
Ta	0.31	2.36	1.93	0.44	2.17	0.13	0.33	0.32	0.31	0.27
Ti				7074	11031		9292		8753	
K				913	6392		1577		1328	
P				567	1396		611		524	
$^{87}\text{Sr}/^{86}\text{Sr}$	0.703153±8	0.703729±9	0.703651±8	0.703239±12	0.704141±12	0.702870±12	0.702893±8	0.703129±11	0.703021±23	
$^{143}\text{Nd}/^{144}\text{Nd}$	0.513129±9	0.512873±9	0.512880±9	0.513090±6	0.512919±16	0.513115±8	0.513093±5	0.513110±8	0.513163±14	

TABLE 1a (continued)

(a)	12-9-9	12-9-13	12-9-14	14-10-1	14-10-3	14-10-4	14-10-7	14-10-11	15-11-1	15-11-3
Rb	1.61	1.46	1.59	0.97	0.93	2.27	0.72			1.53
Sr	129	120	112	74	72	98	58			111
Ba	13	12	14	10	10	31	12			15
La	1.85	1.73	2.02	1.94	2.02	3.61	2.04	2.56	3.55	3.7
Ce	5.82	5.35	6.09	6.27	6.46	9.52	6.37	8.11	11.08	11.43
Pr	0.95	0.94	0.97	1.12	1.07	1.45	1.10	1.42	1.78	1.92
Nd	4.98	4.57	5.31	6.15	6.25	7.63	6.33	8.04	10.22	10.63
Sm	1.67	1.57	1.74	2.34	2.46	2.50	2.34	2.93	3.47	3.58
Eu	0.72	0.65	0.71	0.91	0.91	0.94	0.96	1.12	1.21	1.33
Gd	2.09	2.01	2.28	3.20	3.20	3.22	3.06	4.41	4.93	4.65
Tb	0.43	0.37	0.45	0.66	0.69	0.65	0.68	0.77	0.82	0.93
Dy	2.83	2.47	3.19	4.44	4.48	4.19	4.21	5.48	5.66	5.95
Ho	0.59	0.54	0.63	0.98	0.99	0.89	0.98	1.18	1.18	1.27
Er	1.76	1.6	1.8	2.86	2.90	2.60	2.77	3.40	3.56	3.72
Tm	0.25	0.24	0.26	0.44	0.44	0.39	0.43	0.49	0.53	0.56
Yb	1.76	1.54	1.73	2.73	2.88	2.52	2.68	2.47	3.45	3.57
Lu	0.33	0.24	0.27	0.46	0.47	0.43	0.42	0.46	0.46	0.54
Y	17	18	17	23	22	20	18			31
Zr	52	52	49	61	60	64	49			101
Nb	1.67	1.67	1.64	1.83	1.81	3.86	1.41			3.18
Hf	1.11	1.11	1.25	1.34	1.23	1.53	1.51			1.97
Ta	0.17	0.17	0.2	0.18	0.17	0.42	0.20			0.29
Ti				8693		9952				
K				581		1743				
P				480		698				
$^{87}\text{Sr}/^{86}\text{Sr}$				$0.703072 \pm 11$	$0.703010 \pm 7$	$0.703256 \pm 12$	$0.703010 \pm 10$	$0.702998 \pm 13$	$0.703085 \pm 11$	
$^{143}\text{Nd}/^{144}\text{Nd}$				$0.513054 \pm 7$	$0.513055 \pm 6$	$0.512968 \pm 5$	$0.513117 \pm 5$	$0.513090 \pm 5$	$0.513000 \pm 4$	



(a)	15-11-4	15-11-5	21-3-1	21-3-9	23-4-1	22-5-1
Rb	1.17	1.68	6.7		2.36	7.23
Sr	86	113	222		96	28
Ba	24	16	54		7	50
La	4.14	2.82	8.68	7.18	1.02	5.40
Ce	11.86	8.45	22.52	19.67	3.67	14.63
Pr	1.96	1.43	3.20	2.83	0.74	2.27
Nd	10.91	7.71	15.37	13.21	4.69	11.4
Sm	3.72	2.61	4.24	3.77	1.84	3.25
Eu	1.34	1.01	1.50	1.32	0.75	1.17
Gd	4.93	3.59	5.40	4.69	2.91	4.08
Tb	0.96	0.66	0.88	0.78	0.58	0.71
Dy	6.03	4.29	5.32	5.09	3.85	4.48
Ho	1.33	0.95	1.15	1.07	0.88	0.99
Er	3.80	2.71	3.26	2.96	2.56	2.89
Tm	0.58	0.39	0.48	0.40	0.40	0.39
Yb	3.72	2.55	2.92	2.33	2.48	2.05
Lu	0.54	0.39	0.45	0.20	0.41	0.28
Y	21	31	33		29	28
Zr	73	101	137		64	75
Nb	2.57	3.32	9.67		1.28	1.51
Hf	1.86	2.12	3.4		1.52	2.25
Ta	0.35	0.31	1.02		0.16	0.19
Ti						
K						
P						
$^{87}\text{Sr}/^{86}\text{Sr}$	$0.703099 \pm 7$	$0.703090 \pm 12$	$0.703127 \pm 10$	$0.703107 \pm 12$	$0.702841 \pm 11$	$0.702893 \pm 10$
$^{143}\text{Nd}/^{144}\text{Nd}$	$0.513046 \pm 5$	$0.513036 \pm 5$	$0.513027 \pm 5$	$0.513010 \pm 5$	$0.513044 \pm 6$	$0.513055 \pm 7$

TABLE 1b

Sr and Nd isotopic data for SEAPSO samples

(b)	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$
S1-1	$0.703186 \pm 11$	$0.513038 \pm 9$
S1-2	$0.703186 \pm 9$	$0.512978 \pm 19$
S1-6	$0.703410 \pm 12$	$0.513026 \pm 3$
S2-2	$0.703122 \pm 12$	$0.513103 \pm 6$
S3-1	$0.702904 \pm 14$	$0.513092 \pm 15$
S3-3	$0.702836 \pm 12$	$0.513159 \pm 7$
S3-4	$0.702908 \pm 14$	$0.513163 \pm 18$
S4-1	$0.703007 \pm 9$	$0.513061 \pm 16$
S4-3	$0.703119 \pm 9$	$0.513118 \pm 20$
S4-4	$0.703037 \pm 11$	$0.513107 \pm 18$
S5-2	$0.703216 \pm 9$	$0.513003 \pm 17$
S5-3	$0.703299 \pm 10$	$0.513004 \pm 19$
S5-4	$0.703161 \pm 10$	$0.512969 \pm 16$

and the more enriched basalts (OIB-type). N-type basalts from the N-S and N15° segments and some samples from the TJ are depleted in Rb, Ba, Sr La, Ce, Nb, Hf, Ta and have REE patterns that

are either flat or are depleted in LREE relative to HREE [(La/Yb)<sub>n</sub>, 0.3–0.9] (Fig. 3c–d). This type is very similar to the type 1 basalts from the Fiji Fracture Zone identified by Price and Kroenke (1991) and Sinton et al. (1991).

### Sr and Nd isotope ratios

The isotopic compositions of basalts from the NFB are reported in Table 1a–b. The large variation in  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7028–0.7041) and  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51281–0.51320) indicates significant isotopic heterogeneity in the source region of NFB basalts. The Sr and Nd isotopic data for NFB basalts fall mostly within the mantle array (Fig. 4). The N160° basalts and some samples from the TJ show marked Sr and Nd isotopic variations (0.7029–0.7041 and 0.51281–0.51313). Individual segments record significant isotopic variation. Higher  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios among OIB-like basalts

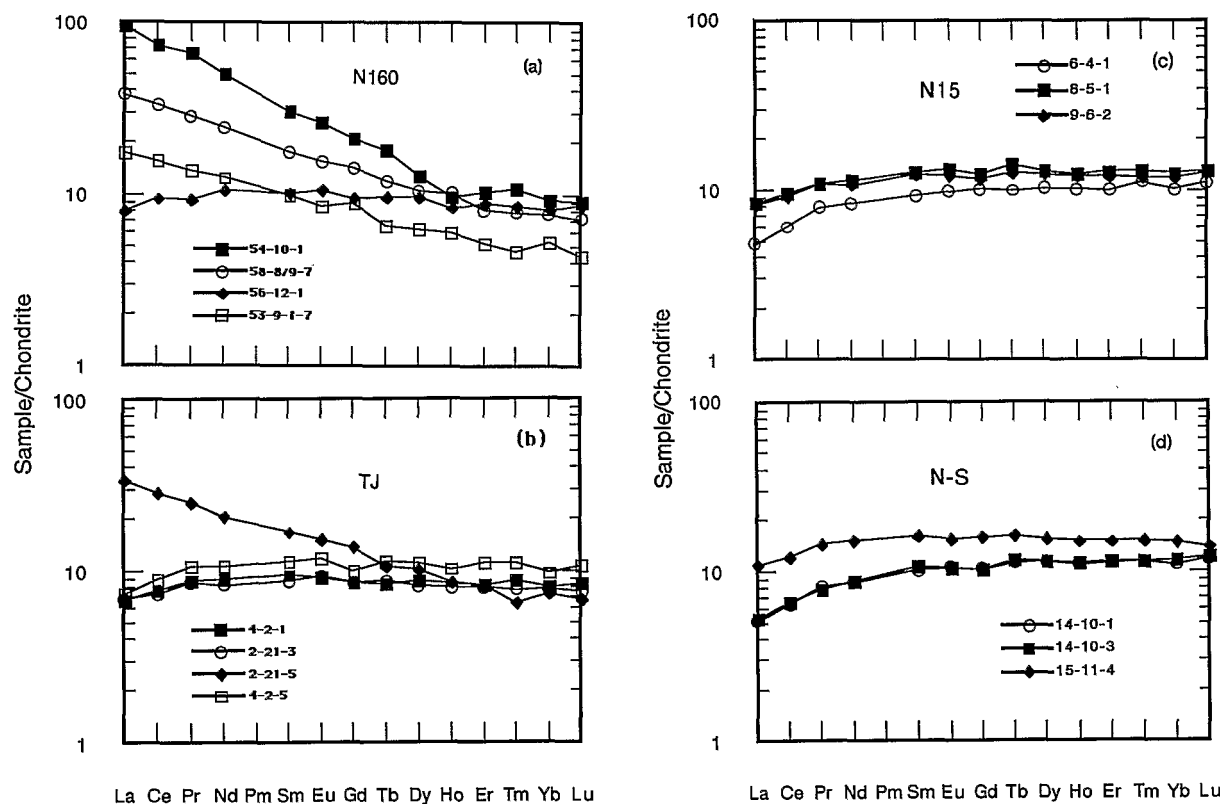


Fig. 3. Chondrite-normalized REE patterns for representative basalts from different segments in the NFB [normalized values from Masuda et al. (1973)]. (a) N160° segment, (b) TJ, (c) N15° segment, (d) N-S segment.

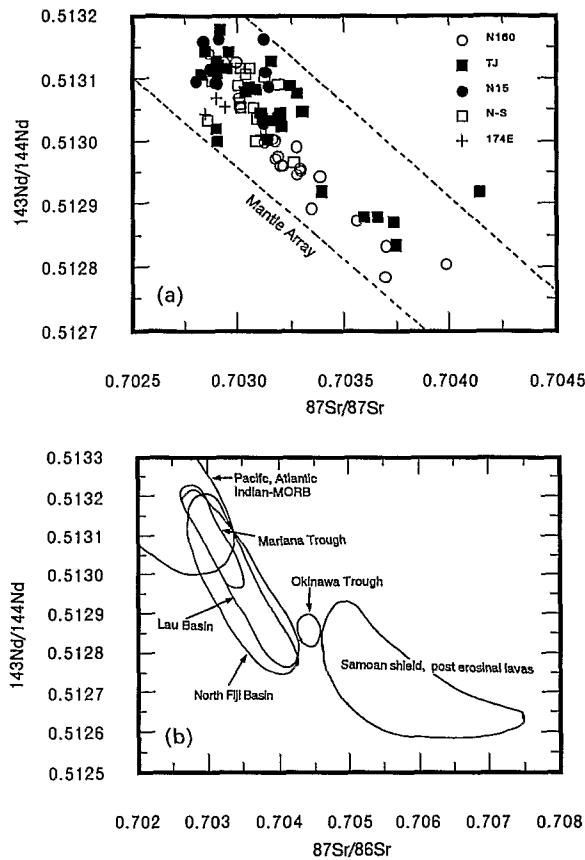


Fig. 4. (a) Sr–Nd isotopic compositions of the NFB basalts. The linear trend of the data is sub-parallel to the mantle array. Note that N160° and TJ basalts span the range from N-type to OIB-like fields. (b) Variation of Sr–Nd isotopic ratios in different tectonic systems. Data for the Okinawa Trough and Samoa are from Honma et al. (1987) and Wright and White (1986/87), respectively. Fields for the Pacific and other areas based on literature.

are striking and more characteristic of intra-oceanic arc or oceanic island basalts (OIB). N4-2-21-5 from the TJ plots out of the mantle array, suggesting contamination with sea water or hydrothermal fluids, because its trace element contents and element/element ratios resemble ones having corresponding Nd isotopic ratios. N-type basalts from the N–S and N15° segments, including some samples from TJ have relatively high  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51300–0.51319), which are slightly lower than ones for typical N-MORB (0.51320, White et al., 1987).  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios for these segments fall within the range 0.7029–0.7033, and are systematically higher than the average of 0.7025 for typical

N-MORB (Hofmann and Hart, 1978). Sr and Nd isotopic ratios from 174°E are in the ranges 0.7028–0.7033 and 0.51301–0.51306, respectively, which are similar to those of N–S and N15° segment samples. There is a strong inverse Sr–Nd isotopic correlation among NFB basalts with the slope of a regressed  $-0.29$  similar to that for N-MORB ( $-0.26$ ) (Fig. 4, White, 1985). As seen in the Sr–Nd isotopic diagram, the data fall mostly within the mantle array. However, the isotopic data for OIB-like lavas are outside the N-MORB field defined by White and Hofmann (1982). The apparent OIB character of the isotopic data with marginally enriched  $^{87}\text{Sr}$  and depleted  $^{143}\text{Nd}$  corresponds to selected trace element enrichments (Rb, Ba, Sr, La, Ce, Zr, Nb, Ta) noted above for the mantle source of OIB. The Sr and Nd isotopic data for N-MORB-like basalts in the NFB are comparable with those of depleted MORB in the Lau Basin (Volpe et al., 1988) and Mariana Trough (Volpe et al., 1987, 1990). As to limited data for N-type basalts in the NFB, its isotopic ratios fall within the range of N-MORB from the EPR, MAR and Indian Ocean (White and Hofmann, 1982; Macdougall and Lugmair, 1986; Price et al., 1986; Ito et al., 1987; White et al., 1987). With regard to isotopic composition and geographic sampling suites, it is important to note that the analyzed isotopic variation from the N160° and TJ entirely span the range of all analyzed NFB basalts. Most of the basalts from Stations 54 and 58, where topographical features are very complex (Price et al., 1990; Eissen et al., 1991; Price and Kroenke, 1991), have higher  $^{87}\text{Sr}/^{86}\text{Sr}$  and lower  $^{143}\text{Nd}/^{144}\text{Nd}$  isotopic ratios and strong LILE, LREE and HFS element enrichments which are similar to those from the South Pandora Ridge and Rotuma (Price et al., 1990; Price and Kroenke, 1991). In contrast, the N–S and N15° segments, which have a smooth morphology and medium-spreading rate (Auzende et al., 1991; Tanahashi et al., 1991) similar to the EPR, have N-MORB isotopic characteristics, as well as depleted trace element abundances. The basalts from closely spaced sampling sites at the TJ have extreme isotopic variability, which implies heterogeneity through the underlying mantle. It is evident from a Sr and Nd isotopic compositions that there are distinct gaps in measured  $^{87}\text{Sr}/^{86}\text{Sr}$  and

$^{143}\text{Nd}/^{144}\text{Nd}$  values between the south and the north segments which could be bounded at the TJ (Fig. 5). Our trace element and isotopic data show a latitudinal variation from  $22^\circ$  to  $15^\circ\text{S}$ , of increasing enrichment toward the north, suggesting that they are related to a greater contribution from an OIB-like source component.

## Discussion

### Mixing of different sources

Most of the significant variations in isotopic ratios and trace element contents from OIB-like to N-type NFB basalts is a consequence of variation in the mantle source region from which the original parental basaltic magmas were derived, although some aspect of the geochemical variation are explicable in terms of low pressure crystal fractionation (Eissen et al., 1991). The correlations

shown in Figs. 4 and 6 are best explained by a mixing process. Our new Sr and Nd isotopic and trace element data presented here allow us to test a two-component mixing model for the evolution of the source region of the NFB rift system, previously proposed on the basis of Sr-isotope, LILE and REE data (Price et al., 1990; Price and Kroenke, 1991). The principal component, end-member A, in the mantle source region beneath the N-S and N15° segments is depleted mantle similar to N-MORB (Table 2; A on Fig. 6). It is characterized by high  $^{143}\text{Nd}/^{144}\text{Nd}$  and low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. While, end-member B is LILE- and LREE-enriched OIB-like source similar to the composition of 54-10-1, which has low  $^{143}\text{Nd}/^{144}\text{Nd}$ , Zr/Nb and Hf/Ta ratios, and high  $^{87}\text{Sr}/^{86}\text{Sr}$ , and Ti/K ratios. Based on the asymptotes of the mixing curves, end-member A has  $\text{Ba}/\text{Sr}=1.04$ ,  $\text{Zr}/\text{Nb}=3.78$ ,  $\text{Hf}/\text{Ta}=1.04$ , and  $(\text{La}/\text{Yb})_n=10.15$ , whereas end-member B has  $\text{Ba}/\text{Sr}=10.14$ ,  $\text{Zr}/\text{Nb}=149.62$ ,  $\text{Hf}/\text{Ta}=11.56$ ,  $\text{Ti}/\text{K}=15.00$  and  $(\text{La}/\text{Yb})_n=0.47$ . A mixing model using these end-members is shown in Fig. 6a-f. The Zr/Nb and Hf/Ta versus  $(\text{La}/\text{Yb})_n$  for both

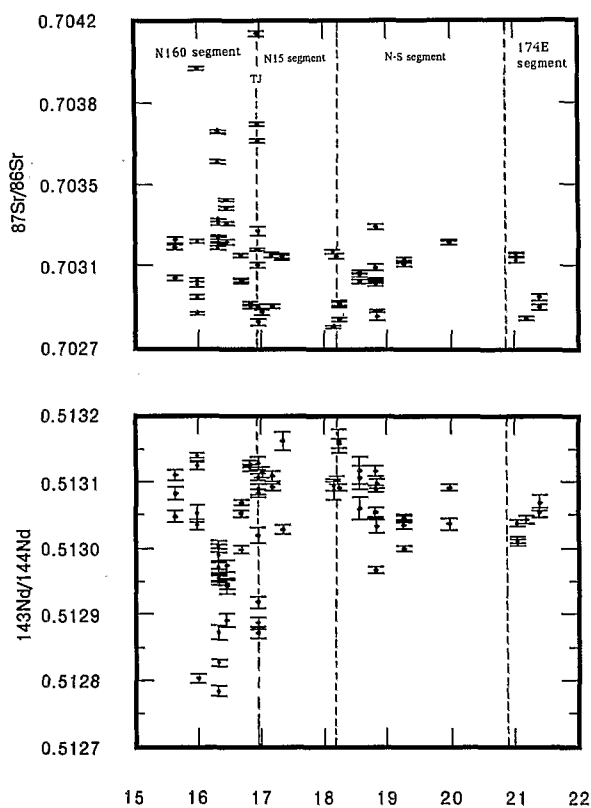


Fig. 5. Variation of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  isotopic ratios as a function of latitude in the NFB (see the text for discussion).

TABLE 2

Trace and isotope composition of end-members A and B for source mixing model

Element (ppm)	End-member A	End-member B
Sr	86	392
Ba	12	408
Zr	66	237
Nb	1.33	62.8
La	1.8	35.9
Ce	5.79	71.9
Nd	6.0	35.6
Yb	2.52	2.33
Hf	1.51	4.71
Ta	0.13	4.53
Ti	8715	19,245
K	581	15,000
Ba/Sr	0.14	1.04
Zr/Nb	49.62	3.78
Hf/Ta	11.56	1.04
Ti/K	15	1.28
$(\text{La}/\text{Yb})_n$	0.47	10.15
$(\text{Ce}/\text{Yb})_n$	0.59	7.86
$^{87}\text{Sr}/^{86}\text{Sr}$	0.702650	0.704000
$^{143}\text{Nd}/^{144}\text{Nd}$	0.513200	0.512805

end-members are fairly well constrained by asymptotes of the data arrays, as well as Nd isotope values. On a plot of  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $(\text{La}/\text{Yb})_n$  (Fig. 6a), Sr ratios of N-type basalts are vertically displaced to higher Sr ratios, suggesting contamination from sea water or subducted slab-derived materials (Eissen et al., 1991, 1994-this issue). An additional test of the two component mixing model was done by plotting the  $(\text{Ce}/\text{Yb})_n$  and Ba/Sr data against Ti/K (Fig. 6e-f). The match between the data and those predicted from the model can be examined in Fig. 6a-f. Correspondences are generally good between the data and the calculated binary-mixing curves, suggesting that the chemical variations of NFB basalts reflect the mixing of varying proportions of melts derived from the two sources (Price et al., 1990).

*Nature of magma sources*

There is a clear correlation between basalt composition and tectonic setting along the axial ridge

(Figs. 4 and 5). Substantial variability exists for basalts recovered within the NFB. The major and trace element data give a similar trend (Eissen et al., 1991, 1994-this issue). On the longer wavelength scale delineated by ridge segmentation there is a tectonic control on basalt composition: both chemical and isotopic compositions correlate with evolutionary stage of rift system. Most basalts from the N-S and N15° segments are depleted in trace elements and have low Sr and high Nd isotopic ratios which are characteristics of N-MORB. In contrast, nearly all basalts from the TJ and N160° segment have relatively high LILE and LREE and HFS element abundances coupled with isotopic compositions that are OIB-like to intermediate characteristic. The presence of N-type basalt to OIB-like component in TJ basalt magma sources indicates that they coexist under this area, as small enriched veins or plums. However, the segregation of OIB and N-type basalt sources seems not to be a general feature of at least the

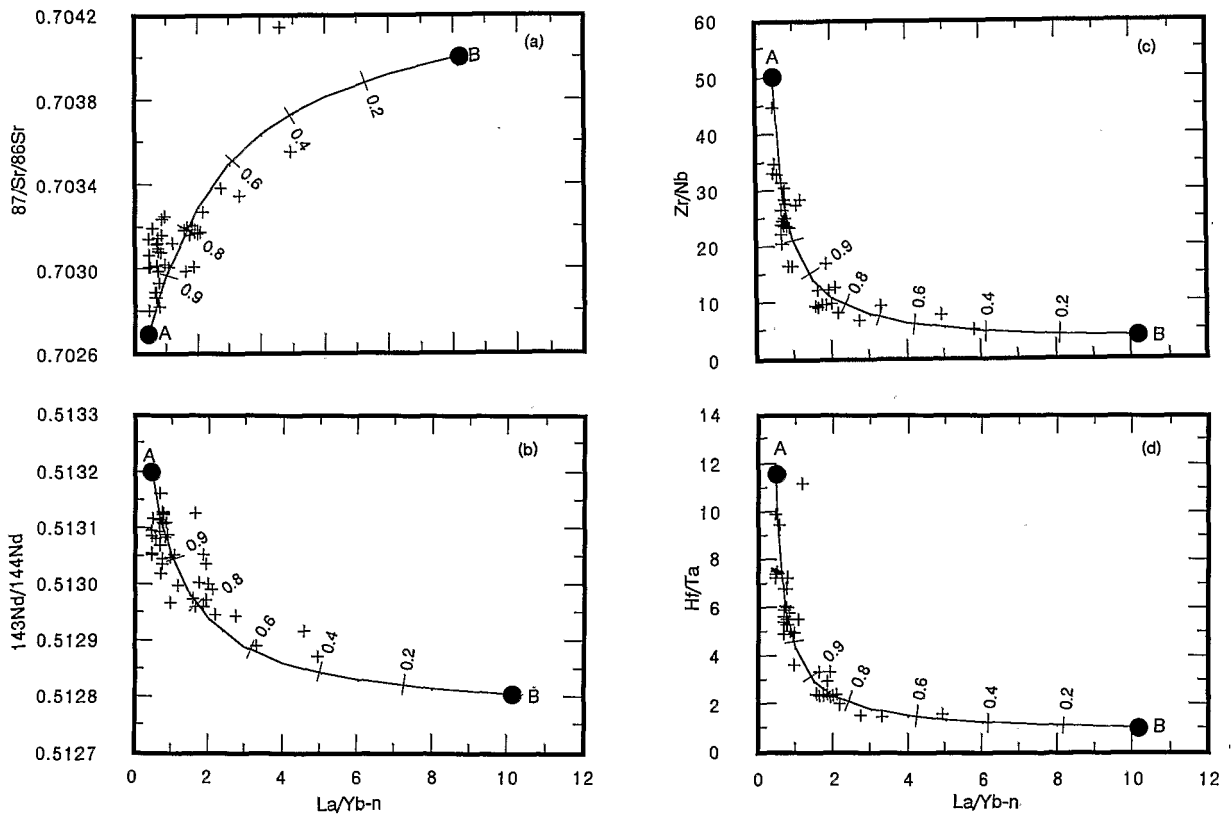


Fig. 6a-d.

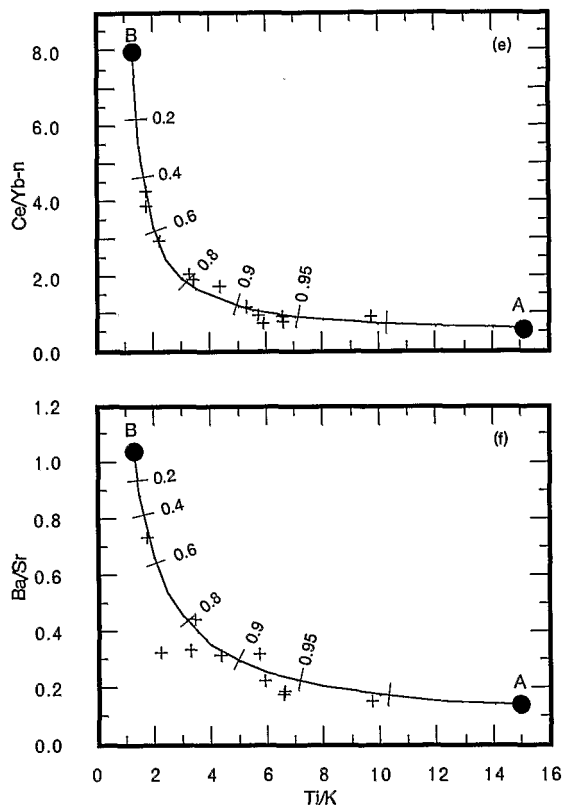


Fig. 6.  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$ , Zr/Nb, Hf/Ta versus  $(\text{La}/\text{Yb})_n$ , and  $(\text{Ce}/\text{Yb})_n$ , Ba/Sr versus Ti/K. The composition of end-member A and B are from Table 2. The solid lines indicate mixing trajectories, with numbers shown on the curve being the fraction of end-member A involved in the mixture. (a)  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $(\text{La}/\text{Yb})_n$ , (b)  $^{143}\text{Nd}/^{144}\text{Nd}$  versus  $(\text{La}/\text{Yb})_n$ , (c) Zr/Nb versus  $(\text{La}/\text{Yb})_n$ , (d) Hf/Ta versus  $(\text{La}/\text{Yb})_n$ , (e)  $(\text{Ce}/\text{Yb})_n$  versus Ti/K, (d) Ba/Sr versus Ti/K.

NFB mantle, which is indicated by the successive regional Sr–Nd isotopic array of NFB basalts. The data for relatively immobile trace elements normalized to C1 chondrite abundances (Anders and Grevesse, 1989) are shown in Fig. 7a–d. The presence of positive anomalies for Ta may be a characteristic of NFB basalt magmatism. The Ta anomaly is clearly intrinsic to the NFB basalt parental magmas and is not an artifact of crystallization processes: the positive Ta anomaly apparently reflects an earlier enrichment of the NFB basalt mantle in Ta, which could be due to the presence of Ta-bearing mineral phases such as rutile, perovskite and sphene (Sun and McDonough, 1989), that preferentially retain Ta.

It is important to note that the negative Nb anomaly begins to develop only in N-type basalts from mainly the southern segments. This implies an effect from subducted slab-derived materials which are enriched in Sr and depleted in Nb (Sun and McDonough, 1989), resulting in increasing Sr/Nb ratios (25–45 compared with less than 6–12 for most OIB-like basalts), as suggested by Eissen et al. (1990, 1994–this issue). Also, although our Sr isotopic data for N-type basalts are in range of N-MORB, they nevertheless show slight  $^{87}\text{Sr}/^{86}\text{Sr}$  enrichment at a given Nd isotopic ratio, supporting that magma sources for the N-type basalts were slightly modified by subducted slab-derived materials.

#### Magma chambers

As stated earlier, trace element and isotopic heterogeneity exists in the mantle for the NFB basalt source. Samples by *Nautila* dives at Station 4 were recovered from sites very close near each other (Auzende et al., 1991; Urabe et al., 1990). The trace element compositions and isotopic ratios in the sampling sites have quite different characteristics. This suggests that the TJ is a tapping place of mixing magma sources or multi-magma sources. The totality of the spreading axis data suggests that isotopic and elemental heterogeneity occurs at a very fine scale in the mantle in the NFB. The reported data here are greatly consistent with the observation of fine-scale Pb–Sr–Nd isotopic variations in the EPR (Dupré et al., 1981; Macdougall and Lugmair, 1986; White et al., 1987) and Mariana Trough or Lau Basin (Volpe et al., 1987, 1988, 1990). Batiza and Vanko (1984) and Zindler et al. (1984) have proposed that isotopic variation in rocks from small seamounts in the EPR are due to the presence of small scale, large magnitude heterogeneities in the upper mantle. Several workers have suggested that there is a correlation between topographic segmentation of oceanic ridges and magma generation, as to the scale of magma production (Schouten and Klitgord, 1982; Francheteau and Ballard, 1983; Macdonald et al., 1984; Thompson et al., 1985). Langmuir et al. (1986), White et al. (1987), Fornari et al. (1988) and Reynolds et al. (1992) indicated that the scale

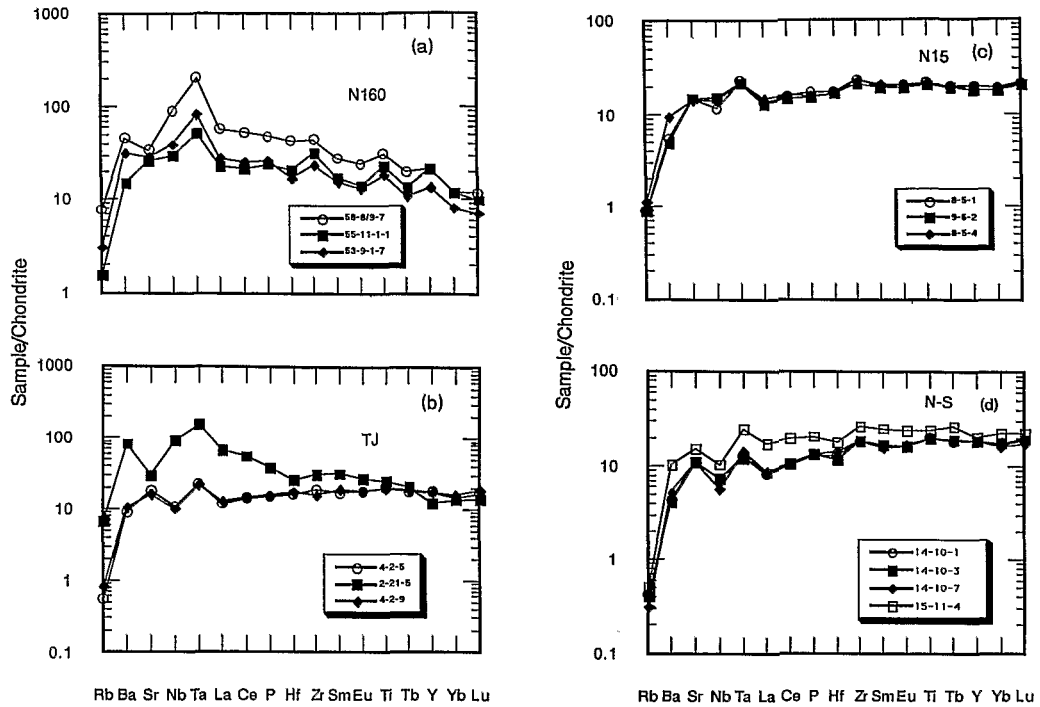


Fig. 7. Chondrite-normalized trace element diagrams for representative basalts from different tectonic segments in the NFB. (a) N160° segment, (b) TJ, (c) N15° segment, (d) N-S segment (see text for discussion).

is not long-wavelength features but rather much smaller scale ridge segments (5–40 km) which reflect volcanism related to individual magma batches. Similarly, our data suggest that individual melting episodes may supply lavas along portions of the axial ridge no more than a few kilometers in length, at least, in the NFB.

### Summary and conclusions

It is apparent that the geochemical and isotopic diversity in NFB basalts is dependent on the availability of heterogeneous mantle source components. The characteristics of the LILE, REE and HFS elements, and Sr–Nd isotopic ratios of NFB basalts demonstrate that at least two different magma source components were mixed and tapped. One is a depleted mantle source and the other is a LILE, LREE and HFS element enriched OIB-like source. Sr and Nd isotopic compositions exhibit a variation along the ridges, as well as a variation in REE and HFS elements such as Zr, Ta, Nb and Ti. Higher  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7041) and

lower  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51281) ratios were found in the N160° and TJ segments, supporting the inference that magmas from these segments are dominated by an OIB-like mantle source. The relatively lower  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7029–0.7030) and higher  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51300–0.51312) ratios found in the central ridges (N–S and N15° segments) are similar to those of N-MORB, suggesting predominance of a depleted mantle source under these segments. The coexistence of OIB-type, T- and N-type basalts with such diverse isotopic and trace elemental characteristics along a relatively short segment of axial ridge gives insight into the fine-scale nature of source variability in the NFB. The general agreement of the two component mixing model with data indicates that most NFB basalt melts result from the mixture of a depleted mantle and a LILE, LREE and HFS element enriched OIB-like source.

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## The North Fiji Basin basalts and their magma sources: Part II. Sr-Nd isotopic and trace element constraints

M. Nohara<sup>a</sup>, K. Hirose<sup>b</sup>, J.-P. Eissen<sup>c</sup>, T. Urabe<sup>a</sup> and M. Joshima<sup>a</sup>

<sup>a</sup>*Geological Survey of Japan, Ibaraki, 305, Japan*

<sup>b</sup>*University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113, Japan*

<sup>c</sup>*Centre ORSTOM de Brest, B.P. 70, 29280 Brest Cedex, France*

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