

Petrogenesis of anomalous K-enriched MORB from the Southwest Indian Ridge: 11°53'E to 14°38'E

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Abstract. Glassy pillow basalts with unusual geochemical characteristics for mid-ocean ridge basalt (MORB) have been dredge sampled from the Southwest Indian Ridge between 12 and 15°E during Leg ANT IV/4 of the *F.S. POLARSTERN*. Lavas from 4 of 6 dredges are moderately nepheline normative, highly K-enriched (0.5–1.77 wt% K₂O) alkali basalts and hawaiites. Mg-numbers indicate that many of the lavas are fairly primitive (Mg No. = 63–67), yet show extreme enrichment in incompatible elements; e.g. Nb (24–60 ppm), Ba (170–470 ppm) and Sr (258–460 ppm). Incompatible-element ratios such as Zr/Nb (3–5) and Y/Nb (0.46–1.1) are extremely low even for E-type (enriched) MORB, whereas (La/Yb)_n ratios are particularly high (3.4–7.8). ⁸⁷Sr/⁸⁶Sr (0.70290–0.70368), ¹⁴³Nd/¹⁴⁴Nd (0.51302–0.51284) and ²⁰⁶Pb/²⁰⁴Pb (18.708–19.564) isotopic ratios further indicate the geochemically 'enriched' nature of these lavas, which range from the compositional field for depleted N-type (normal) MORB towards the composition of Bouvet Island lavas. Mutually correlated incompatible-element and Sr-, Nd- and Pb-isotopic ratios allow a fairly well constrained model to be developed for the petrogenesis of these unusually alkalic mid-ocean ridge lavas. The alkalic nature and degree of enrichment in incompatible elements is ascribed to particularly low degrees of partial melting (3–5 wt%), at greater than usual depth, of a source region that has experienced prior geochemical enrichment (by veining) related to the upwelling Bouvet mantle plume. To account for the observed compositional variations, a model is proposed whereby mixing between partial melts derived from these geochemically enriched silicate veins, and an incipient to low percentage (± 2%) melt from the surrounding geochemically depleted sub-oceanic asthenosphere occurs as a consequence of increasing degree of melting with adiabatic upwelling. Eruption of these alkalic lavas in this spreading ridge environment is attributed to a temporary hiatus in tholeiitic volcanism and associated spreading along this section of the South-

west Indian Ridge, related to readjustment of spreading direction to a more stable plate geometry.

Introduction

It is well established that the majority of primitive mid-ocean ridge basalts (MORB) have particularly low abundances of high-field-strength (HFS) elements (e.g., Nb, Zr, Ta) and large-ion-lithophile (LIL) elements (e.g., K, Rb, Ba) and, when normalised to chondrites, are depleted in the light-rare-earth elements (LREE) relative to the heavy-rare-earth elements (e.g. BVSP (Basaltic Volcanism Study Project) 1981, and references therein). Exceptions to this generalization have been shown to occur along spreading ridges in the vicinity of on-ridge or near-ridge mantle plumes or hotspots where MORB with so-called enriched geochemical characteristics may occur (Schilling et al. 1983; Schilling et al. 1985; le Roex 1987). The latter variety of MORB, commonly referred to as E-type (enriched), T-type (transitional) or P-type (plume) MORB, possesses moderately elevated LIL- and HFS- element abundances, and has chondrite normalised abundances of the LREE greater than the heavy REE. Geochemical characteristics of E-type MORB the world over are remarkably similar (le Roex 1987), having moderately elevated K₂O [0.10–0.30 wt% at Mg No. > 65, where Mg No. = atomic Mg × 100/(Mg + Fe²⁺)], low Zr/Nb and Y/Nb (6–16 and 1–4, respectively) and elevated (La/Sm)_n ratios (1–6; where subscript *n* denotes chondrite normalized). These geochemical characteristics contrast with those commonly associated with depleted N-type MORB [i.e. K₂O typically < 0.15 wt% at Mg No. > 65; Zr/Nb > 16; Y/Nb > 8; (La/Sm)_n < 1.0; BVSP (1981)].

Dickey et al. (1977) and le Roex et al. (1983) have documented the abundance of geochemically enriched (T- and P-type) MORB (interspersed with normal or N-type MORB) along the Southwest Indian Ridge (SWIR) to the west of 11°E. These authors attribute the geochemically enriched character of these MORB samples to the influence of the upwelling Bouvet mantle plume, located at

~ 53°S 3°E, on the composition of the surrounding sub-oceanic mantle. Dredge sampling along the SWIR immediately to the east of 11°, between ~ 12°E and ~ 15°E, during Leg ANT IV/4 of the *F.S. POLARSTERN* has also recovered MORB with geochemically enriched characteristics. However, samples from four of the six dredge hauls have distinctly anomalous major and trace element compositions even for E-type MORB. In particular, K_2O abundances are extremely high (0.5–1.77 wt%), the lavas are moderately to strongly Ne-normative, and in some samples Zr/Nb ratios are unusually low (< 4), and $(La/Yb)_n$ ratios are particularly high (6–7.8), even for E-type MORB.

Basalts with comparable compositions to these K-enriched lavas, to the authors' knowledge, have not been sampled previously from the spreading axis of a mid-ocean ridge. In this article we report on the major and trace element and isotopic characteristics of these unusually alkalic lavas and investigate possible models for their petrogenesis and the geochemical evolution of the underlying sub-oceanic mantle.

Analytical techniques

Bulk-rock samples have been analysed for major and trace elements using XRF (X-ray fluorescence) techniques in the Department of Geochemistry, University of Cape Town. Sample preparation and data-reduction procedures have been described by Duncan et al. (1984), and associated errors and detection limits (based on counting statistics) are similar to those reported by le Roex and Dick (1981). Quench glass and mineral major-element data were obtained using a Cameca CAMEBAX microprobe (Department of Geochemistry, University of Cape Town), with on-line data reduction following the

method of Bence and Albee (1968), using factors from Albee and Ray (1970).

Rare-earth-element data were obtained using gradient ion chromatography (le Roex and Watkins 1990). Relative standard deviations associated with this technique are as follows; La = 0.6%; Ce = 1.5%; Pr = 2.1%; Nd = 3.7%; Sm = 2.3%; Eu = 3.1%; Gd = 1.8%; Tb = 5.6%; Dy = 2.6%; Er = 1.7%; Yb = 4.1%. Isotopic data for Sr, Nd and Pb were acquired using a VG Sector mass spectrometer at the Hawaii Institute of Geophysics, University of Hawaii. Methodology and blank levels are described by Mahoney et al. (in press).

Geological setting and sampling

Between 12 and 15°E the Southwest Indian Ridge is extremely slow spreading (~ 0.80 cm/year half-rate) and topographically and magnetically poorly defined (Norton 1976). The study area lies between two morphologically distinct regions of the ridge system; to the west the SWIR comprises a number of well defined short ridge segments laterally offset to the left by long, deep transform faults (Sclater et al. 1976), while to the east of the study area (between 15 and 25°E) the SWIR comprises two long (~ 300 km), essentially undisturbed ridge segments offset slightly by a short left-lateral transform fault at ~ 20°E (Hamilton 1989). Three short-offset fracture zones, named 'R', 'S' and 'A' by Norton (1976), occur in the area of interest. A Seabeam map of the study area (Fig. 1) compiled during Leg ANT IV/4 of the *F.S. POLARSTERN*, indicates the poorly defined central axis of the ridge, and illustrates the absence of any positive regional bathymetric anomaly. Bouvet Island, believed to mark the surface expression of a deep-seated mantle plume (Morgan 1973), is located ~ 700 km along the ridge to the west.

Samples on which this study is based were collected from depths between 3,200 and 4,400 m at six dredge localities (Fig. 1). Coordinates and tectonic setting of individual dredges are reported in Table 1, and sample numbers are given in the text in the form PS4-x-y where x is the dredge number and y the individual sample number.

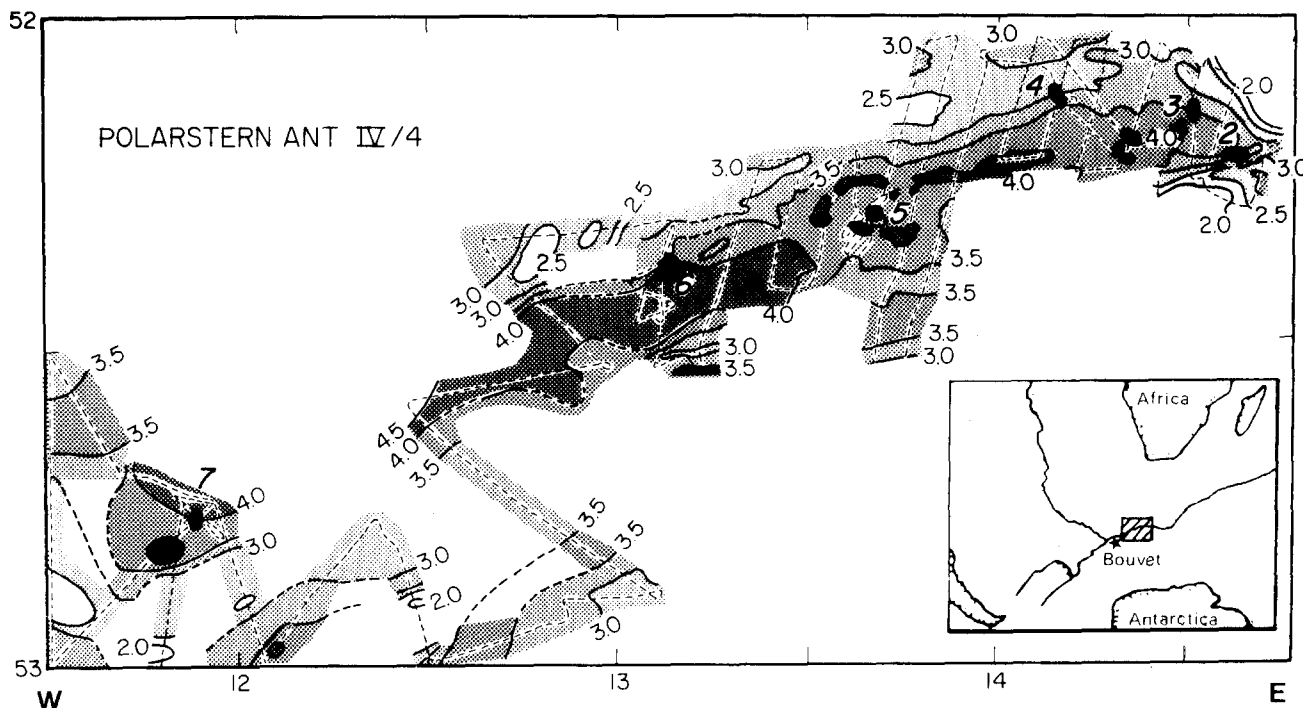


Fig. 1. Bathymetric map of the SWIR between 11.5 and 14.5°E as determined by SEABEAM swath mapping. Dredge locations are shown by solid symbols and associated dredge number and contours

are given in thousands of metres. This map was compiled as part of a joint University of Witwatersrand-University of Cape Town-Woods Hole Oceanographic Institution collaborative program

Table 1. Coordinates and tectonic setting of dredge samples from Leg ANT IV/4 of the *F.S. POLARSTERN*

Dredge no.	Depth (m)	Coordinates	Tectonic setting
2	~ 3,200	52°13'S 14°38'E	S. flank axial valley
3	~ 3,300	53°07'S 14°30'E	N. wall of axial valley
4	~ 3,600	52°06'S 14°07'E	Fracture zone wall
5	~ 3,800	52°17'S 13°41'E	N. side axial high in rift valley
6	~ 4,000	52°21'S 13°08'E	Base of N wall of axial valley
7	~ 4,400	52°46'S 11°53'E	S. flank axial valley

Petrography

A summary of the general petrographic characteristics of lavas recovered in the individual dredge hauls is given in Table 2. Samples from dredges 2, 3, 5 and 6 are fragments of pillow basalt with the majority having quenched glassy rinds. Following the classification scheme of Bryan (1983) the lavas in these dredges include olivine, olivine-plagioclase and olivine-plagioclase-pyroxene basalt (Table 2), with some of the more evolved lavas of dredge 3 being strictly classified as hawaiite (following le Bas et al. 1986). Textures range from aphyric through microporphyritic to highly plagioclase phyric. Olivine (Fo_{86-67}) and zoned plagioclase (An_{83-57}) occur as phenocrysts in the more porphyritic lavas and as microphenocrysts in the aphyric and microporphyritic lavas. Clinopyroxene ($\text{Wo}_{47-45}\text{En}_{47-36}\text{Fs}_{7-17}$) occurs as a microphenocryst phase in lavas from dredges 2 and 3, and equant Cr-spinel ($\text{Cr}/\text{Cr} + \text{Al} = 0.47-0.54$) occurs as inclusions in olivine in the most primitive lavas from dredges 2 and 5.

Dredges 4 and 7 recovered only a few fragments of holocrystalline basalt, all but two of which have highly evolved compositions

(mugearite, basaltic andesite), are highly vesicular, and have rounded morphologies. Given that the sample area lies beneath the path of westward drift of icebergs originating from Antarctica, the South Sandwich Islands and Bouvet Island, and in the absence of convincing evidence to the contrary (e.g. pillow-fragment morphology, remnant quench glass), these samples were interpreted as being glacial erratics. The two remaining samples (PS4-4-68 and 4-101) have pillow-basalt morphology and are believed to have been erupted on the sea-floor. They are highly altered, aphyric basalts with olivine, plagioclase and clinopyroxene microlites.

Bulk rock composition

Forty-one samples from this area have been analysed for major and trace elements by XRF, and some 84 glass fragments have been analysed by electron microprobe. In Tables 3 and 4 we report representative bulk-rock and glass analyses, respectively, and the full data sets can be obtained from ALR or HJBD on request. A subset of samples (selected to cover the compositional range) have been analysed for the rare-earth elements and for Sr, Nd and Pb isotopes; these data are reported in Tables 5 and 6. All chemical data have been normalized to 100% on a volatile-free basis before plotting, and CIPW norms and Mg numbers have been calculated assuming an $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio of 0.15 (Brooks 1976).

Major elements

Bulk-rock analyses indicate that the lavas in dredges 2, 3 and 6 are Ne-normative (0.5–7.2% Nepheline) alkali basalts and hawaiites; lavas from dredge 5 are transitional in composition, ranging from mildly Ne-normative (0.3–2.4% Nepheline) slightly Hy-normative (0.4–2.6% Hypersthene). The two basalts analysed from dredge 4 are

Table 2. Summary of petrographic characteristics of POLARSTERN ANT IV/4 lavas from 12–15°E on the Southwest Indian Ridge

Dredge	Texture	Classification ^a	Petrography	No. of samples
2	Microporphyritic through sparsely phyric to highly plagioclase phyric. Quench glass. Highly vesicular.	Olivine-plagioclase-pyroxene basalt	Phenocrysts (1–5 mm) of olivine, plagioclase and clinopyroxene. Microphenocrysts of same plus Cr-spinel in olivine. Plagioclase in porphyritic varieties up to 5 mm, strongly zoned with melt inclusions. Matrix hypocrySTALLINE and relatively fresh	8
3	Aphyric to microporphyritic. Quench glass. Slightly vesicular.	Olivine-plagioclase and olivine-plagioclase-pyroxene hawaiite and olivine-plagioclase-pyroxene basalt	Microphenocrysts of olivine, plagioclase and clinopyroxene. Scarce single plagioclase phenocrysts up to 2 mm. Matrix hypo- to holocrystalline, moderately fresh	9
4	Aphyric to highly plagioclase phyric. Highly vesicular.	Olivine-plagioclase-pyroxene basalt, single mugearite, single basaltic andesite	Olivine, plagioclase ± clinopyroxene microphenocrysts, and phenocrysts up to 2.5 mm in porphyritic varieties. Plagioclase shows complex zoning plus melt inclusions. Matrix is hypocrySTALLINE to holocrystalline, fresh to highly altered (PS4-4-68)	5
5	Aphyric with quench glass	Olivine-plagioclase basalt	Phenocrysts and microphenocrysts of olivine, plagioclase and Cr-spinel. Fresh hypocrySTALLINE matrix	14
6	Aphyric to sparsely plagioclase phyric. Quench glass.	Olivine and olivine-plagioclase basalt	Olivine and plagioclase phenocrysts and microphenocrysts. Quench textures. Moderately fresh hyaline to holocrystalline matrix	4
7	Aphyric	Plagioclase basalt	Plagioclase microlites in fresh hypocrySTALLINE matrix	1

^aClassification based on Bryan (1983) and le Bas et al. (1986)

Table 3. Selected bulk rock analyses of POLARSTERN ANT IV/4 basalts from the Southwest Indian Ridge between 12 and 15°E

	PS4-						
	2-14	2-18	2-24	2-1	2-35	3-14	3-33
	SP	SP	MiP	PP	SP	AP	AP
SiO ₂	50.17	50.06	50.42	49.60	50.85	50.05	47.94
TiO ₂	1.48	1.43	1.62	1.24	1.68	1.85	1.66
Al ₂ O ₃	17.56	17.29	16.75	19.19	16.46	16.57	16.39
FeO ^a	6.97	6.86	7.55	5.72	7.66	8.19	7.86
MnO	0.15	0.17	0.16	0.10	0.15	0.21	0.16
MgO	6.46	7.20	6.52	6.33	6.53	5.84	5.50
CaO	11.16	11.77	10.88	12.19	10.73	10.78	11.72
Na ₂ O	3.51	3.32	3.70	3.22	3.65	3.97	3.74
K ₂ O	1.14	1.03	1.24	0.74	1.30	1.35	1.44
P ₂ O ₅	0.33	0.31	0.37	0.22	0.39	0.43	0.41
LOI	1.15	0.97	1.00	0.71	1.12	1.20	1.93
H ₂ O-	0.49	0.40	0.41	0.36	0.38	0.45	0.57
Total	100.60	100.80	100.60	100.40	100.90	100.90	99.33
Zr	136	130	148	105	155	169	159
Nb	39	37	43	24	45	52	55
Y	23	22	26	21	25	27	25
Rb	17.7	17.4	23	10.7	24	69	34
Ba	278	258	301	171	311	383	390
Sr	383	380	371	358	368	414	459
Co	36	37	35	34	35	38	40
Cr	220	298	200	347	183	54	119
Ni	86	114	78	111	74	53	57
V	205	203	222	151	231	251	233
Zn	56	53	60	55	63	72	66
Cu	47	53	52	41	53	57	47
Sc	27	30	29	25	31	28	25
Zr/Nb	3.5	3.5	3.4	4.4	3.4	3.3	2.9
Y/Nb	0.59	0.59	0.60	0.88	0.56	0.52	0.45
Zr/Y	5.9	5.9	5.7	5.0	6.2	6.3	6.4
Ba/Nb	7.1	7.0	7.0	7.1	6.9	7.4	7.1
Ti/Zr	65.2	65.9	65.6	70.8	65.0	65.6	62.6
Mg No. ^b	65.1	67.9	63.5	66.4	63.2	58.9	58.5

^aFeO = total iron as FeO^bMg No. = atomic Mg* 100/(Mg + Fe²⁺) with Fe₂O₃/FeO = 0.15

AP = aphyric; SP = sparsely phyric; PP = plagioclase phyric; MiP = microporphyritic

Hy-normative tholeiites. Corresponding residual quench glass analyses are slightly less undersaturated than the bulk-rock compositions and range from slightly Ne-normative (0.05–0.3% Nepheline) to moderately Hy-normative (up to 8% Hypersthene).

Lavas from dredges 5 and 6 and sample PS4-4-68 have relatively primitive compositions with Mg No. ranging from 64 to 69.7 and MgO ranging from 6.8 to 9.1 wt%. Dredge 5 lavas are sufficiently similar in composition to one another (Table 3) to indicate that they probably originate from a single flow unit. In contrast, basalts from dredges 2 and 3 show a substantial range in composition from moderately primitive (Mg No. = 67.9, MgO = 7.2 wt%) to moderately evolved (Mg No. = 49.5, MgO = 4.66 wt%). The two highly plagioclase phyric lavas from dredge 2 (PS4-2-1, 2-31) have elevated Al₂O₃ contents (> 19 wt%). Quench glass analyses of these samples do not show any enrichment in Al₂O₃ (Table 4), suggesting that the high bulk-rock Al₂O₃ is a result of plagioclase accumulation.

All the lavas have moderately elevated TiO₂ (1.1–2.2 wt%), P₂O₅ (0.22–0.53 wt%) and, with the exception of those from dredge 4, particularly high K₂O (0.4–1.77 wt%) abundances (Table 3, Fig. 2). Of this group, lavas from dredge 5 and one from dredge 6 (PS4-6-2) are least enriched in K₂O (0.48–0.56 wt% and 0.4 wt%, respectively), whereas dredge 2 and 3 and the two remaining dredge 6 lavas (PS4-6-1, 6-3) are exceptionally enriched in K₂O, with abundances ranging from 0.75 wt% to a maximum 1.77 wt% (Fig. 2). The lowest K₂O contents (0.75 wt%) found in this latter subset of samples occur in the porphyritic dredge 2 lavas (PS4-2-1, 2-31) and reflect dilution by plagioclase accumulation. The quench glasses from these dredges have comparable potassium abundances to the bulk-rock samples (Table 4), confirming that the extreme potassium enrichment is characteristic of the parental magmas and not the result of alteration processes.

The extreme enrichment in K₂O in the samples from 12–15°E is well illustrated in Fig. 2 where compositional

Table 3 (continued) Selected bulk rock analyses of POLARSTERN ANT IV/4 basalts from the Southwest Indian Ridge between 12 and 15°E

PS4-								
3-34	3-6	4-68	4-101	5-36	5-9	6-1	6-2	6-3
SP	AP	AP	AP	AP	AP	SP	AP	SP
49.65	49.49	49.32	49.77	50.34	50.35	50.95	50.17	51.13
1.48	2.16	1.42	3.82	1.44	1.44	1.67	1.69	1.66
16.53	16.26	16.45	14.21	16.28	16.27	16.91	16.23	16.88
7.24	9.59	7.20	12.65	8.10	8.03	7.60	9.02	7.55
0.20	0.16	0.12	0.22	0.19	0.16	0.18	0.18	0.17
6.51	4.66	7.77	4.22	9.05	9.21	6.80	7.96	6.83
12.21	9.60	8.95	8.71	10.10	10.06	10.24	9.68	10.28
3.79	4.00	3.55	3.51	3.46	3.57	3.57	3.94	3.83
0.96	1.77	0.15	1.34	0.52	0.55	0.93	0.41	0.97
0.29	0.53	0.17	0.67	0.23	0.23	0.32	0.29	0.32
1.07	1.57	3.49	0.84	0.74	0.82	0.94	0.88	1.07
0.37	0.65	1.57	0.16	0.38	0.22	0.46	0.17	0.44
100.30	100.40	100.20	100.30	100.80	100.90	100.60	100.60	101.10
117	196	123	296	129	129	158	164	154
34	66	7.3	47	15.6	16.2	29	16.4	29
24	33	30	41	29	29	32	37	32
17.5	43	1.6	22	9.0	7.9	14.9	7.3	16.4
277	473	9.0	251	93	93	197	77	192
352	454	150	433	214	216	263	212	258
48	40	39	42	47	47	37	44	36
71	8	88	13	309	313	223	274	213
109	26	165	12	186	191	101	153	97
218	296	200	331	214	205	234	228	223
66	87	61	141	65	64	61	72	58
61	34	161	21	47	49	50	50	49
28	25	35	30	33	32	35	34	32
3.4	3.0	16.8	6.3	8.3	8.0	5.4	10.0	5.3
0.71	0.50	4.16	0.87	1.86	1.79	1.10	2.26	1.10
4.9	5.9	4.0	7.2	4.4	4.4	4.9	4.4	4.8
8.1	7.2	1.2	5.3	6.0	5.7	6.8	4.7	6.6
75.8	66.1	69.2	77.4	66.9	66.9	63.4	61.8	64.6
64.4	49.5	68.5	40.2	69.2	69.8	64.3	64.0	64.6

Table 4. Selected quench glass analyses of POLARSTERN ANT IV/4 basalts from the Southwest Indian Ridge between 12 and 15°E

PS4-											
	2-14	2-18	2-24	2-31	3-14	3-6	5-12	5-36	5-9	6-1	6-2
SiO ₂	51.28	51.18	52.09	51.11	51.30	50.98	51.55	51.64	51.55	52.28	51.49
TiO ₂	1.80	1.70	1.80	1.55	1.93	2.36	1.75	1.56	1.54	1.78	1.75
Al ₂ O ₃	15.85	15.81	16.06	15.91	16.01	15.97	16.18	16.30	16.50	16.29	16.22
FeO ^a	8.14	7.89	8.02	7.66	9.22	10.30	8.38	7.98	7.76	7.82	8.94
MnO	0.18	0.11	0.15	—	—	0.21	0.20	—	0.22	0.11	0.17
MgO	6.13	6.46	6.20	6.82	5.36	4.63	7.18	7.16	7.31	6.59	7.04
CaO	10.71	11.30	10.75	11.97	7.95	9.85	10.35	10.41	10.35	10.11	9.74
Na ₂ O	3.56	3.34	3.50	3.04	5.03	2.75	3.82	3.73	3.61	3.66	4.32
K ₂ O	1.27	1.14	1.22	1.03	1.47	1.72	1.34	1.41	0.41	0.89	0.40
P ₂ O ₅	0.42	0.40	0.44	0.34	0.45	0.45	0.29	0.26	0.23	0.30	0.23
Total	99.34	99.33	100.20	99.43	98.72	99.22	100.00	99.45	99.48	99.83	100.30
Mg No. ^b	60.4	62.4	61.0	64.3	54.0	47.6	63.4	64.5	65.6	63.0	61.4

^aFeO = total iron as FeO^bMg No. = atomic Mg*100/(Mg + Fe²⁺) with Fe₂O₃/FeO = 0.15

fields for T-type MORB from the western end of the SWIR, least evolved hawaiites from Bouvet Island, and highly alkaline basanites from Tristan da Cunha are shown for comparison. This obvious enrichment in K₂O

is not accompanied by a comparable enrichment in either TiO₂ (Fig. 3) or P₂O₅ (Table 3); a factor consistent with the expected difference in incompatibility of these elements during partial melting of sub-oceanic mantle (i.e.

Table 5. Rare-earth-element analyses for selected POLARSTERN ANT IV/4 samples from the Southwest Indian Ridge between 12 and 15°E. Data were determined using gradient ion-chromatography (le Roex and Watkins, 1990)

	PS4-2-1	PS4-2-14	PS4-3-14	PS4-3-34	PS4-5-36	PS4-6-1	PS4-6-2	PS4-4-68
La	11.6	20.3	29.2	17.3	8.96	14.9	10.7	4.80
Ce	24.9	40.3	53.7	37.1	23.7	34.4	27.4	14.6
Pr	3.03	4.75	6.29	4.33	3.11	4.37	3.55	2.34
Nd	12.5	18.6	24.5	18.0	14.1	18.6	15.7	11.8
Sm	2.96	4.01	5.24	4.00	3.71	4.64	4.51	4.09
Eu	1.02	1.41	1.72	1.36	1.21	1.62	1.58	1.20
Gd	3.19	4.23	5.19	4.24	4.33	5.17	5.45	4.61
Tb	0.50	0.67	0.82	0.67	0.74	0.85	0.96	0.76
Dy	3.00	3.98	4.92	4.07	4.85	5.30	6.11	5.16
Er	1.65	2.32	2.78	2.27	2.81	3.13	3.72	2.98
Yb	1.47	1.99	2.47	2.10	2.45	2.89	3.55	2.76
(La/Sm) _n	2.4	3.1	3.4	2.8	1.5	2.0	1.5	0.72
(La/Yb) _n	5.2	6.7	7.8	5.9	2.4	3.4	2.0	1.15

Table 6. Sr, Nd and Pb isotopic data for quench glass and rock powders from selected POLARSTERN ANT IV/4 dredge samples from the Southwest Indian Ridge between 12 and 15°E

	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb
PS4-2-1	0.70338	0.512876	19.243 ± 10	15.632 ± 8	39.315 ± 24
PS4-3-14	0.70352	0.512837	19.254 ± 8	15.642 ± 6	39.305 ± 18
PS4-4-68 ^a	—	—	18.737 ± 12	15.556 ± 12	38.429 ± 32
PS4-4-101 ^a	0.70368	0.512852	19.564 ± 3	15.649 ± 3	39.157 ± 8
PS4-5-36	0.70292	0.513020	18.769 ± 7	15.560 ± 6	38.623 ± 19
PS4-6-1	0.70309	0.512951	18.867 ± 5	15.572 ± 4	38.822 ± 12
PS4-6-2 ^a	0.70290	0.513004	18.741 ± 3	15.551 ± 2	38.541 ± 6

^a determined on rock powder after leaching following the procedure by Mahoney (1988)

Isotopic fractionation corrections are $^{148}\text{NdO}/^{144}\text{NdO} = 0.242436$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.1194$. Data are reported relative to Hawaii Institute of Geophysics standard values: for La Jolla Nd, $^{143}\text{Nd}/^{144}\text{Nd} = 0.511855$; for BCR-1, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512630$; for NBS 987 Sr, $^{87}\text{Sr}/^{86}\text{Sr} = 0.71024$; for E and A Sr, $^{87}\text{Sr}/^{86}\text{Sr} = 0.70802$. The total range measured for La Jolla Nd is ± 0.000012 ; for NBS 987 it is ± 0.000022 . Pb isotopic ratios are corrected for fractionation using NBS 981 standard values of Todt et al. (1983). Within-run errors on individual sample measurements for Sr or Nd are less than or equal to the above external uncertainties on the La Jolla and NBS 987 standards in all cases. Total procedural blanks are 10–40 picograms for Pb, < 20 picograms for Nd, and < 200 picograms for Sr; all are negligible

$D^K < D^P < D^{Ti}$; Sun and McDonough 1989). The K/P ratios of the most enriched lavas (6.4 ± 0.2) are consequently greater than typical for T-type MORB from this region (3.9 ± 1.1).

Non-porphyrific dredge 2 and 3 lavas describe a good correlation between K_2O and Mg No. and have K_2O abundances substantially higher than, for example, an inferred Bouvet Island parental magma would have (Fig. 2). Together with samples PS4-6-1 and 6-3, dredge 2 and 3 lavas have K_2O contents comparable to the highly alkaline basanites from Tristan da Cunha at similar Mg No. Primitive dredge 5 lavas have lower K_2O contents, which are however still significantly higher than primitive T-type MORB to the west (Fig. 2). Samples PS4-4-68 and PS4-6-2 fall within the field for T-type MORB from the SWIR (Fig. 2).

Trace elements

Ferromagnesian trace elements in these lavas correlate broadly with Mg No.; Ni, for example, ranges from ~ 190 ppm in the primitive dredge 5 lavas to as low as 8 ppm in the most evolved dredge 3 and 4 lavas (Table 3; Fig. 3). More notable, and in accord with their very high K_2O contents, dredge 2 and 3 and two of the dredge 6 lavas (PS4-6-1, 6-3) have extremely high Nb (24–60 ppm), Ba (170–470 ppm) and Sr (258–460 ppm) abundances. Shown in Fig. 3 are fields for T-type MORB from the SWIR to the west of 11°E together with Bouvet Island hawaiites and Tristan da Cunha basanites; the extreme enrichment in Nb and Ba in these 12–15°E lavas is clear. Dredge 5 lavas are less enriched in these elements, but still have higher abundances compared to primitive T-type

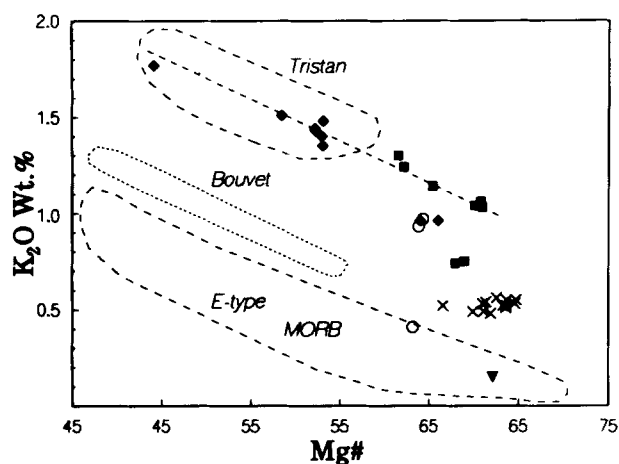


Fig. 2. Variation in K_2O with respect to Mg number, Mg #, in lavas from the SWIR between 12 and 15°E. Symbols as follows: Solid squares, dredge 2; solid diamonds, dredge 3; solid triangles, dredge 4; crosses, dredge 5; open circles, dredge 6. Compositional fields for T-type MORB from the western SWIR, 0–11°E (le Roex et al. 1983), Bouvet Island (le Roex and Erlank 1982) and Tristan da Cunha (le Roex et al. 1990) are shown for comparison

MORB from the western end of the SWIR, and have a similar composition to that which an inferred parental magma to the Bouvet Island hawaiites might have (Fig. 3).

Dredge 2 and 3 lavas show remarkably well constrained compositional variations, certain of which are depicted in Fig. 4. It is clear that, for most elements, the lavas from these two dredges define colinear correlations which are qualitatively consistent with control by fractional crystallization. However, an exception is the covariation of Ba with Zr where two distinct trends are defined (dredge 2 $Ba/Zr = 1.9 \pm 0.2$; dredge 3 $Ba/Zr = 2.4 \pm 0.1$), which clearly indicates differences in the source regions of the lavas from these two adjacent dredges.

In Table 5 we report rare-earth element (REE) abundances for selected lavas. Chondrite normalized REE patterns (Fig. 5) range from being slightly light REE depleted (PS4-4-68) to strongly enriched (dredges 2 and 3; $(La/Yb)_n = 3.4–7.8$). The plagioclase phyric, Al_2O_3 -rich lava PS4-2-1 does not show any significant Eu anomaly, and the similarity between lavas from dredges 2 and 3 is well illustrated in terms of their sub-parallel REE patterns.

The extreme enrichment in incompatible elements in dredge 2 and 3 lavas and samples PS4-6-1 and 6-3 is also reflected in their very low Zr/Nb (3–5) and Y/Nb (0.46–1.1) ratios, which are substantially lower than P-type MORB from further to the west along the SWIR or Bouvet Island lavas ($Zr/Nb = 6.5$; $Y/Nb = 0.88$; le Roex et al. 1983; le Roex and Erlank 1982). In contrast, dredge 5 lavas have incompatible-element ratios that fall within the range of most E-type MORB the world over (le Roex 1987), having moderately low Zr/Nb (~ 8) and Y/Nb (1.8)

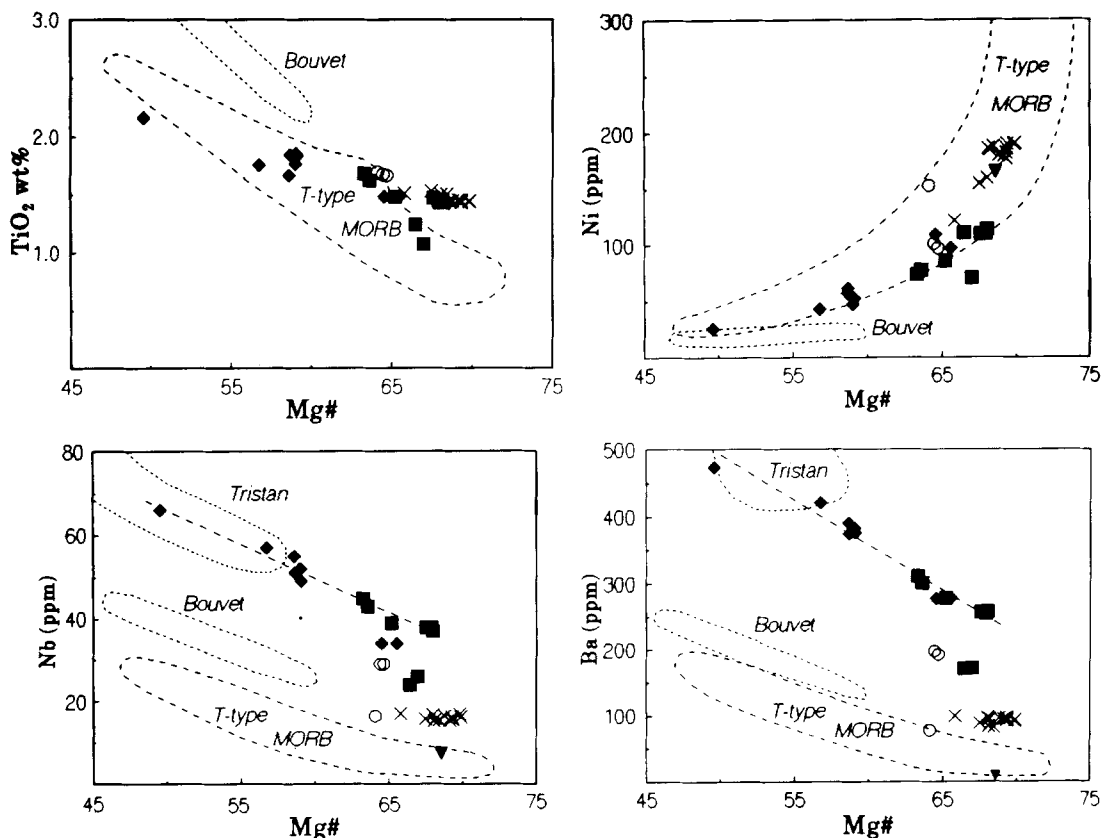


Fig. 3. Variation of selected minor and trace elements with respect to Mg number, Mg #, in lavas from the SWIR between 12 and 15°E. Compositional fields for T-type MORB from the western SWIR,

Bouvet Island and Tristan da Cunha are shown for comparison. Symbols and sources of data as in Fig. 2

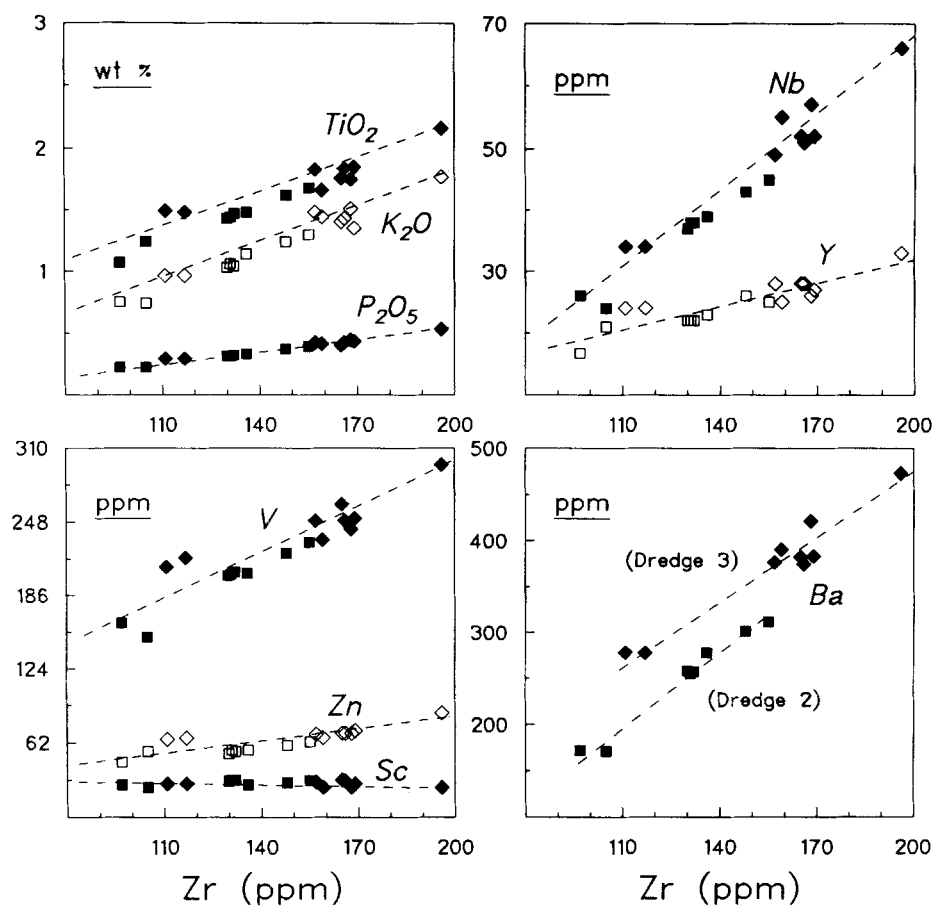


Fig. 4. Minor and trace element variations in dredge 2 and 3 lavas. Symbols as follows: dredge 2, open and filled squares; dredge 3, open and filled diamonds

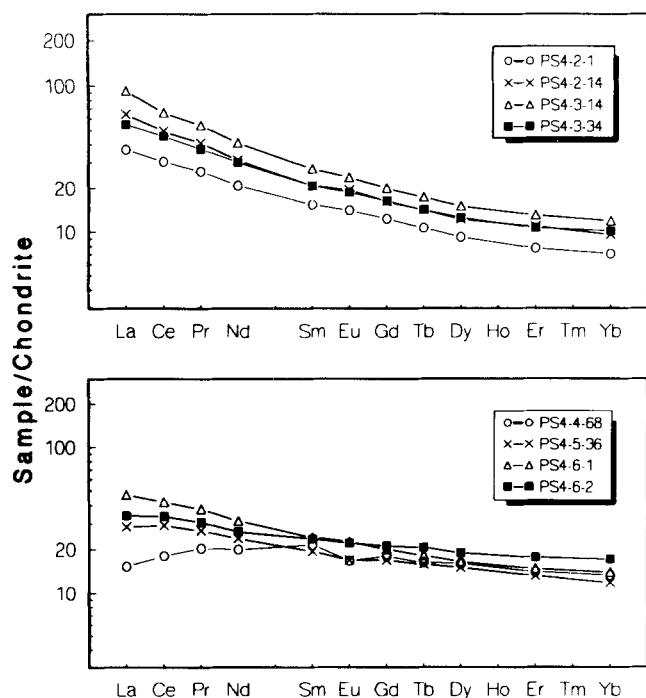


Fig. 5. Chondrite normalized rare-earth-element patterns of lavas from the SWIR between 12 and 15°E. Data are normalized to chondritic values for Leedy/1.2 (Masuda et al. 1973)

ratios and $(\text{La/Yb})_n$ ratios (2.4) slightly greater than chondritic. Sample P4-4-68 has trace-element characteristics similar to N-type MORB, whereas PS4-4-101 is indistinguishable from P-type MORB and Bouvet Island lavas from further to the west. Incompatible minor and trace-element ratios (e.g. Zr/Nb , Y/Nb , La/Nb , Ba/Nb , K/Ba , K/P , K/Rb , P/Nb) of lavas from dredges 2, 3, 5 and 6 are all highly correlated, with the sense of the variations being consistent with the relative bulk-distribution coefficients (e.g. Sun and McDonough 1989).

Isotopes

Six samples were selected for Sr-, Nd- and Pb-isotopic analysis and the data are reported in Table 6, and illustrated graphically in Figs. 6 and 7. The lavas have moderately radiogenic Sr ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70290\text{--}0.70368$), unradiogenic Nd ($^{143}\text{Nd}/^{144}\text{Nd} = 0.51302\text{--}0.51284$) and $^{206}\text{Pb}/^{204}\text{Pb} = 18.737\text{--}19.564$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.551\text{--}15.649$ and $^{208}\text{Pb}/^{204}\text{Pb} = 38.429\text{--}39.315$. Sample PS4-4-101 has an isotopic composition similar to Bouvet Island lavas and to P-type MORB from the SWIR to the west of 11°E (Figs. 6, 7).

The two samples analysed from dredges 2 and 3 have subtly different isotopic compositions (Table 6) and, despite having more enriched trace-element compositions,

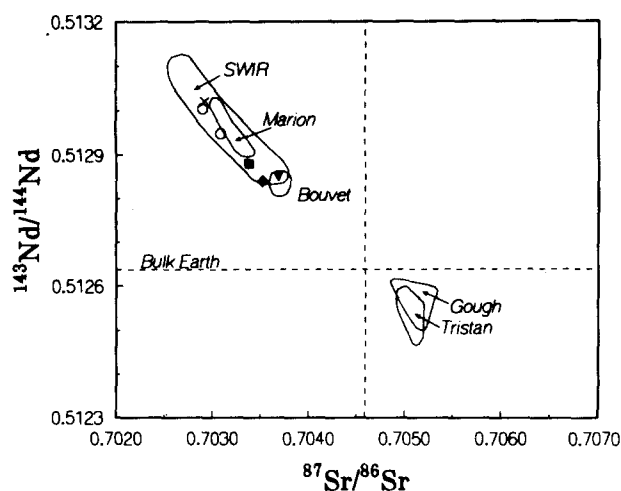


Fig. 6. $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$ correlation diagram for POLARSTERN ANT IV/4 lavas. Compositional fields for western SWIR lavas, Bouvet Island, Tristan da Cunha, Gough Island, and Marion Island are shown for comparison. Symbols as for Fig. 2. Sources of data as for Fig. 2 and le Roex (1985), Hart (1988)

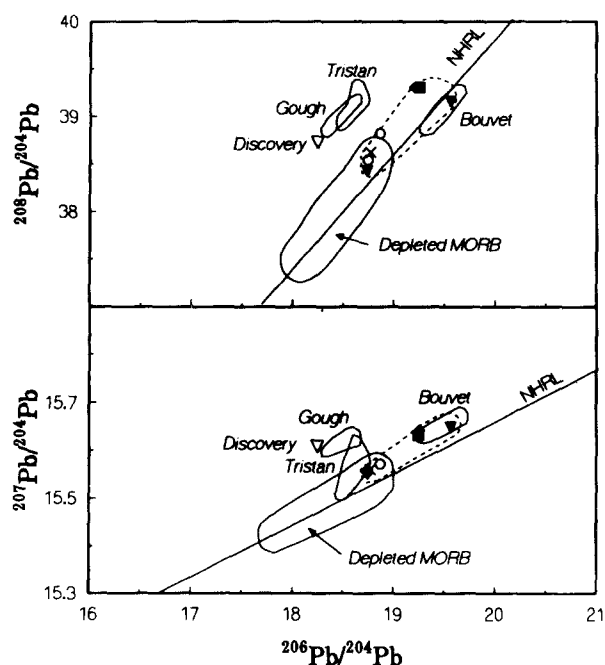


Fig. 7. Lead-lead isotopic variation in POLARSTERN ANT IV/4 lavas. Sources of data for compositional fields as for Fig. 6 plus Sun (1980) for Discovery. NHRL, Northern hemisphere reference line (Hart 1984). Symbols as for Fig. 2

have slightly less radiogenic Sr and more radiogenic Nd than Bouvet Island lavas. These lavas also have slightly higher $^{208}\text{Pb}/^{204}\text{Pb}$ ratios (relative to $^{206}\text{Pb}/^{204}\text{Pb}$) than available data for Bouvet Island (Fig. 7). In terms of a Sr-Nd correlation diagram (Fig. 6) the data fall within the field determined by le Roex et al. (1983) for enriched MORB from the SWIR to the west of 11°E , and extend from the depleted MORB field towards the isotopic composition of Bouvet Island lavas.

There are few published Pb-isotopic data for this Southern Ocean region with which to compare these new data. However, Mahoney et al. (1989) have delineated distinct isotopic fields for Indian Ocean MORB (including data from the central and eastern end of the SWIR) relative to Atlantic and Pacific MORB. In this respect, lavas from this region of the SWIR show greater affinity to Atlantic and Pacific MORB and are very distinct from Indian Ocean MORB, having generally higher $^{206}\text{Pb}/^{204}\text{Pb}$ ratios.

Petrogenesis

Particularly striking features of the geochemistry of these lavas from $12\text{--}15^\circ\text{E}$ are the well correlated compositional variations shown by dredge 2 and 3 lavas, and the extreme enrichment in K_2O , Nb and other highly incompatible elements. The within-suite compositional variations (dredge 2 and 3 lavas; Fig. 4) can be well accounted for by fractional crystallization of observed phenocryst phases, or in the case of samples PS4-2-1 and 2-31 by the accumulation of plagioclase. It has been demonstrated elsewhere that low-pressure fractional crystallisation is an important process acting on the composition of MORB along the slow spreading SWIR (e.g. le Roex et al. 1982, 1983; le Roex and Dick, 1981) and we will not discuss this aspect of the data in any detail.

Of more fundamental interest with respect to the current data set is the unusually alkaline and geochemically enriched nature of these mid-ocean ridge lavas. Generation of such strongly alkali enriched, Ne-normative lavas as found in dredges 2, 3 and 6 suggests unusual conditions of petrogenesis for a mid-ocean spreading-ridge environment. Moreover, the geochemically enriched nature of these lavas, as reflected by their radiogenic-isotope and incompatible-trace-element compositions, requires that their mantle source region is itself enriched compared to sub-oceanic mantle giving rise to normal depleted mid-ocean ridge basalts (N-type MORB). An important question is whether the alkaline nature and extreme enrichment in incompatible elements shown by these lavas reflects simply this geochemical enrichment of their mantle source region, or whether unusual partial melting processes have, in addition, contributed to their geochemical characteristics.

Source region enrichment

The excellent correlations between incompatible-trace-element ratios and isotopic ratios (e.g. Fig. 8) indicate that the former are behaving in a manner analogous to the isotopic ratios, and that they are not being fractionated significantly due to small differences in bulk-distribution coefficients during the partial melting process giving rise to these lavas. Furthermore, the mutual geochemical correlations, such as illustrated in Figs. 8 and 9, suggest that the geochemical enrichment shown by these lavas from $12\text{--}15^\circ\text{E}$ does not reflect random source heterogeneity as in the 'plum-pudding' type model of Davies (1984). They point rather to some common process whereby the

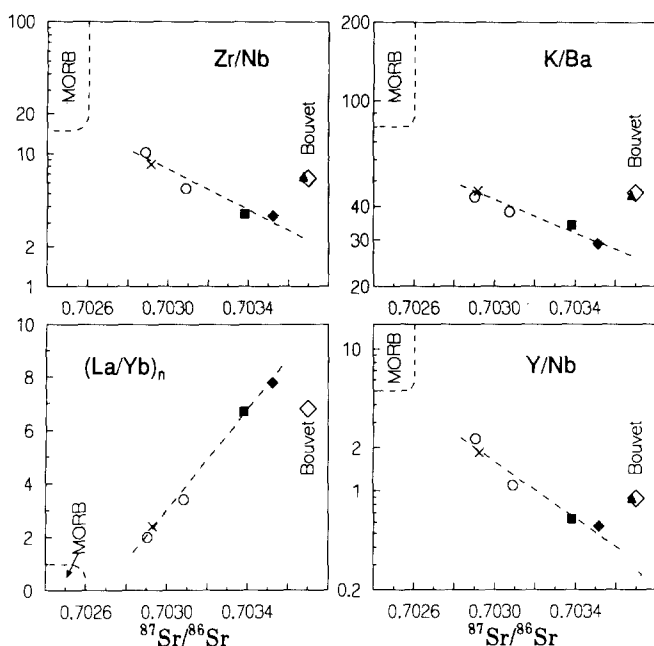


Fig. 8. Covariation of selected trace-element ratios and $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios of lavas from the SWIR between 12 and 15°E. Field for depleted N-type MORB from the western SWIR (le Roex et al. 1983) is shown for comparison. Data for Bouvet Island are from le Roex and Erlank (1982) and O'Nions et al. (1977). The similarity between sample PS4-4-101 (open square) and Bouvet Island lavas is clearly evident (REE data are not available for PS4-4-101). Symbols as for Fig. 2.

sub-oceanic mantle in this region has been enriched geochemically by a component with a restricted, and identifiable geochemical signature. The most likely process capable of generating such correlations is mixing between two broadly homogeneous end-members, and we investigate this hypothesis further through the remainder of this section.

Any simple two-component mixing model involving depleted MORB mantle as one end-member and an enriched component as the other, obviously must satisfy observed variations in incompatible-trace-element and isotopic ratios. Figures 6 through 9 depict the covariation of a number of such ratios and it is evident that the samples generally lie on well defined trends, qualitatively consistent with mixing between a geochemically depleted MORB mantle component (having high Zr/Nb, Y/Nb, P/Nb, K/Ba, $^{143}\text{Nd}/^{144}\text{Nd}$, coupled with low Ba/Rb, Zr/Y, La/Yb, $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$) and a geochemically enriched component with opposing chemical and isotopic characteristics.

The proximity of this region of the SWIR to the Bouvet hotspot (insert to Fig. 1), and the evidence for associated geochemically enriched lavas occurring along the ridge to as far east as 11°E (le Roex et al. 1983), suggest that the geochemical enrichment in these 12–15°E lavas may relate to the upwelling Bouvet mantle plume. Such a model is qualitatively consistent with Sr, Nd, $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ isotopic variations which define trends from the field of depleted N-type MORB towards the composition of Bouvet Island (Figs. 6, 7). However, with

the exception of sample PS4-4-101, which has a composition similar to P-type MORB further to the west, the lavas trend to slightly higher $^{208}\text{Pb}/^{204}\text{Pb}$ ratios (at a given $^{206}\text{Pb}/^{204}\text{Pb}$ ratio) than the field of Bouvet Island lavas (Fig. 7), although they lie within the field for other SWIR lavas in the immediate vicinity of Bouvet Island (Kurz, MD personal communication 1989). This slight inconsistency may reflect the very limited published Pb isotopic data, numbering 3 analyses, for Bouvet Island (Sun 1980).

It has been shown by le Roex et al. (1983) that compositional variations defined by P- and T-type MORB from the SWIR between 1°W and 11°E are highly correlated and extend from the composition of Bouvet Island magmas towards depleted N-type MORB. These lavas were interpreted to derive from a 'mixed' source region comprising normal depleted sub-oceanic mantle variably veined by a low-percentage partial melt derived from the upwelling Bouvet mantle plume. Although the lavas from between 12 and 15°E describe well constrained mixing trends (Fig. 9), they do not always pass through the composition of Bouvet Island lavas — inferred in this model to represent the geochemically enriched end-member. In fact, the most enriched POLARSTERN lavas (dredges 2 and 3) have incompatible-trace-element characteristics that are even *more* enriched than the lavas of Bouvet Island. Furthermore, whereas some of the correlations are colinear with those described by P- and T-type MORB from the SWIR further to the west, others are oblique to these trends (Fig. 9). Two obvious explanations for this discrepancy are that either the enriched component does not relate to the Bouvet mantle plume, or the incompatible-trace-element ratios in question have been fractionated in the enriched component relative to those characteristic of the Bouvet Island lavas, prior to the mixing responsible for the observed compositional arrays.

Partial melting

Although, as indicated above, much of the first-order geochemical character of these 12–15°E lavas can be accounted for by derivation from a mantle source region that has experienced an enrichment event, in detail it is evident that such a simplistic model is not applicable. For example, small differences in certain trace and minor-element ratios (e.g. K/Ba, P/Nb, K/P, Ba/Rb), between the most enriched end-member of the 12–15°E mixing trends and Bouvet Island lavas (e.g. Fig. 9) are consistent with the fractionation expected to result from the effect of differences in relative bulk-distribution coefficients of the elements during low degrees of partial melting (assuming an order of incompatibility as proposed by Sun and McDonough 1989). Moreover, the extreme absolute enrichment in highly incompatible elements (e.g. K, Nb) suggests derivation of the lavas by particularly low degrees of melting.

If, as a first approximation, one assumes that the lavas derived from a source region enriched by the upwelling Bouvet mantle plume, an indication of the degree of melting required to achieve the absolute enrichment in incompatible elements in the melts and the necessary change in selected incompatible-element ratios can be

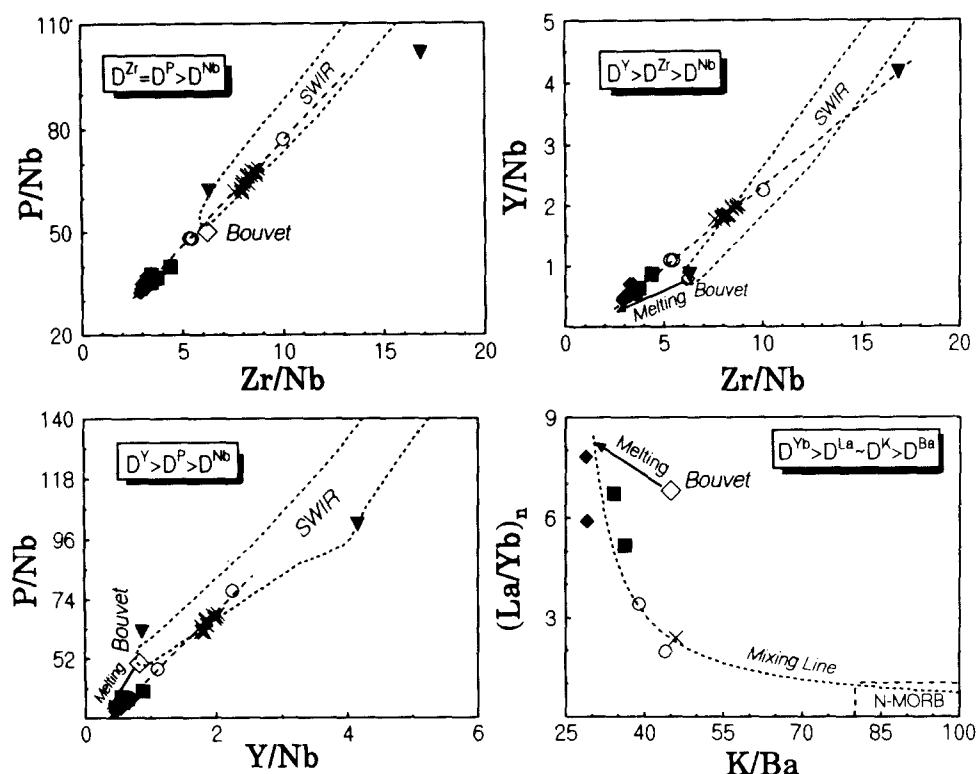


Fig. 9. Covariation of selected incompatible-element ratios in lavas from the SWIR between 12 and 15°E. Corresponding correlations for T- and P-type MORB from the western end of the SWIR (le Roex et al. 1983) are shown for comparison. Symbols as in Fig. 2. The melting trajectories shown on these diagrams are for illustrative purposes and should be regarded as semi-quantitative. They have been calculated assuming ~2% melting of a source capable of

giving rise to Bouvet Island lavas by ~8% melting, and a relative order of element incompatibility as proposed by Sun and McDonough (1989), i.e. $D^{Ba} < D^{Nb} \sim D^K < D^{La} < D^P \sim D^{Zr} < D^Y < D^{Yb}$ and distribution coefficients from the literature. The mixing line for $(La/Yb)_n - K/Ba$ has been calculated following Langmuir et al (1978). See text for further discussion

calculated (Fig. 10). In these diagrams the depleted mantle component is assumed to have an $^{87}Sr/^{86}Sr$ ratio of 0.7024 (similar to the lowest value measured from this general region; le Roex, unpublished data) and incompatible-element abundances capable of giving rise to depleted MORB found along the SWIR by 10–25% batch melting (see caption to Fig. 10 for compositions). The enriched component is taken as having $^{87}Sr/^{86}Sr = 0.7037$ (equivalent to average Bouvet Island lava), and incompatible-element abundances capable of giving rise to a primary Bouvet Island magma (or P-type MORB) by 8–10% melting (see caption to Fig. 10 for compositions). The field of primitive N-, T- and P-type MORB described by le Roex et al. (1983) from the SWIR to the west is shown on these diagrams for reference.

Johnson et al. (1990) have recently argued that trace-element compositions of abyssal peridotites from this region of the SWIR are more consistent with melt production by fractional melting processes than by batch melting. However, whereas fractional melting may have a profound influence on the composition of the residual source, the *accumulated* melt fraction does not differ strongly from that obtained by batch melting (eg. Prinzhofer et al. 1989). For simplicity we have therefore adopted a batch-melting model. The calculations used in

constructing these diagrams (see caption to Fig. 10 for input parameters) indicate that the enriched dredge 2, 3, 5 and 6 lavas could be derived by low degrees of melting (~3–5%) of a variably enriched source region, similar to that giving rise to enriched MORB from nearer Bouvet Island by 8–25% melting. Although admittedly simplistic, the model shows not only that the absolute enrichment in K_2O and Nb (and other incompatible trace elements — not depicted) can be accounted for, but that the necessary variation in key incompatible-trace-element ratios (e.g. Zr/Nb, La/Sm etc.) can also be readily achieved.

Similarly, the observed fractionation in K/Ba ratio (Fig. 9) can be achieved by ~2% melting of a spinel lherzolite source (capable of giving rise to Bouvet Island magmas by 8–10% partial melting; le Roex et al. 1983), and assuming a bulk $D^{Ba} \sim 0.001$ and bulk $D^K \sim 0.02$. Although the fractionation in K/Ba and K/Rb ratios would be achieved even more readily by the presence of residual amphibole or phlogopite, the negative correlation between these ratios and K/P ratio provides compelling evidence against the presence of one of these minerals as a residual phase. Melting trajectories shown in the other diagrams in Fig. 9 have similarly been calculated at 2–3% melting and using published peridotite mineral distribution coefficients.

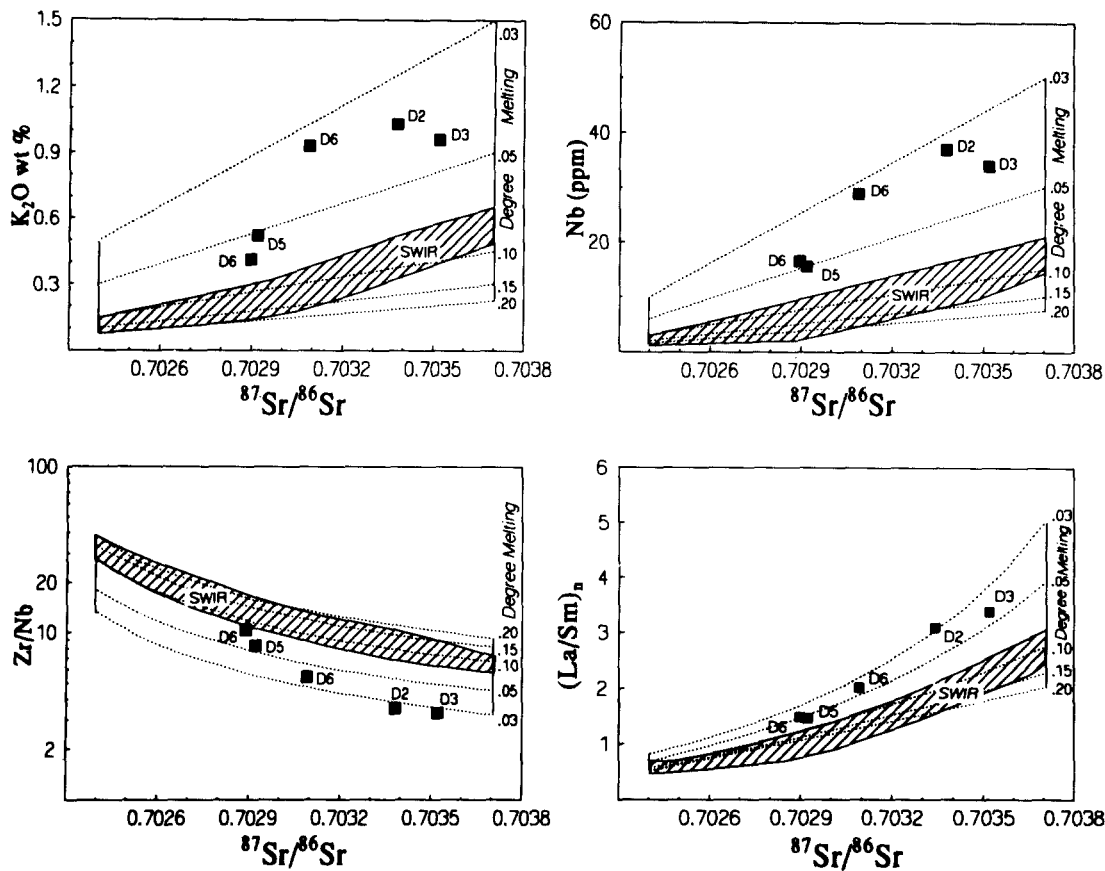


Fig. 10. Calculated batch-melting grids for selected incompatible elements and element ratios with respect to variation in $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of a 'mixed' mantle source, with superimposed compositions of dredge 2, 3, 5 and 6 lavas. The generalized fields for T- and P-type MORB from the western end of the SWIR (le Roex et al. 1983) are shown for comparison. Input parameters: a mixed mantle source ranging in composition from that capable of giving rise to depleted MORB from the SWIR by ~ 10 – 20% melting, to that capable of giving rise to Bouvet Island lavas (and P-type MORB from the SWIR) by ~ 8 – 10% melting. End-member source compositions as follows: depleted mantle — $^{87}\text{Sr}/^{86}\text{Sr} = 0.7024$; $\text{K}_2\text{O} = 0.015\%$; $\text{Nb} = 0.3$ ppm; $\text{Zr}/\text{Nb} = 40$; $(\text{La}/\text{Sm})_n = 0.5$. Source mineralogy — Ol

(olivine) = 0.55, Opx (orthopyroxene) = 0.25, Cpx (clinopyroxene) = 0.18, Sp (spinel) = 0.02 melting in proportions 0.1 : 0.2 : 0.68 : 0.02 (Johnson et al. 1990). Enriched mantle — $^{87}\text{Sr}/^{86}\text{Sr} = 0.7037$; $\text{K}_2\text{O} = 0.03\%$; $\text{Nb} = 1.5$ ppm; $\text{Zr}/\text{Nb} = 9.7$; $(\text{La}/\text{Sm})_n = 1.5$. Source mineralogy — Ol = 0.55, Opx = 0.20, Cpx = 0.15, Gt (garnet) = 0.10 melting in proportions 0.03 : 0.03 : 0.44 : 0.50 (Johnson et al. 1990). REE distribution coefficients from Frey et al. (1978), $D^{\text{Zr}/\text{cpx}} = 0.20$ and $D^{\text{Nb}/\text{cpx}} = 0.02$ (McCallum and Charette 1978), $D^{\text{K}/\text{cpx}} = 0.02$ (Philpotts and Schnetzler, 1970), $D^{\text{Zr}/\text{gt}} = 0.65$ and $D^{\text{Nb}/\text{gt}} = 0.03$ (Shimizu and Allegre 1978), the rest assumed equal to 0.001. See text for further discussion

Generation of dredge 2, 3 and 6 lavas by particularly low degrees of partial melting is also consistent with their Ne-normative character and the extreme absolute enrichment shown in alkali and other incompatible elements. McKenzie and Bickle (1988) have discussed in detail theoretical parameterization models for melt generation and have argued that in normative Diopside-Olivine-Silica and Anorthite-Olivine-Silica ternary projections most primitive MORB lie close to a $1,280^\circ\text{C}$ isotherm. With increasing degree of melting along each isotherm the melts change from Ne-normative to more silica-rich compositions (Fig. 11); a concept supported by experimental petrology (e.g. Falloon and Green 1988). The most primitive lavas from dredges 2 and 3, and to a lesser degree 5 and 6, plot well into the low-percentage melt, Ne-normative field on these projections, and also to the low- T side of the $1,280^\circ\text{C}$ isotherm (Fig. 11). The work by McKenzie and Bickle (1988) and Klein and Langmuir (1987) therefore would support a model whereby these alkaline lavas have been generated by particularly low

degrees of melting, in a cooler thermal environment than that typically found beneath most mid-ocean ridges.

Independent evidence in support of unusually low degrees of melting for a spreading ridge environment is found in the study of abyssal peridotites from this area. Three of six dredge hauls collected from $\sim 13^\circ\text{E}$ contain residual mantle peridotites. These peridotites are particularly enriched in diopside (average modal content is olivine : orthopyroxene : clinopyroxene : spinel = 64.5 : 25.2 : 9.2 : 1.1), and lie at the extreme low-melting end of the modal mantle melting trend previously found for the Southwest Indian Ridge (Dick et al. 1984).

Mixing as a consequence of melting

A further constraint that must be considered in any model for the generation of these anomalously incompatible element enriched 12 – 15°E lavas is found in the excellent correlations between normative Ne content (argued above

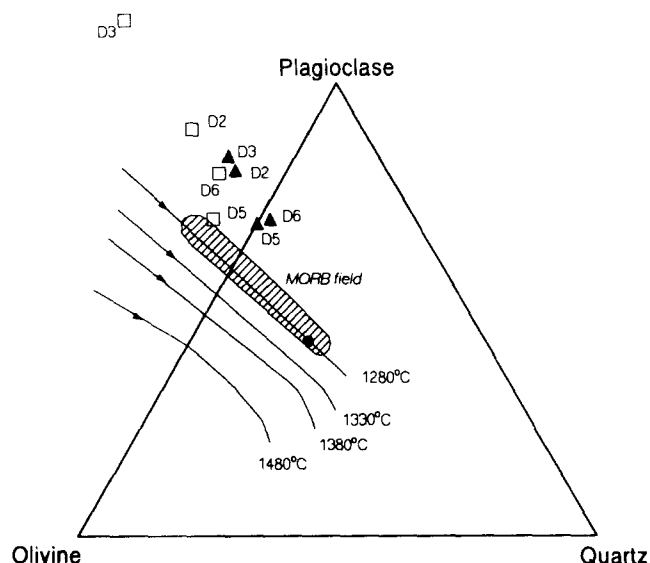


Fig. 11. Projection of POLARSTERN 4 lavas from Diopside onto the olivine-plagioclase-quartz plane following the method of Walker et al. (1979). Open squares are most primitive (Mg No. > 0.65) bulk-rock compositions, and solid triangles are most primitive quench glass analyses from the individual dredges. Isotherms are taken from the parameterization model of McKenzie and Bickle (1988); the solid dot is the point average of melts generated at 1,280°C (see McKenzie and Bickle 1988, for discussion). The shaded field demarcates most primitive MORB (MgO > 9.0%) compositions following McKenzie and Bickle (1988).

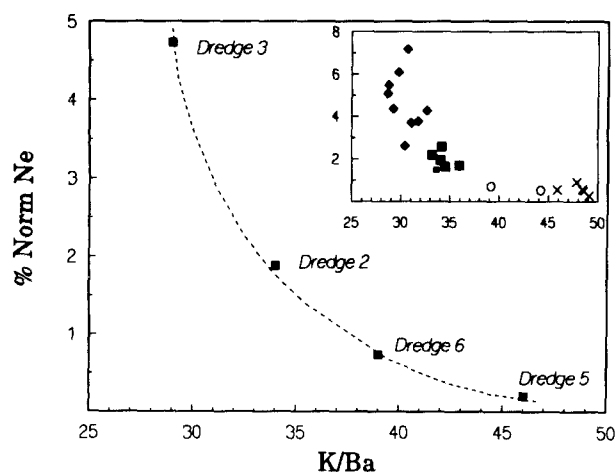


Fig. 12. Covariation between average normative Ne content and K/Ba ratio of the Ne-normative lavas from individual POLARSTERN ANT IV/4 dredges. Insert shows data for individual dredges. Symbols as in Fig. 2

to relate inversely to degree of partial melting), and incompatible-element and isotopic ratios (Figs. 12, 13). These correlations, in conjunction with Figs. 8 and 9, suggest that the degree of geochemical enrichment of the lavas, as reflected by their incompatible-element ratios and isotopic composition, decreases as the degree of melting increases. Such correlations argue against the rather simpl-

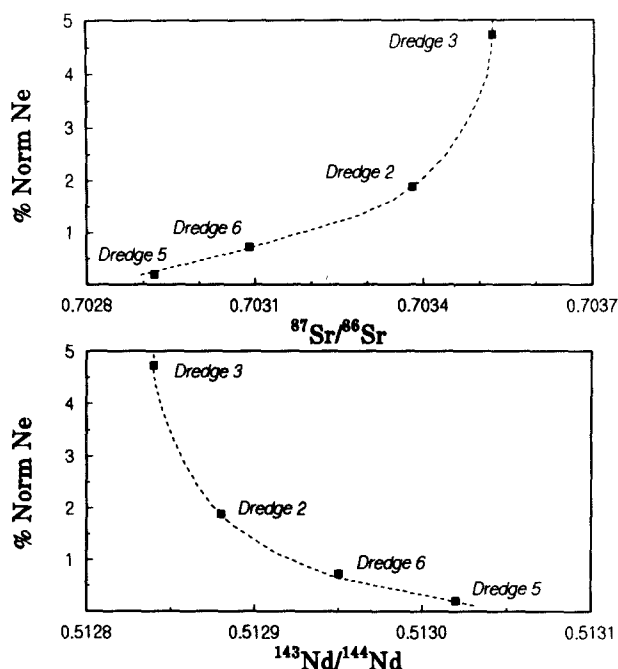


Fig. 13. Covariation between average normative Ne content and $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of the lavas from individual POLARSTERN ANT IV/4 dredges

istic model depicted in Fig. 10, since this would require the very fortuitous situation that the degree of melting decreased systematically as the source region became more enriched.

The mixing trends shown by these lavas (Figs. 6–9) are more consistent with a model in which mixing is a consequence of small but increasing degrees of melting of a source region in which the enriched component comprises an evenly distributed and small proportion (< 3%?) of the geochemically depleted host mantle. With increasing melting there is progressive contamination of the initial melts by low-percentage partial melts ($\leq 1\text{--}2\%$) extracted from the geochemically depleted wall rock. It is clear from Fig. 10 that although the incompatible-element ratios in question will be fractionated to some extent during the partial melting process, the dominant control on the correlations shown in Fig. 10 relates to the progressive mixing by contamination. This model is similar to that proposed by Chen and Frey (1985) to account for the geochemical character of the post-erosional alkaline volcanics on Haleakala, Hawaii. It is also similar to that proposed by McKenzie and Bickle (1988) and Klein and Langmuir (1987) in their concept of a melting column beneath a spreading ridge, where the volume of melt progressively increases as the melt rises up the melting column towards the surface through continued interaction with the wall rock. Prinzhofer et al. (1989) similarly have argued, on the basis of numerical calculations, that melts erupted from a (pyroxenite) veined peridotite mantle show compositional variations that are dominated by mixing between the two end-member melts, and that fractionation of incompatible-element ratios is of secondary importance.

Petrogenetic model

Taking all the available data into account, the geo-tectonic model that we would propose to account for the petrogenesis of these geochemically enriched, alkali basalts found between 12 and 15°E on the SWIR can be expressed as follows. Low degree (2–3%) melts formed in the cooler outer regions of the upwelling Bouvet mantle plume (centred some 700 km to the west) have invaded the surrounding, depleted, sub-oceanic asthenosphere in the form of silicate veins. The effect of the low degree of melting has been to fractionate the incompatible-element ratios in the melt relative to those characteristic of the lavas erupted at the present day surface expression of the Bouvet mantle plume, yet maintain similar isotopic characteristics. Radial mantle flow away from the rising plume has introduced some of this geochemically enriched mantle beneath this section of the SWIR. The geochemically enriched component in this contaminated mantle is assumed to be a low-melting-temperature fraction which, on the scale of subsequent melting, is uniformly distributed.

As this contaminated mantle rises beneath the spreading axis, adiabatic melting is initiated and the enriched component is the first fraction to enter the melt to produce a Ne-normative alkaline magma. After 2–3% melting the enriched (vein) component is exhausted and, with further rise and pressure release, continued melting incorporates increasing amounts of normal geochemically depleted sub-oceanic mantle. The mixing that takes place as a consequence of this increased contribution of partial melt derived from the depleted wall rock causes the composition of the rising magmas to become progressively less Ne-normative, and leads to a progressive change in incompatible-element and isotopic ratios towards the composition of normal depleted MORB. This process of mixing as a consequence of melting accounts for the very coherent mixing trends displayed by the data. The systematic change in incompatible-element ratios shown by these lavas is therefore dominantly the result of this mixing, and is *not* due to fractionation as a result of small differences in distribution coefficients between the respective elements during the partial melting event leading to these ridge-axis lavas (significant fractionation of these ratios did occur earlier as a result of the very low degrees of melting of the outer portion of the Bouvet plume). The overall degree of melting must remain low (< 5%) so as to maintain the Ne-normative character of the lavas.

The apparent absence of extensive recent volcanic activity along this section of the SWIR, inferred from the very poorly defined central magnetic anomaly, suggests that spreading and associated magma supply along the two sections of ridge in question are in a state of quiescence. The confused topography and unusual physiographic complexity of this section of the SWIR may be related to the postulated change in spreading direction (~ 10° counter-clockwise) along the American-Antarctic Ridge and the SWIR at ~ 20 million years (Barker and Lawver 1988). We suggest that this shift in plate motion created a new zone of crustal extension across a broad region in order to accommodate the new geometry and spreading direction. The present day local complexity of

this terrain indicates that it is poorly organized and is still evolving towards a stable geometry. The area may therefore overlie a region of diffuse mantle upwelling, unlike that occurring at typical ridges, but similar to that occurring beneath extensional terrains during early rifting in mid-plate regions.

We suggest that the reason for the unusually low degrees of melting beneath this section of the SWIR and for the eruption of these alkaline magmas relates to the absence of well established volcanic activity due to this current tectonic reorganization. Under normal conditions of spreading one would expect any high-pressure, low-volume alkaline melts to coalesce with, and be diluted by, more voluminous (tholeiitic) melts in conduits en route to the surface (to give rise perhaps to more typical T-type MORB). The proposed absence of a well established plumbing system containing tholeiitic magma beneath this section of ridge, coupled with a generally cooler thermal regime, has allowed these low-volume Ne-normative melts to reach the surface and erupt with their geochemical character primarily intact. The lavas in question may therefore be equivalent to the low-percentage, Ne-normative initial melts inferred by McKenzie and Bickle (1988) to represent the extreme end-member in a MORB mixing array (albeit derived from a geochemically enriched mantle, rather than from typical depleted MORB mantle).

The apparent lack of tholeiitic magmatism along this section of the Southwest Indian Ridge (sample PS4-4-68 is an exception) may reflect either the final stages of volcanic activity prior to the magma supply shutting down for a time, or the first stage of new volcanic activity on a ridge segment that has experienced a volcanic and tectonic hiatus. In this regard, evidence for the formation of Ne-normative alkaline magmas during the waxing and waning stages of tholeiitic volcanism is well established in areas such as Hawaii (Clague 1987). Once the heat flow is increased, and associated magma generation and eruption rate are better developed, we suggest that the geochemical consequence will be similar to that observed in T- and P-type MORB from the SWIR further to the west, as described by le Roex et al. (1983).

In summary, the majority of lavas dredged from the SWIR between 12 and 15°E are moderately primitive MORB yet show extreme enrichment in incompatible elements, are Ne normative, and have highly fractionated incompatible element ratios. It is proposed that these lavas result from unusually low (< 5%) degrees of melting of a source region that has experienced prior geochemical enrichment by means of veining by low percentage (~ 2%) partial melts derived from the upwelling Bouvet mantle plume. The ranges in composition (normative, isotopic and incompatible-element ratios) observed in these lavas are interpreted to result from low-percentage partial melts of this contaminated mantle source region incorporating progressively greater amounts of normal depleted asthenosphere with increasing degree of melting. These geochemically enriched lavas are therefore interpreted as marking the eastern extent of influence (15°E) of the Bouvet mantle plume on the composition of the surrounding sub-oceanic mantle.

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