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Crust-mantle evolution in the vicinity of the Bouvet Triple Junction – A synthesis

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Detailed petrologic and geochemical studies of lavas from the vicinity of the Bouvet triple junction indicate that the lavas show a wide range in compositional differentiation extending from Mg-rich picrite basalts to Fe-Ti rich ferrobasalts. Furthermore, in addition to normal geochemically 'depleted' mid-ocean ridge basalt (MORB), geochemically 'enriched' MORB occurs in abundance throughout the region but is absent to the east of 15°E.

Tectonic location (e.g. fracture zone or ridge axis) is shown to exert an important control on the degree of low pressure fractional crystallization experienced by the lavas prior to eruption, but has little effect on degree of geochemical 'enrichment' or source region composition.

An integrated model is proposed whereby the mantle source region of 'enriched' lavas from the Southwest Indian and American-Antarctic Ridges is invaded by low volume partial melts related to the upwelling Bouvet mantle plume. The mantle source region of 'enriched' MORB from the southern Mid-Atlantic Ridge has been enriched by a similar process but related to the upwelling of the geochemically distinct 'Shona' mantle plume.

Noukeurige petrografiese en geochemiese studies van lawa uit die omgewing van die Bouvet-driepuntaansluiting dui aan dat die lawa 'n breë spektrum van verskille in samestelling dek wat strek van Mg-ryke pikrietbasalt tot Fe-Ti-ryke ferrobasalt. Benewens normale geochemies 'verarmde' middeoseaanrifbasalt (MORB) kom geochemies 'verrykte' MORB in oorvloed dwarsdeur die gebied voor, maar is oos van 15°O afwesig.

Daar is gevind dat die tektoniese ligging (bv. by die breuksone of die rif-as) in hoë mate die graad van fraksionele kristallisasie by lae druk, waaraan die lawa voor uitbarsting blootgestel is, beheer, maar slegs 'n geringe uitwerking het op die graad van geochemiese 'verryking' of die samestelling volgens die oorspronggebied.

'n Samevattende model word voorgestel waarvolgens die manteloorspronggebied van 'verrykte' lawa uit die Suidwes-Indiese en Amerika-Antarktika spreisones binnegedring is deur klein volumes gedeeltelik gesmelte materiaal wat deur die opwellende Bouvet-mantelpluim veroorsaak is. Die manteloorspronggebied van 'verrykte' MORB van die suidelike Mid-Atlantiese rif is deur 'n soortgelyke proses verryk, maar is aan die opwelling van die geochemies kenmerkende 'Shona'-mantelpluim gekoppel.

Introduction

This paper summarizes the results from a series of coordinated studies of the igneous rocks of the Southern Ocean basin as part of the Southern Ocean Lithosphere Project (SOLP). Our work has been primarily concerned with oceanic basalts erupted along the mid-ocean ridges and now forming, beneath a thin sediment cover, the floor of the ocean basins. Mid-ocean ridge basalts (MORB) have been extensively studied in most of the major oceanic regions throughout the world. The Southern Ocean covers a large but previously little studied portion of the earth's volcanic crust. Over the past ten years that situation has substantially changed. Cooperative programmes with several institutions and several countries, plus the developing capability to dredge deep water ocean bottom samples using local ships, have allowed systematic sampling of the ocean ridge systems surrounding southern Africa. This report deals with the composition and petrology of the ridge basalts, the relations between basalt composition and tectonic setting and the influence of 'hot spots' (or mantle plumes) on the nature of oceanic basalts.

Tectonic Setting

The Bouvet triple junction, at ~54.5°S, 1°W, marks the bifurcation of the Mid-Atlantic Ridge (MAR) into the Southwest Indian Ridge (SWIR), which trends in a NE direction towards the Central Indian Ocean triple junction, and the American-Antarctic Ridge (AAR) which trends in a SW direction towards the Scotia Arc located at ~24°W (Fig. 1). The SWIR and the AAR are both extremely slow spreading ridge systems with half spreading rates of 0.86 and 0.90 cm yr^{-1}, respectively, while the southern end of the MAR has a moderate spreading rate of 1.6 cm yr^{-1} (Sclater *et al.* 1976, Lawver & Dick 1983).

The AAR and the western end of the SWIR are characterized by short ridge segments offset by long, deep transform faults, the most prominent being the Bullard, Conrad and Vulcan on the AAR, and the Bouvet, Islas Orcadas and Shaka transecting the western end of the SWIR. In contrast, the southern end of the MAR has no major offsets within the region sampled between the triple junction and the Agulhas fracture zone at ~47°S.

Lawver *et al.* (1982) have noted that the Bouvet triple junction is currently in a ridge-transform-transform configuration, and to maintain this geometry it is necessary that the triple junction episodically jumps back up the MAR. Such a northward jump requires the elongation of the SWIR and AAR with the initiation of new spreading centers adjacent to the triple junction. The most recent extension of the SWIR is the Spiess Ridge (Fig. 1). Further details on the geophysics of the region can be found in Sclater *et al.* (1976), Lawver *et al.* (1982) and Lawver & Dick (1983).

Analytical

During the course of this study 520 bulk rock samples have been analysed for 10 major and 14 trace elements by X-ray fluorescence (XRF) techniques. In addition, over 3000 major element mineral analyses of phenocryst, microphenocryst and xenolith phases, and ~600 quench basaltic glass major element analyses have been completed using electron microprobe analysis.

Rare earth elements were analysed using instrumental neutron activation analysis techniques (Ila & Frey 1984) at the Massachusetts Institute of Technology. In all 36 samples were analysed for their rare earth element contents. Sr and Nd isotopic analyses were conducted on 37 samples using the mass spectrometer facilities of Prof. S.R. Hart at the Massachusetts Institute of Technology. These methods have been described by Hart & Brooks (1977) and Zindler *et al.* (1979).

Mineralogy and Geochemistry of Southern Ocean lavas

The majority of samples dredged from the Southern Ocean ridge systems comprise fragments of pillow basalt with selvages of quench basaltic glass. In most samples, textures range from aphyric through microporphyritic to sparsely and moderately plagioclase phyric. Highly plagioclase phyric lavas are particularly common along the American-Antarctic Ridge and at scattered localities along the Southwest Indian Ridge and southern Mid-Atlantic Ridge. A single dredge haul from the southern Mid-Atlantic Ridge is characterized by the occurrence of abundant highly olivine phyric (picrite) basalt.

Olivine and plagioclase are ubiquitous mineral constituents in the samples studied, while Cr-spinel microphenocrysts are common in the more primitive lavas. Clinopyroxene occurs as an important phenocryst phase in the majority of fracture zone basalts and in many of the ridge axis samples from the western end of the Southwest Indian Ridge and from the southern end of the Mid-Atlantic Ridge. Highly evolved ferrobasalts from the Spiess Ridge segment of the Southwest Indian Ridge contain titanomagnetite microphenocrysts, while titanomagnetite and ilmenite are common matrix phases in the hypabyssal rocks. Plagioclase in particular shows complex zoning patterns (normal, reverse and oscillatory zoning) and commonly contains melt inclusions. Olivine and clinopyroxene phenocrysts tend to show more uniform and moderate degrees of normal zoning.

Analysed samples from the ridge systems are all basaltic in composition and include both extrusive (basalt) and intrusive (diabase) varieties. With few exceptions the basalts are olivine normative tholeiites; a few of the more evolved lavas contain normative quartz and some lavas are slightly nepheline normative (up to 1.2 % Ne, with Fe_2O_3/FeO = 0.15). Whole rock compositions of aphyric lavas range from primitive basalt with 8 to 10 per cent MgO and high Mg# ranging from 65 to 70 (Mg# = 100Mg/Mg + Fe^{2+} in atomic percentages), to highly evolved ferrobasalts with high iron contents (total iron expressed as FeO = 10 to 14 %) and TiO_2 (2 – 4 %) contents and low Mg# (35 – 45). Incompatible minor elements such as P and K correlate with degree of differentiation (e.g. Mg#) and high absolute abundances of Al_2O_3 and MgO correlate respectively with modal plagioclase (Al_2O_3 reaches 24 % in the most plagioclase phyric basalts) and olivine (MgO reaches 16 % in the olivine phyric picrite basalts from the southern MAR). Representative whole rock analyses are given in Table 1.

Ferromagnesian trace elements have a wide range in concentration in aphyric Southern Ocean basalts (e.g. Ni = 15 – 250 ppm; Cr = 5 – 600 ppm) and show a general negative correlation with Mg#. Absolute incompatible trace element abundances generally correlate positively with degree of differentiation and are also extremely varied (e.g.

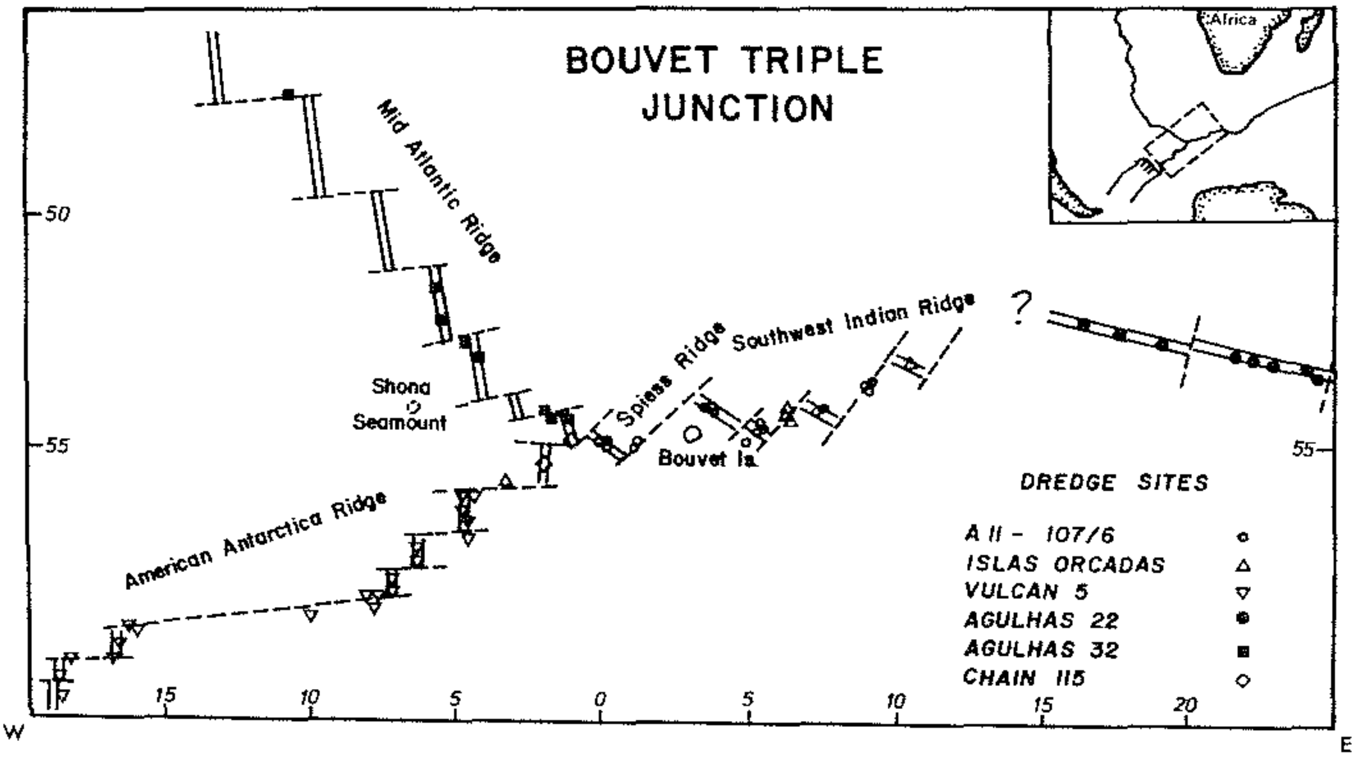

Fig. 1. Sketch map of the Bouvet triple junction area in the Southern Ocean showing localities of individual dredge hauls and overall sample coverage.

Table 1

Major and trace element analyses of selected basalts from the Southern Ocean. FeO* = all iron as FeO; Mg# = atomic Mg*100/(Mg + Fe^{2+}) with Fe_2O_3/FeO = 0.15; AP = aphyric, MiP = microporphyritic; SP = sparsely phyric; PP = highly plagioclase phyric; OP = highly olivine phyric; Fz = fracture zone; R = ridge axis; N, T and P refer to type of MORB. Data from le Roex *et al.* (1983, 1985, 1987).

	Southwest Indian Ridge (AII-107-)							Southern Mid-Atlantic Ridge (AG32-)						American-Antarctic Ridge (V5-)					
	31-4	36-11	56-27	57-2	57-16	58-12	66-16	3-75	3-36	7-36	6-2	9-1	10-1	25-1	30-60	38-15	27-34	38-13	33-66
	MiP	PP	PP	AP	AP	OP	AP	AP	OP	SP	PP	MP	AP	SP	SP	MP	AP	OP	OP
	R	FZ	R	R	R	R	FZ	FZ	FZ	FZ	R	R	R	R	R	FZ	R	FZ	FZ
	T	N	N	T	N	P	T	N	N	N	N	T	T	N	N	N	T	T	P
SiO_2	51.14	50.06	48.71	50.29	49.97	48.04	48.74	49.44	47.65	50.23	50.36	50.58	50.53	50.39	50.20	50.58	50.42	50.35	49.08
TiO_2	2.72	1.36	0.76	1.87	1.45	1.57	1.80	1.93	1.85	1.45	1.45	1.79	1.60	1.78	1.80	1.55	1.78	1.27	2.04
Al_2O_3	13.96	16.97	18.39	15.00	15.61	16.21	15.12	14.62	12.50	15.18	14.61	14.14	14.95	16.59	15.69	16.30	15.86	17.45	16.06
FeO^*	12.22	7.87	8.91	9.99	9.85	10.53	9.83	11.26	11.73	10.12	10.33	11.01	10.13	9.45	9.48	9.10	8.56	8.85	10.18
MnO	0.21	0.15	0.14	0.18	0.18	0.17	0.16	0.18	0.19	0.18	0.19	0.20	0.19	0.18	0.18	0.18	0.17	0.14	0.22
MgO	4.73	6.83	8.83	8.50	8.78	9.53	8.21	7.01	13.62	7.30	7.71	6.67	7.20	6.56	8.33	7.34	7.22	7.62	8.13
CaO	8.72	12.25	12.22	10.79	11.14	8.43	10.84	10.86	8.89	11.53	11.57	10.88	11.60	11.18	10.47	10.99	11.09	11.13	8.66
Na_2O	4.42	3.29	2.33	2.53	2.83	3.22	2.50	2.84	2.69	2.45	2.56	2.81	2.94	3.28	3.15	3.17	3.33	2.79	3.24
K_2O	0.85	0.27	0.05	0.37	0.16	0.74	0.41	0.28	0.24	0.39	0.19	0.38	0.39	0.27	0.38	0.29	0.71	0.35	1.08
P_2O_5	0.48	0.14	0.06	0.22	0.13	0.40	0.17	0.20	0.22	0.20	0.14	0.20	0.20	0.21	0.23	0.20	0.28	0.13	0.44
LOI	0.81	1.00	0.32	0.46	0.64	1.70	2.29	1.02	0.86	0.96	0.37	0.52	0.89	0.87	0.88	0.82	0.75	1.79	1.43
Total	100.26	100.19	100.65	100.20	100.74	100.54	100.07	99.64	100.44	99.93	99.48	99.18	100.62	100.76	100.78	100.52	100.17	101.87	100.56
Zr	272	93	44	129	89	141	88	123	118	111	94	122	108	140	140	116	137	76	170
Nb	29	2.0	ND	10.8	ND	22	9.5	6.0	5.6	5.5	4.9	9.9	7.3	1.8	8.2	4.3	15.6	6.1	27
Y	51	30	25	34	30	24	24	44	41	36	32	34	31	41	38	35	29	20	24
Rb	16.3	4.7	ND	6.8	2.2	4.8	8.9	5.3	5.8	7.8	3.9	6.6	4.7	3.1	4.7	3.0	7.4	7.6	10.5
Ba	171	22	ND	70	11.3	112	29	36	47	56	46	80	68	<2.3	46	11.8	113	78	173
Sr	256	152	76	200	114	505	188	116	102	117	116	176	183	150	193	148	337	218	562
Co	39	41	50	49	53	53	56	49	68	45	49	48	46	48	49	42	44	46	52
Cr	22	269	187	321	362	286	509	212	994	271	197	52	202	209	332	306	270	317	258
Ni	23	100	176	166	185	204	226	95	524	99	788	38	67	77	166	100	87	131	116
V	227	247	27	275	257	166	259	331	318	259	288	310	277	267	245	236	235	171	188
Zn	120	77	55	92	82	88	122	100	99	88	85	95	81	84	87	82	74	97	98
Cu	62	69	91	65	76	49	84	52	46	59	63	57	64	47	51	54	55	67	53
Sc	31	37	41	40	40	31	35	41	37	39	43	44	42	35	37	35	36	28	27
La	–	4.2	1.5	8.9	3.5	17.4	5.9	–	–	–	–	–	–	4.8	7.4	5.0	11.1	6.2	20.8
Ce	–	11.9	5.4	21.6	11.3	37.6	14.9	–	–	–	–	–	–	18.1	22.6	17.5	30.1	14.4	46.5
Nd	–	9.5	4.2	14.1	9.5	18.9	10.6	–	–	–	–	–	–	14.2	15.1	12.6	18.0	9.2	22.8
Sm	–	3.09	1.73	4.55	3.37	4.11	3.07	–	–	–	–	–	–	4.68	4.68	3.81	4.42	2.93	5.25
Eu	–	1.16	0.74	1.69	1.27	1.46	1.16	–	–	–	–	–	–	1.61	1.59	1.38	1.59	1.11	1.77
Tb	–	0.77	0.45	0.95	0.84	0.69	0.65	–	–	–	–	–	–	1.03	0.88	1.12	0.76	0.66	0.81
Yb	–	2.84	2.81	3.52	3.42	2.38	2.09	–	–	–	–	–	–	3.99	3.53	3.25	2.73	1.80	2.07
Lu	–	0.44	0.44	0.47	0.48	0.35	0.32	–	–	–	–	–	–	0.60	0.53	0.49	0.40	0.28	0.30
Zr/Nb	9.4	47	>22	11.8	>38	6.8	9.3	21	21	20	19.1	12.3	14.8	78	17.1	27	8.8	12.5	6.3
Y/Nb	1.8	15	>12	3.1	>13	1.1	2.5	7.4	7.3	6.6	6.5	3.4	4.3	23	4.6	8.1	1.9	3.3	0.9
Zr/Y	5.3	3.1	1.8	3.8	3.0	6.3	3.6	2.8	2.9	3.1	2.9	3.6	3.5	3.4	3.7	3.3	4.7	3.8	7.1
Ti/Zr	60	88	104	87	98	64	123	94	94	78	92	88	89	76	78	80	78	100	72
La/Sm_N	–	0.83	0.53	1.19	0.63	2.58	1.17	–	–	–	–	–	–	0.63	0.96	0.80	1.53	1.29	2.42
Mg#	43.9	63.7	66.7	63.3	64.3	64.7	62.8	55.7	70.2	59.2	60.2	55.1	59.0	58.4	64.0	62.0	63.1	63.5	61.8

Zr = 60 - 360 ppm; Nb = 1 - 47 ppm; Ba = 2 - 300 ppm; La = 1.5 - 31 ppm). There are no obvious systematic differences in trace element abundance ranges between lavas from the different ridge systems, although there are some differences in the mutual variations in some diagnostic incompatible trace element ratios between lavas from the southern MAR and those from the SWIR and AAR (see later discussion).

Certain incompatible trace element ratios are diagnostic of mid-ocean ridge basalt types (Sun *et al.* 1979) and ratios such as Zr/Nb, Y/Nb, chondrite normalized La/Sm (La/Sm_N) and Zr/Y are particularly applicable for characterizing basalts from this region of the Southern Ocean (le Roex *et al.* 1983, 1985). For example, plots of Zr versus Nb (Fig. 2a) or chondrite normalized REE abundances (Fig. 2b) serve to distinguish three types of lave which occur within the region, viz. N-, T- and P-type MORB. Geochemically depleted N-type MORB is the most common variety of MORB, occurs in varied abundance throughout the region, and has the following incompatible trace element characteristics (Table 2); high Zr/Nb (17 - 102) and Y/Nb (5 - 34) ratios, low Zr/Y (2 - 4) ratios and LREE depletion (La/Sm_N = 0.5 - 1.0).

Geochemically enriched plume or P-type MORB is the least abundant variety with low Zr/Nb (5.8 - 6.8) and Y/Nb

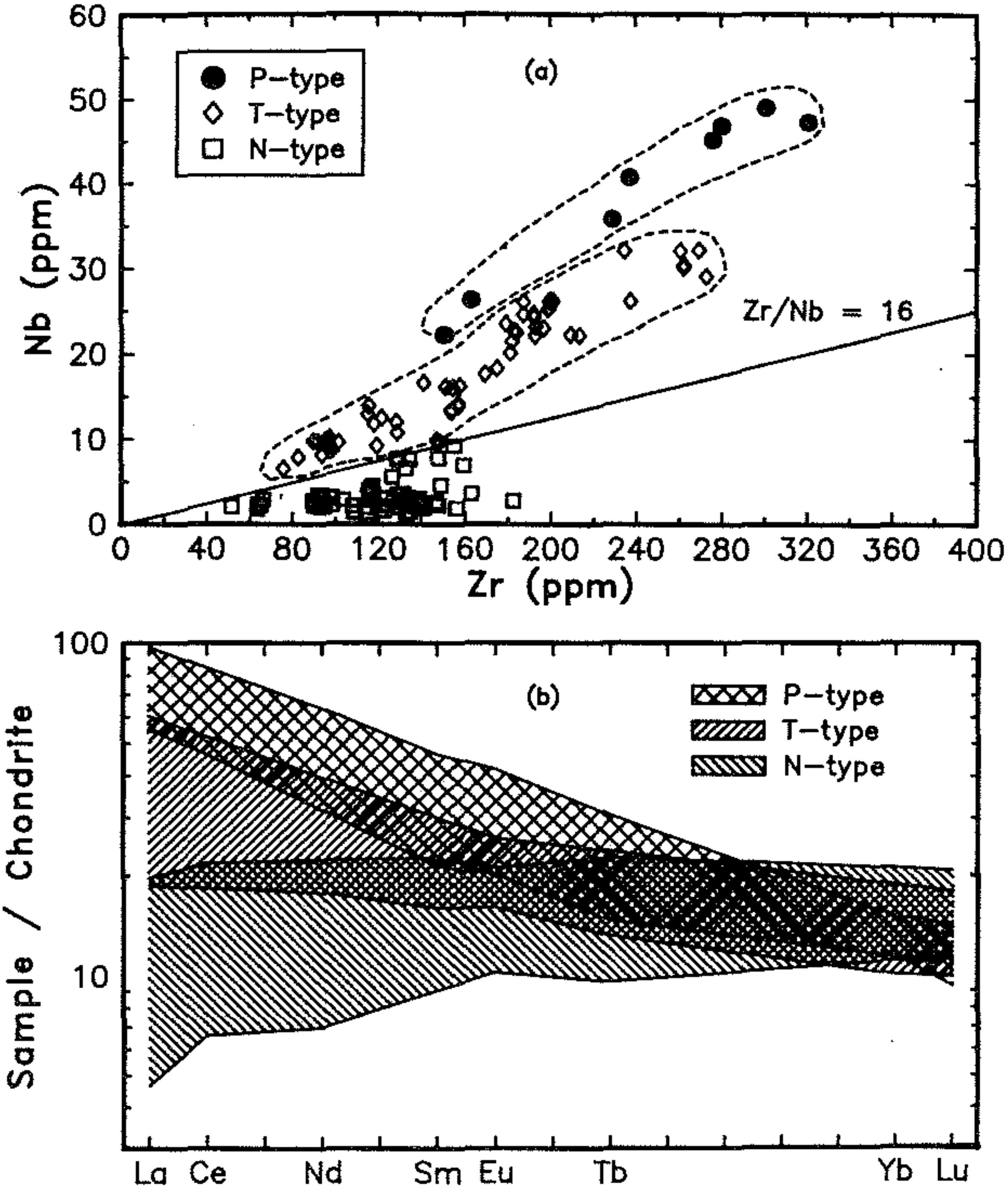

Fig. 2. Variations in Zr-Nb (a) and chondrite normalized rare earth elements (b) in Southern Ocean MORB. A chondritic Zr/Nb ratio of 16 is shown for reference in (a). N-type MORB is geochemically 'depleted'. P-type MORB is geochemically 'enriched' and T-type MORB is 'transitional' between the two. Chemical characteristics of the three varieties of MORB are summarized in Table 2.

(0.9 – 1.2) ratios, high Zr/Y ratios (6 – 8) and strong chondrite normalized LREE enrichment (La/Sm_N = 2.1 – 2.6). T-type MORB is geochemically transitional with relatively low Zr/Nb (8.0 – 16) and Y/Nb (1.3 – 5.0) ratios, intermediate Zr/Y ratios (3 – 7) and slight chondrite normalized LREE enrichment (La/Sm_N = 1.1 – 2.0).

Although a large number of samples have been grouped into the depleted MORB category, there is a significant range in degree of depletion reflected by these lavas. Figure 3 depicts a number of histograms illustrating variations in Zr/Nb ratio (a sensitive indicator of enrichment/depletion in MORB) in lavas from the three ridge systems, and it is

Table 2

Summary of diagnostic trace element ratios in basalts from the southern Mid-Atlantic Ridge and the Southwest Indian and American-Antarctic Ridges (le Roex *et al* 1983, 1985, 1987). Data from Bouvet from le Roex & Erlank (1982).

	Southern M.A.R.		S.W.I.R. and A.A.R.			Bouvet
	N-type	T-type	N-type	T-type	P-type	
Zr/Nb	16-38	8.0-16	17-78	7.7-15.5	5.8-6.8	6.4
Y/Nb	5.2-15.7	2.1-5.0	4.6-23	1.3-4.3	0.9-1.2	0.9
Zr/Y	2.0-3.6	2.9-4.0	1.8-4.2	3.1-7.1	6.1-7.9	7.5
Ti/Zr	73-117	75-100	65-125	60-127	64-81	78
Zr/Ba	1.8-4.2	1.4-1.8	1.7>33.6	0.9-5.0	1.0-1.3	1.2
$^{87}Sr/^{86}Sr$	0.70290-0.70356	0.70339-0.70364	0.70246-0.70297	0.70291-0.70370	0.70356-0.70364	0.70365-0.70376[a]
$^{143}Nd/^{144}Nd$	0.51303-0.51286	0.51282-0.51289	0.51302-0.51312	0.51301-0.51284	0.51295-0.51286	0.51282-0.51285[b]

[a] O'Nions & Pankhurst (1974)
[b] O'Nions *et al*. (1977)

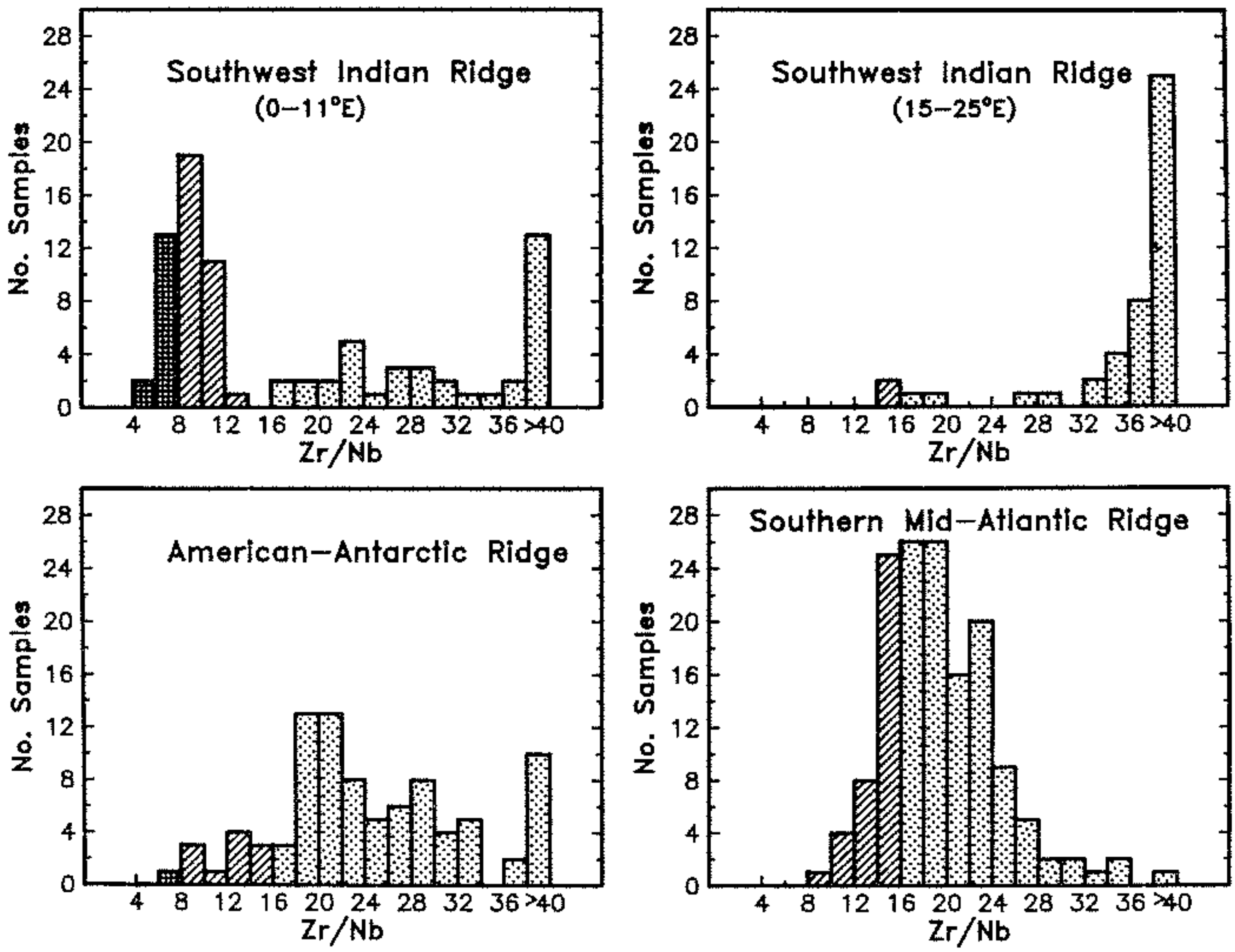

Fig. 3. Histograms of Zr/Nb ratio (as measure of source region depletion/enrichment) in Southern Ocean MORB showing varied abundances of N- (stippled), T- (shaded) and P-type (cross-hatched) MORB on the different ridge systems.

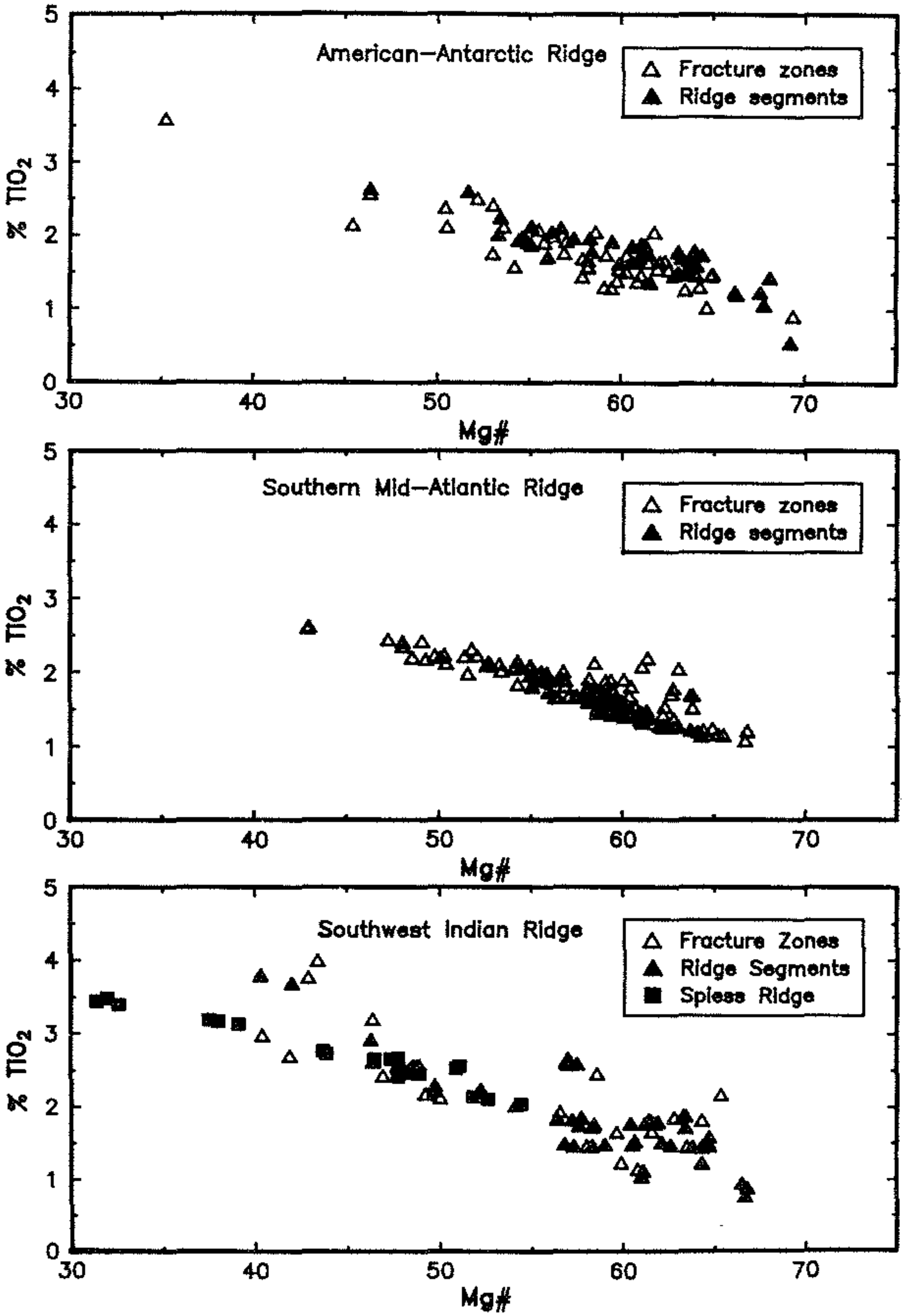

Fig. 4. Variation in TiO_2 with respect to Mg# (100Mg/Mg + Fe^{2+} in atomic percentage) in ridge axis and fracture zone basalts from the Southern Ocean.

evident that not only do Zr/Nb ratios in N-type MORB range from slightly greater than chondritic (i.e. ~16) to over 100, but there appears to be a systematic difference in degree of depletion shown by N-type MORB from the different ridges (and therefore by implication their source regions). N-type MORB to the east of 15°E is the most depleted with Zr/Nb ratios generally greater than 40, while N-type MORB from the southern MAR and the AAR is the least depleted with the majority of basalts having Zr/Nb ratios in the range 16 – 25, i.e. only slightly greater than chondritic. This observation is borne out by other trace element ratios of the lavas.

Sr and Nd isotope ratios of selected N-, T- and P-type MORB correlate with their incompatible trace element ratios, although there is some degree of overlap between the different MORB types: N-type MORB from the SWIR and AAR have low $^{87}Sr/^{86}Sr$ = 0.70246 – 0.70297, and high $^{143}Nd/^{144}Nd$ = 0.51302 – 0.51312 ratios; T-type MORB have intermediate $^{87}Sr/^{86}Sr$ = 0.70291 – 0.70370, and $^{143}Nd/^{144}Nd$ = 0.51301 – 0.51284 ratios; and P-type MORB have high $^{87}Sr/^{86}Sr$ = 0.70356 – 0.70364, and low $^{143}Nd/^{144}Nd$ = 0.51295 – 0.51286 ratios. The range in isotopic ratios fall within the typical mantle array on a Sr-Nd correlation diagram, and the samples extend from compositions typical for depleted MORB to compositions similar to those of the Bouvet Island lavas (i.e. $^{87}Sr/^{86}Sr$ = 0.7037, $^{143}Nd/^{144}Nd$ = 0.51284).

In terms of their Sr and Nd isotopic composition, MORB from the southern MAR are unusual in that even those with 'depleted' incompatible trace element characteristics are clearly 'enriched' with respect to isotope ratios when compared to normal 'depleted' MORB from areas such as the Kane fracture zone (Machado *et al.* 1982). In this respect southern MAR basalts are similar to those from the Central Indian triple junction (Price *et al.* 1986).

Influence of tectonic setting on lava composition

One of the fundamental aims of this study has been to attain an understanding of the influence of tectonic setting on the compositions of lavas erupted at contrasting tectonic environments in the Southern Ocean. Such knowledge is a prerequisite to using the compositions of oceanic basalts from diverse tectonic settings – e.g. ridge axes, fracture zones, oceanic islands, seamounts – to infer source region characteristics and ultimately the composition and evolution of the Southern Ocean mantle as a whole.

Comparison of the composition of lavas found at ridge axes and fracture zones, shows that fracture zone basalts tend to reflect a greater range in differentiation than ridge axis basalts. This difference is particularly well illustrated in terms of the greater range in Mg#, greater range in incompatible elements such as TiO_2, Zr or Y, and in the greater relative abundance of low Mg# lavas, shown by fracture zone basalts relative to ridge basalts (le Roex & Dick 1981, le Roex *et al.* 1982, 1983, 1987). Figure 4 shows a plot of TiO_2 versus Mg# for basalts from ridge segments and fracture zones from the three ridge systems, and it is clear that the fracture zone basalts from the AAR and southern MAR tend towards higher concentrations of TiO_2 and lower Mg# than do the ridge axis basalts. This observation is equally true for other incompatible elements. The SWIR does not show as clear a difference between ridge and fracture zone basalts in Figure 4, but with the exception of the Spiess Ridge basalts (see later discussion), a greater number of fracture zone basalts have high TiO_2 and low Mg# than ridge basalts (see Fig. 7 in le Roex *et al.* 1983).

Quantitative modelling techniques, using least squares approximations and trace element partitioning equations (Bryan *et al.* 1969, Gast 1968), have been applied to individual lava suites from ridge segments and fracture zones to determine whether the overall range in degree of differentiation shown by Southern Ocean basalts can be attributed to fractional crystallization of observed phenocryst phases. Results of these studies show that the range in differentiation can in general be quantitatively accounted for by simple low-pressure fractionation of observed phenocryst phases.

The more highly fractionated nature of fracture zone basalts compared to ridge axis basalts from the circum-Antarctic ridge systems and the southern MAR can be attributed to the fracture zone basalts having on average experienced greater degrees (~40 – 76 %) of low pressure fractional crystallization than the ridge axis lavas (10 – 30 %) (le Roex & Dick 1981, le Roex *et al.* 1983). Fractionating minerals comprise the phenocryst assemblage olivine ± plagioclase ± clinopyroxene in proportions consistent with the modal mineralogy of the lavas. A typical example of a least squares calculation and the corresponding trace element modelling is given in Table 3 where a highly evolved ferrobasalt from the Islas Orcadas fracture zone is derived from a less fractionated parental magma by ~40 per cent crystallization of plagioclase (~23 %), clinopyroxene (~15 %) and minor olivine (~1 %). It is clear that both the major and trace element variations are well satisfied by this model.

Le Roex *et al.* (1982) have shown that the basalts from the Spiess Ridge segment of the Southwest Indian Ridge are an exception to the above mentioned generalization that fracture zone lavas tend to have experienced greater degrees of fractional crystallization than the ridge basalts from the Southern Ocean. Lavas dredged from this ridge segment are all highly fractionated ferrobasalts (Total iron as FeO = 10.3 – 14.3 %; TiO_2 = 2.0 – 3.4 %; MgO = 6.0 – 3.5 %) which contrasts sharply with basalt compositions normally found on slow spreading ridge systems. Quantitative modelling shows that the compositional variation found in the Spiess Ridge lavas can be attributed to extensive (up to 65 %) fractional crystallization of plagioclase and clinopyroxene, in approximately equal proportions, minor olivine and, in the most evolved samples, titanomagnetite.

In studies of other ridge systems the occurrence of highly fractionated ferrobasalts has been correlated with spreading rates as ferrobasalts are more abundant on fast spreading ridges, e.g. the East Pacific Rise (Clague & Bunch 1976). This is obviously not the case for the slow spreading Spiess Ridge segment where we have concluded that low rate of magma supply, relative to spreading rate, is the overriding control on the production of ferrobasalt rather than simply spreading rate (le Roex *et al.* 1982). A similar model has been proposed to account for the more evolved magma compositions found at fracture zones relative to ridge axes (le Roex & Dick 1981, le Roex *et al.* 1983). Under these conditions of low magma supply a given magma batch would undergo little replenishment and consequently experience more extreme fractionation than under conditions of more frequent supply and mixing with new batches of primitive magma.

The greater spread in composition in fracture zone basalts stems from the fact that such basalts were originally erupted at the ridge-transform intersections, away from the central zone of magmatic activity and in a cooler heat flow regime than is found mid-way between two adjacent transform fault

Table 3

Least squares approximation and related trace element model relating the average Islas Orcadas fracture zone ferrobasalt to the most primitive basalt from the region. Table reproduced from le Roex *et al*. (1983). Distribution coefficients used in the trace element modelling from le Roex & Dick (1981) and le Roex *et al*. (1982).

	Parental Magma			Mix	
	Obs.	Calc.	Diff.	Variable	wt. %
SiO_2	50.71	50.79	0.08	Ferrobasalt	60.43
TiO_2	1.59	1.68	0.09	Plag (An_{76})	23.00
Al_2O_3	16.93	16.88	−0.05	Cpx (†)	15.47
FeO*	8.78	8.59	−0.19	Oliv (Fo_{81})	1.02
MnO	0.16	0.18	0.02		
MgO	6.16	6.17	0.01	Total	99.91
CaO	12.40	12.28	−0.12		
Na_2O	2.79	2.72	−0.07	†$Wo_{36}En_{47}Fs_{16}$	
P_2O_5	0.20	0.20	0.20		

Sum of squares of residuals = 0.08

Trace elements:

	Parental Magma	Ferrobasalt	
	Obs.	Calc.	Obs.
Zr	116	183	183
Nb	13	21	23
Y	30	43	42
Sr	235	211	224
Sc	34	36	37
Ga	17	19	20
Ni	72	34	30
V	247	335	337

offsets (Forsyth & Wilson 1984). Magma chambers in these distal regions are therefore more ephemeral and subject to more rapid cooling (from the influence of the adjacent cold lithospheric plate) than basalts erupted from near the center of a well established spreading ridge. This hypothesis is supported by recent work by Christie & Sinton (1981) who note that East Pacific ferrobasalts are predominantly associated with the tips of propagating rifts (where rifting is being initiated, and magma chambers are ephemeral) and tend to grade to less differentiated compositions away from the propagating tips (where spreading is well established and magma chambers may have attained a steady state).

Within this context, le Roex *et al*. (1982) have proposed that the abundance of ferrobasalt on the northern end of the Spiess Ridge is the result of its unique tectonic setting adjacent to the northward migrating Bouvet triple junction (Sclater *et al*. 1976, Lawver *et al*. 1982). The Spiess Ridge marks the site of the most recent breakthrough of the SWIR through the colder African plate in response to the northward migration of the triple junction. This has resulted in a balance between magma supply and cooling rate that has favoured large degrees of fractionation; the raised topography of the area may in addition further facilitate the eruption of evolved magmas.

The cooler thermal regime associated with ridge-transform intersections (Forsyth & Wilson 1984) can result in lavas erupted at such localities being generated by slightly lower degrees of partial melting than typical for spreading ridge basalts. This effect, known as the transform fault effect (TFE, Langmuir & Bender 1984), is not strongly manifested in basalts from Southern Ocean fracture zones. However, some evidence for a TFE is seen in fracture zone basalts from the southern MAR in that they tend to have elevated absolute abundances of incompatible elements (e.g. TiO_2 and Zr) for a given Mg#, and lower Mg# for a given Ni content relative to associated ridge axis basalts (le Roex *et al*. 1987). Lowering the degree of melting has a greater influence on incompatible element abundances than on Mg#, and also has a greater influence on Mg# than Ni in view of the high bulk Ni distribution coefficient for mantle assemblages.

One final aspect that needs to be specifically addressed is the question of whether fracture zone basalts and ridge axis basalts systematically tap distinct source regions. Incompatible element ratios (e.g. Zr/Nb, Y/Nb, La/Sm) and Sr and Nd isotopic ratios are not readily fractionated during partial melting or fractional crystallization processes and are therefore particularly useful for characterizing source region composition (Erlank & Kable 1976, Pearce & Norry 1979, Hofmann & Hart 1978). The relative abundance of geochemically enriched and depleted lavas from fracture zones and ridge axes from the three ridge systems of the Southern Ocean are compared in Figure 5 where it is evident that no systematic differences occur in the type of lava erupted at these two contrasting tectonic settings, and by implication in the nature of the source regions giving rise to the lavas. Both tectonic environments show a similar distribution of geochemically 'depleted' (i.e. Zr/Nb > 16, $(La/Sm)_N < 1$) and geochemically 'enriched' (i.e. Zr/Nb < 16, $(La/Sm)_N > 1$) basalt types.

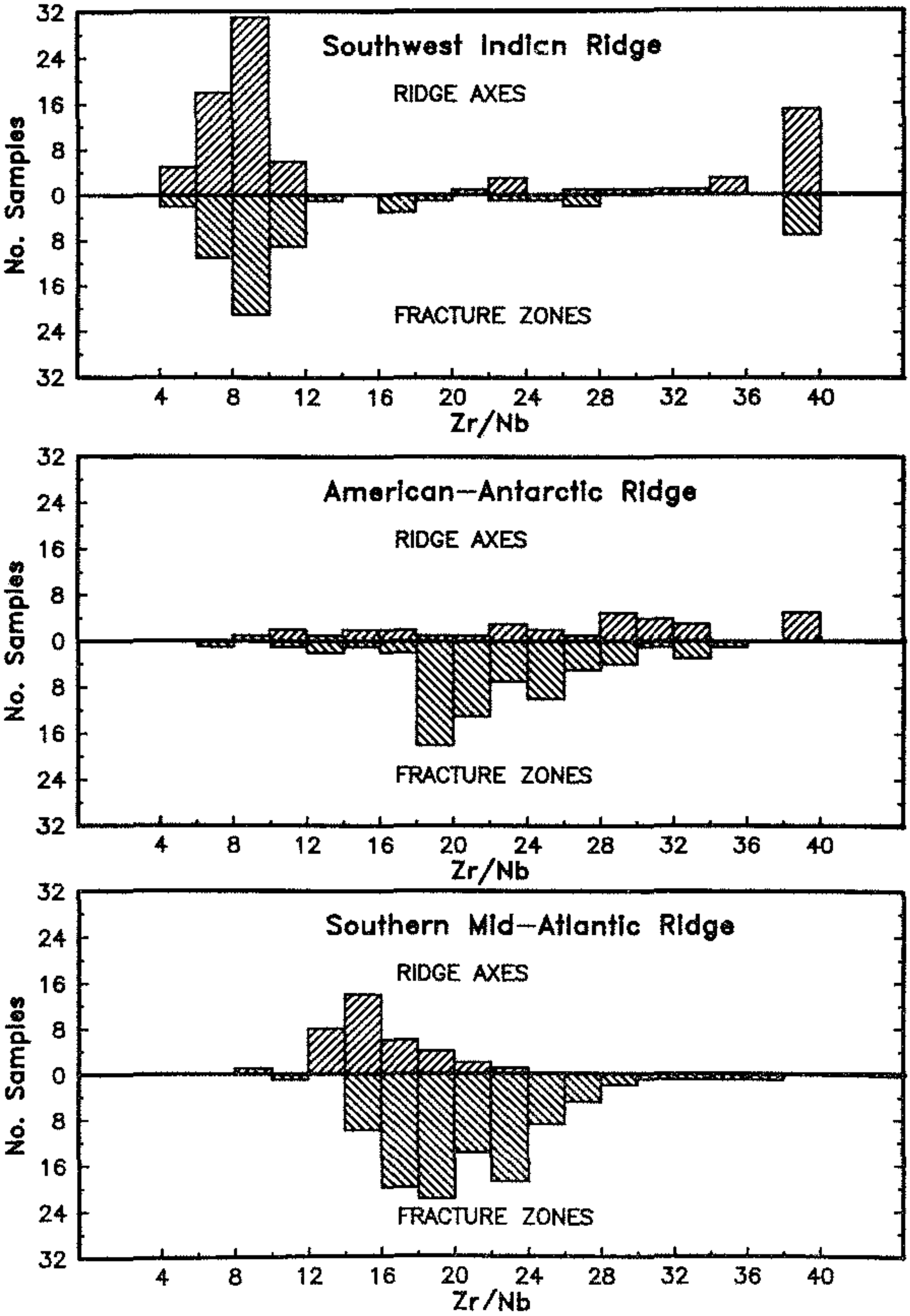

Fig. 5. Histograms contrasting the variation in Zr/Nb ratio (as measure of source region depletion/enrichment) in Southern Ocean ridge axis and fracture zone basalts.

In summary, comparison of the geochemistry of basalts erupted at the contrasting tectonic settings of fracture zones, established ridge segments and at the position of recent ridge jumps, indicates that tectonic setting can have an important influence on the composition of the erupted lavas. The dominant difference is the degree of fractional crystallization experienced by the magmas, with greater fractionation being favoured at fracture zone and recent ridge jump settings. This difference is primarily due to the lower heat flow regime associated with the latter two

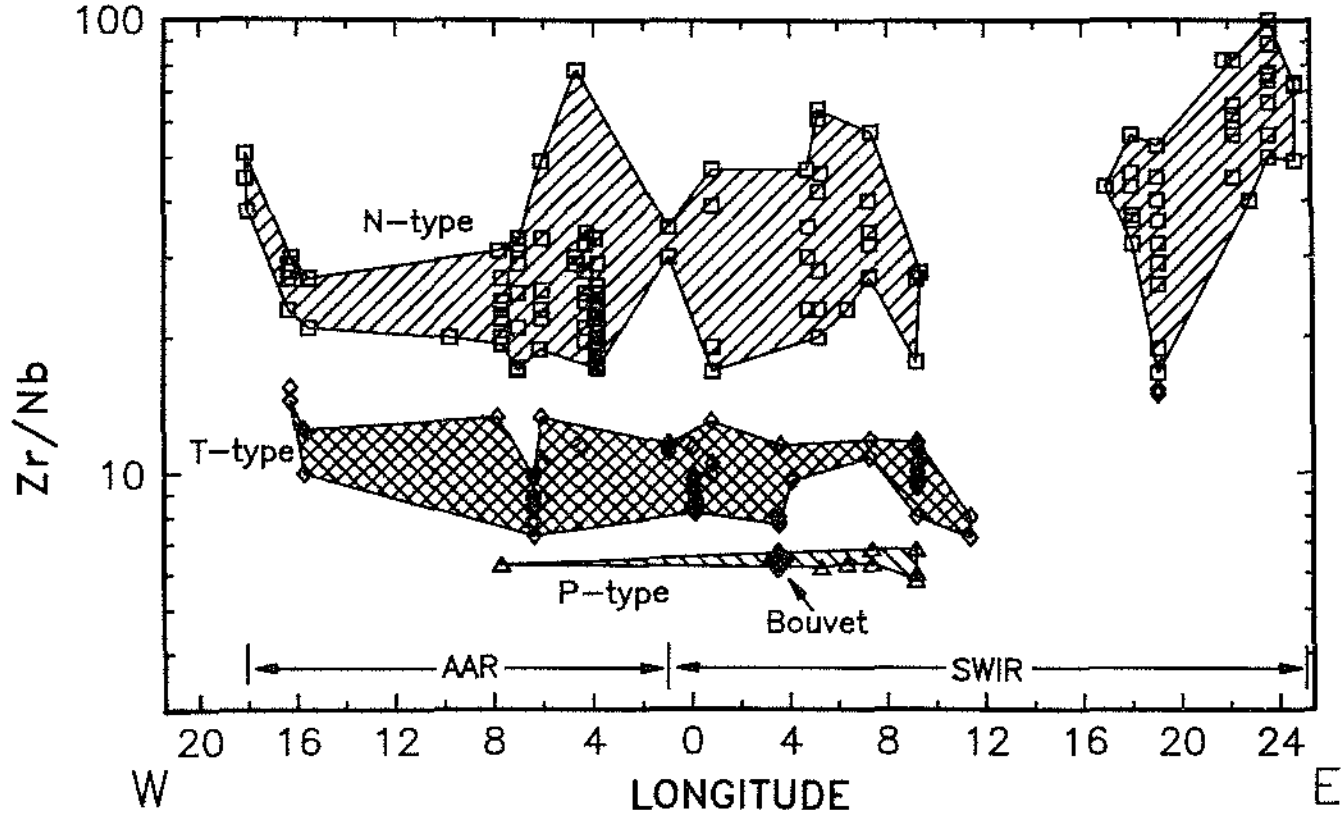

Fig. 6. Variation in Zr/Nb ratio with respect to longitude along the Southwest Indian and American-Antarctic Ridges. Data for Bouvet from le Roex & Erlank (1982).

tectonic environments. Lower heat flow may also have influenced the degree of partial melting experienced by some fracture zone basalts.

Influence of mantle plumes on the evolution of the Southern Ocean mantle

It has long been postulated (e.g. Morgan 1972, Johnson *et al*. 1973) that Bouvet Island, located immediately to the west of the Southwest Indian Ridge and to the southeast of the triple junction (Fig. 1), marks the surface expression of a deep seated mantle plume or hotspot (see Morgan (1972, 1973) and Allégre & Turcotte (1985) for a discussion of mantle plumes or hotspots). In the first study of lavas from the Bouvet triple junction region Dickey *et al*. (1977) noted that lavas dredged from the ridge axis to the immediate east of Bouvet Island and from the Spiess Ridge segment of the SWIR were geochemically enriched and appeared to reflect the influence of the Bouvet hotspot. These authors noted that the plume influence did not appear to extend to the west of the triple junction. One of the major objectives of our studies in the Southern Ocean has been to investigate the nature and particularly the geographical extent of any hotspot influence on the lavas of the circum-Antarctic ridge systems and sub-oceanic mantle in this region.

The geochemically distinct characteristics of hotspot volcanism relative to normal ridge axis volcanism has allowed us to address this problem by investigating specific isotope and incompatible trace element ratios in the lavas of the relevant ridge systems. To avoid possible alteration effects the immobile incompatible trace element ratios Zr/Nb, Y/Nb and Zr/Y and the isotopic ratios of $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ are emphasized. As mentioned previously, these ratios are diagnostic of source region composition and as such provide insight into the nature of the sub-oceanic mantle beneath these ridge systems. Hotspot lavas have low Zr/Nb (<~8), Y/Nb (<1) and $^{143}Nd/^{144}Nd$ (<0.51290) ratios, and high Zr/Y (>~6) and $^{87}Sr/^{86}Sr$ (>0.7030) ratios.

Trace element and isotopic variations in ocean floor lavas from throughout the study area serve to distinguish three compositional groupings: N-, T- and P-type MORB. All three lava types show similar variations in terms of major element composition, but are readily distinguished in terms of incompatible trace element and isotopic variations, the most important of which are given in Table 2. Figure 6 illustrates the geographic distribution of geochemically enriched and depleted MORB along the SWIR and AAR in terms of the variation in Zr/Nb ratio of the lavas with respect to longitude. Normal, geochemically depleted MORB is the most abundant variety (see also Fig. 3) and occurs throughout the region, while geochemically enriched T-type MORB occurs in abundance on the SWIR to the west of 11°E and at scattered localities along the entire length of the AAR. Highly enriched P-type MORB has only been recovered from the western end of the SWIR and from a single locality on the AAR. Geochemically enriched MORB is apparently absent to the east of 15°E on the SWIR. In contrast to the western end of the SWIR, where enriched and depleted MORB occur juxtaposed throughout the region and in approximately equal abundance, enriched MORB is comparatively scarce (~12 %) along the AAR (Fig. 3). Enriched and depleted MORB are juxtaposed throughout the sampled region of the southern MAR and occur in approximately equal abundance (Fig. 3).

Despite the difference in abundance of enriched MORB

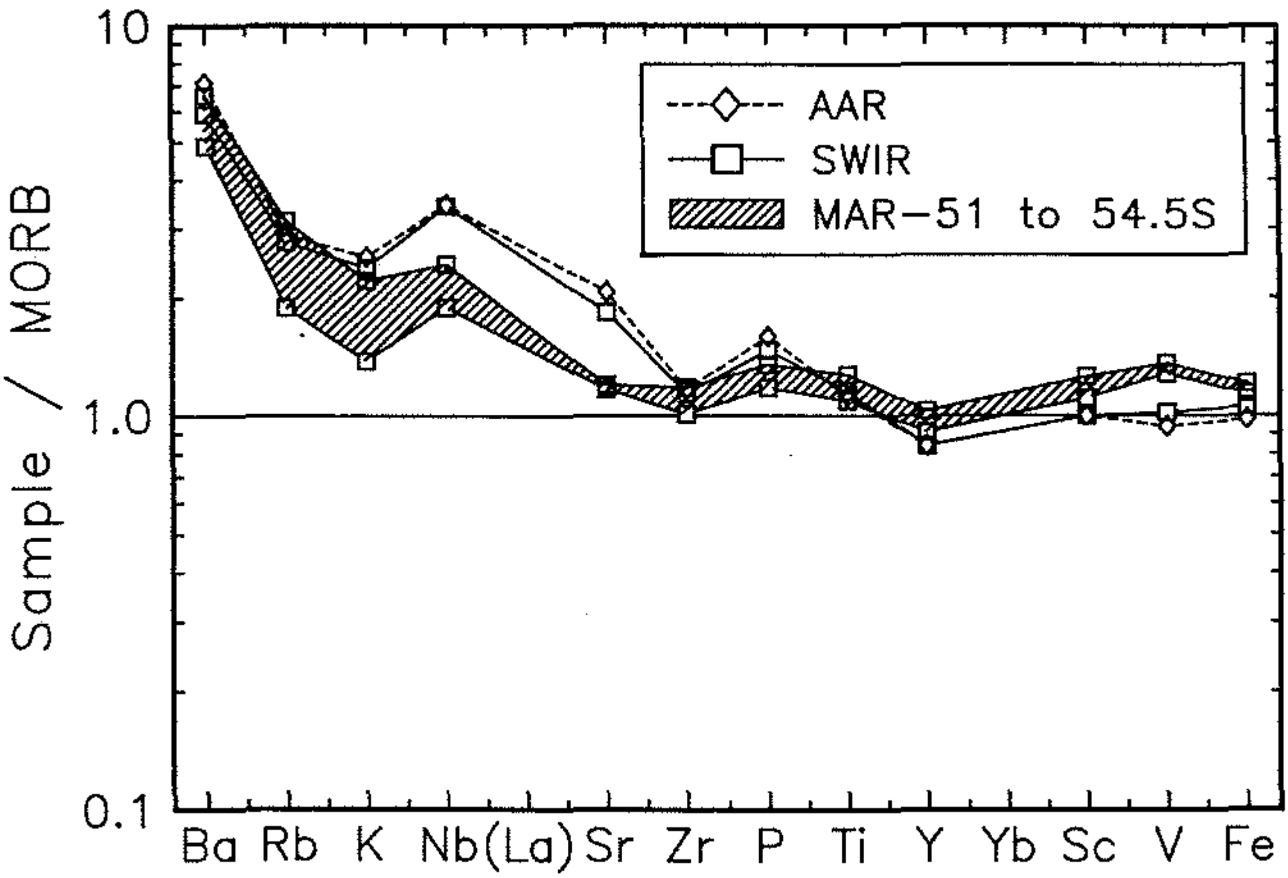

Fig. 7. Abundance variations of incompatible elements in average enriched MORB from the Southwest Indian, American-Antarctic and southern Mid-Atlantic Ridges. Data are normalized to average depleted MORB from the American-Antarctic Ridge (le Roex *et al.* 1985).

along the SWIR and AAR, the inherent geochemical characteristics of enriched lavas from these two ridge systems are indistinguishable. Figure 7 shows the average abundance patterns (normalized to average depleted MORB from the AAR, le Roex *et al.* 1985) for a number of incompatible trace and minor elements in enriched MORB from the AAR and the SWIR. The two patterns are extremely similar, and show subtle differences (particularly with respect to Nb, Sr and P) from those typical of enriched MORB from the southern MAR (Fig. 7). On its own this difference is not unequivocal, but taken in conjunction with isotopic differences (see later discussion) is significant.

Incompatible trace element and Sr and Nd isotopic ratios of MORB from this region are well correlated and those from the SWIR and the AAR have geochemical characteristics which range from compositions similar to depleted MORB, to compositions indistinguishable from those of the Bouvet Island lavas (Fig. 8) and, by implication, the Bouvet mantle plume (le Roex *et al.* 1983, 1985). The similarity and coherence of compositional variations of enriched MORB from the SWIR and AAR is taken to imply that the geochemical enrichment experienced by these lavas is the result of a specific process related to a specific source and not to arbitrary enrichment which has occurred with time in the mantle source regions of these lavas. In contrast, enriched MORB from the southern end of the MAR have inherent geochemical characteristics which are distinct from those associated with enriched lavas from the SWIR, AAR and from the Bouvet mantle plume (Fig. 8). Enriched MORB from the southern MAR extend to more radiogenic Sr and less radiogenic Nd isotopic compositions, relative to Zr/Nb ratio, than the SWIR and AAR basalts.

Geochemical variations within and between the different MORB types from the SWIR and AAR are consistent with mixing between two major components; a heterogeneous, depleted end-member (similar in composition to that characteristic of typical depleted sub-oceanic mantle or N-type MORB) and an enriched end-member of very restricted composition corresponding to the Bouvet hotspot (le Roex *et al.* 1983, 1985). Although the mixing relationships are well constrained, they do not allow one to distinguish readily between magma mixing and source region mixing as being the most likely process by which the mixing occurred. However, the lack of geochemical gradient away from the postulated location of the Bouvet mantle plume (Fig. 6), the extreme distances from the present plume location over which geochemically enriched lavas have been identified (~1800 km), and the large transform offsets separating occurrences of enriched MORB from the plume location have led to a source region mixing model being favoured (le Roex *et al.* 1983, 1985). The model of source region mixing is also consistent with the close juxtaposition of enriched and depleted lavas at several locations along the SWIR and AAR.

Mixing in the source region can be modelled using two components. The components used in the modelling are heterogeneous depleted asthenosphere (source region to MORB) and an enriched component equivalent in composition to P-type MORB and the Bouvet hotspot. The model describes a depleted asthenosphere veined by

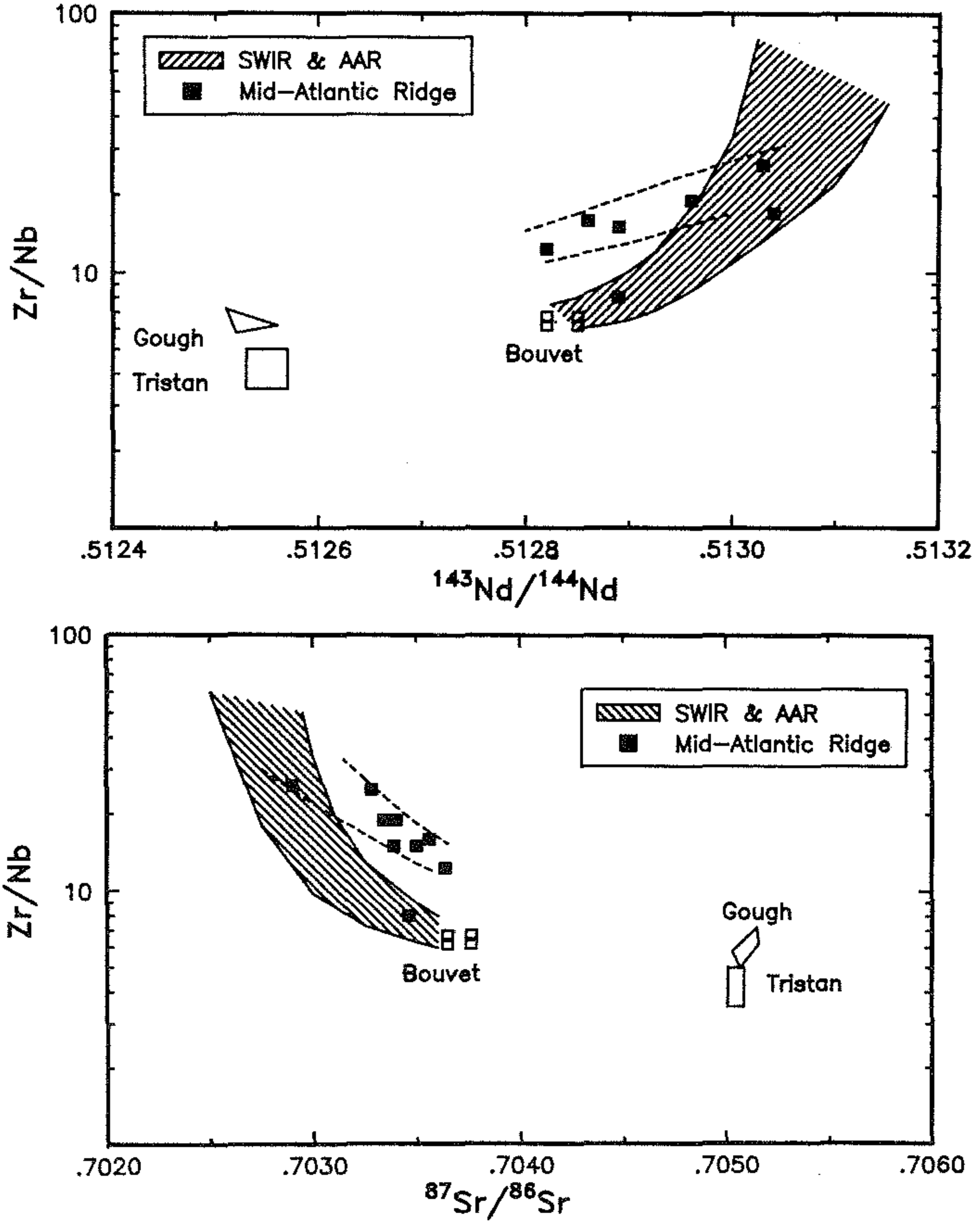

Fig. 8. Variation of Zr/Nb ratio with $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios in Southern Ocean lavas. Data for Bouvet and Tristan from O'Nions *et al.* (1977) and le Roex & Erlank (1982) and for Gough from Le Roex (1985).

enriched silicate magma equivalent to low volume (2 – 4 %) partial melts generated within the garnet stability field (and associated with the Bouvet plume). Partial melting within domains with greater, lesser or no vein component would give rise to P-, T- and N-type MORB. Quantitative application of mixing and partial melting equations (Langmuir *et al.* 1978, Shaw 1970) shows that such a physical model can generate the range of SWIR and AAR basalts.

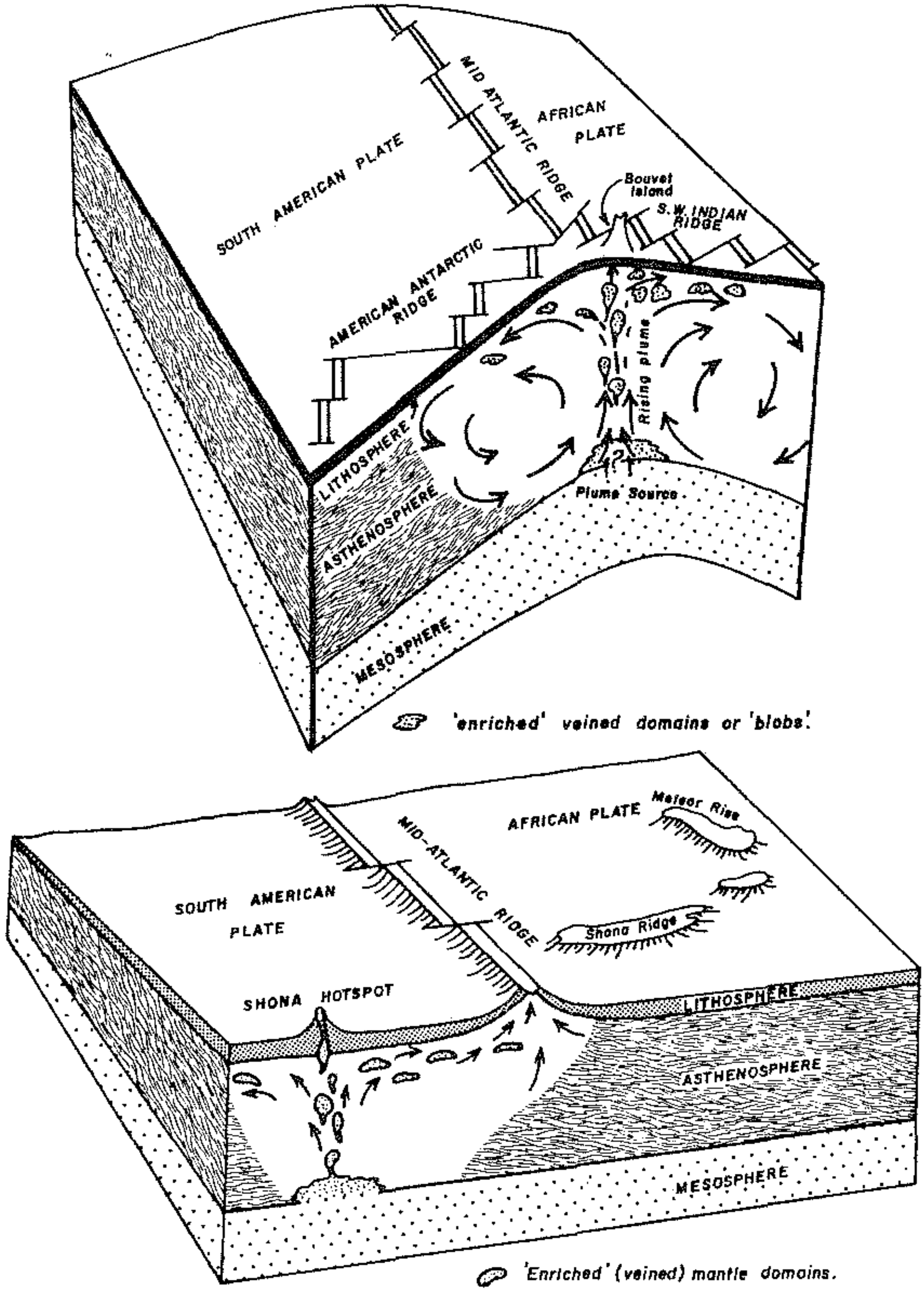

Fig. 9. Schematic diagrams showing possible models for the evolution of the Southern Ocean lithosphere and asthenosphere in the vicinity of the Bouvet triple junction. In these models, upwelling associated with the Bouvet (a) and Shona (b) mantle plumes has led to the veining of domains of originally depleted mantle by small volume partial melts, generated within the garnet stability field. Radial asthenospheric flow away from the rising plumes has led to the lateral dispersion of these enriched domains beneath the Southwest Indian and American-Antarctic Ridges (Bouvet hotspot) and the southern Mid-Atlantic Ridge (Shona hotspot).

Lateral dispersion by asthenospheric flow of variable veined mantle domains, away from the rising plume (Fig. 9a) allows the erupton of P-type and T-type basalts at considerable distances from the plume location.

Geochemical variations in southern MAR basalts also conform to theoretical mixing relationships and this has led to a similar model, to that proposed for the SWIR and AAR, being suggested for the evolution of the mantle beneath the southern end of the MAR (Fig. 9b). However, the model differs in that the source of the low volume partial melts leading to the enrichment in this region is not the Bouvet mantle plume (le Roex *et al.* 1987). The isotopic systematics of these lavas require that the enriched end-member is more radiogenic in Sr and less radiogenic in Nd than the Bouvet hotspot. These characteristics closely resemble those of the Gough, Tristan or Discovery hotspots. On this basis, and coupled with geophysical evidence and plate tectonic reconstruction requirements, the existence of a previously unrecognized hotspot, located at 54.5°S, 6°W, to the northwest of the Bouvet triple junction has been proposed (Hartnady & le Roex 1985). It is believed that the enriched component identified in the geochemistry of the southern MAR lavas originates from the upwelling associated with this proposed hotspot (named the Shona hotspot), believed to coincide with the Shona seamount (Fig. 1).

In summary, a preliminary model for the evolution of the mantle beneath the Southern Ocean since the breakup of Gondwanaland is as follows. Depleted, heterogeneous sub-oceanic mantle has existed beneath the Southern Ocean since its opening ~130 m.y. ago and has the following characteristics: $(La/Sm_N) < 1$, lower than bulk earth Rb/Sr ratio, low $^{87}Sr/^{86}Sr$ ratio, high $^{143}Nd/^{144}Nd$ ratio relative to bulk earth estimates and higher than chondritic Zr/Nb ratio. This mantle has been the source of depleted N-type MORB erupted along the Southern Ocean spreading ridges since the breakup of Gondwanaland. Since their inception, upwelling of the Bouvet and Shona mantle plumes has led to the development of mantle domains, in the immediate vicinity of the rising plumes, which are geochemically enriched due to the invasion of low volume partial melts (generated within the garnet stability field) which have the following characteristics: strong chondrite normalized light rare earth element enrichment, higher than bulk earth Rb/Sr ratio, lower than chondritic Zr/Nb ratio and possibly, though not necessarily, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios which are respectively higher and lower than normal depleted MORB. If $^{143}Nd/^{144}Nd$ – Sm/Nd correlations in the SWIR lavas are interpreted to have age significance, then this enrichment could have occurred approximately 220 m.y. ago (le Roex *et al.* 1983). Asthenospheric flow away from the rising plumes and towards the passively spreading SWIR and AAR (Bouvet) and MAR (Shona) has led to lateral dispersion of these enriched mantle domains in a predominantly E-W direction. Subsequent melting of these enriched domains, as they enter areas of high heat flow beneath spreading ridge segments, has led to the production of T-type (moderate vein/mantle ratios) and P-type (high vein/mantle ratios) MORB. The apparent absence of geochemically enriched MORB with a 'Shona' type signature along the AAR, or with a 'Bouvet' type signature along the southern MAR, suggests that there is no major N-S component of asthenospheric flow in this region.

The absence of enriched MORB to the east of 15°E on the SWIR suggests that this portion of the SWIR lies outside the asthenospheric flow pattern in the vicinity of the rising Bouvet plume. Moreover, the orientations of the ridge segments along the SWIR change at this point from striking NW-SE to a more E-W direction. Asthenospheric flow in the vicinity of the spreading ridges would therefore be predominantly N-S and not from the direction of the upwelling Bouvet mantle plume. However, it should also be noted that the section of the SWIR to the west of ~15°E has been created since anomaly 34 time when a major westward jump of the MAR occurred with the establishment of the Bouvet triple junction in its current configuration adjacent to the Bouvet hotspot. It is only the section of ridge created since the Bouvet hotspot was in the immediate vicinity of the Southwest Indian Ridge (i.e. 1°W – 15°E) that appears to show any evidence of plume influence.

Conclusions

The detailed sampling and geochemical analysis undertaken during this study has resulted in the ridge systems in the vicinity of the Bouvet triple junction now being amongst the most intensively studied in the world. Results arising from this collaborative research effort have allowed us to recognize a number of future research directions in the Southern Oceans. These can be broadly subdivided into tectonic control on magma evolution, the interaction of mantle plumes with the depleted sub-oceanic mantle, and the ultimate source regions of these plumes.

Much is still to be learnt about the details of tectonic control on the evolution of sub-axial magma chambers and their eruptive products. In particular, detailed geophysical surveying and dredging of well established ridge-transform intersections are needed (along the lines of those done in the Tamayo transform region; Bender *et al.* 1984). Such a study would allow a more detailed investigation of the influence of the thermal regime on the generation of partial melts and their subsequent evolution prior to eruption.

The recognition of spatially associated hotspots with geochemically distinct signatures in the Southern Ocean has important implications with regard to hotspot source regions and mantle convective patterns. An obvious follow-up to this discovery is to concentrate on the detailed sampling of seamounts associated with the postulated paleotracks of the Bouvet and Shona (and even Gough, Tristan and Discovery) hotspots. Geochemical analysis of such material, when integrated with geophysical evidence, would allow: (i) Further characterization of the Shona hotspot signature; (ii) determination of whether the unique geochemical signature of individual hotspots (or groups of hotspots) have remained constant with time; and (iii) geochemical mapping of the paleopositions of these Southern Ocean hotspots. Such information would be invaluable for constraining plate tectonic reconstructions.

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