Reprinted From *Island Arcs, Deep Sea
Trenches and Back-Arc Basins,*
Maurice Ewing Series, Volume I

GEOCHEMISTRY OF VOLCANIC ROCKS FROM THE ISLAND ARCS AND MARGINAL BASINS OF THE SCOTIA ARC REGION

John Tarney, Andrew D. Saunders and Stephen D. Weaver

Department of Geological Sciences, University of Birmingham, England

Abstract. The main petrological and geochemical features of the igneous rocks from three island arc/marginal basin systems in the Scotia Arc are discussed and compared. (a) Fast active spreading behind the primitive intraoceanic S. Sandwich arc has been underway for 8 m.y. The back-arc basalts are slightly enriched in large ion lithophile (LIL) elements and are more radiogenic than normal mid ocean ridge (MOR) basalts. (b) Volcanism in the S. Shetland Is. has been of low-K calc-alkaline type since the Jurassic. On cessation of active spreading in Drake Passage ca 4 m.y. ago, a small marginal basin began to open up Bransfield Strait, behind the arc. Recent volcanism in Bransfield Strait has characteristics transitional between calc-alkaline and MOR tholeiite, and may be related to mantle diapirism behind the arc. The off-axis volcano of Penguin Is. is mildly alkaline. (c) On the continental margin of S. Chile, a narrow marginal basin developed behind an active continental-based calc-alkaline andesitic arc in the Jurassic, but the basin was closed and uplifted in the Cretaceous, preserving the marginal basin floor as a pillow lava-sheeted dyke-gabbro complex. Although the complex is affected by low-grade metamorphism, the fresher rocks have a geochemistry which is transitional between MOR and continental tholeiites. Whereas basalts in marginal basins with a long history of back-arc spreading are essentially similar to MOR basalts, magmas generated during the early stages of back-arc spreading seem to have more LIL-enriched characteristics, particularly where spreading was initiated along a continental margin. This may reflect some vertical LIL-element heterogeneity in the mantle rather than variations in partial melting conditions. The LIL-depleted mantle source for MOR basalts may be deep rather than shallow.

Introduction

The Scotia Sea, bounded by the extended loop of the Scotia Arc linking the Antarctic Peninsula with S. Chile, is at present situated near the junction of two major plates, the S. American and the Antarctic. During the Mesozoic and early Tertiary there was subduction of S.E. Pacific ocean lithosphere under S. Chile and the Antarctic Peninsula, but this segment of the S.E. Pacific is now coupled with the Antarctic Plate. Marine geophysical studies in the Scotia Sea (Barker, 1972; Barker and Griffiths, 1972) have revealed a complex pattern of magnetic anomalies which are linked to various phases of sea floor spreading since the mid-Tertiary. This resulted in the formation of a number of microplates, some of them no doubt quite short-lived.

In at least three situations in the area subduction has been associated with some form of back-arc spreading. It is the purpose of this paper to summarise available geochemical data on the igneous rocks produced as a result of back-arc spreading in relation to the geochemistry of the associated island arc volcanics. In the first situation, that of the East Scotia Sea (Fig. 1), relatively fast back-arc spreading behind the primitive intraoceanic S. Sandwich island arc has been underway for almost 8 m.y. In the second situation, bordering the Antarctic Peninsula, back-arc spreading may have been initiated relatively recently behind the continental-based S. Shetland volcanic arc, giving rise to the extensional feature of Bransfield Strait. The active or recently active volcanoes of Deception Is., Bridgeman Is. and Penguin Is. lie close to what may be the axis of back-arc spreading. In the third situation, in southern Chile, a small marginal basin opened up behind a continental-based arc in the Late Jurassic, linked to subduction of Pacific Ocean floor. But by the mid-Cretaceous the back-arc spreading had ceased, the basin was closed, and the oceanic floor uplifted and preserved as an ophiolite complex.

The three examples of back-arc spreading are of course not related in time, nor even perhaps by equivalent mechanisms. They are however relatively youthful features; in the case of the S. Chile fossil marginal basin it was an episode of back-arc spreading that was abruptly ended not long after it had got underway. They do therefore provide an insight into the type of magmatism associated with the initial stages of back-arc activity. In the equivalent early stage of development of mid-ocean ridges it is possible to argue that, in the case of the E. African Rift-Red

Sea system for instance, magmatism changes from alkaline to ocean floor tholeiite type with time (Gass, 1970). Since back-arc spreading is closely associated with subduction, one might expect a corresponding transition from island arc tholeiite or calc-alkaline magmatism to oceanic tholeiite with time, particularly if models such as that of Karig (1971) are correct in suggesting that mantle diapirs split the volcanic arc. Finally, it is important to establish whether or not there are any significant geochemical differences between mid-ocean ridge and marginal basin basalts because of suggestions (e.g. Dewey, 1976) that many ophiolite complexes could represent obducted marginal basin rather than oceanic lithosphere.

The three marginal basin examples will be described separately and then compared in the final discussion.

The South Sandwich Arc and the S. Sandwich Spreading Centre

At the easternmost extremity of the Scotia Arc, the S. Atlantic section of the S. American plate is subducting at a relatively high rate (ca 8 cm yr^{-1}) below the Scotia Sea. Approximately 80 km above the subducting plate lie the volcanic islands of the S. Sandwich Arc, which are at present erupting magmas of the island arc tholeiite series. The chemical characteristics of these magmas are very similar to the Tongan suite (Ewart et al., 1972) in having relatively low LIL element abundances, variable light-RE depleted rare earth patterns with both positive and negative europium anomalies, and rather uniform $^{87}Sr/^{86}Sr$ ratios of about 0.704 (Baker, 1976; Hawkesworth et al., 1976).

Marine geophysical investigations by Barker (1972) and Barker and Griffiths (1972) have established that there is rapid spreading (ca 4 cm yr^{-1} half-rate) behind the arc some 440 km west of the trench (Figs. 1 and 2). Well defined magnetic anomalies indicate that spreading has been underway for approximately 8 m.y. It would appear from the distribution of magnetic anomalies that the arc itself could be resting on lithosphere generated during the spreading episode, unless there was asymmetric spreading or a jump in the axis of spreading during the initial stages of back-arc activity. In the first case there is an implication that the initial sinking and subduction of the S. American plate under the relatively young oceanic lithosphere of the mid-Scotia Sea was accompanied by spreading immediately west of the trench, and that the volcanic arc developed later on this newly generated lithosphere. Alternatively, following a Karig (1971) model, the present volcanic arc might be superimposed on an older buried frontal arc with the remnant arc being positioned some 500 km to the west. The tectonic configuration at present is that of a small D-shaped plate (the Sandwich

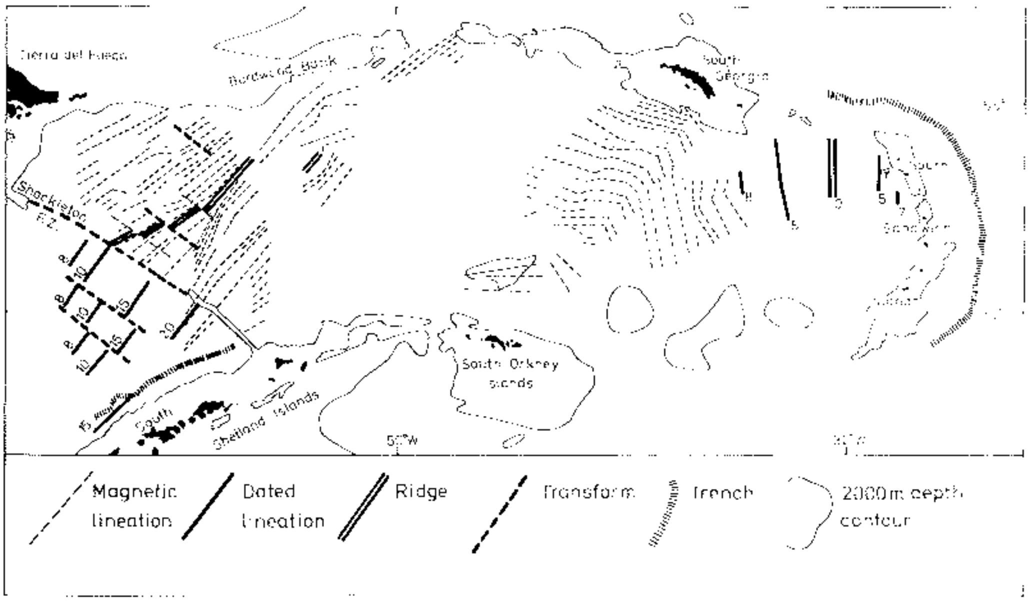

Figure 1. Map of the Scotia Arc showing pattern and ages of magnetic lineations in the Scotia Sea (after Barker and Griffiths, 1972). Dredge hauls 20, 22, 23 and 24 were located at points along the S. Sandwich spreading centre near 30°W while dredge hauls 17, 16 and 12 were located west of the spreading centre, progressively nearer the point of inception of spreading 8 m.y. ago.

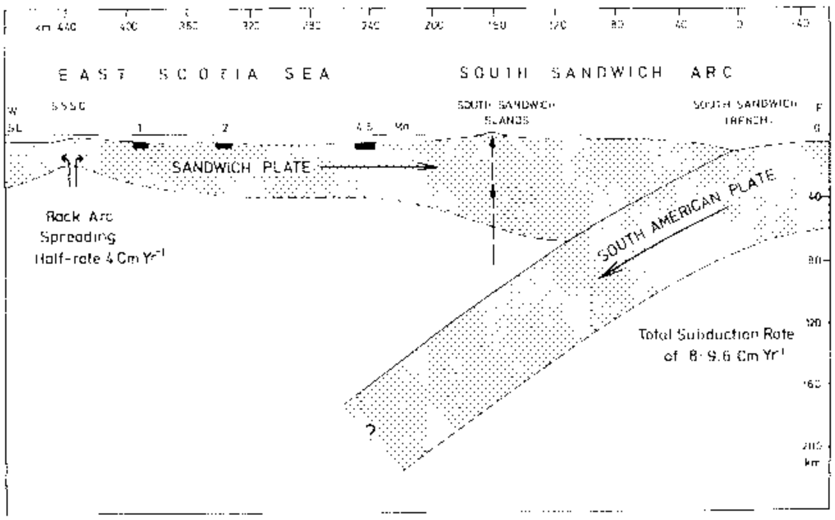

Figure 2. True scale section across the S. Sandwich Arc and the S. Sandwich back arc spreading centre (based on Barker, 1972 and Forsyth, 1975).

Plate) moving eastwards and growing by accretion at the back-arc spreading centre at a rate of 8 cm yr^{-1}, and moreover almost totally enclosed by the S. American-Antarctic Plates.

In an attempt to clarify the situation and to examine the geochemistry of basalts formed by back-arc spreading, dredging was carried out by RRS Shackleton to recover basalts from various points along the axis of the spreading centre and also at intervals westwards along the charted magnetic anomaly tracks to the point of commencement of spreading. Dredge hauls along the spreading axis yielded adequate pillow basalt fragments, but unfortunately the recovery from the older scarps was small in proportion to the glacial debris, and only obvious pillow basalts were analysed. Those basalts recovered are fresh. The majority carried phenocrysts of olivine and/or plagioclase, with little groundmass alteration.

Average analyses of basalts from the axis of the spreading centre and from older scarps are shown in Table 1. The basalts range from quartz-normative to olivine-normative tholeiites. Although the major element chemistry of these basalts is broadly similar to that of other mid-ocean ridge tholeiites, they are significantly enriched in some lithophile elements (K, Rb, Ba, Ce, La, P) and are rather poorer in Ni. It is possible to rule out sea water alteration or contamination as a cause of these higher LIL element abundances for several reasons (Saunders and Tarney, 1976). On the one hand Sr-isotope ratios are uniform within each dredge haul, and little difference in trace element chemistry is observed between the centres and glassy margins of pillows. On the other hand there is a strong degree of covariance between various lithophile elements in samples from different dredge hauls. This can be illustrated (Fig. 3) by plotting various lithophile elements against Zr, an incompatible element with very low crystal-melt distribution coefficients for most igneous minerals. These variations would appear to be mostly dependent upon the degree of partial melting because the compositional variations can be related only by appealing to some clinopyroxene fractionation, yet clinopyroxene is not a phenocryst phase in any of the basalts (with the exception of dredge 24).

The strong geochemical coherence between Zr, Ti, Sr and P in the Scotia Rise basalts may indicate that these elements are located in one mantle mineral phase (probably clinopyroxene). On the other hand the fact that K, Rb and Ba show a similar distribution for each dredge haul, but with obvious differences between dredge hauls, suggests that these elements may be located in another mineral phase (?phlogopite) and that the relative proportions of these two phases may vary in the mantle source. There is no apparent correlation with the petrological character of the basalts (whether quartz-normative or olivine-normative) and hence with differing P, T or pH_2O conditions during partial melting. Instead this would seem to indicate some degree of mantle inhomogeneity.

Rare-earth patterns for Scotia back-arc basalts (Fig. 4) are slightly light-RE enriched compared with normal MOR basalts, and lack Eu anomalies. The overall RE abundances correlate with other LIL-element abundances (i.e. those samples richer in REE are also richer in Zr, Sr, P, Ti, etc.) and appear to be largely a function of degree of partial melting.

Strontium isotope ratios for the same samples are higher than those for normal MOR basalts, but

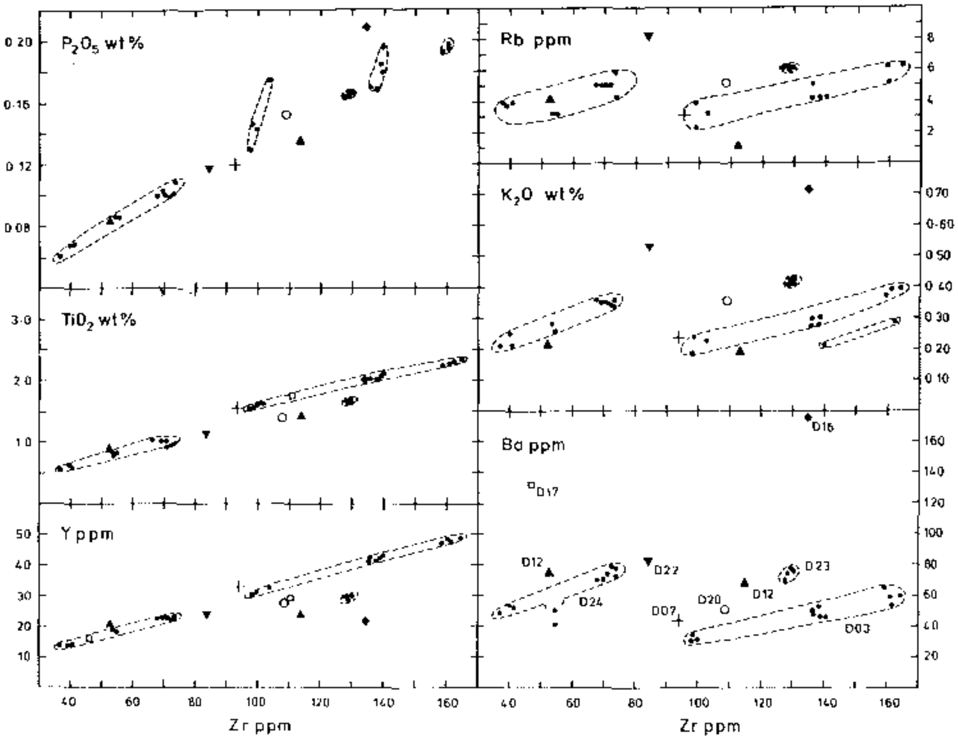

Figure 3. Incompatible element variations in Scotia Sea basalts. Zirconium is used as a fractionation index. Key to dredge hauls given in Ba v. Zr plot. Dashed lines enclose range of samples from each dredge haul. D20-D24 from back arc spreading centre. D12-D17 were located west of the spreading axis (see text). Data on basalts from two dredge hauls (D03 and D07) in the W. Scotia Sea are included for comparison.

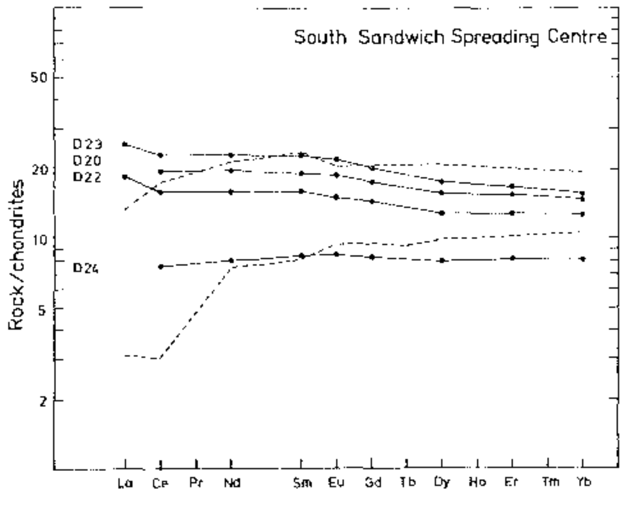

Figure 4. Chondrite-normalised REE patterns for basalts from the S. Sandwich spreading centre. Dashed lines indicate range for normal MOR basalts.

are uniform within each dredge. There is only an approximate correlation of $^{87}Sr/^{86}Sr$ with Rb/Sr ratio, suggesting that the present Rb/Sr ratios, which are higher than those in normal MOR basalts, may reflect only relatively recent mobility of Rb in the source region of the back-arc basalts.

Some of the basalts recovered from the older scarps in the east Scotia Sea (dredge hauls 12, 16 and 17) are rather more enriched in LIL elements compared with those from the spreading axis, but there is no obvious systematic variation with distance from the spreading centre, at least with the small number of samples recovered. It is possible of course that these more LIL-enriched samples may represent the products of off-axis volcanic activity.

One of the samples from Dredge 12 (i.e. located close to the point of inception of spreading) has some geochemical characteristics of basalts of the island arc tholeiite (IAT) series: low Zr, Ti, Ni and P_2O_5. While this might be taken as evidence for the presence of a remnant island arc before the present episode of back-arc spreading was initiated, there are other geochemical characteristics (high Cr, low Fe/Mg ratio) which do not conform with those of the

Table 1 Analyses of Marginal Basin and Associated Island Arc Basic Volcanics

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
N	44	1	4	11	1	1	1	1	1	1	1	20	1	22	34	6
SiO_2	50.40	50.69	50.24	52.77	47.70	49.50	49.36	50.22	51.50	51.41	48.87	53.94	51.64	48.55	50.54	48.72
TiO_2	1.42	1.13	1.64	0.85	1.75	2.06	0.74	0.56	0.98	0.73	1.23	0.65	1.57	1.79	1.44	1.56
Al_2O_3	14.62	15.75	14.41	15.21	11.55	13.00	14.06	19.59	15.35	16.47	15.44	18.54	15.62	11.10	11.76	12.47
tFe_2O_3	8.81	8.19	9.74	9.98	11.74	14.50	10.85	10.60	9.70	10.72	10.59	7.29	9.50	14.25	13.24	11.86
MnO	0.17	0.17	0.18	0.18	0.24	0.25	0.21	0.17	0.19	0.23	0.19	0.13	0.18	0.22	0.23	0.21
MgO	8.13	8.08	7.99	6.28	9.80	8.28	9.16	5.60	5.83	6.64	9.07	5.19	6.43	8.66	7.89	8.89
CaO	11.10	10.85	11.01	10.57	12.18	8.51	11.16	12.53	10.82	9.80	10.10	9.73	9.83	11.35	9.82	7.01
Na_2O	3.11	2.39	3.44	2.29	1.19	3.26	1.29	1.67	2.52	3.24	3.74	3.59	4.16	1.55	1.97	4.26
K_2O	0.36	0.53	0.42	0.30	0.69	0.72	0.21	0.11	0.45	0.51	0.53	0.56	0.31	0.39	0.23	0.33
P_2O_5	0.15	0.12	0.17	0.09	0.26	0.21	0.08	0.04	0.25	0.15	0.30	0.06	0.21	0.14	0.24	0.20
Trace elements in p.p.m.																
Cr	263	196	269	171	137	296	129	24	178	81	508	68	139	152	115	248
Ni	72	66	67	32	21	124	11	11	52	23	163	26	35	30	27	79
Cu	76	68	88	120	77	-	26	74	-	-	-	-	-	-	-	-
Zn	67	69	69	70	103	111	76	-	-	-	82	63	76	82	70	105
Ga	16	13	16	13	17	20	14	13	-	-	22	20	22	17	18	14
Rb	5	8	6	4	20	12	4	2	6	5	5	12	3	12	8	3
Sr	195	195	214	148	414	337	143	153	361	514	550	332	342	140	191	121
Y	28	24	29	20	16	22	21	11	25	14	12	10	28	21	32	29
Zr	109	84	129	60	47	135	53	41	105	60	80	71	156	53	122	130
Nb	4	3	8	1.5	2	18	3	2	5	3	2	1	2	1	3	6
Ba	51	83	74	63	131	176	74	46	144	183	186	110	114	96	92	163
La	6	7	9	3	5	12	7	-	11	8	10	3	8	4	9	6
Ce	12	14	18	7	17	22	13	3	21	21	26	10	23	10	22	17
Pb	3	4	3	2	5	4	5	-	8	5	7	5	6	3	2	3
Th	1	1	1	1	1	3	1	-	1	1	3	2	1	1	2	1
Fe*/Mg	1.23	1.18	1.41	1.87	1.70	2.13	1.37	2.19	1.93	1.87	1.33	1.59	1.68	1.91	1.95	1.55
K/Rb	654	537	581	619	286	511	396	522	612	864	936	380	830	270	239	913
Rb/Sr	0.03	0.04	0.03	0.03	0.05	0.04	0.03	0.01	0.02	0.01	0.01	0.04	0.01	0.09	0.04	0.02
Ba/Rb	10.2	10.1	12.8	14.3	6.5	15.0	16.8	23.0	23.6	37.4	35.5	8.9	36.8	8.0	11.5	53
Ba/Sr	0.26	0.43	0.36	0.42	0.32	0.52	0.52	0.30	0.40	0.36	0.34	0.33	0.33	0.69	0.48	1.4
Zr/Nb	27	28	16	40	23	7.5	18	20	21	20	40	71	78	53	41	22
$^{87}Sr/^{86}Sr$	.7028	.7032	.7030	.7032	-	-	-	.7038	-	-	-	-	-	-	-	-

N = no. of analyses in means.

S. SANDWICH. Nos. 1-4 from spreading axis (dredge hauls 20, 22, 23 and 24). Nos. 5-7 from progressively older scarps west of spreading axis (dredge hauls 17, 16 and 12). No. 8 Island arc tholeiite from Bristol Is. (after Baker, 1976; Hawkesworth et al., 1976).

S. SHETLAND. No. 9 Calc-alkali basalt, Byers Peninsula (Mesozoic). No. 10 calc-alkali basalt, Fildes Peninsula (Tertiary). No. 11 Penguin Is. alkali basalt. No. 12 Bridgeman Is. basaltic andesite. No. 13 Deception Is. basalt (all Recent).

SARMIENTO, S. CHILE. No. 14, gabbros. No. 15 sheeted dykes. No. 16 pillow lavas.

island arc tholeiite series. In fact the suite of samples from Dredge 24, on the spreading axis itself, has even closer similarities to the IAT series in that Zr, Ti, Ni, P and REE levels are relatively low, the basalts are quite silica-rich (51.5-53.5% SiO_2) and, as a result of olivine and pyroxene fractionation, there is a fair range of Fe/Mg ratios. However, Cr levels are higher than in most arc tholeiites and $^{87}Sr/^{86}Sr$ ratios much lower than in any arc tholeiite.

In summary, basalts from the S. Sandwich back-arc spreading centre are more LIL-element enriched, have more light-RE enriched rare-earth patterns and have higher $^{87}Sr/^{86}Sr$ ratios than normal MOR basalts. However they are within the range encompassed by MOR basalts from Iceland (O'Nions et al., 1976) and some other areas along the mid-Atlantic ridge (e.g. 45°N, Erlank and Kable, 1976). Some of the basalts, both at the present spreading axis, and those generated 8 m.y. ago at the inception of spreading, have geochemical characteristics transitional towards arc tholeiites. However, considering the observed systematic chemical variations and the Sr-isotope differences between the back-arc basalts (Saunders and Tarney, 1976) and the adjacent S. Sandwich arc tholeiite volcanics (Baker, 1976, Hawkesworth et al., 1976) it seems unlikely that the chemistry of the arc tholeiite series could be duplicated exactly by further fractionation of Scotia Sea basalt magmas. Finally, there is no positive evidence, admittedly on the basis of limited sample recovery, of any major change in the composition of the basalts generated during the back-arc spreading episode.

The South Shetlands Island Arc and Bransfield Strait Marginal Basin

The South Shetland Island Arc, with a volcanic history extending back into the Mesozoic, is separated from the Antarctic Peninsula by the long narrow trough of Bransfield Strait (Fig. 5). The marine seismic investigations by Ashcroft (1972) supplemented by the gravity data of Davey (1971) and earlier geological investigations (bibliography in Ashcroft, 1972 and Baker et al., 1975) have established that the arc is based on 15 km thick continental crust. This is confirmed by the presence of quartzite and high-grade gneiss blocks in the volcanics and the fact that 3 km of U. Palaeozoic sediments (equivalent to the Trinity Peninsula Series of the Antarctic Peninsula) are exposed on Livingston Island.

About 100-120 km northwest of the arc is a 5 km deep trench, the site of subduction of 15-20 m.y. old oceanic crust generated at the spreading centre in the West Scotia Sea south of Cape Horn

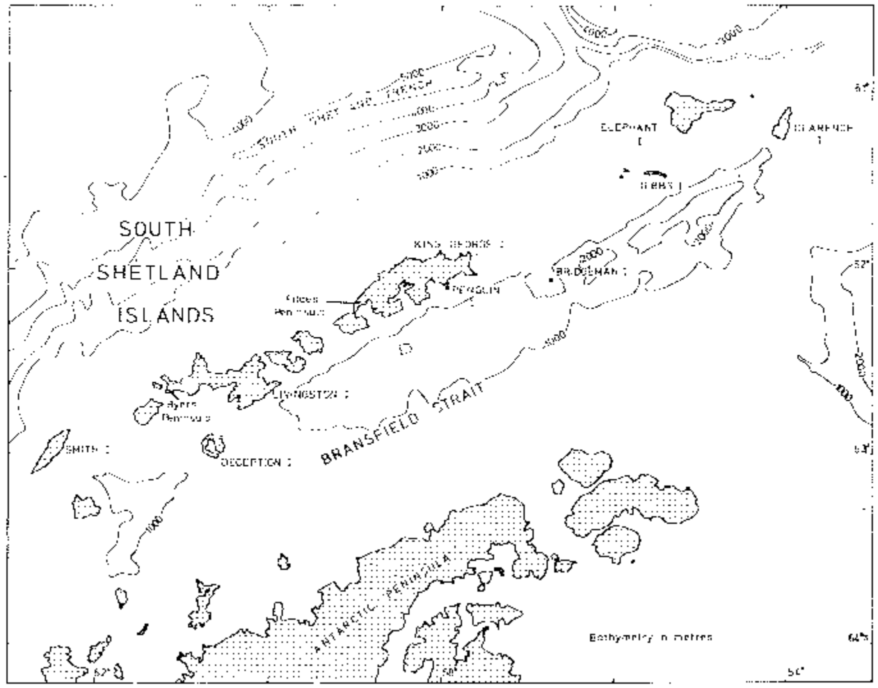

Figure 5. The S. Shetland island arc, separated from the Antarctic Peninsula by the extensional trough of Bransfield Strait. The active and recent volcanoes of Deception Is. and Bridgeman Is. lie along the axis of the trough while Penguin Is. lies just north of the axis.

(Griffiths and Barker, 1971). Low density sediments up to 6 km thick occur in the arc-trench gap.

Bransfield Strait (Fig. 6) is a graben feature at least 400 km long, 65 km wide and 4 km deep, partly filled with low density sediments 1-2 km thick. Major normal faults downthrowing towards the Strait occur along the south-east coast of the Shetland Islands, their presence being supported by both geological and seismic data. The mantle lies at a depth of only 14 km below the axial trough, but is of abnormally low velocity (7.6-7.7 km sec^{-1}). An unusually thick basaltic crust is suggested by the fact that rocks of 6.5-6.9 km sec^{-1} velocity occur only 5 to 6 km below the deep central trough and can be traced for 250 km along strike.

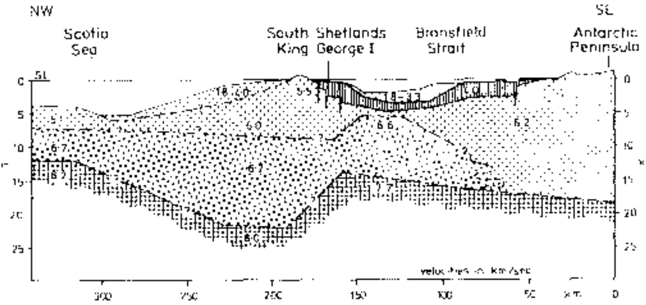

Figure 6. Crustal structure of the S. Shetland Is. and Bransfield Strait (after Ashcroft, 1972).

There seems little doubt that Bransfield Strait is a back-arc extensional feature and that its floor is oceanic in character. However it also seems to be a fairly young feature, probably less than 3-4 m.y. old. Two recent volcanoes, Deception Is. and Bridgeman Is., are located some 200 km apart along the axis of the trough and there are other bathymetric features interpreted as submarine volcanoes along the same axis (Ashcroft, 1972). Recent volcanic activity has also been recorded on Penguin Is. (just SE of King George Is.) some 20 km NW of the axis. It would seem that as spreading ceased, or slowed down, in Drake Passage during the last few million years (Barker and Griffiths, 1972), continuing subduction under the S. Shetland arc was accompanied by extension in Bransfield Strait and movement of the S. Shetland Is. northwestwards away from the Antarctic Peninsula. At the same time the locus of volcanic activity moved southeastwards to be centred over the axis of back-arc spreading (Deception and Bridgeman) with minor off-axis activity (Penguin). The situation thus provides an unusual opportunity to examine the geochemical nature of magmas produced at the inception of back-arc spreading. However with the cessation of subduction at the S. Shetland trench it is not possible to predict that back-arc spreading will necessarily continue in Bransfield Strait.

The volcanic history of the S. Shetlands, and the active volcano of Deception in particular, has been the subject of a number of investigations (Hawkes, 1961 a, b; Baker et al., 1975). To provide a more comprehensive geochemical picture we have, within the last year, sampled more extensively the volcanics of the region. The results will be published in full elsewhere, but the following summarises the more important features bearing upon the mechanism of back-arc spreading.

A series of dominantly basalt, basaltic andesite and andesite lavas with occasional dacites and rhyodacites characterises the S. Shetland arc from the Jurassic to the Late Tertiary. Plutonic intrusions ("Andean Intrusive Suite") of Late Cretaceous age are also present. Basalts are less conspicuous amongst the Jurassic volcanics, but are more important components of the Tertiary lava sequence. On the other hand more salic lavas are commoner in the Jurassic sequence. Aphyric basalts and andesites occur, but the majority of lavas have phenocrysts of plagioclase and olivine with or without clinopyroxene, hypersthene, hornblende and (rarely) titanomagnetite.

Chemically (Table 1) the lavas have low K_2O and Rb contents and fairly high K/Rb and low Rb/Sr ratios similar to arc tholeiites of primitive island arcs (Jakes and Gill, 1970). However, elements such as Sr, Ba, Zr and Cr are higher than in arc tholeiites, and rare-earth patterns are light-RE enriched, unlike any so far reported for members of the island arc tholeiite series. The lavas would therefore be better regarded as members of a low-K, high alumina calc-alkaline volcanic series. The Tertiary lavas have in fact rather lower K and Rb contents than those erupted earlier in the Jurassic.

With the extensional opening of Bransfield Strait there is a change in the character of the volcanics. Of the two volcanoes lying along the spreading axis, Bridgeman Is. is largely made up of high-alumina basalts and baslatic andesites rich in plagioclase phenocrysts but with minor clinopyroxene and olivine phenocrysts. Deception Is. however, horseshoe shaped as a result of caldera collapse and breaching by the sea, has a longer history of crystal fractionation, displaying a range of rock types from basalt (50% SiO_2) to rhyodacite (70% SiO_2). The basalts and basaltic andesites may be aphyric, but most lavas have plagioclase phenocrysts, with additional olivine and clinopyroxene in the more basic lavas, hypersthene in the intermediate and fayalitic olivine in the salic lavas.

The lavas of the off-axis volcano of Penguin Is. however are mildly alkaline (up to 5% <u>ne</u>) olivine basalts with phenocrysts of olivine, minor spinel and clinopyroxene.

The strong mineral fractionation observed at Deception produces considerable enrichment of incompatible elements such as K, Rb, Ba, Zr, Nb, Pb and Th in the salic volcanics compared with their values in the basalts, but Sr values fall

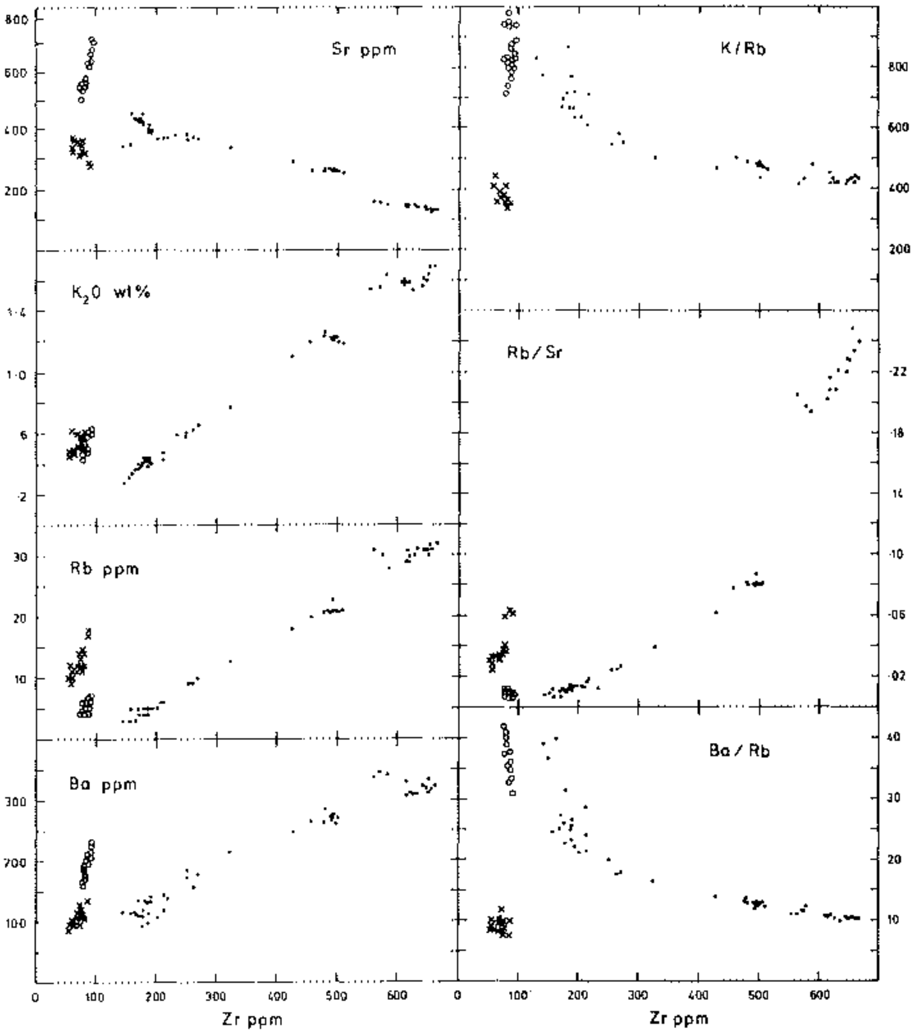

Figure 7. Plots of incompatible elements and element ratios against zirconium for Deception (filled circles), Penguin (open circles) and Bridgeman (crosses) lavas.

as a result of plagioclase fractionation. There is a similar, but smaller, degree of enrichment in the 'less incompatible' elements, Na, Ce, La and Y. The highly incompatible element, Zr, can be used as an indicator of the degree of fractionation since it is not contained in any significant quantity in the phenocrystic minerals. Plots against Zr produce smoother trends for incompatible elements than those against SiO_2 or Fe/Mg which are more useful in dealing with cumulates. At the same time it allows meaningful comparisons to be drawn with the Bridgeman and Penguin magmas.

Although it is not possible to reproduce more than a small fraction of the data here, most such Zr-normalised plots link the Deception volcanics as much with the Penguin alkali olivine basalts as with the Bridgeman lavas, suggesting that Deception and Penguin parental magmas have been generated from similar mantle sources. Plots of K_2O, Rb, Sr, Ba, K/Rb, Rb/Sr and Ba/Rb against Zr (Fig. 7) emphasise this relationship and demonstrate the low Rb/Sr ratios of the Deception-Penguin lavas. $^{87}Sr/^{86}Sr$ ratios as low as 0.703 have been recorded for some Deception lavas (Baker et al., 1975). Bridgeman lavas have much higher Rb/Sr and lower K/Rb and Ba/Rb ratios, suggesting that the mantle source may have been geochemically slightly different, at least with respect to these elements, at the time of magma generation.

There would seem to be no way of generating the Deception and Penguin magmas by fusion of the subducting Scotia Sea oceanic crust, since Rb/Sr ratios are lower and K/Rb and Ba/Rb ratios are higher in the volcanics than in the subduct-

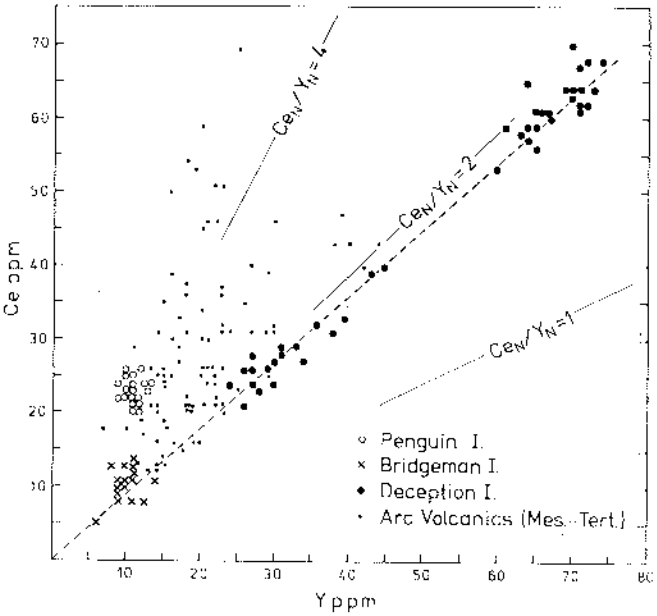

Figure 8. Ce v. Y plots for Deception, Penguin and Bridgeman lavas and for the Jurassic and Tertiary calc-alkaline volcanics of the S. Shetlands arc.

ing oceanic crust. This is also confirmed by the high Cr and Ni contents of the Deception, and especially the Penguin basalts, which suggests mantle derivation. The association of alkaline Penguin and calc-alkaline Deception magmas geographically is not without precedence: the association is not uncommon in other island arcs (c.f. Arculus, 1976). However the off-axis Penguin magma seems to have been generated at greater depth. This is indicated by the fact that whereas basic magmas from both volcanoes have similar Ce contents, Y levels are much lower in the Penguin basalts, suggesting that garnet may have been a stable residual phase during magma generation, holding back Y (and possibly some Zr too). Ce/Y ratios are in fact lower in the Deception (and Bridgeman) volcanics than in any of the earlier S. Shetlands calc-alkaline volcanics. If Y behaviour reflects that of the heavy REE, this suggests that chondrite normalised REE patterns are less fractionated than for the older volcanics, though not as flat as those of MOR basalts. Shallower level melting for the production of the Deception and Bridgeman magma types would be consistent with a model invoking the uprise of a hot mantle diapir to account for the back-arc extension in Bransfield Strait. There is a strong linear relationship between Ce and Y throughout the whole series of Deception lavas, demonstrating that, if Y follows the heavy REE, rare-earth patterns are essentially unaffected by extensive crystal fractionation.

In summary, the Deception and Bridgeman magmas appear to have been generated through relatively shallow level melting of mantle which has some geochemical features (low K, Rb, Rb/Sr, ^{87}Sr/^{86}Sr; high K/Rb, Ba/Rb) characteristic of the source for MOR basalts. Yet the differentiation trends are broadly calc-alkaline, but with some Fe/Mg enrichment. The geochemistry is thus transitional between calc-alkaline and mid-ocean ridge. This would be consistent with a model of mantle diapirism splitting the volcanic arc during the initial stages of back-arc spreading. It would appear however that Ba and Sr levels are still high, and that further spreading would be necessary before basalts with true MOR geochemistry were to be generated in Bransfield Strait.

Mesozoic Marginal Basin Floor Ophiolites from S. Chile

The tectonic setting of the 'Rocas Verdes' marginal basin ophiolites from southernmost Chile has been described by Dalziel and co-workers (c.f. Dalziel et al., 1974; Bruhn and Dalziel, this vol.). Briefly, just before the opening of the S. Atlantic, extension behind a Jurassic continental-based island arc caused rifting and the development of a narrow marginal basin composed of oceanic crust. Extension ceased and the basin was closed and uplifted in the mid-Cretaceous, preserving the marginal basin floor as an ophiolite complex composed of gabbros, sheeted dykes and pillow lavas, with minor plagiogranite. The present outcrop pattern suggests that the marginal basin may have been as much as 100 km wide originally near Cape Horn, narrowing to less than 30 km northwards (near 51°S), and probably over 1000 km in length. The original tectonic situation, particularly in the northern area, may have been similar to the S. Shetlands arc and Bransfield Strait. Moreover the thick mafic crust in the latter, if typical of small marginal basins, may explain the absence of an ultramafic component in the Chilean ophiolites.

As with most other ophiolite complexes, the rocks have suffered low-grade (zeolite- to greenschist facies) metamorphism. The metamorphic affects however appear unrelated to the localised deformation which occurred during basin closure, or to the intrusion of the batholiths of the Cordillera, but are more directly linked to the hydrothermal activity associated with the spreading episode itself (Stern et al., 1976; Saunders et al., 1976). Many of the rocks analysed have in fact suffered low grade metamorphism, but some only to a very limited extent. Nevertheless the geochemical effects accompanying the hydrothermal activity can be allowed for in discussing the primary chemistry.

Mean analyses of gabbros, sheeted dykes and pillow lavas from the Sarmiento Complex are presented in Table 1, and are based on the range of 70 samples analysed and discussed by Saunders et al. (1976). Most of the lavas and dykes fall in the MOR basalt field on Pearce and Cann (1973) discrimination diagrams, but REE patterns are light-RE enriched ($La_N/Yb_N=2$) compared with MOR basalts or even Scotia Sea basalts. The levels of Zr, Y, Sr and Ti are thus comparable with those in MOR basalts. However the gabbros have lower values of incompatible elements such as Zr, Ce, La, Sr and P_2O_5, as may be expected if the gabbros are partly cumulates. There is a wide range of Fe/Mg ratios (0.8 to 4.6) in the dykes and gabbros, and there is a reasonable degree of correlation of Cr, Ni, Zr and TiO_2 with Fe/Mg ratio, indicating considerable crystal fractionation or variable degrees of partial melting (or both) during development of the complex. The fractionation trend is tholeiitic, there being no silica enrichment with increasing Fe/Mg ratio (except in the late stage plagiogranites). Most of the rocks are quartz- rather than olivine-normative. This, coupled with the low alumina contents and relatively flat rare-earth patterns would seem to indicate relatively shallow-level melting. The plagiogranites are rich in Zr, La, Ce and Y, thus inviting comparison with the dacitic Deception lavas, and suggesting moreover that the plagiogranites may be late stage differentiates of the mafic rocks.

There is a much poorer degree of correlation of incompatible elements such as K, Rb and Ba with Zr or with Fe/Mg ratio, although they correlate fairly well with each other. Values for K_2O, Rb and Ba are higher and much more uniform in the fresher dykes and gabbros, where K/Rb ratios are very much lower than in MOR basalts. The amphibolised and chloritised dykes and gabbros have much lower K and Rb values and K/Rb ratios are much higher, suggesting loss of Rb and K during the hydrothermal alteration; this is not unexpected since minerals such as chlorite, hornblende and epidote hold little K or Rb in their structures. More extreme effects are seen in the pillow lavas which are spilitised and have high Na_2O contents.

We would regard the K_2O, Rb and Ba contents of the fresher dykes and gabbros (ca 0.5% K_2O, 13 p.p.m. Rb, 90 p.p.m. Ba) as more typical of the initial magmas. This, together with the more fractionated REE patterns, would imply a mantle source rather more enriched in these elements compared with that for MOR basalts. Finally, we note that the geochemical characteristics of the magmas are transitional towards continental tholeiites rather than calc-alkaline magmas. This would be more consistent with the development of the marginal basin slightly behind rather than within an active pre-existing arc.

Discussion

Comparison of the tectonic settings of the three different marginal basin situations and the geochemistry of the volcanic products suggests that there may be no single uniform mechanism responsible for back-arc spreading. Whereas the geochemistry of the Bransfield Strait volcanics would be consistent with the initial stages of splitting of the calc-alkaline volcanic arc, the back-arc products in S. Chile and the Scotia Sea are essentially tholeiitic. Much may depend of course on the relative activity of the mantle diapir producing the back-arc extension. Slow uprise might produce transitional characteristics, as in Bransfield Strait, whilst rapid active diapirism may account for the essentially tholeiitic volcanism in the Scotia Sea and S. Chile.

None of the marginal basin igneous products is as geochemically depleted in lithophile elements as MOR basalt, but each shows some transitional characteristics. Furthermore, although the tectonic situations are not exactly equivalent, there appears to be an increase in the 'depleted' characteristics of the marginal basin volcanics in going from Bransfield Strait, through S. Chile to the Scotia Sea (i.e. with increasing stages of opening of the back-arc basins). Basalts from marginal basins with a longer history of back-arc spreading, such as those behind the Mariana (Hart et al., 1972) and Tongan (Hawkins, 1976) arcs are much closer to MOR basalts in their geochemistry. Note however that in S. Chile and Bransfield Strait the basaltic magmas were generated in subcontinental lithosphere.

Geochemical and isotopic variations in basalts along the mid-Atlantic ridge have been linked with the uprise of LIL-element enriched deep mantle plumes(e.g. Schilling, 1973). While the Zr-normalised plots of the marginal basin rocks also suggest that differences in lithophile element abundances and ratios are partly a function of mantle inhomogeneity, we feel that the three cases of back-arc spreading examined here would be just as compatible with a LIL-enriched mantle source which is shallow rather than deep. For instance, in the initial stages of back-arc spreading the influence of a deep mantle plume would seem to be precluded by the presence of the subducting slab. Yet it is at this stage in their development that marginal basin products seem to display more LIL-element enriched characteristics.

Acknowledgements. Geochemical studies in the Scotia Arc were supported by the Natural Environment Research Council, U.K. We thank the British Antarctic Survey, the Royal Navy, D. H. Griffiths and P. Barker for logistic support; B.A.S., I.W.D. Dalziel, M. J. de Wit and C. R. Stern for donating samples; R. K. O'Nions and R. J. Pankhurst for carrying out Sr isotope and REE determinations; G. L. Hendry and N. Donnellan for their help with XRF analysis and S. E. DeLong, I. Ridley and R. Bruhn for their comments on the manuscript.

REFERENCES

Arculus, R. J., Geology and geochemistry of the alkali-basalt-andesite association of Grenada, Lesser Antilles island arc, Geol. Soc. Amer. Bull., 87, 612-624, 1976.

Ashcroft, W. A., Crustal structure of the South Shetland Islands and Bransfield Strait, *Brit. Antarct. Surv. Sci. Rept.*, **66**, 1-43, 1972.

Baker, P. E., The South Sandwich Islands: II. Petrology and Geochemistry, *Brit. Antarct. Surv. Sci. Rept.*, in press, 1976.

Baker, P. E., I. McReath, M. R. Harvey, M. J. Roobol, and T. G. Davies, The geology of the South Shetland Islands: V. Volcanic evolution of Deception Island, *Brit. Antarct. Surv. Sci. Rept.*, **78**, 1-81, 1975.

Barker, P. F., A spreading centre in the east Scotia Sea, *Earth Planet. Sci. Lett.*, **15**, 123-132, 1972.

Barker, P. F., and D. H. Griffiths, The evolution of the Scotia Ridge and Scotia Sea, *Phil. Trans. Roy. Soc. Lond.*, **A271**, 151-183, 1972.

Bruhn, R. L., and I. W. D. Dalziel, Destruction of the Early Cretaceous marginal basin in the Andes of Tierra del Fuego (this volume).

Dalziel, I. W. D., M. J. de Wit, and K. F. Palmer, Fossil marginal basin in the southern Andes, *Nature*, Lond., **250**, 291-294, 1974.

Davey, F. J., Marine gravity measurements in Bransfield Strait and adjacent areas, in *Antarctic Geology and Geophysics*, edited by R. J. Adie, pp. 39-45, Universitetsforlaget, Oslo, Norway, 1971.

Dewey, J. F., Ophiolite obduction, *Tectonophysics*, **31**, 93-120, 1976.

Erlank, A. J., and E. J. D. Kable, The significance of incompatible elements in Mid-Atlantic Ridge basalts from 45°N with particular reference to Zr/Nb, *Contrib. Mineral. Petrol.*, **54**, 281-291, 1976.

Ewart, A., W. B. Bryan, and J. B. Gill, Mineralogy and geochemistry of the younger volcanic islands of Tonga, S.W. Pacific, *J. Petrol.*, **14**, 429-465, 1973.

Forsyth, D.W., Fault plane solutions and tectonics of the South Atlantic and Scotia Sea, *J. Geophys. Res.*, **80**, 1429-1443, 1975.

Gass, I. G., Tectonic and magmatic evolution of the Afro-Arabian dome, in *African Magmatism and Tectonics*, edited by T. N. Clifford and I. G. Gass, Oliver & Boyd, Edinburgh, Scotland, 1970.

Griffiths, D. H., and P. F. Barker, Review of Marine Geophysical Investigations in the Scotia Sea, in *Antarctic Geology and Geophysics*, edited by R. J. Adie, pp. 3-11, Universitetsforlaget, Oslo, Norway, 1971.

Hart, S. R., W. E. Glassley, and D. E. Karig, Basalts and sea floor spreading behind the Mariana island arc, *Earth Planet. Sci. Lett.*, **15**, 12-18, 1972.

Hawkes, D. D., The Geology of the South Shetland Islands, I. The petrology of King George Island, *Sci. Rept. Falkland Is. Dependencies Survey*, 26, 1-28, 1961a.

Hawkes, D. D., The Geology of the South Shetland Islands, II. The geology and petrology of Deception Island, *Sci. Rept. Falkland Is. Dependencies Survey*, 27, 1-43, 1961b.

Hawkesworth, C. J., R. K. O'Nions, and R. J. Pankhurst, A geochemical study of island-arc and back-arc tholeiites from the Scotia Sea, *Earth Planet. Sci. Lett.*, in press, 1976.

Hawkins, J.W., Petrology and geochemistry of basaltic rocks of the Lau Basin, *Earth Planet. Sci. Lett.*, **28**, 283-298, 1976.

Jakes, P., and J. Gill, Rare earth elements and the island arc tholeiite series, *Earth Planet. Sci. Lett.*, **9**, 17-28, 1970.

Karig, D. E., Origin and development of marginal basins in the western Pacific, *J. Geophys. Res.*, **76**, 2542-2561, 1971.

O'Nions, R. K., R. J. Pankhurst, and K. Gronvold, Nature and development of magma sources beneath Iceland and the Reykjanes Ridge, *J. Petrol.*, in press, 1976.

Pearce, J. A., and J. Cann, Tectonic setting of basic volcanic rocks determined using trace element analysis, *Earth Planet. Sci. Lett.*, **19**, 290-300, 1973.

Saunders, A. D., and J. Tarney, Geochemistry of basalts from the back-arc spreading centre in the Scotia Sea, in preparation, 1976.

Saunders, A. D., J. Tarney, C. R. Stern, and I. W. D. Dalziel, Geochemistry of marginal basin floor mafic igneous rocks from S. Chile, in preparation, 1976.

Schilling, J. G., Icelandic mantle plume: Geochemical study of the Reykjanes Ridge, *Nature*, Lond., **242**, 565-567, 1973.

Smellie, J. L., and P. D. Clarkson, Evidence for pre-Jurassic subduction in western Antarctica, *Nature*, Lond., **258**, 701-702, 1975.

Stern, C. R., M. J. de Wit, and J. R. Lawrence, Igneous and metamorphic processes associated with the formation of Chilean ophiolites and their implication for ocean floor metamorphism, seismic layering and magnetism, *J. Geophys. Res.*, in press, 1976.