Sills of the Theron Mountains, Antarctica: evidence for long distance transport of mafic magmas during Gondwana break-up

P.T. Leat & A.V. Luttinen*
*British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK *Present address: Department of Geology, Gustaf H≅llstr minkatu 2 (PO Box 64), 000014 University of Helsinki, Finland*

B.C. Storey
Gateway Antarctica, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

I.L. Millar
British Antarctic Survey, c/o NERC Isotope Geosciences Laboratory, Keyworth, Nottingham NG12 5GG, UK

ABSTRACT: The Theron Mountains, Antarctica expose Jurassic mafic sills intruded into flat-lying Permian sedimentary rocks. The sills form some 30% of the outcrop and most are highly concordant, although there are a few cross-cutting relationships. New fieldwork and analytical data suggest that there are four types of sills. The most abundant group chemically correlates with the Mount Fazio Chemical Type of Ferrar tholeiites from Victoria Land, and a second correlates with the distinctive Scarab Peak Chemical Type of Ferrar tholeiites. Two other chemical groups are compositionally close to certain low-Ti-Zr and high-Fe, high Ti-Zr lavas and intrusions in the central Lebombo Monocline and in Dronning Maud Land. The sills provide evidence for long-distance transport of magmas during initial stages of Gondwana break-up.

1 INTRODUCTION

Dykes represent the pathways along which magma is transported from source regions to points of eruption or emplacement, and thus the normal sense of magma flow through dykes must be vertical. But it has long been known that some magmas are transported laterally though the crust in dykes. Lateral magma flow in fissure systems away from central volcanoes has been well documented in Hawaii (Fiske & Jackson 1972) and Iceland (Sigurdsson & Sparks 1978). Several authors have argued that magma is commonly transported laterally in dykes in the mid-ocean ridge environment (Michael et al. 1989, Embley & Chadwick 1994, Fox et al. 1995). In these ocean island and ocean ridge environments, lateral flow is up to about 100 km. Greater distances of lateral flow of over 2000 km are thought to have occurred in 'giant' dyke swarms emplaced in continental crust (e.g. Mackenzie dyke swarm, Canada, Baragar et al. 1996). Theoretical treatments show that there are no physical reasons why basaltic magmas cannot flow laterally in dykes for distances of hundreds or even thousands of kilometers in dykes of a few tens of metres wide (e.g. Macdonald et al. 1988, Fialko & Rubin 1999). 'Giant' dyke swarms are thought to represent the subvolcanic feeder systems of continental flood basalt provinces (Ernst & Buchan 1997). This raises the question of the distances that basaltic magmas might have travelled by lateral flow in dykes before their eruption as flood basalt lavas. Thompson & Gibson (1991) argued that flood basalt volcanism may be concentrated not above the point of impact of a mantle plume, but above the point of maximum melt generation, in areas where lithosphere was thinned by previous tectonic events. If magmas are transported for great distances laterally, the site of eruption may be even further removed from the mantle sources, and may simply reflect the point where magma was most easily erupted from laterally propagating dykes.

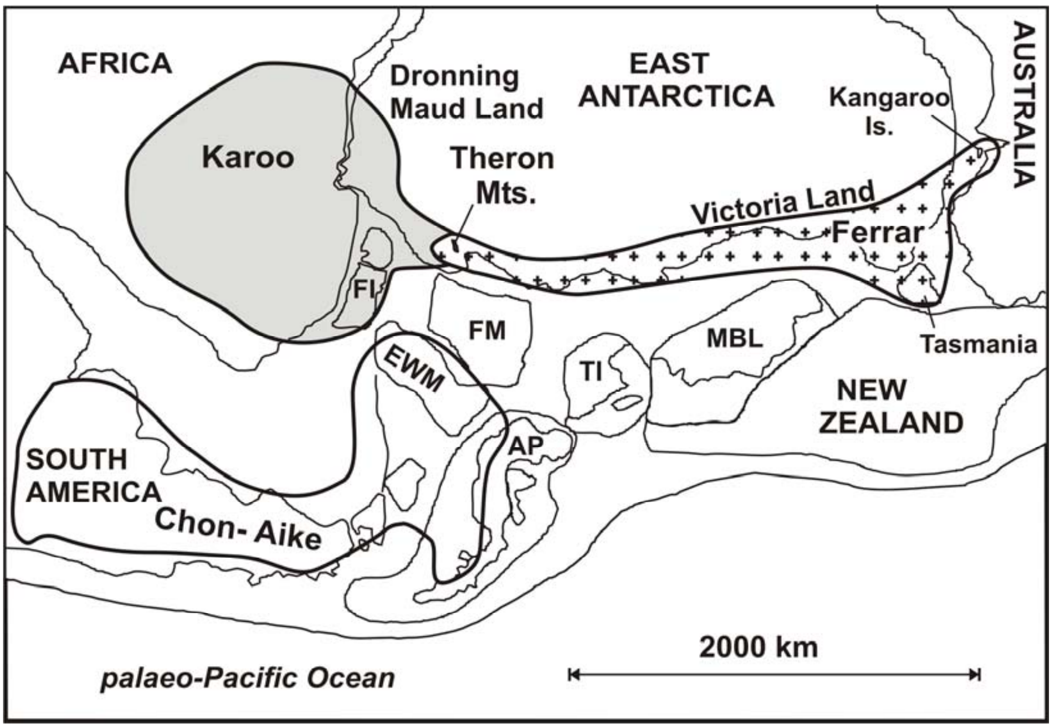

Figure 1. Sketch map of the Karoo-Ferrar magmatic province modified after Pankhurst et al. (1998) showing the position of the Theron Mountains in relation to main areas of Jurassic magmatism in Gondwana. The Karoo and Ferrar sub-provinces are mainly basaltic, whereas the Chon Aike province is dominantly rhyolitic (Pankhurst & Rapela 1995, Pankhurst et al. 1998, Riley et al. 2001).

2 THE KAROO-FERRAR MAGMATIC PROVINCE

The Karoo-Ferrar magmatic province (Fig. 1) is the most voluminous large igneous province associated with the break-up of Gondwana. The Karoo sub-province of southern Africa consists mainly of extensive mafic lavas, sills, and dykes, and silicic volcanic rocks (Erlank 1984, Sweeney et al. 1994, Marsh et al. 1997). The Dronning Maud Land sub-province in Antarctica forms the conjugate margin to the Karoo magmatism (Fig. 2) and consists mainly of mafic lavas and dykes, and rare sills and gabbro intrusions (Harris et al. 1990, Luttinen & Furnes 2000, Riley et al. 2005). By contrast, the Ferrar sub-province consists dominantly of mafic sills and lavas (Kirkpatrick Basalt), with relatively few dykes (Kyle 1980, Kyle et al. 1981, Fleming et al. 1992). The Dufek and Forrestal layered mafic intrusions in the Pensacola Mountains also are believed to belong to the Ferrar sub-province (Ford & Kistler 1980, Kyle et al. 1981).

The main part of the Karoo-Ferrar magmatic province was erupted rapidly. Riley & Knight (2001) reviewed Ar-Ar ages for the entire province and found that, when all ages are recalculated to a common monitor, nearly all fall within a 3-4 million year period at ca. 182 Ma. They also found that, according to the Ar-Ar data, the peak in magmatism was slightly earlier in the Karoo area (183 Ma) than in the Ferrar (180 Ma). The few available U-Pb ages date both the Ferrar and Karoo within 1-2 million years of 183 Ma (Encarnación et al. 1996, Minor & Mukasa 1997).

The Ferrar sub-province is distinguished from the Karoo not only by geographical positions, but also by magma compositions. Ferrar rocks are characteristically relatively homogenous, low-Ti tholeiitic basalts that have very high initial $^{87}Sr/^{86}Sr$ ratios of >0.7086 ($Sr_t > +61$), and consistently negative.Nd_t (-1.9 to -6.6) (Kyle et al. 1980, Hergt et al. 1989, Brewer et al. 1992, Fleming et al. 1995). Two sub-types of Ferrar tholeiites have been documented. The dominant type is called Mount Fazio chemical type (MFCT). The less abundant type, which has relatively high Si, Ti, Fe and Zr abundances, has been documented only among the uppermost lavas of the

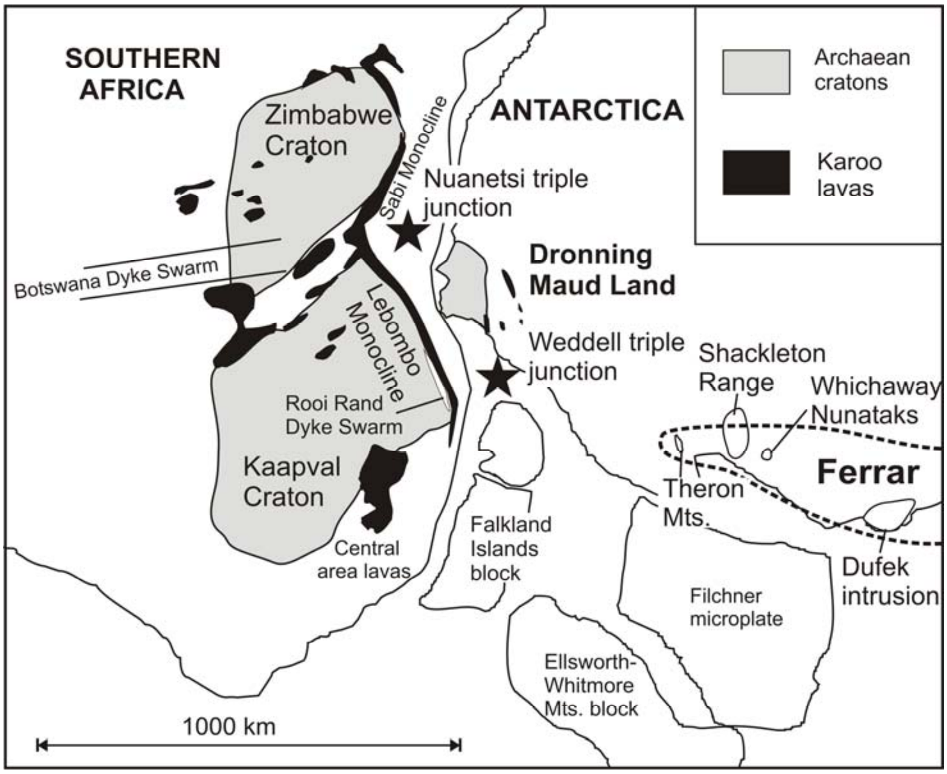

Figure 2. Map showing the relationship of the Karoo flood lavas of southern Africa with the conjugate Antarctic margin. The Nuanetsi and Weddell triple junctions are after Elliot & Fleming (2000).

Kirkpatrick Basalt and is called Scarab Peak chemical type (SPCT) (Fleming et al. 1992, Elliot et al. 1999). The Karoo sub-province is characterized by chemical heterogeneity of lava and dyke compositions on several scales. A regional distinction between high-Ti and low-Ti mafic rocks has long been recognized (Cox et al. 1967, Erlank 1984). Sweeney et al. (1994), however, divided the lavas in the Lebombo Monocline into three types, high-Ti, high-Zr, low-Fe basalts (HTZ), high-Ti, high-Zr, high-Fe basalts (high-Fe) and low-Ti, low-Zr basalts (LTZ). Both high- and low-Ti types of the Karoo are markedly heterogeneous in composition, e.g. there are marked compositional local variations among the low-Ti group of the central area around Lesotho (Marsh et al. 1987). MORB-like dykes are restricted to the Rooi Rand dyke swarm which parallels the Lebombo Monocline (Duncan et al. 1990).

The LTZ basalts of southern Lebombo have been correlated with the CT1 group of Antarctic basalts identified in Vestfjella, Dronning Maud Land (Fig. 3) (Luttinen & Furnes 2000). Magma compositions in Dronning Maud Land are diverse, and include high- and low-Ti types. The MORB-like group CT2 straddles the boundary between LTZ and HTZ groups and correlated with the Rooi Rand dykes, but low-Ti group CT3 cannot be correlated with South African types (Luttinen & Furnes 2000). Other low-Ti lavas occur in Kirwanveggen and Heimfrontfjella in Dronning Maud Land (Harris et al. 1990), whereas Ahlmannryggen and adjacent areas contain a very varied group of low- and high-Ti dykes (Harris et al. 19991, Riley et al 2005).

Lateral flow of magma has been postulated by White (1997) and Storey et al. (2001) to have been important in the magmatism of the Karoo-Ferrar province. However, the only part of the province where significant attempts have been made to establish whether basaltic magmas flowed long distances within the crust is the Ferrar (Fleming et al. 1997, Storey & Kyle 1997, Elliot et al. 1999, Elliot & Fleming 2000). The main evidence that Ferrar magmas were transported laterally is the compositional homogeneity of the basalts over distances of some 3500 km. This contrasts with the regional variation of compositions in the Karoo part of the province. More specific evidence is the fact that the highly distinctive SPCT basalts are spread over 1600 km. Since all the SPCT are thought to have erupted from a common magma chamber, this demands lateral flow (Elliot et al. 1999). Elburg & Goldberg (2000) found that dykes from the Botswana dyke swarm have similar Ar-Ar ages and compositions to lavas of the northern Lebombo Monocline and argued that the dykes were emplaced by lateral flow from a source near the monocline (Fig. 2).

The point where the Karoo and the Ferrar sub-provinces types overlap or are transitional into one another is regarded as being in the Theron Mountains (Brewer et al. 1992). This paper describes the geochemistry of basalt sills from the Theron Mountains, and discusses their importance in models of lateral flow of magmas in the Karoo-Ferrar province.

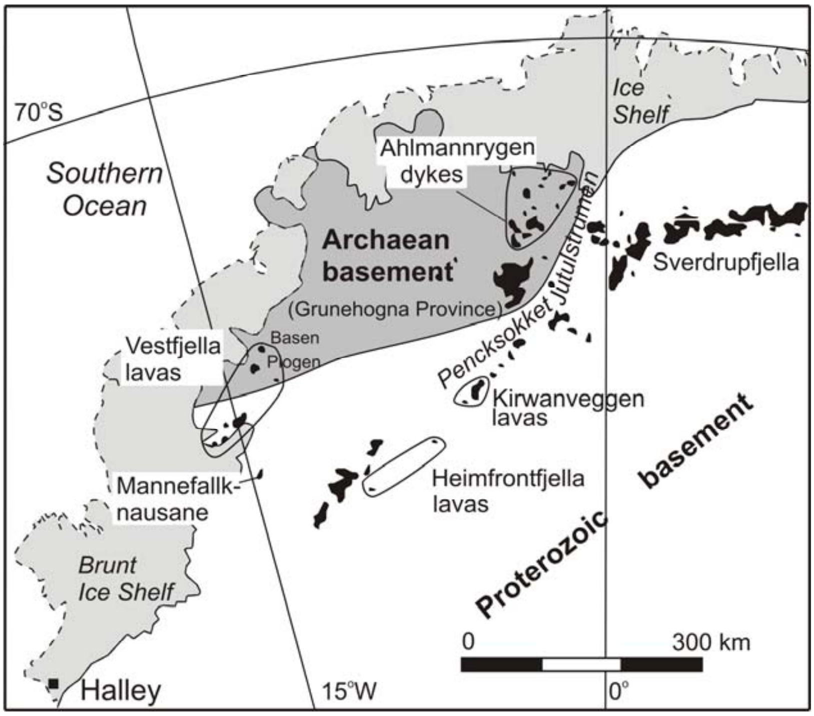

Figure 3. Map showing the distribution of Jurassic lavas and intrusive rocks in Dronning Maud Land

3 GEOLOGY OF THE THERON MOUNTAINS

The Theron Mountains is a north-west-facing series of cliffs with a total length of 110 km and a height of some 760 m (Fig. 4). Geologically, they comprise flat-lying sedimentary rocks intruded by mafic sills and dykes (Brook 1972a, b). The sedimentary rocks are clastic mudstones to sandstones that were water-lain in a terrestrial environment and contain coal seams. A sparse *Glossopteris* flora indicates a Permian age (Brook 1972b). The sills form some 30% of the outcrop and are normally highly concordant with the sedimentary bedding, although a few low-angle cross-cutting relationships occur. Most of the sills range from 1 to 50 m in thickness, but the thickest sill, the ‘Scarp-Capping Sill’ of Brook (1972b) is up to 200 m thick. The greatest number of sills exposed at any locality is eight, at Marø Cliffs (Fig. 4). The total number of exposed sills is difficult to determine because of breaks in exposure between cliff sections, but is probably 10-15, and the 43 samples analysed by Brewer et al. (1992) clearly include multiple analyses of some sills. Some of the thicker sills developed cumulate layering. Dykes are rare and appear to be either offshoots of sills or belong to an older episode. None of the exposed dykes are feeders of the sills. Given the absence of evidence for vertical magma ascent, the impression gained is that the magmas originated elsewhere and migrated laterally to the Theron Mountains area.

Ar-Ar dating shows that the sills are Jurassic, and are within the range of the Karoo-Ferrar magmatism (Brewer et al. 1996). The recalculated (for comparison to the rest of the province) ages are 172.1 to 181.5 ± 2.5 Ma (Riley & Knight 2001), which is at the youngest end of the range for reliable province-wide ages.

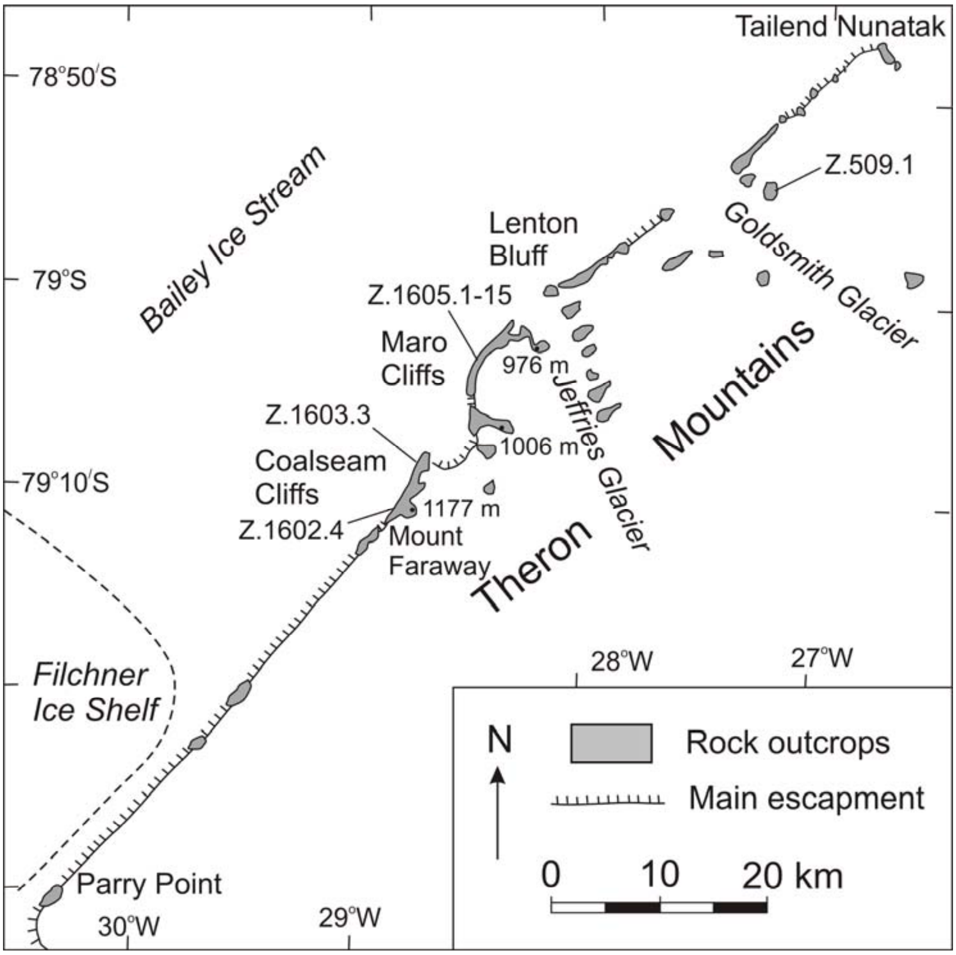

Figure 4. Sketch map of the Theron Mountains (after Brook 1972b), showing locations of samples discussed the text.

4 GEOCHEMISTRY OF THE THERON SILLS

The geochemistry of sills from the Theron Mountains was first described by Brook (1972a) who established that several different chemical types are present. Subsequent work by Brewer & Brook (1991) and Brewer et al. (1992) used the collections of Brook. The data used in this paper are mainly from samples collected by P.T. Leat and B.C. Storey in 1998. Comparisons are made to the earlier data set. Selected new data for Theron sills are presented in Tables 1 and 2. Major and trace element abundances were measured using standard XRF methods at the University of Keele (UK). Trace element abundances were determined by ICP-MS Plasmaquad at the University of Durham (UK). ICP-MS methods, precisions and detection limits are similar to those of Pearce et al. (1995). Sr and Nd isotope analyses were carried out at the NERC Isotope Geosciences Laboratory (UK), using standard techniques (Pankhurst & Rapela 1995). The $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$. Three repeated analyses of NBS987 during the course of this study gave $^{87}Sr/^{86}Sr = 0.710259 \pm 0.000018$ (2σ). The $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Repeated analyses of Johnson-Matthey Nd yielded $^{143}Nd/^{144}Nd = 0.511122$, corresponding to 0.511858 for the La Jolla standard.

We identify four chemical types among the sills (Fig. 5). This is less than the seven groups identified by Brewer et al. (1992), although we have followed their names for the groups as closely as possible.

Table 1. Representative major and trace element analyses of sills from the Theron Mountains, Antarctica.

Sample	Z.1605.3	Z.1605.6	Z.1605.11	Z.1603.3	Z.1605.15	Z1602.4	Z.1605.10	Z.1605.13
Group	Series 1	Series 1	Series 1	Sill C	Sill C	Sill A	Sill A	Sill B
Major elements by XRF (wt.%)								
SiO_2	51.95	53.07	51.17	53.89	56.11	48.88	47.84	51.80
TiO_2	0.87	0.98	0.65	2.51	2.03	2.38	2.37	3.06
Al_2O_3	15.22	15.06	15.69	12.09	12.25	14.55	14.11	12.91
Fe_2O_3(T)	9.95	10.01	10.16	17.24	15.79	16.95	17.47	15.49
MnO	0.16	0.16	0.17	0.20	0.19	0.22	0.22	0.21
MgO	8.60	8.18	8.35	3.23	2.70	4.82	5.05	4.00
CaO	9.88	9.67	11.18	7.65	6.88	8.58	8.88	7.72
Na_2O	1.83	1.74	1.75	2.05	2.28	2.46	2.58	2.75
K_2O	0.86	1.02	0.48	1.44	1.70	1.25	1.18	1.73
P_2O_5	0.20	0.26	0.14	0.20	0.26	0.28	0.28	0.43
LOI	0.67	0.12	0.65	-0.05	0.14	-0.38	0.01	0.57
Total	100.2	100.3	100.4	100.5	100.3	100.0	100.0	100.7
Trace elements by XRF (ppm)								
Cr	477	620	497	53	52	99	99	77
Y	29	36	24	46	56	58	55	77
Zr	113	136	75	175	224	221	214	323
Trace elements by ICP-MS (ppm)								
Sc	39.4	40.6	44.6	47.1	41.0	37.4	39.1	34.6
V	191	189	228	482	318	269	274	386
Cr	674	759	706	2	8	65	74	42
Co	39.7	40.6	43.0	50.3	42.2	48.3	50.7	35.9
Ni	54	61	42	25	15	33	35	36
Cu	38	41	44	169	208	142	135	196
Zn	80	82	74	126	120	138	143	143
Ga	15.7	15.8	14.7	20.9	21.4	23.1	23.7	23.1
Rb	24.91	29.85	19.83	56.69	72.70	43.18	41.03	46.27
Sr	166	150	140	154	160	200	205	286
Y	29.5	34.8	25.1	47.2	56.4	53.9	54.6	72.2
Zr	116.1	141.9	73.5	190.8	236.6	227.7	228.6	269.2
Nb	5.59	6.81	3.73	10.31	12.31	9.81	9.77	19.22
Cs	2.04	1.69	5.86	2.39	5.24	1.45	0.84	4.20
Ba	228.0	303.6	139.4	361.0	435.9	297.8	283.1	599.2
La	12.93	15.75	8.43	22.03	28.16	21.71	21.80	34.42
Ce	27.63	34.19	18.04	46.72	59.74	49.21	49.49	75.55
Pr	3.83	4.79	2.48	6.31	8.13	7.15	7.24	10.89
Nd	16.62	20.74	10.76	26.87	34.35	31.82	32.18	48.11
Sm	3.79	4.69	2.62	6.37	8.01	7.82	7.85	11.55
Eu	1.14	1.27	0.85	1.60	1.90	2.05	2.03	2.76
Gd	4.34	5.20	3.27	7.17	8.78	8.97	8.77	12.51
Tb	0.74	0.89	0.59	1.24	1.51	1.49	1.5	2.08
Dy	4.64	5.51	3.78	7.54	9.22	9.06	9.01	12.33
Ho	1.01	1.21	0.84	1.62	1.96	1.88	1.88	2.54
Er	2.87	3.36	2.43	4.47	5.44	5.17	5.14	6.81
Tm	0.489	0.573	0.417	0.756	0.917	0.849	0.842	1.116
Yb	2.93	3.45	2.55	4.54	5.52	5.05	5.02	6.51
Lu	0.50	0.57	0.43	0.75	0.90	0.82	0.82	1.04
Hf	2.90	3.53	1.88	5.06	6.31	5.96	5.86	6.96
Ta	0.36	0.42	0.25	0.69	0.82	0.60	0.59	1.07
Pb	4.90	5.97	4.21	9.22	11.54	6.95	6.88	8.95
Th	2.03	2.24	1.73	6.17	7.80	4.34	4.35	4.11
U	0.50	0.53	0.49	1.60	1.92	0.86	0.87	0.97

Table 2. Isotope analyses of sills from the Theron Mountains, Antarctica.

Sample	Z.1605.3	Z.1605.6	Z.1605.11	Z.1603.3	Z.1605.15	Z1602.4	Z.1605.10	Z.1605.13
Group	Series 1	Series 1	Series 1	Group C	Sill C	Sill A	Sill A	Sill B
Sm/^{144}Nd	0.1750	0.1682	0.1736	0.1621	0.1603	0.1840	0.1637	0.1678
^{143}Nd/^{144}Nd	0.512355	0.512367	0.512421	0.512402	0.512395	0.512547	0.512537	0.512545
εNd(180)	-5.0	-4.6	-3.7	-3.8	-3.9	-1.5	-1.2	-1.2
^{87}Rb/^{86}Sr	0.495	0.666	0.512	1.189	1.447	0.690	0.631	0.512
^{87}Sr/^{86}Sr(0)	0.710072	0.711282	0.709495	0.713013	0.712535	0.708097	0.706891	0.706213
^{87}Sr/^{86}Sr(180)	0.708805	0.709577	0.708185	0.709971	0.708831	0.706330	0.705275	0.704903
εSr(180)	64.2	75.1	55.4	80.7	64.5	29.0	14.1	8.8

^{87}Rb/^{86}Sr calculated from Rb and Sr data measured by XRF.

4.1 *Series 1*

This group is the same as Series 1 of Brewer et al. (1992) with the exclusion of one dyke (sample Z.509.1, see below). Series 1 sills are the most common type in the Theron Mountains. There are at least six sills of the type, ranging in thickness from 0.3 to 32 m. Some of the samples are cumulitic, extending the range of the group to low-Si, high-Mg compositions (Fig. 5). Others are micropegmatitic producing slightly high Ti abundances (Fig. 5). However, the group as a whole has distinctively low Ti, Fe and Zr abundances. Three samples from the group have high εSr(180) values, relative to the other groups, of 55.4 to 75.1, and low εNd(180) values of -3.7 to -5.0 (Table 2). These values are similar to most Series 1 samples of Brewer et al. (1992), but with more restricted ranges.

4.2 *Sill A*

This is the same as Group A of Brewer et al. (1992). The samples have distinctive low Si abundances, and moderately high Ti (Fig. 5). The sill occurs at Marø Cliffs and at Coalseam Cliffs. Although outcrop between these cliffs is not continuous, it is likely the same sill occurs in both places. At Marø Cliffs, Sill A cuts a Series 1 sill and is the 'Third Phase Sill' of Brook (1972b). At Coalseam Cliffs, it forms the 'Basal Sill' of Brook (1972b). It is probable that this sill was the last one in the Theron Mountains to be intruded. Sill A samples are fractionated basalts, with about 5% MgO and characteristic low SiO_2 abundances (Table 1). Two samples from the sill have relatively low, but significantly different, εSr(180) values of 14.1 and 29.0 (Table 2). It is possible that the higher value is a result of addition of radiogenic Sr by hydrothermal processes, although both samples share about the same low degree of alteration. The samples have very similar εNd(180) values of -1.2 and -1.5. The sample with the more radiogenic Sr is similar to the majority of Group A samples of Brewer et al. (1992).

4.3 *Sill B*

This is the same as Group B of Brewer et al. (1992). There is only one sill in the group, the 15 m thick 'Apparent Branch Sill' at Marø Cliffs, which is also the 'Basal Sill' at Lenton Bluff (Brook 1972b). Sill B cuts and is cut by Series 1 sills at Lenton Bluff. The sill has the highest abundances of Ti, Na, and most other incompatible elements in the Theron Mountains sills (Table 1), and the highest LREE/HREE and lowest La/Nb ratios. The sill has a relatively high εNd(180) value of -1.2 and a low εSr(180) value of 8.8 (Table 2).

4.4 *Sill C*

This comprises both Groups C and D of Brewer et al. (1992). All our samples and those of Brewer et al. (1992) come from the 200 m thick 'Scarp Capping Sill' of Brook (1972b). This sill has no cross-cutting relationships with other sills. Many of the samples from this sill with relatively high Ti and low Si are cumulitic. The samples are strongly fractionated, with < 3.3 wt.% MgO, and <11 ppm Cr (according to ICP-MS data). It is distinctively high in Fe, Si, Th, U and

Pb (Table 1). The samples have a very small range of εNd(180) values of -3.8 to -3.9 (Table 2). This is within the range of Series 1, and a smaller range than Brewer et al. (1992) reported for their groups C and D. Sill C εSr(180) values are similar to those of Series 1.

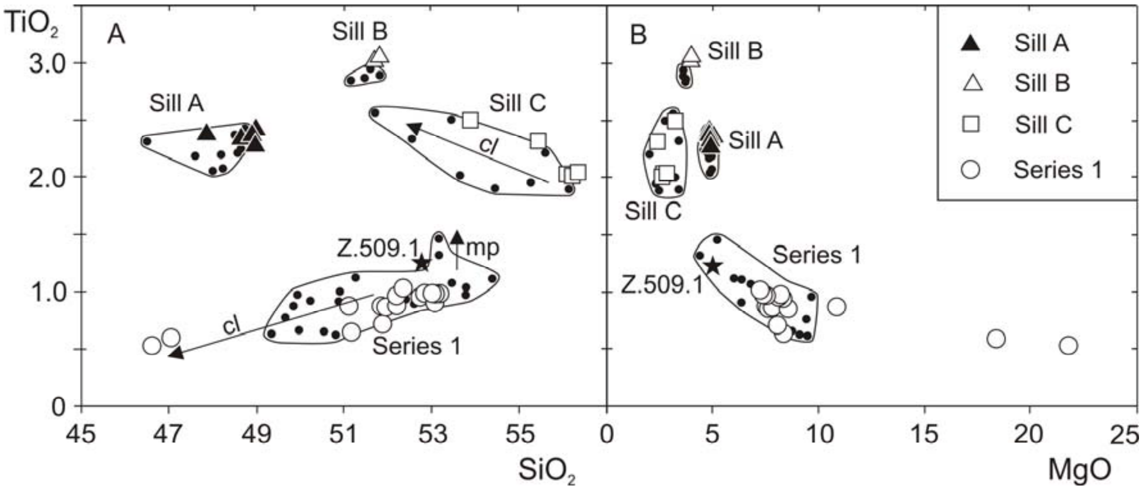

Figure 5. Major element variations in the intrusive rocks of the Theron Mountains; A, TiO_2 versus SiO_2 and B, TiO_2 versus MgO. Filled circles are data from Brewer et al. (1992), and fields are drawn around these data to show the groupings. The star is dyke sample Z.509.1. Other large symbols are the new data from this study. In A, arrows labelled cl indicate trends produced by post-emplacement cumulate processes in samples of Series 1 and Sill C. Arrows point toward cumulates. The arrow mp indicates a trend in Series 1 produced by development of micropegmatites.

Table 3. Comparison of Theron Mountains Series 1 and Sill C with Ferrar MFCT and SPCT.

Rock	Theron Mts. Series 1 Z.1605.3	MFCT Portal Peak	Theron Mts. Sill C Z.1605.15	SPCT Victoria Land
SiO_2	51.95	53.85	56.11	57.08
TiO_2	0.87	0.78	2.03	1.98
Al_2O_3	15.22	14.36	12.25	12.06
Fe_2O_3(T)	9.95	10.49	15.79	16.51
MnO	0.16	0.15	0.19	0.20
MgO	8.6	6.04	2.70	2.32
CaO	9.88	10.49	6.88	6.79
Na_2O	1.83	2.11	2.28	2.42
K_2O	0.86	0.78	1.70	1.83
P_2O_5	0.20	0.13	0.26	0.26
Ba	228	210	436	399
Rb	24.9	19.5	72.7	72
Sr	166	151	160	129
Zr	116	103	237	232
Y	29.5	22	56.5	56
Nb	5.59	5	12.31	9
Ti/Y	177	213	216	212
Ti/Zr	44.9	45.4	51.5	51.1
Zr/Y	3.93	4.68	4.19	4.14
Nb/Y	0.19	0.23	0.22	0.16

MFCT column is average of sill chilled margins, Portal Peak (Hergt et al. 1989). SPCT column is mean of SPCT lavas (Elliot et al. 1999).

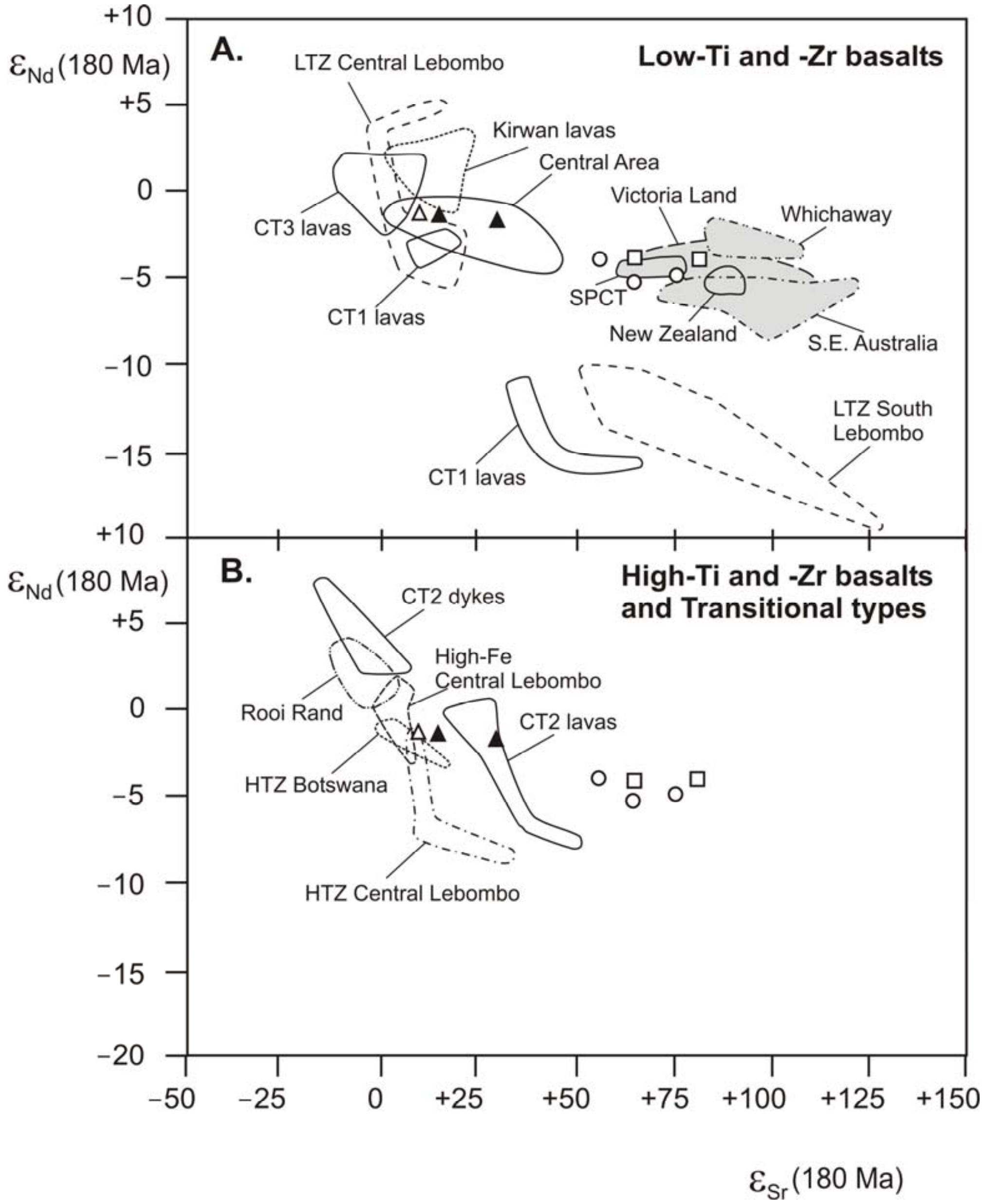

Figure 6. Plots of εNd versus εSr calculated to 180 Ma comparing Theron Mountains sills (symbols as in Figure 5) to selected Ferrar and Karoo magma types. A. Therons data compared to low-Ti, low Zr basalts. The Ferrar tholeiite field (shaded, after Leat et al. 2000) comprises MFCT samples from Victoria Land, Southeast Australia and New Zealand: the SPCT field (Victoria Land) is shown separately. Whichaway Nunataks intrusions contain both MFCT and SPCT (Brewer 1989). The LTZ central and south Lebombo fields are from Sweeney et al. (1994), CT1 and CT3 lavas from Luttinen & Furnes (2000), and Kirwan lavas from Harris et al. (1990). B. Therons data compared to high-Ti, high-Zr basalts. CT2 lavas are from Luttinen & Furnes (2000), high-Fe and HTZ Central Lebombo fields from Sweeney et al. (1994), HTZ Botswana dyke swarm from Elburg & Goldberg, (2000), and Rooi Rand dykes from Hawkesworth et al. (1984).

4.5 *Sample Z.509.1*

This sample was included in Series 1 by Brewer et al. (1992). It is a 6 m thick dyke which crops out near the top of the escarpment. Cross-cutting relationship with sills are not exposed. It is elementally similar to Series 1, having slightly higher Ti, Fe and Zr, but has a much lower εSr(180) value of 31.0 (Brewer et al. 1992). We therefore exclude this sample from Series 1. Because of uncertainty about its age, we do not consider it further.

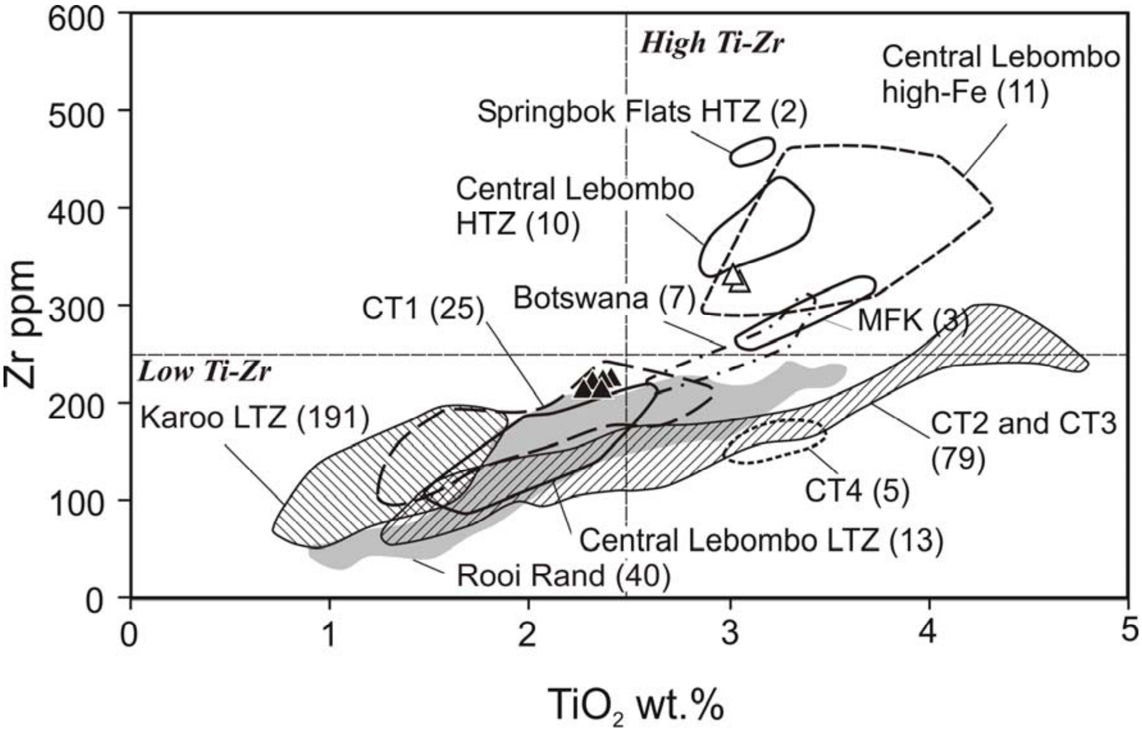

Figure 7. Plot of Zr versus TiO_2 comparing Theron sills A and B with Karoo basalts in southern Africa and Dronning Maud Land, Antarctica (symbols as in Figure 5). The field for Karoo LTZ is by far the most heavily populated, containing low-Ti, low-Zr lavas and intrusions from the Central Area, South Africa, (54), south Lebombo (31), Springbok Flats (17), Botswana (2), Kirwanveggen (26), and Vestfjella (61). The central Lebombo LTZ field contains low-Ti-Zr basalts from the Sabie River Basalt Formation. The CT1 field contains dolerites like CT1 lavas from Vestfjella, Dronning Maud Land. Note that CT2 and CT3 basalts and dykes (70+CT3), CT4 dolerites from Vestfjella, Dronning Maud Land, and the Rooi Rand dolerite dykes from South Lebombo have higher Ti/Zr ratios than the main Karoo LTZ field, with which they do not overlap. There are many fewer high-Ti, high-Zr rocks. These are: central Lebombo HTZ and central Lebombo high-Fe, high Ti-Zr basalts and dykes and high-Fe basalts and dykes from Sabie River Basalt Formation respectively, Springbok Flats high Ti-Zr basalts, high Ti-Zr dolerites from the Botswana swarm, and MFK: high-Fe sills from Mannefallknausane, Dronning Maud Land. A few atypical samples have been excluded from the fields of Karoo LTZ and Rooi Rand. Data sources: this study, Marsh et al. (1997), Erlank (1984), Sweeney et al., (1994), Harris et al. (1990), Luttinen et al. (1998), Luttinen & Furnes (2000), Elburg & Goldberg (2000).

5 CORRELATION OF MAGMA TYPES

In this section we attempt to correlate the chemical groups with magma types in the Karoo-Ferrar province. We first deal with Series 1 and Sill C, as we shall argue that these are closely related.

5.1 *Series 1 and Sill C*

We correlate Series 1 with the Ferrar sills and lavas of the Transantarctic Mountains. This goes beyond Brewer et al. (1992), who correlated only part of Series 1 with the Ferrar. Specifically, Series 1 correlates with Mount Fazio Chemical Type (MFCT), which is the dominant chemical type among the Ferrar tholeiites (Fleming et al. 1992, Elliot et al. 1999). This correlation is clear in Table 3, which compares a Series 1 sill with average chilled margin of the Portal Peak sills, Transantarctic Mountains (Hergt et al. 1989). Series 1 and MFCT also have similar Nd and Sr isotopic ratios (Fig. 6). Some samples of Series 1 have marginally lower εSr(180) than MFCT, a point also evident in the data of Brewer et al. (1992).

We correlate the Sill C with the Scarab Peak chemical type (SPCT) of the Ferrar subprovince. Hitherto, SPCT has only been identified in lavas of the Transantarctic Mountains in Victoria Land (Fleming et al. 1992, Elliot et al. 1999). In Table 3, a Sill C sample and average SPCT lava (Elliot et al. 1999) are more-or-less identical. They also have similar Sr and Nd isotopic ratios (Fig. 6), although the two Sill C samples have εNd(180) values of -3.8 and -3.9, slightly less negative than the SPCT in Victoria Land which have εNd(180) values of -4.2 to -4.4 (Fleming et al. 1992, Elliot et al. 1999).

Table 4. Comparison of Theron Mountains Sill A with Karoo basalts.

Rock	Theron Mts. Sill A Z.1605.10	Lebombo LTZ RSS-169	Vestfjella LTZ 116-KHG	Vestfjella LTZ AL/B19c	Rooi Rand SL A114
SiO_2	47.85	49.75	50.22	47.74	50.58
TiO_2	2.37	2.57	2.05	2.05	2.17
Al_2O_3	14.11	12.50	14.67	15.83	12.86
Fe_2O_3(T)	17.47	17.27	14.52	14.10	15.20
MnO	0.22	0.24	0.19	0.15	0.25
MgO	5.05	4.83	5.20	5.93	5.21
CaO	8.88	9.24	9.18	10.43	10.08
Na_2O	2.58	2.49	2.35	2.75	2.93
K_2O	1.18	0.74	1.29	0.78	0.51
P_2O_5	0.28	0.38	0.32	0.23	0.19
Ba	283	213	497	185	149
Rb	41.0	17.4	18	13	11
Sr	205	208	357	358	224
Zr	228.6	211	189	173	158
Y	54.6	46	30	28	34
Nb	9.77	13.4	7	8	
Ti/Y	260	336	409	439	383
Ti/Zr	62	73	65	71	82
Zr/Y	4.2	4.6	6.3	6.2	4.6
Nb/Y	0.18	0.29	0.33	0.25	0.24

Major elements recalculated to 100% volatile free. Sample RSS-169, low-Ti-Zr dolerites, central Lebombo (Sweeney et al. 1994); 116-KHG and AL/B19c are representative CT1-like dykes from Vestfjella, Dronning Maud Land (Luttinen unpubl.); A114 is a Rooi Rand dolerite dyke, Lebombo (Erlank 1984).

5.2 *Groups A and B*

Despite differences in Si and Ti abundances, sills A and B are clearly similar in trace element abundances (Table 1) and ratios, and are considered together. Correlations of the sills are first considered in the TiO_2 versus Zr diagram (Fig. 7), in which they are compared to a wide range of Karoo-Ferrar basalts. We have not plotted picritic or nephelinitic Karoo rocks in the diagram, as the Theron Mountains samples clearly do not belong to those magma types. In the figure, Sill A samples are similar to three other groups; the LTZ group of central Lebombo (Sweeney et al. 1994), basaltic dykes in Vestfjella that are similar to CT1 lavas (A. Luttinen, unpubl.), and Rooi Rand dykes (Erlank 1984). A similar dyke has also been reported from the Kirwanveggen (Harris et al. 1991). The vast majority of low-Ti basalts from the Karoo area (including the entire central area of South Africa, Sabie River Basalts in southern Lebombo, Kirwanveggen, Heimfrontfjella and CT1 lavas of Vestfjella) have significantly lower Ti and Zr abundances than Sill A, and are clearly not directly related to it. The field for this majority of low-Ti basalts in Figure 7 does not overlap with the more extended field of either LTZ basalts of central Lebombo or Rooi Rand dykes, and seems to form a different group. In Table 4, a Sill A sample is compared to a LTZ sample from Lebombo, two dykes from Vestfjella and a Rooi Rand dyke. The samples are similar, and there is a close match of trace element abundances and ratios in Figure 8. Nevertheless, the Sill A sample has a distinctive high Y (and HREE) abundance(s) which is not matched in the other samples. We conclude that the closest matches for Sill A are the LTZ basalts of central Lebombo, similar dykes in Vestfjella, and certain Rooi Rand dykes.

Table 5. Comparison of Theron Mountains Sill B with Karoo basalts.

Rock	Theron Mts. Sill B Z.1605.13	MFK high-Fe MK-15	Lebombo high-Fe RSC-035	Lebombo HTZ RSS-002	Botswana HTZ ME98B6
SiO_2	51.75	50.99	50.33	52.84	50.78
TiO_2	3.06	3.08	2.96	3.32	3.39
Al_2O_3	12.90	12.28	12.25	13.18	13.42
Fe_2O_3(T)	15.47	17.20	18.17	11.66	14.17
MnO	0.21	0.22	0.25	0.15	0.18
MgO	4.00	3.81	4.22	5.01	4.79
CaO	7.71	8.37	7.08	8.82	9.40
Na_2O	2.75	2.31	2.83	1.93	2.40
K_2O	1.73	1.21	1.30	2.53	1.05
P_2O_5	0.43	0.53	0.59	0.55	0.42
Ba	599	436	431	830	467
Rb	46.3	39	40	50	18 .3
Sr	286	158	403	1110	617
Zr	269.2	269	301	425	302 .2
Y	72.2	72	59	37	47 .0
Nb	19.22	17	24	27	17 .4
Ti/Y	254	257	294	527	431
Ti/Zr	68	69	58	46	67
Zr/Y	3.7	3.7	5.1	11.5	6.4
Nb/Y	0.27	0.24	0.41	0.73	0.37

Major elements recalculated to 100% volatile free. Sample MK-15 is a sill from Mannefallknausane, Dronning Maud Land (Luttinen unpubl.); RSC-035 and RSS-002 are high-Fe and high Ti-Zr samples respectively from the Sabie River Basalt Formation, central Lebombo (Sweeney et al. 1994); ME98B6 is a high Ti-Zr dolerite from the Botswana dyke swarm (Elburg & Goldberg 2000).

In the TiO_2 versus Zr diagram (Fig. 7), Sill B samples plot in the high-Ti and high Zr quadrant. Few basalts in the Karoo province plot in this field. Possible correlatives with Sill B are: HTZ and high-Fe basalts and dolerites from central Lebombo (Sweeney et al. 1994), HTZ basalt dykes of the Botswana dyke swarm (Elburg & Goldberg 2000), and sills from Mannefallknausane, Dronning Maud Land (A. Luttinen, unpubl.). Compositionally similar dykes also occur in the Ahlmannryggen area, Dronning Maud Land (Harris et al. 1991). The CT2, CT4 and some CT3 lavas and dykes from Vestfjella have comparable Ti contents, but have much lower Zr/Ti ratios than Sill B. The rocks closest to Sill B are compared in Table 5 and Figure 8. The HTZ basalt from central Lebombo is the poorest fit. The high-Fe basalt of Lebombo is similar to Sill B, except for lower Y and HREE abundances in the former. The sill from Mannefallknausane is more-or-less identical to Sill B.

The central Lebombo lava sequence is over 2 km thick, and appears to represent volcanism along a zone of rapidly thinning lithosphere. Sweeney et al. (1994) suggested that erupted magma compositions could be explained by mixing between asthenosphere-derived melts and melts of lithospheric mantle generated at different depths, and hence with different amounts of residual garnet. The high-Fe lavas of central Lebombo were the last-erupted basalts in the sequence, and contain the least amount of the lithospheric component (Sweeney et al. 1994). These compositions converge with low-Ti ones near the asthenosphere-derived end-member. Sills A and B from the Theron Mountains are similar to low-Ti-Zr and high-Fe magmas respectively from central Lebombo. Their high Y and HREE abundances relative to most of the Lebombo lavas suggests that garnet was mostly absent from their source regions. This is consistent with magma generation at low pressures under rapidly thinning lithosphere beneath the Lebombo Monocline, mostly at lower pressures than garnet stability. It is therefore likely that the magmas represented by sills A and B were generated late in the magma generation episode. This is consistent with the late relative emplacement of most of the chemically similar lavas and dykes in Tables 4 and 5. The high-Fe lavas were the last-emplaced series in the central Lebombo area (Sweeney et al. 1994), the Rooi Rand dykes cut the Sabie River Basalts, and the LTZ CT1-like dykes in Vestfjella intrude, and were therefore emplaced after, the main lava series.

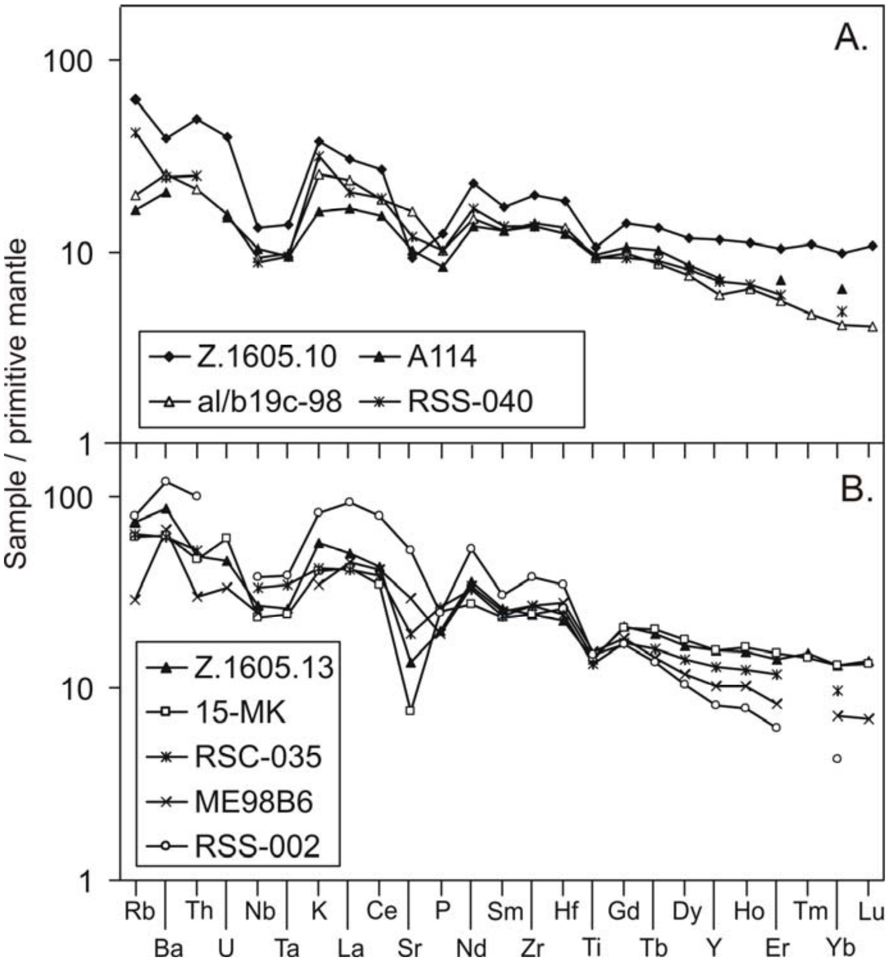

Figure 8. Primitive mantle-normalized multi-element diagrams for Theron Mountains sills A and B and compositionally similar lavas and intrusions in the Karoo-Dronning Maud Land region. A. Sill A sample Z.1605.10 compared to the most similar low-Ti-Zr samples: A114, Rooi Rand dykes, Lebombo (Erlank 1984); AL/B19c-98 is a low Ti-Zr dolerite dyke from Vestfjella, Dronning Maud Land (A. Luttinen, unpubl.); RSS-040 is a low Ti-Zr lava, Sabie River Basalt Formation, central Lebombo (Sweeney et al. 1994). B. Sill B sample Z.1605.13 compared to the most similar high-Ti-Zr samples: 15-MK is a high-Fe sill from Mannefallknausane, Dronning Maud Land (A. Luttinen, unpubl.); RSS-002, and RSC-035 are high Ti-Zr, and high-Fe samples respectively from the Sabie River Basalt Formation, Central Lebombo (Sweeney et al. 1994); ME98B6 is a high Ti-Zr dolerite from the Botswana dyke swarm (Elburg & Goldberg 2000). Normalizing values from Sun & McDonough (1989).

6 IMPLICATIONS FOR MAGMA FLOW

The identification of SPCT sills in the Theron Mountains is critical to arguments about whether Ferrar magmas were emplaced from a common source by lateral flow. Elliot et al. (1999) documented SPCT lavas distributed over 1600 km in the Transantarctic Mountains. They argued from this lateral spread that the SPCT magmas must have been transported laterally within the crust from a single source magma chamber. They and Elliot & Fleming (2000) further suggested that the source magma chamber was in the Weddell triple junction area (Ferris et al. 2000), some 2000 km from the nearest SPCT outcrop in the Transantarctic Mountains. Our identification of SPCT in the Theron Mountains increases the distance over which SPCT has been identified to 3000 km, which provides major support for the lateral flow model for SPCT. We would further identify four high-Ti samples reported from Whichaway Nunataks (Brewer 1989) as SPCT, although SPCT is apparently absent from Ferrar (MFCT) dykes in the Shackleton Range (Techmer et al. 1995). SPCT is therefore a very widely distributed magma type. The Theron Mountains are only some 500 km from the putative source in the Weddell triple junction area, supporting ideas that the Ferrar originated there.

The presence of MFCT in the Theron Mountains means that this magma type is even more widely distributed than SPCT, extending, with remarkably little compositional variation, some 3500 km from the Theron Mountains to Australia. It is therefore likely that this magma type was also emplaced by lateral transport.

Sills A and B correlate most closely with the LTZ and high-Fe lavas of central Lebombo, a few scattered dykes in Vestfjella and a sill in Mannefallknausane, Dronning Maud Land. Their high Y and REE abundances indicate that garnet was not abundant in the source mantle, and they probably were generated at relatively shallow depths below the thinned crust of a rift zone. The geological relationship of sills A and B in the Theron Mountains, and their correlatives, also indicate relatively late emplacement. By far the greatest volumes of these magmas were erupted along the Lebombo Monocline, at a time when it was a zone of rapid crustal thinning. We therefore propose that it is likely that the magmas of the Vestfjella dykes, the Mannefallknausane sill, and Theron Mountains sills A and B also were generated in the Lebombo Monocline zone of extension and were transported laterally. The central Lebombo, Vestfjella, Mannefallknausane and Theron Mountains form a linear trend some 500 km long in reconstructed Gondwana (Figs. 2, 3), possibly indicating the zone of lateral dyke emplacement.

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