Antarctic Science 26(4), 389–399 (2014) © Antarctic Science Ltd 2014 doi:10.1017/S0954102013000916

Geochemistry of the 1100 Ma intrusive rocks from the Ahlmannryggen region, Dronning Maud Land, Antarctica

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Abstract: The recognition of a Mesoproterozoic large igneous province (LIP) across large parts of southern Africa has been strengthened by recent geochronology, geochemistry and petrology. The *c.* 1100 Ma Umkondo province has been recognized across parts of Botswana, Zimbabwe, South Africa and Mozambique where tholeiitic sills, dykes and rare lava flows have been correlated into a single magmatic province emplaced in the interval 1108–1112 Ma. The extension of the province into the Dronning Maud Land region of Antarctica has been suggested by several workers, but detailed analyses of geochemistry and petrogenesis are lacking, as are comparative studies. This study investigates 25 dykes and sills of the Borgmassivet intrusions which include several of the major diorite sills of the province, up to 300 m in thickness. The dykes and sills are also considered to be *c.* 1100 Ma and they were emplaced, in part, synchronously with the Ritscherflya Supergroup sedimentary sequence. The Borgmassivet intrusions are characterized by geochemical signatures that suggest the magmas were either extensively contaminated by continental crust or derived from an enriched lithospheric mantle source, where the enrichment was related to earlier subduction. The limited geochemical range of the Borgmassivet and Umkondo intrusions are probably not consistent with significant levels of crustal contamination. Furthermore, the trace element ratios indicate a source in the sub-lithospheric mantle, followed by gabbroic fractionation and interaction with lithospheric wall rocks.

Received 10 July 2013, accepted 18 October 2013, first published online 22 January 2014

Key words: dolerite, Kalahari, Mesoproterozoic, Umkondo

Introduction

The recognition of large igneous provinces (LIPs) older than Phanerozoic in age can be difficult. A combination of poor preservation and the absence of good geochronological control can hamper the correlation of units/intrusions over a large area. The Umkondo LIP of southern Africa has been dated in the interval 1108–1112 Ma, it can be traced over large parts of the Kalahari Craton and was emplaced synchronously with widespread intraplate magmatism in Laurentia (Hanson *et al*. 2004). An even wider extent for the Mesoproterozoic Umkondo LIP has been proposed, several workers (e.g. Krynauw *et al*. 1988, Bullen *et al*. 2012) have suggested that the province extends into present day East Antarctica (Dronning Maud Land) based on similar geological relationships between the sills and the sedimentary successions, as well as similar geochronology (Moyes *et al*. 1995, Grosch *et al*. 2007). However, there has been very little geochemistry reported on the mafic sills from Dronning Maud Land. The purpose of this paper is to interpret the geochemistry of the Borgmassivet intrusions and related dykes and sills of the Ahlmannryggen, and to compare them to the extensive Mesoproterozoic sill complexes of southern Africa.

Umkondo large igneous province

The Umkondo dolerites of eastern Zimbabwe form massive sills and dykes, and intrude the Proterozoic Umkondo Group sedimentary rocks. This sedimentary succession (> 3.5 km thickness) of siliclastic and carbonate rocks may represent an offshore basin of the Umkondo continental margin (Stocklmayer 1981). There is evidence from parts of the province that the magmatism and sedimentation were penecontemporaneous with field examples of sill emplacement into wet, partially lithified sediments (e.g. Krynauw *et al*. 1988, Curtis & Riley 2003). The Umkondo intrusive rocks are reported from elsewhere across southern Africa (Botswana, South Africa and Mozambique; Hanson *et al*. 1998) and are seen to intrude both Archaean and Proterozoic basement and supracrustal units.

Tholeiitic basaltic lavas, which are the extrusive equivalents of the Umkondo dolerites (Munyanyiwa 1999), are rare in the province but have been identified from isolated parts of the Umkondo Group stratigraphy and are thought to have formed part of a much more extensive province. The sills are the most striking aspect of the Umkondo LIP, with individual intrusions up to 300 m in thickness (Bullen *et al*. 2012). The sills are associated with minor granophyre zones, which have been dated by

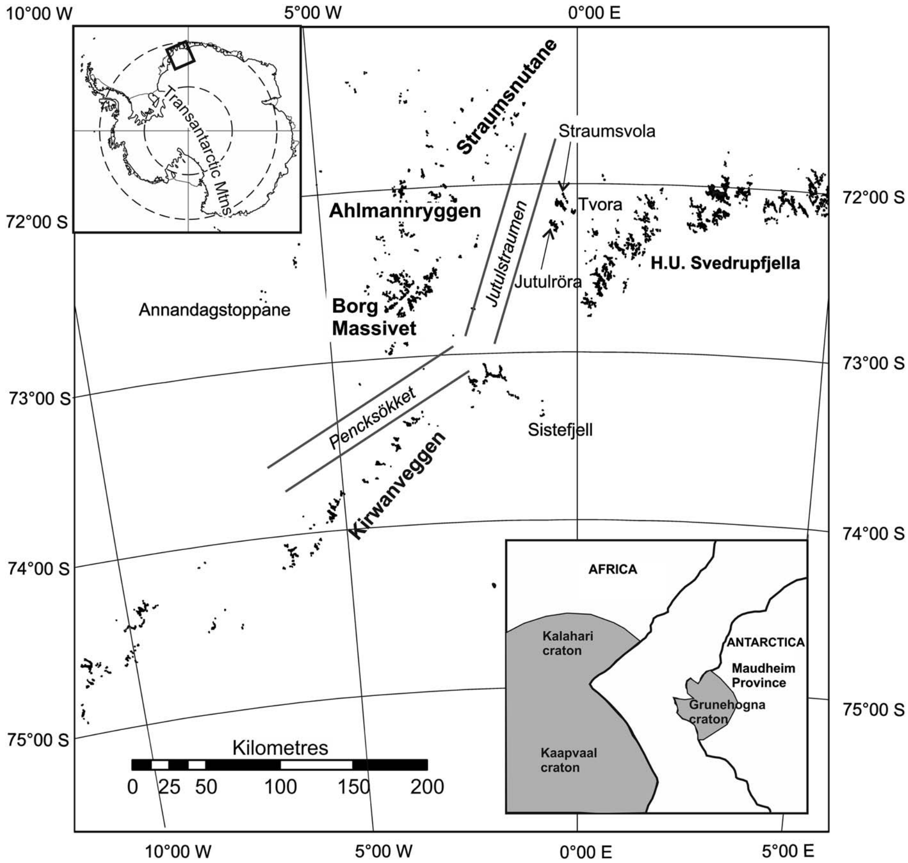

Fig. 1. Location map of rock outcrops in western Dronning Maud Land (Antarctica) from Vestfjella to H.U. Svedrupfjella. The inset is a pre-break-up Gondwana reconstruction of Africa and Antarctica showing the extent of the Kaapvaal-Grunehogna Craton and the outcrop of Early–Middle Jurassic Karoo igneous rocks.

Hanson *et al*. (1998) as a proxy for dating the emplacement of the mafic intrusives. They reported a uranium-lead (U-Pb) zircon age of 1105 ± 2 Ma for the sills from eastern Zimbabwe, which is in close agreement with the U-Pb zircon and baddeleyite ages of 1108–1112 Ma reported by Hanson *et al*. (2004) for sills from eastern Zimbabwe, as well as intrusions from South Africa and Botswana.

Geological setting of western Dronning Maud Land

The geography of western Dronning Maud Land is summarized in Fig. 1. It can be subdivided into two distinct geological provinces: the Grunehogna province, which includes the Ahlmannryggen, Borgmassivet and Straumsnutane areas (Fig. 1), together with outlying nunataks to the west, is characterized by weakly metamorphosed and deformed sedimentary, and volcanogenic rocks of the Ritscherflya Supergroup that have been extensively intruded by large-scale tholeiitic sills and dykes of the Borgmassivet intrusions (Wolmarans & Kent 1982). The basement to the Ritscherflya Supergroup is thought to be Archaean-age granitoids, whilst the Grunehogna Craton is interpreted as part of the Archaean Kaapvaal Craton of southern Africa prior to Gondwana break-up (Martin & Hartnday 1986). The basement of the Grunehogna Craton is exposed only within a small area at Annandagstoppane, in the form of an S-type granite, which has been dated (U–Pb zircon) at 3067 ± 8 Ma (Marschall *et al*. 2010), an age that is coeval with the granitoids and volcanic rocks in the Swaziland and Witwatersrand blocks of the Kaapvaal Craton (Schoene *et al*. 2008). The close similarity of basement and supracrustal geology between the Grunehogna and Zimbabwe-Kaapvaal (southern Africa) provinces suggest that both areas formed part of a contiguous crustal province from Archaean time until the Mesozoic break-up of Gondwana (Groenewald *et al*. 1991). To the south and east of the Grunehogna province lie the Kirwanveggen and H.U. Svedrupfjella regions (Fig. 1) that form part of the Mesoproterozoic Maud province, an extension of the Namaqua-Natal metamorphic province of southern Africa (Jacobs *et al*. 1993), which is formed of amphibolite to granulite facies gneisses of the Svedrupfjella Group (Groenewald *et al*. 1995). Adjacent to the inferred boundary of the Grunehogna Craton, the Svedrupfjella Group is dominated by hornblende biotite orthogneiss of the Jutulrøra Formation. The crustal boundary between these two distinct geological provinces lies unexposed beneath the Pencksokket and Jutulstraumen ice streams (Fig. 1). However, a recent high-resolution aerogeophysical survey

https://doi.org/10.1017/S0954102013000916 Published online by Cambridge University Press

suggests that this boundary has been reactivated along the Jutulstraumen ice stream by a continental rift that was either amagmatic along its axis or contains a thick sedimentary succession (Ferraccioli *et al.* 2005a, 2005b).

The Ritscherflya Supergroup consists of *c.* 2 km thickness of relatively undeformed sedimentary and volcanogenic rocks of the Ahlmannryggen and Jutulstraumen groups. The Ritscherflya Supergroup has been interpreted as a sedimentary sequence of shallow marine, tidal flat, braided stream and alluvial fan deposits (Wolmarans & Kent 1982). The volcanogenic sedimentary rocks of the Jutulstraumen Group, which form the upper part of the Ritscherflya Supergroup have been correlated geochemically with the Borgmassivet intrusions (Moyes *et al.* 1995). Moyes *et al.* (1995) attempted to date the lithification age of the Högfonna Formation of the Ritscherflya Supergroup using a combination of rubidium-strontium (Rb-Sr) and samarium-neodymium (Sm-Nd) whole rock geochronology. Assuming a homogenized source region, they obtained ages of 1085 ± 27 Ma (Rb-Sr) and 1180 ± 367 Ma (Sm-Nd). Direct dating of the Borgmassivet intrusions has also proved difficult with Rb-Sr and Sm-Nd whole rock geochronology yielding ages in the range 842 ± 15 to 1429 ± 124 Ma (Moyes *et al.* 1995), although Wolmarans & Kent (1982) produced a Rb-Sr whole rock isochron of 1073 ± 40 Ma based on seven mafic sills from the Ahlmannryggen. A further emplacement date of the mafic sills has been obtained from the granitic zone at the sill-sediment interface; the granite-granophyre-syenite units (Nils Jörgennutane suite) are interpreted to be the result of contact melting under hydrous conditions (Moyes *et al.* 1995). These contact melts have also been dated by Moyes *et al.* (1995), who obtained Rb-Sr whole rock ages in the range 939 ± 29 to 1008 ± 16 Ma. More recently, a U-Pb zircon age of *c.* 1107 Ma (no error published) for a mafic sill from the Borgmassivet intrusions has been reported by Frimmel (2004), whilst a U-Pb age of 1130 ± 7 Ma (Frimmel 2004) for detrital grains from tuff beds at the base of the Ritscherflya Supergroup is a good indication of the age of onset of sedimentation. There are also several reports of zircon overgrowth ages and leucosome development in the interval 1098–1112 Ma (Grosch *et al.* 2007), which are interpreted to be the result of thermal metamorphism associated with Umkondo/Borgmassivet age magmatism. Therefore, the age for the intrusion of the Borgmassivet intrusive mafic sills is considered to be close to 1100 Ma, which is coeval with the Umkondo LIP of southern Africa (1100 Ma; Hanson *et al.* 1998). This date is also close to the inferred lithification age of the Ritscherflya Supergroup sedimentary rocks (1085 ± 27 Ma; Moyes *et al.* 1995) and, therefore, supports the field observations of Krynauw *et al.* (1988) and Curtis & Riley (2003) that the Borgmassivet intrusions were emplaced into wet, partially lithified sediments. This interpretation was based on several observations, for example, destruction of sedimentary structures, large-scale soft-sediment deformation (including sediment balls and flame structures), pegmatites at the sedimentary-igneous contact, and fusion of sedimentary rocks. Many of these features are typical of the establishment of a fluidized system (Kokelaar 1982). Krynauw *et al.* (1988) interpreted the wet sediment-sill interaction to have taken place at shallow crustal levels (< 1.6 km or ≤312 bar) with stationary fluidization of the host sediments occurring within a 3 m zone of the sill contact. Not all of the Ritscherflya Supergroup sedimentary rocks in contact with the Borgmassivet intrusions have been fluidized, for example, the Schumacherfjellet Formation, which may have been completely lithified at the time of intrusion and indicates that wet sediment only occurred in pockets.

Intrusive history of western Dronning Maud Land

Mafic intrusions are widespread across western Dronning Maud Land and several generations of emplacement have been documented (Grantham 1996, Zhang *et al.* 2003, Riley *et al.* 2005, 2009), although from field observations alone it remains difficult to identify different dyke generations. At least five separate intrusive episodes have been identified in western Dronning Maud Land.

176–178 Ma

At least two distinct episodes occurred at *c.* 178 Ma. A high concentration (> 500 dykes over 10 km^2) of basanite/tephrite dykes were emplaced at *c.* 178 Ma associated with the Straumsvola nepheline syenite pluton (Fig. 1; Riley *et al.* 2009). There is also an event at *c.* 178 Ma of north-south trending dolerite dykes from the Ahlmannryggen region, intruding metasedimentary rocks of the Ritscherflya Supergroup, which were interpreted to form part of the later stages of the Karoo magmatic province (Riley *et al.* 2005). The dykes are parallel to the Jutulstraumen ice stream, which occupies a major crustal lineament (Fig. 1).

190 Ma

A suite of east-west trending dolerite dykes have been recognized from the Ahlmannryggen region where they intrude Ritscherflya Supergroup metasedimentary rocks (Riley *et al.* 2005). The dykes are parallel to the Pencksokket subglacial trough (Fig. 1), which also represents a major tectonic feature of the area (Ferraccioli *et al.* 2005a). The dykes include a geochemically depleted group and have been interpreted as one of the earliest expressions of the Karoo magmatic province. However, there is a degree of doubt regarding the *c.* 190 Ma age given that several of the ^{40}Ar-^{39}Ar ages do not fulfil all criteria for a reliable plateau age (Riley *et al.* 2005).

Table I. Whole rock analyses of dolerite dykes/diorite sills from Ahlmannryggen, Dronning Maud Land.

Sample	Z.1802.2	Z.1815.1	Z.1818.1	Z.1818.2	Z.1821.1	Z.1821.2	Z.1825.2	Z.1827.1	Z.1827.2	Z.18.28.6	Z.18.29.1	Z.1831.1	Z.1831.2
Latitude (S)	72°16.077'	72°02.671'	72°02.597'	72°02.597'	72°01.880'	72°01.880'	71°59.647'	71°59.551'	71°59.551'	71°59.685'	71°59.542'	72°02.722'	72°02.722'
Longitude (W)	003°22.043'	002°48.161'	002°39.611'	002°39.611'	003°23.789'	003°23.789'	003°21.091'	003°21.824'	003°21.824'	003°18.502'	003°20.967'	003°31.767'	003°31.767'
Altitude (m)	1565	1237	1243	1243	1319	1319	1279	1280	1280	1141	1148	1142	1142
SiO_2	52.28	47.44	52.43	48.37	53.6	48.8	54.12	52.2	52.4	53.35	50.62	53.82	55.19
TiO_2	0.68	1	1.01	1.07	0.84	0.82	0.75	0.95	0.88	0.75	0.7	0.71	0.68
Al_2O_3	14.29	9.8	13.19	14.19	14.55	13.61	14.75	14.76	14.88	14.31	13.05	14.51	14.64
Fe_2O_3(T)	10.3	15.52	12.42	18.18	10.39	15.12	10.5	10.7	10.19	10.55	12.3	10.72	11.66
MnO	0.17	0.18	0.18	0.25	0.16	0.19	0.15	0.16	0.15	0.16	0.19	0.17	0.23
MgO	7.47	11.18	5.49	5.32	6.46	5.46	6.19	7.29	7.53	6.06	6.47	6.06	6.17
CaO	10.04	11.77	10.07	9.41	8.91	9.62	9.13	10.77	10.51	8.7	11.23	8.87	7.46
Na_2O	1.96	1.4	2.41	2.36	2.05	2.68	1.91	1.89	1.83	2.21	2.52	2.03	2.18
K_2O	0.97	0.16	1.2	0.2	1.43	0.32	1.13	0.67	1	1.34	1.25	1.29	1.35
P_2O_5	0.1	0.25	0.12	0.44	0.09	0.22	0.1	0.1	0.1	0.1	0.09	0.1	0.11
LOI	1.34	1.26	0.91	0.2	1.98	2.19	1.79	0.66	1.19	2.38	0.91	1.57	0.92
Total	99.7	99.99	99.45	100.01	100.37	100.4	100.56	100.01	100.53	100.03	99.5	99.95	100.69
mg-number	59.0	58.8	46.7	36.7	55.2	41.7	53.9	57.4	59.4	53.2	51.0	52.8	51.2
Cr	337	784	30	8	55	36	102	106	125	105	130	120	76
Ni	94	475	81	41	79	77	64	85	89	82	80	78	122
Co	43.4	44.2	47.4	48.8	48.2	48.5	38.1	48.6	48.1	43.9	45.4	45.3	51.0
Ga	14.94	17.05	17.05	17.76	16.68	16.23	14.11	16.03	15.94	17.1	16.61	16.48	17.62
Rb	36.25	58.13	34.47	52.68	85.13	98.73	44.72	32.18	42.81	74.52	51.39	72.94	93.85
Sr	129.5	147.5	126.3	128.5	118.2	124.4	118.1	129.5	134.6	132.2	125.0	136.2	128.3
Y	21.2	28.2	29.5	30.3	22.9	22.4	19.8	22.5	21.0	24.1	23.5	23.5	23.3
Zr	90	129	126	129	102	98	91	90	83	108	109	108	58
Nb	4.58	6.37	6.04	6.17	4.85	4.66	4.3	4.34	3.96	4.9	5.1	5.08	5.91
Cs	1.32	2.62	0.76	2.57	2.58	2.35	3.45	3.77	2.14	3.35	6.69	2.61	6.51
Ba	244	399	231	289	479	546	193	171	241	349	212	290	314
Sc	33	39	42	44	39	38	33	44	44	33	32	32	36
La	12.0	19.5	17.0	17.4	13.5	13.1	13.2	11.5	11.1	15.6	16.3	16.4	15.9
Ce	25.4	41.0	36.3	37.3	28.7	28.0	27.8	24.2	23.7	32.8	34.5	34.3	33.0
Pr	3.29	5.33	4.76	4.92	3.78	3.68	3.63	3.24	3.23	4.28	4.46	4.48	4.28
Nd	13.5	21.4	19.0	20.1	15.1	14.8	14.5	13.4	13.2	17.0	17.8	17.8	16.8
Sm	3.05	4.51	4.25	4.47	3.35	3.34	3.12	3.11	3.02	3.8	3.85	3.83	3.61
Eu	0.88	1.15	1.11	1.16	0.9	0.92	0.84	0.9	0.88	1.01	1.01	1.06	0.92
Gd	3.46	4.7	4.7	4.79	3.75	3.73	3.22	3.47	3.35	4.04	3.92	3.91	3.81
Tb	0.570	0.760	0.800	0.820	0.620	0.620	0.550	0.590	0.560	0.670	0.660	0.660	0.630
Dy	3.5	4.6	4.91	5.01	3.8	3.8	3.33	3.59	3.53	4.05	3.99	4.02	3.88
Ho	0.73	0.98	1.06	1.09	0.81	0.81	0.71	0.78	0.77	0.86	0.84	0.83	0.82
Er	2.03	2.71	2.92	3.04	2.21	2.2	1.97	2.14	2.14	2.35	2.33	2.32	2.26
Tm	0.340	0.460	0.490	0.520	0.370	0.360	0.330	0.360	0.360	0.390	0.390	0.390	0.380
Yb	2.03	2.76	2.91	3.03	2.18	2.19	1.95	2.14	2.11	2.31	2.3	2.28	2.28
Lu	0.33	0.45	0.48	0.49	0.36	0.36	0.31	0.36	0.34	0.39	0.39	0.38	0.37
Hf	2.36	3.48	3.43	3.57	2.79	2.7	2.48	2.44	2.39	2.93	2.98	2.95	1.84
Ta	0.320	0.430	0.450	0.460	0.360	0.350	0.310	0.300	0.290	0.350	0.360	0.360	0.400
Pb	5.3	11.01	21.38	10.48	7.94	5.4	3.55	3.92	5	7.1	7.57	9.23	7.85
Th	3.38	6.5	5.5	5.6	4.44	4.38	4.27	3.2	3.11	4.93	5.24	5.12	5.23
U	0.63	1.01	1.08	1.13	0.86	0.85	0.7	0.59	0.58	0.84	0.86	0.84	0.96
Rb		58.13	34.47			98.73	44.72	32.18		74.51		72.94	
Sr		147.54	126.26			124.38	118.08	129.54		132.2		136.2	
$^{87}Rb/^{86}Sr$		1.1420	0.7909			2.3024	1.0977	0.7194		1.6343		1.5500	
$^{87}Sr/^{86}Sr_n$		0.72577	0.72162			0.73332	0.72517	0.71805		0.72860		0.72957	
$^{87}Sr/^{86}Sr_{1100}$		0.7094	0.7103			0.7004	0.7095	0.7078		0.7052		0.7074	
Sm		4.64	4.28			3.46	3.79	3.25		3.78		3.69	
Nd		21.13	18.55			15.03	16.98	13.71		16.38		16.65	
$^{147}Sm/^{144}Nd$		0.1328	0.1393			0.1393	0.1350	0.1434		0.1396		0.1339	
$^{143}Nd/^{144}Nd_n$		0.511912	0.512034			0.511999	0.511947	0.512083		0.512005		0.511942	
εNd_{1100}		-6.0	-4.5			-5.1	-5.6	-4.0		-5.1		-5.6	

Table I. Continued.

Sample	Z.1831.3	Z.1831.4	Z.1832.1	Z.1835.1	Z.1836.1	Z.1837.1	Z.1838.2	Z.1838.3	Z.1838.4	Z.1804.1	Z.1817.1	Z.1820.1
Latitude (S)	72°02.636'	72°02.561'	72°02.667'	72°03.036'	71°59.270'	71°59.366'	71°57.563'	71°57.624'	71°57.682'	72°14.998'	72°03.630'	
Longitude (W)	003°31.886'	003°32.007'	003°31.789'	003°24.047'	003°31.372'	003°24.213'	003°19.568'	003°19.599'	003°19.785'	003°23.718'	002°42.797'	
Altitude (m)	1172	1177	1182	1422	975	999	1081	1076	1115	1522	1306	
SiO_2	54.86	54.79	55.04	45.14	52.05	52.44	52.15	53.64	53.58	52.7	46.74	53.39
TiO_2	0.8	0.72	0.73	1.31	0.73	0.8	0.76	0.77	0.79	0.47	0.67	0.9
Al_2O_3	13.63	14.65	14.69	10.44	14.1	13.75	14.13	14.41	14.48	13.95	8.45	14.85
Fe_2O_3(T)	10.61	9.93	10	11.45	11.77	11.34	10.99	10.44	10.3	10.41	11.8	10.58
MnO	0.16	0.15	0.15	0.17	0.21	0.18	0.17	0.17	0.16	0.17	0.17	0.17
MgO	5.32	5.8	6.02	8.8	6.94	6.31	6.55	6.07	6	9.31	21.81	6.45
CaO	8.96	7.98	9.13	15.16	5.35	10.22	10.36	9.7	9.92	9.29	7.19	9.18
Na_2O	2.6	1.84	1.93	2.93	3.85	2.13	2.17	1.92	1.95	1.73	1.18	1.78
K_2O	0.87	1.65	0.9	0.36	0.74	0.83	0.97	0.85	0.42	0.84	0.52	1.46
P_2O_5	0.11	0.11	0.11	0.22	0.1	0.1	0.1	0.1	0.1	0.08	0.1	0.1
LOI	1.39	1.67	1.5	4.68	3.51	1.16	0.95	1.7	1.43	1	1.54	1.34
Total	99.46	99.41	100.33	100.75	99.5	99.4	99.4	99.83	99.26	100.02	100.15	100.05
mg-number	49.8	53.6	54.4	60.4	53.9	52.5	54.1	53.5	53.6	64.7	79.1	44.4
Cr	66	148	145	1582	101	102	131	138	110	95	672	55
Ni	59	72	73	485	123	85	81	81	85	109	537	75
Co	44.9	43.1	43.2	61.3	49.0	48.6	47.3	48.5	44.9	52.4	92.9	44.1
Ga	16.84	16.75	16.84	14.76	15.92	17.54	17.39	17.49	17.59	13.56	10.56	16.89
Rb	21.04	91.71	33.94	6.8	37.41	33.07	45.25	35.34	14.99	36.46	23.56	40.62
Sr	133.8	140.2	136.4	308.3	570.3	137.0	134.5	157.9	134.5	107.3	105.1	214.0
Y	28.3	25.4	25.6	16.9	22.9	24.3	24.9	24.9	24.3	16.5	13.4	25.2
Zr	133	122	123	73	99	109	115	114	109	68	56	99
Nb	6.35	5.86	5.87	6.15	5.08	4.9	5.3	5.28	4.93	3.17	3.23	5.65
Cs	0.77	2.5	2.26	4.77	1.78	1.63	4.67	1.82	1.57	1.67	4.26	2.03
Ba	424	609	340	128	287	299	219	295	199	184	132	274
Sc	35	33	33	30	38	35	34	35	35	30	28	37
La	19.2	19.1	19.3	6.8	14.6	15.4	16.8	16.7	14.9	9.6	7.8	17.5
Ce	41.5	40.4	40.5	16.7	30.5	32.6	35.8	35.4	32.0	20.5	16.4	36.8
Pr	5.49	5.21	5.25	2.6	3.99	4.28	4.66	4.63	4.24	2.62	2.21	4.76
Nd	21.9	20.6	20.8	12.2	16.0	17.3	18.6	18.4	17.1	10.6	9.3	19.0
Sm	4.7	4.34	4.32	3.22	3.52	3.83	4	3.98	3.83	2.37	2.13	4
Eu	1.15	1.11	1.1	1.18	0.95	1.07	1.06	1.04	1.02	0.69	0.65	1.08
Gd	4.77	4.37	4.26	3.52	3.67	3.93	4.01	4.01	3.9	2.66	2.35	4.18
Tb	0.800	0.710	0.720	0.570	0.620	0.670	0.680	0.680	0.660	0.440	0.380	0.700
Dy	4.84	4.32	4.34	3.19	3.8	4.05	4.1	4.11	4.08	2.69	2.29	4.2
Ho	1.01	0.91	0.91	0.62	0.8	0.85	0.86	0.86	0.85	0.57	0.48	0.89
Er	2.82	2.53	2.54	1.55	2.21	2.33	2.38	2.38	2.34	1.59	1.25	2.43
Tm	0.470	0.420	0.430	0.240	0.370	0.390	0.400	0.390	0.390	0.270	0.200	0.400
Yb	2.83	2.56	2.51	1.34	2.16	2.32	2.37	2.35	2.3	1.63	1.22	2.4
Lu	0.46	0.41	0.42	0.21	0.35	0.38	0.39	0.39	0.38	0.27	0.21	0.39
Hf	3.66	3.34	3.34	1.99	2.64	2.92	3.1	3.04	2.93	1.78	1.51	2.79
Ta	0.440	0.410	0.410	0.370	0.370	0.350	0.370	0.370	0.350	0.230	0.210	0.400
Pb	15.06	9.27	8.17	1.59	8.61	5.82	8.59	7.78	4.78	5.06	2.92	8.82
Th	6.48	6.05	5.98	0.39	4.5	4.8	5.26	5.25	4.78	3.28	1.68	5.92
U	1.2	0.98	0.97	0.1	0.85	0.81	0.86	0.86	0.81	0.64	0.35	1
Rb										36.46	23.56	40.62
Sr										107.3	105.1	214.0
$^{87}Rb/^{86}Sr$										0.9848	0.6492	0.5497
$^{87}Sr/^{86}Sr_n$										0.72385	0.71522	0.71897
$^{87}Sr/^{86}Sr_{1100}$										0.7098	0.7059	0.7111
Sm										2.49	2.34	4.04
Nd										10.76	9.98	18.48
$^{147}Sm/^{144}Nd$										0.1398	0.142	0.1323
$^{143}Nd/^{144}Nd_n$										0.512001	0.511948	0.51193
εNd_{1100}										-5.2	-6.5	-5.6

204 Ma

A swarm of dolerite dykes cut the Mesoproterozoic Svedrupfjella Group orthogneisses at Jutulrøra, Straumsvola and Tvora (Fig. 1). The dykes are typically parallel to the Jutulstraumen subglacial rift (north-south) and are steeply dipping, with thicknesses often in excess of 10 m. They have been dated in the interval 202–206 Ma and do not correspond to any other recognized magmatic event in western Dronning Maud Land (Riley *et al*. 2009).

1100 Ma

The Mesoproterozoic dykes and sills of the Borgmassivet intrusions only crop out in the Ahlmannryggen and Borgmassivet region of western Dronning Maud Land, to the west of the Jutulstraumen ice stream and north of the Pencksokket, situated on the Grunehogna Craton (Fig. 1). No Mesoproterozoic intrusions are located in the neighbouring Maudheim province. This suite of intrusions is the subject of this paper.

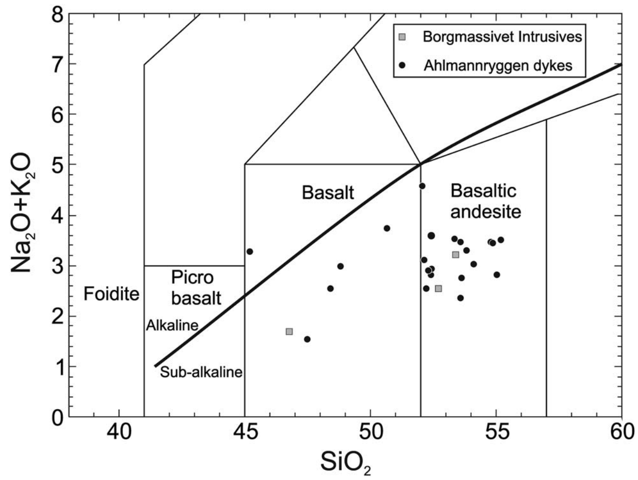

Fig. 2. Total alkali *vs* SiO_2 diagram (wt%) for the Ahlmannryggen dykes and Borgmassivet intrusions. The samples are basalt or basaltic andesite and are classified as quartz tholeiites based on their CIPW norms, with the exception of two samples which are olivine tholeiites (Z.1815.1 and Z.1835.1).

Previous work

Several workers have investigated the Mesoproterozoic Borgmassivet intrusions of western Dronning Maud Land, making links between the exposures in Antarctica and southern Africa (Groenewald *et al*. 1991), and also with the relative timings of the intrusions and the deposition of the Ritscherflya Supergroup (Krynauw *et al*. 1988). However, there has been only a limited number of publications on the geochemistry of the Borgmassivet intrusions. Moyes *et al*. (1995) presented Rb-Sr and Sm-Nd whole rock data, but only representative whole rock geochemistry was provided. Grosch *et al*. (2007) presented geochemical data on several intrusions from the Grunehogna Craton, but this work was mostly focussed on amphibolites from the metamorphic Maud Belt complex, although they did recognize the Umkondo geochemical signature in several of the intrusive rocks.

Sample descriptions

Samples from 25 dykes and sills from the Ahlmannryggen region were selected for analysis. The samples are mostly fine grained dolerite intrusions that typically have glassy-aphyric chilled margins, but more vesicular, rubbly centres. Unlike the Mesozoic dyke suites of western Dronning Maud Land the Mesoproterozoic dykes do not exhibit a preferred strike orientation but show significant variation, although those dykes > 3 m in thickness are often close to north-south in orientation (008°–022°). Eight of the samples are from sills which are mostly fine grained sill tops or minor (< 3 m thickness) intrusions. However, three samples (Z.1804.2, Z.1818.2, Z.1824.1) were taken from the more ‘classic’ Borgmassivet intrusions. These gabbroic sills are typically subophitic, medium crystalline with clinopyroxene, plagioclase, biotite and magnetite. The dolerite sills and dykes are typically fine grained and feldspar-phyric. The plagioclase phenocrysts are set in a groundmass of smaller plagioclase, augite and iron-titanium (Fe-Ti) oxides. Minor amounts of apatite and biotite are occasionally present. The dykes typically have an intergranular or subophitic texture involving euhedral plagioclase and subhedral augite crystals. Olivine was not identified in the Mesoproterozoic sample suite described here.

Geochemistry

Analytical techniques

Powders for geochemical analysis were prepared from 2–3 kg of fresh rock. Samples were reduced to pass a 1700 μm sieve using a hardened steel fly press. The powders were produced using an agate Tema-mill. Sr and Nd isotope compositions were measured at the NERC Isotope Geosciences Laboratory (Keyworth, UK) on a Finnegan-MAT 262 mass spectrometer. Rb-Sr and Sm-Nd analysis followed procedures described by Riley *et al*. (2005). Sr isotope composition was determined in multidynamic peak-jumping mode. During the period of analysis, 22 analyses of the Sr isotope standard NBS987 gave a value of 0.710259 ± 0.000008 (2 sigma errors). Nd isotope composition was determined in static collection mode. Twenty-four analyses of the in-house J&M Nd isotope standard gave a value of 0.511196 ± 0.000022 (2 sigma errors). Reported $^{143}Nd/^{144}Nd$ values were normalized to a value of 0.511130 for this standard, equivalent to 0.511864 for La Jolla.

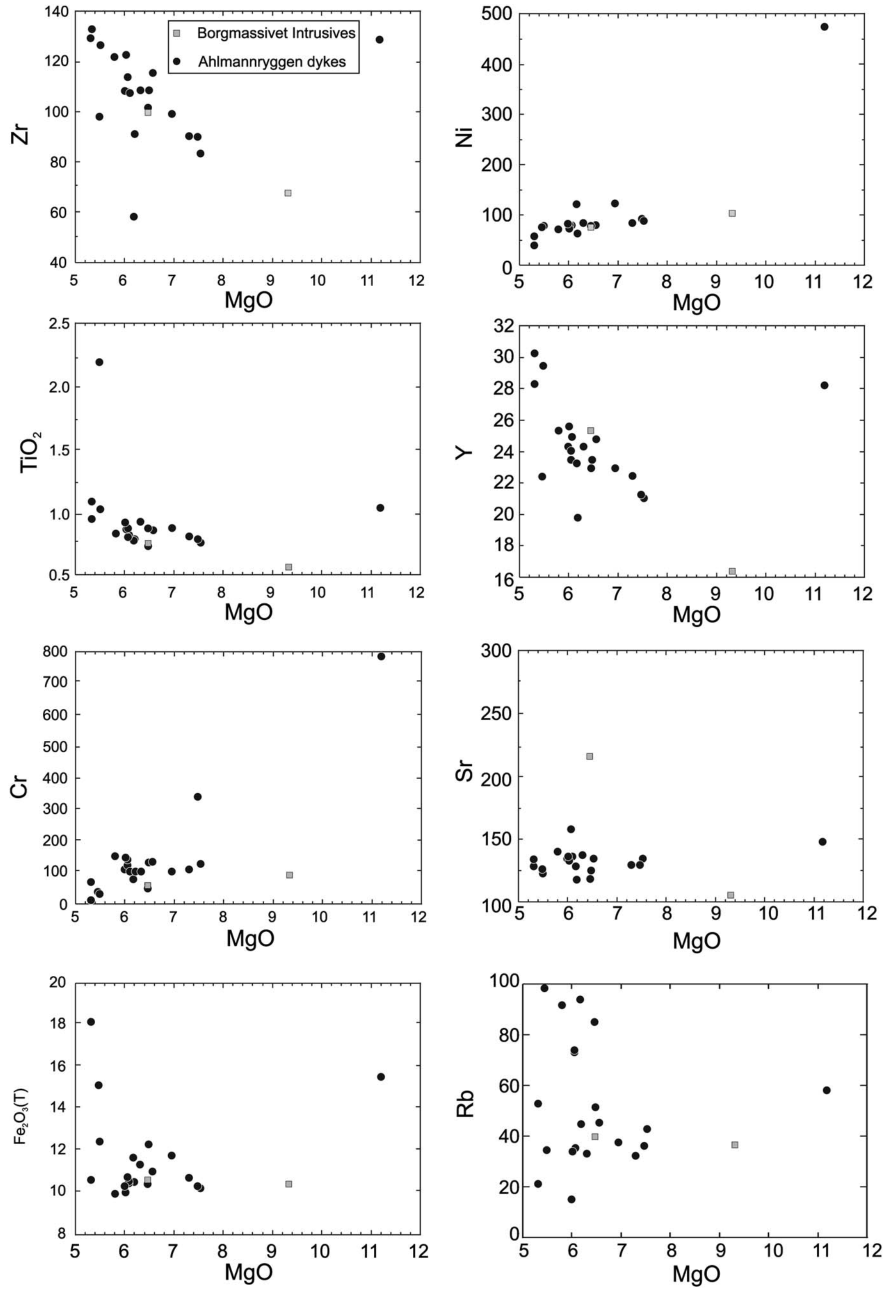

Fig. 3. Variations in Zr, TiO_2, Cr, Fe_2O_3(T), Ni, Y, Sr and Rb *vs* MgO for the Ahlmannryggen dykes and Borgmassivet intrusions. Major oxides in wt% and trace elements in ppm.

Major and selected trace element whole rock analysis was by standard XRF techniques at the Department of Geology, University of Keele following the methods described in Floyd (1986). Higher precision trace element abundances were determined by ICP-MS at the University of Durham. The analytical methods, precision and detection limits are detailed in Ottley *et al*. (2003).

Classification

Major and trace element data, as well as Sr-Nd isotope data, from the Ahlmannryggen intrusive rocks are reported in Table I. The analysed samples are subalkaline and range in composition from basalt to basaltic andesite (Fig. 2). On the basis of the CIPW norms, the samples can be classified as quartz tholeiites, with the exception of two samples (Z.1815.1 and Z.1835.1) which are olivine tholeiites. In the quartz tholeiites, the silica (SiO_2) content ranges from 48.4–55.2 wt% and the magnesia (MgO) content ranges from 5.3–7.5 wt%, indicating the fractionated nature of the Ahlmannryggen intrusive rocks. The data from the Ahlmannryggen intrusions were plotted against MgO (wt%) as an index of differentiation (Fig. 3). Nickel (Ni) is weakly correlated with MgO suggesting at least some control of olivine during differentiation, although olivine was not identified in any of the samples. Aluminium oxide (Al_2O_3)

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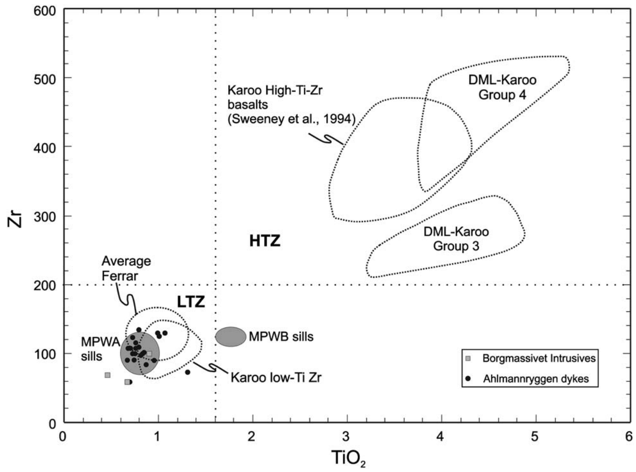

Fig. 4. Variation in Zr *vs* TiO_2 for Ahlmannryggen dykes and Borgmassivet intrusions shown in comparison to MPWA and MPWB sills (Bullen *et al*. 2012), Karoo-age dykes from the Ahlmannryggen (Dronning Maud Land (DML) groups 3–4; Riley *et al*. 2005), Karoo low Ti-Zr (LTZ) and high Ti-Zr (HTZ) basalts (Sweeney *et al*. 1994) and average Ferrar (Antonini *et al*. 1999).

increases as MgO decreases, until around 7 wt% MgO when plagioclase fractionation becomes important. Many of the major and trace elements exhibit compositional trends typical of tholeiites, showing negative correlations with MgO for iron (III) oxide (Fe_2O_3(T)), titanium oxide (TiO_2), zirconium (Zr) and yttrium (Y).

The use of incompatible high field strength elements (HFSE; Ti, Zr, Y, Nb) as discriminants between magma types are effective because these elements are largely immobile during low temperature alteration processes (Peate 1997) and ratios between them are not significantly modified by moderate amounts of fractional crystallization or susceptible to variations in the degree of partial melting. Zr can be used as an effective index of differentiation in magmas that do not crystallize zircon. These discriminants are subsequently supported by variations in $^{87}Sr/^{86}Sr$, εNd, rare earth elements (REE) and other major and trace elements and their ratios.

The Ahlmannryggen Mesoproterozoic intrusions are all low Ti-Zr (LTZ) tholeiites with $TiO_2 < 1.5$ wt% and Zr < 150 ppm (Fig. 4), similar to the Karoo low Ti magma type of Sweeney *et al*. (1994). The intrusive rocks from the Ahlmannryggen chemically overlap with the LTZ Mesoproterozoic post-Waterburg sills (MPWA) of the Umkondo province (southern Africa) (Bullen *et al*. 2012). However, they are distinct from a secondary group of Umkondo dolerite sills (MPWB) which have a slightly higher TiO_2 content (*c*. 2 wt%) and similar Zr values resulting in Ti/Zr ratios of 75–100, compared to Ti/Zr ratios of < 50 for the MPWA sills and the Ahlmannryggen intrusive rocks (Bullen *et al*. 2012). The Ahlmannryggen rocks contain SiO_2 in the range of 45.1–55.2 wt% and have typically low Mg numbers (36.7–60.4; mean 52.8). The intrusive rocks are all light rare earth element (LREE) enriched, with (lanthanum (La)/lutetium (Lu))$_N$ ranging from 3.3–4.8, with La enrichment up to 60 times chondrite (Fig. 5). The samples all have pronounced negative Europium (Eu) anomalies resulting from plagioclase fractionation, but have relatively unfractionated heavy rare earth elements (HREEs), around 10 times chondrite. The REE profiles are almost identical to the MPWA sills of the Umkondo province (Bullen *et al*. 2012), but are quite distinct from the MPWB samples, which are also LREE enriched but lack the flat HREE patterns and negative Eu anomaly.

The multi-element variations, when normalized to primitive mantle, for the Ahlmannryggen intrusive rocks are characterized by distinct troughs at Nb, Sr and Ti

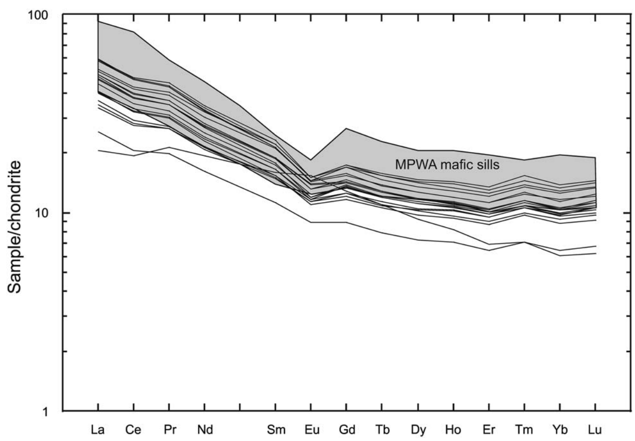

Fig. 5. Chondrite normalized (Nakamura 1974) rare earth element (REE) diagrams for Ahlmannryggen dykes and Borgmassivet intrusions in comparison to the MPWA sills (Bullen *et al*. 2012).

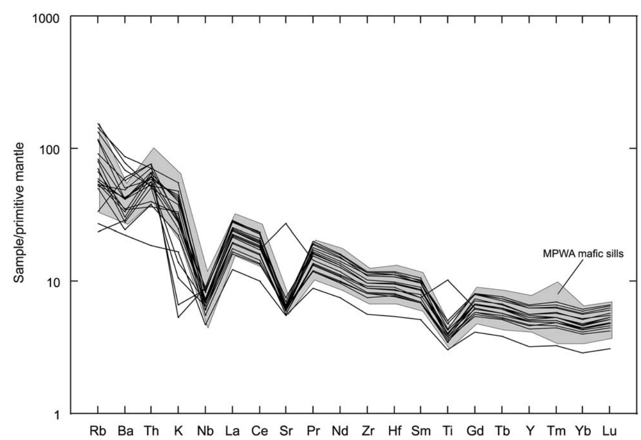

Fig. 6. Primitive mantle normalized incompatible element diagrams for the Ahlmannryggen dykes and Borgmassivet intrusions in comparison to the MPWA sills (Bullen *et al*. 2012). Normalizing values are taken from Sun & McDonough (1989).

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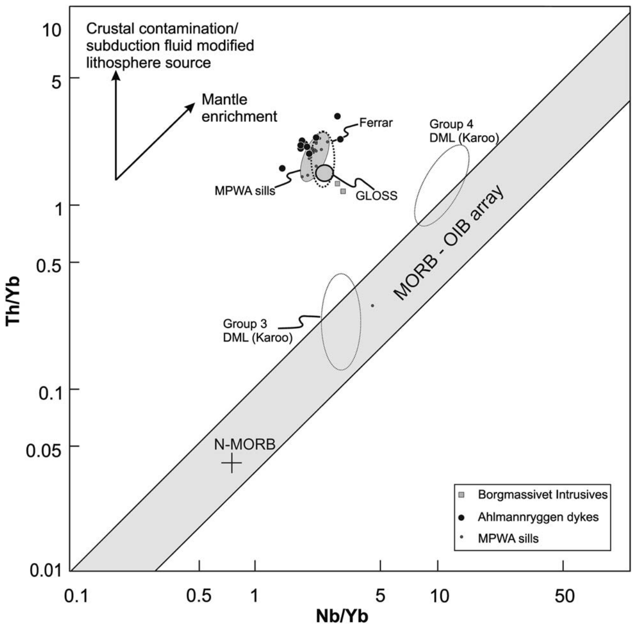

Fig. 7. Variations in Th/Yb *vs* Nb/Yb showing the composition of basic dykes from the Ahlmannryggen dykes and Borgmassivet intrusions relative to the MORB-OIB array (Pearce & Peate 1995). With comparisons to the Karoo-Dronning Maud Land (DML) fields from the Ahlmannryggen (Riley *et al*. 2005), average Ferrar (Molzahn *et al*. 1996), MPWA and MPWB sills (Bullen *et al*. 2012) and average global subducting sediment (GLOSS; Plank & Langmuir 1998).

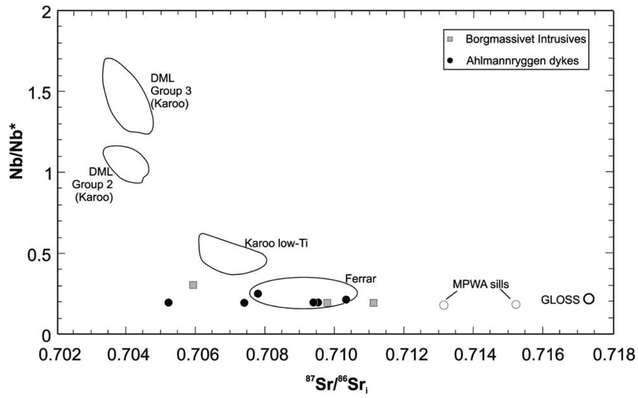

Fig. 8. Nb anomaly, Nb/Nb* ($=Nb_N\sqrt{(Th_N \times La_N)}$) *vs* $^{87}Sr/^{86}Sr$. The Nb anomaly can be used to test the role of sediment contamination in mantle-derived magmas. With comparisons to the Karoo-Dronning Maud Land (DML) group 2 and 3 fields (Riley *et al*. 2005), the MPWA sills (Bullen *et al*. 2012), the Ferrar field (Molzahn *et al*. 1996) and average global subducting sediment (GLOSS; Plank & Langmuir 1998). $^{87}Sr/^{86}Sr = 0.7173$, Sr = 327 ppm, Nb/Nb* = 0.22.

(Fig. 6), although there are some minor deviations in several of the samples. The MPWA mafic sills are plotted for comparison (Bullen *et al*. 2012), indicating almost identical abundances and variation. The Ahlmannryggen intrusions exhibit a tight cluster in the thorium/ytterbium (Th/Yb) *vs* Nb/Yb plot (Fig. 7), where they are plotted relative to the mid-ocean ridge basalt-ocean island basalt (MORB-OIB) array (Pearce & Peate 1995). Data are shown in comparison to the MPWA and MPWB sills (Bullen *et al*. 2012), and relative to dyke and lava suites from the geographically related 180 Ma Karoo and Ferrar igneous provinces of Antarctica (Molzahn *et al*. 1996, Riley *et al*. 2005). The Ahlmannryggen intrusive rocks and Borgmassivet sills plot close to the field of Ferrar magmatic province dolerites at relatively high Th/Yb values. They also have very similar ratios to the field of MPWA sills from the Umkondo province, although these have marginally lower Nb/Yb values. The samples at high Th/Yb values are close in composition to the field of average global subducting sediment (GLOSS; Plank & Langmuir 1998) indicating a significant contribution from continental crust or partial melts of subduction-modified lithosphere.

The Ahlmannryggen intrusive rocks show a range in both $^{87}Sr/^{86}Sr$ and εNd (at 1100 Ma). The $^{87}Sr/^{86}Sr_i$ ratios range from 0.705–0.711, similar to the MPWA samples (0.708–0.715), although one sample (Z.1821.2) has an initial ratio of 0.700 with a very high Rb/Sr ratio. The εNd_i values range from -4.0 to -6.5, also similar to the values from the MPWA sills (-2.8 to -4.9). The isotopic composition of the Ahlmannryggen intrusions is similar to the dyke and sill complex of the Ferrar magmatic province (Riley *et al*. 2006) and indicates a significant contribution from the continental crust or melting of subduction-modified lithosphere. The Nb anomaly ($Nb/Nb^* = Nb_N\sqrt{(Th_N \times La_N)}$ *vs* $^{87}Sr/^{86}Sr_i$ (Fig. 8) has been plotted to test the role of sediment contamination in mantle-derived magmas. As in previous plots, the Ahlmannryggen intrusive rocks overlap with the field of the Ferrar magmatic province at low Nb/Nb* values (< 0.3) and at $^{87}Sr/^{86}Sr_i$ values of 0.708–0.710.

Discussion

One of the key questions concerning the petrogenesis of almost all continental flood basalts is the relative contribution from sublithospheric mantle sources (mantle plume, ambient asthenosphere), lithospheric mantle and continental crust. The predominant rock type throughout many Proterozoic and Phanerozoic flood basalt provinces are LTZ tholeiites, which are chemically and isotopically distinct from oceanic basaltic compositions. This finding has led many workers to highlight the important role of the sub-continental lithospheric mantle in continental flood basalt (CFB) petrogenesis (e.g. Hawkesworth *et al*. 1984).

The intrusions of the Ahlmannryggen and Borgmassivet region are all LTZ rock types with high SiO_2, high $^{87}Sr/^{86}Sr_i$ and low εNd_i, indicating that the magmas were

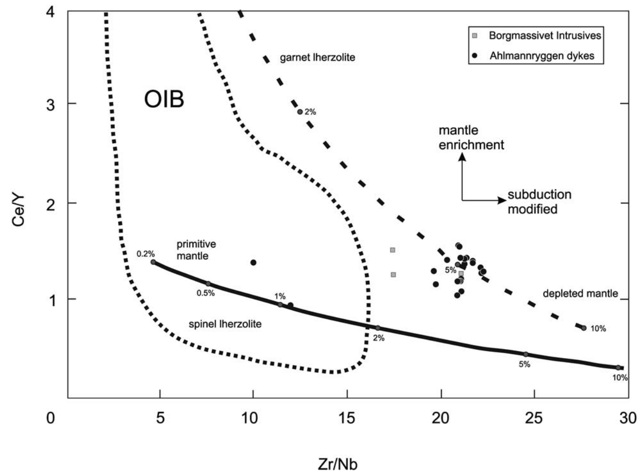

Fig. 9. Ce/Y *vs* Zr/Nb plot for basic dykes/sills from the Ahlmannryggen and Borgmassivet intrusions. Non-modal equilibrium melting curves (Shaw 1970) for primitive mantle (solid line) and depleted mantle (dashed line) (compositions calculated from the average N-MORB composition given by Sun & McDonough 1989). Full details of the distribution coefficients are in Upton *et al*. (2005). OIB = ocean island basalt.

probably extensively contaminated by continental crust or were derived from an enriched lithospheric mantle source, where the enrichment was related to earlier subduction.

The lack of geochemical variation in the Mesoproterozoic intrusions is unusual. The intrusive record of a CFB province often exhibits a much broader geochemical range compared to the extrusive record which is often emplaced over a much shorter interval (e.g. Riley *et al*. 2005).

Interaction between an ascending mafic magma and the surrounding continental crust is almost inevitable at some point prior to eruption or intrusion, although in some cases the chemical changes to the magma may be insignificant. There is no significant correlation between $^{87}Sr/^{86}Sr_i$ and MgO in the Ahlmannryggen intrusive rocks suggesting that combined assimilation and fractional crystallization was not the primary process for the observed variations.

The trace element patterns of the Ahlmannryggen intrusions are characterized by pronounced negative anomalies in the HFSE, typical of arc-related basalts but also typical of many Phanerozoic CFBs. The Ahlmannryggen intrusive rocks are far removed from the MORB-OIB array (Fig. 7) and plot at elevated levels of Th/Yb (> 2), consistent with derivation from subduction-modified lithosphere. Furthermore, the MPWA sills from southern Africa were interpreted to be the product of melts of spinel lherzolite which had incorporated material from subduction-modified lithospheric mantle (Bullen *et al*. 2012).

Distinguishing between a purely lithospheric source and a deeper source which has been contaminated by shallower melts is difficult. Ratios of Zr/Nb and cerium/yttrium (Ce/Y) (Fig. 9) indicate a source region in the garnet lherzolite field, but such ratios will be strongly influenced by any lithospheric contribution, and the flat HREE pattern (Fig. 5) is not supportive of a deeper origin. The grouping of the intrusive rocks at approximately 5% partial melting in the garnet lherzolite field implies a restricted source region, although two samples (Z.1831.2, Z.1835.1) indicate derivation from a shallower source. However, the data from this plot are limited as it is assumed that all of the melting was sub-lithospheric. There remains no overall consensus on the precise role of the lithospheric mantle in the generation of many low Ti tholeiites. Arndt & Christensen (1992) proposed that the ubiquitous negative Nb anomalies in CFBs are the result of sub-lithospheric melts acquiring their 'lithospheric signatures' through partial reaction and chemical exchange with lithospheric mantle wall rocks.

In conclusion, the Ahlmannryggen and Borgmassivet intrusions, as well as the MPWA sills, are very limited in their geochemical range, despite cropping out over a broad geographical area. This lack of geochemical variation is not consistent with significant levels of crustal contamination, whilst melting of an entirely lithospheric source would also lead to a broader compositional range given the predicted source heterogeneities (Bullen *et al*. 2012). Therefore, a primary source in the sub-lithospheric mantle with the melts having undergone some degree of interaction with lithospheric wall rocks and gabbroic fractionation, to account for the low MgO levels observed in the sill/dyke rocks, is the favoured petrogenesis.

Acknowledgements

The field and air operations staff at Halley Research Station are thanked for their support. This paper has benefited from the considered reviews of Chris Harris and Dean Bullen. Chris Ottley supplied the ICP-MS analyses and Dave Emley carried out the XRF analyses.

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