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The nature of the Grenville-age charnockitic A-type magmatism from the Natal, Namaqua and Maud Belts of southern Africa and western Dronning Maud Land, Antarctica

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Abstract: The ~1030–1090 Ma old, locally charnockitic, intrusions which are exposed from Namaqualand in the west, through Natal, into the Maud Province Antarctica in the east, show A-type, within plate granite characteristics. The major and trace element characteristics from all the intrusions are remarkably similar and consistent and are typical of C-Type charnockites. Two-pyroxene thermometry as well as thermometry utilising calibrations from experimental studies of saturation surfaces using Zr, P and Ti suggest temperatures between ~850°C and ~1100°C. Pressure estimates from aureole assemblages suggest depths of emplacement between 30–10 km. Available isotopic data suggest magma sources in Natal and Antarctica were juvenile, probably mantle derived whereas those in Namaqualand suggest a significant crustal contribution.

key words: charnockite, A-type, Natal, Namaqualand, Dronning Maud Land

1. Introduction

Granulite-charnockite terranes are an important feature of the fragmented, ~1–1.2 Ga, metamorphic province which, on reconstruction of Gondwana, extended from Namaqualand in the west, through Natal into western Dronning Maud Land (WDML), Antarctica and northwards into Mozambique and Malawi (Grantham *et al.*, 1988; Arndt *et al.*, 1991; Jacobs *et al.*, 1993; Groenewald *et al.*, 1991) (Fig.1). This paper focusses on the Grenville-age intrusions which are partially to completely orthopyroxene-bearing and conform to the C-type charnockite magmas recognised by Kilpatrick and Ellis (1991, 1992). Other types of charnockitic orthopyroxene-bearing rocks of both igneous and metamorphic genesis of both Grenvillian and Pan African age are recognised in the belt (Moyes, 1993; Ohta *et al.*, 1990; Van der Kerkhof and Grantham, 1999; Mendonidis and Grantham, 1989; Mendonidis *et al.*, 2000; Saunders, 1995; Thomas *et al.*, 1992; Jackson, 1979 amongst others) indicating that the belt represents a major zone of charnockite genesis.

Detailed descriptions of some of the charnockitic A-type units are published elsewhere, but this paper draws the available data together within a regional framework and supplements that data with unpublished major and trace element, isotopic and

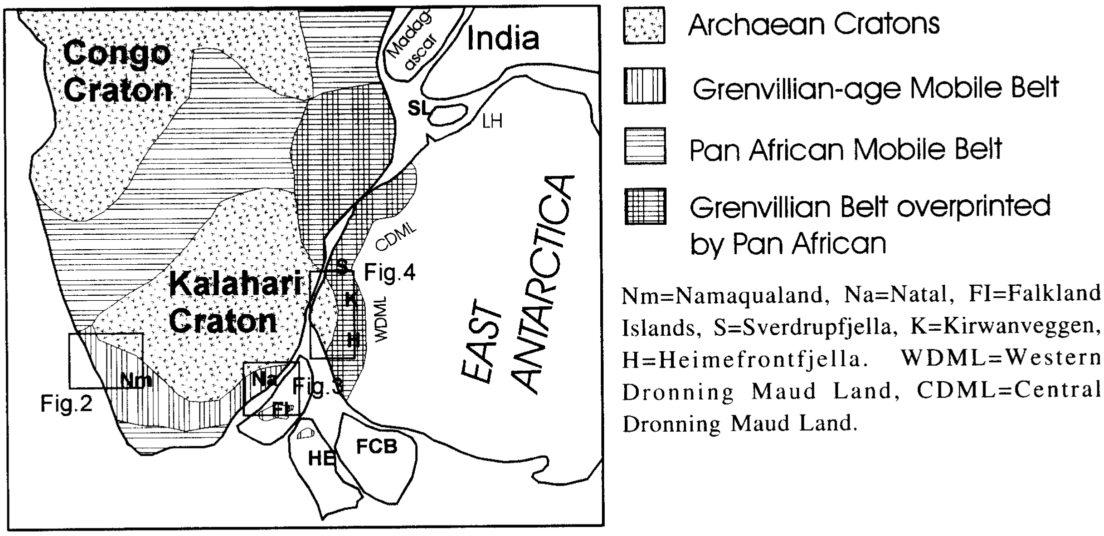


Fig. 1. Reconstruction of Gondwana showing the continuation of the ~1.0–1.2 Ga (Grenville-age) metamorphic belt around the Kalahari Craton from Namaqualand, through Natal into Antarctica and back into south East Africa. Also shown are the approximate localities for Figs. 2, 3 and 4.

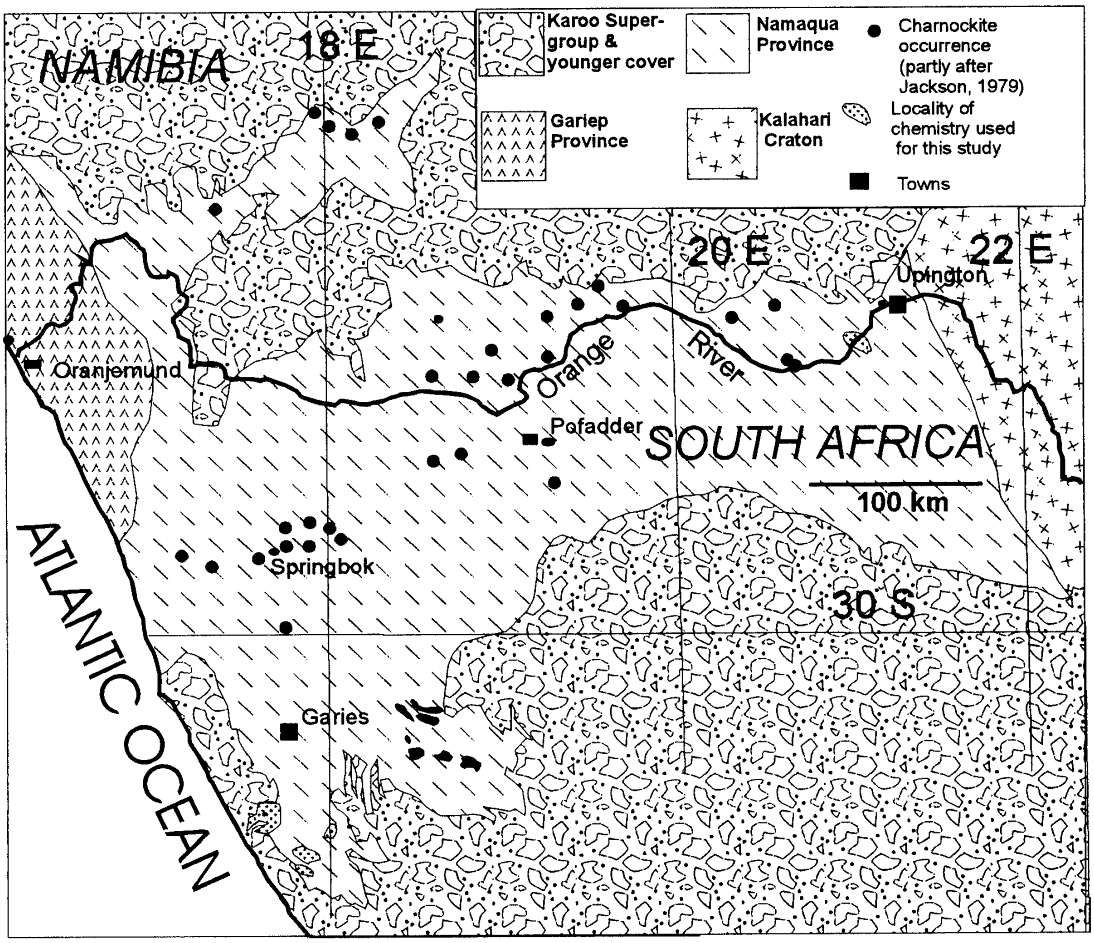


Fig. 2. Charnockite distribution in Namaqualand. Data are from Jackson (1979), Thomas et al. (1996) and Von Backstrom (1964). The localities used for geochemical comparison are from the extreme SW and NE sectors of the Namaqua Metamorphic Province.

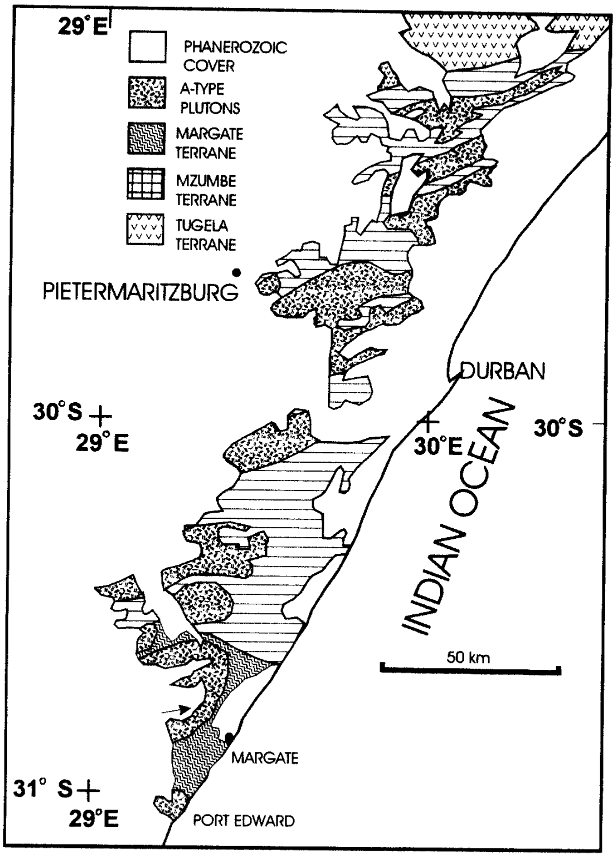


Fig. 3. Distribution of the A-type Oribi Gorge Suite and Munster Suite intrusions in Natal.

mineralogical data after which areas are defined where additional research should be focussed. The geographic distribution of the rocks is shown in Figs. 2, 3, and 4. The charnockites associated with the A-type intrusions are the most commonly and extensively developed charnockites occuring in all three areas. Examples from Natal include the Oribi Gorge Suite (McIver, 1963, 1966; Grantham, 1984; Thomas, 1988; Thomas *et al.*, 1992) as well as the Munster Suite (Mendonidis and Grantham, 1989), from Namaqualand the Spektakel Suite (Jackson, 1979; Thomas *et al.*, 1996; Von Backstrom,1964), from Heimefrontfjella (WDML), the Mannefallknausane granite (Arndt *et al.*, 1991; Jacobs *et al.*, 1996) and from Kirwanveggen (WDML) the Kirwanveggen Megacrystic Orthogneiss (Harris, 1999).

2. Field and textural characteristics

These rocks generally occur as large scale intrusions with rounded pluton shapes (Natal and Namaqualand, Figs. 2 and 3) or shear zone bounded tabular bodies (Kirwanveggen and Heimefrontfjella) except for the Munster suite which forms small irregular intrusions in southern Natal. The rocks are typically characterised by megacrystic porphyritic/porphyroclastic feldspars (commonly >2 cm diameter and up to 6 cm) with dark-green to black colouration when charnockitic (Fig. 5a). The ferromagnesian minerals, quartz and accessory minerals are typically concentrated in the

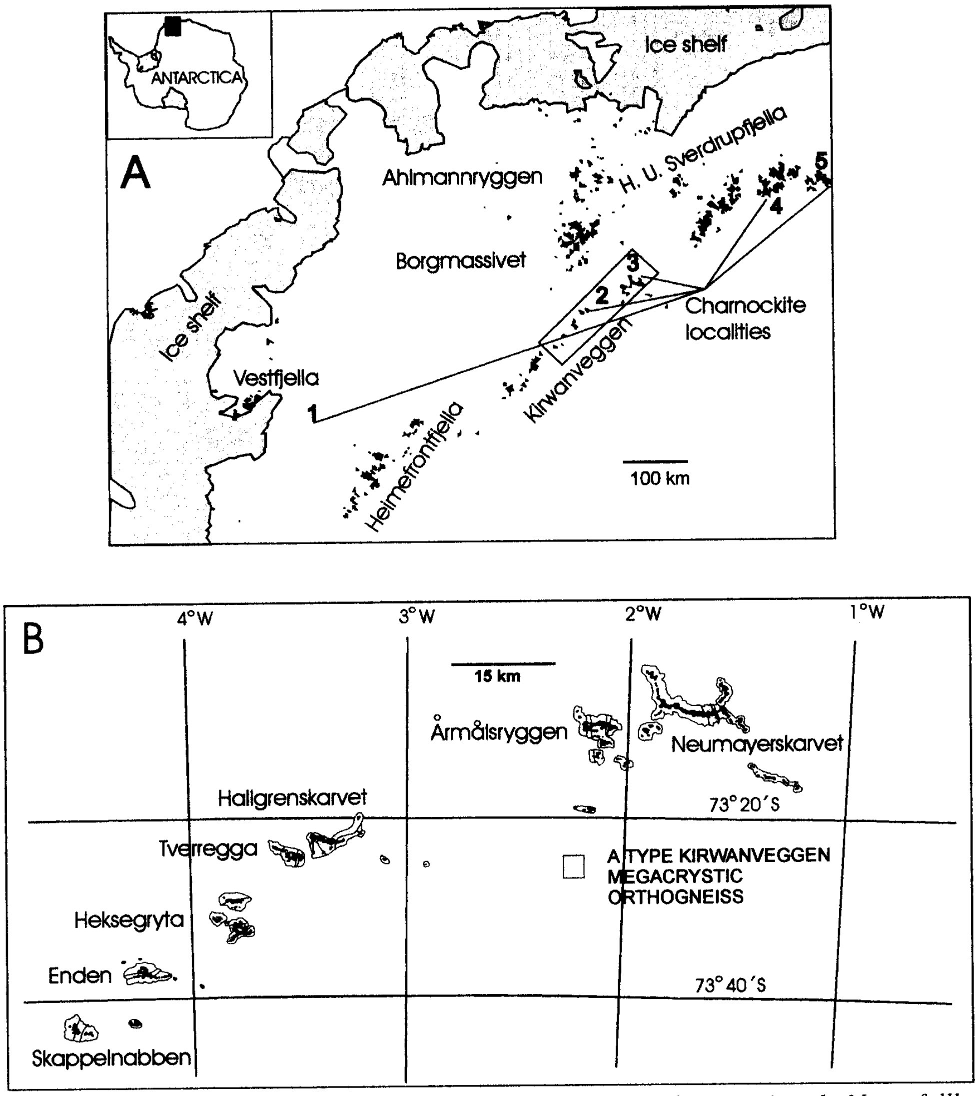


Fig. 4. *(a) Charnockite distribution in western Dronning Maud Land Antarctica. 1=Mannefallknausane, Heimefrontfjella (Arndt et al., 1991), 2=Hallgrenskarvet (pers. commun. C. Jackson), 3=Neumeyerskarvet, 4=Gjelsvikfjella (Moyes, 1993) and 5=Muhlig Hoffmanfjella (Ohta et al., 1990). (b) Distribution of the A-type intrusions in Kirwanveggen.*

interstitial areas to the feldspars (Fig. 5b). In low strain zones Rapakivi textures are commonly preserved (Fig. 5c).

Some bodies are completely orthopyroxene-bearing (pluton at Port Edward, Fig. 3) whereas most are characterised by varying degrees of orthopyroxene-bearing and orthopyroxene free portions. The bodies in WDML are particularly poor in orthopyroxene having suffered extensive retrogression and hydration during the Pan African with orthopyroxene being replaced by garnet and hornblende. In Kirwanveggen orthopyroxene-bearing varieties are preserved only in very-localised patches (Fig. 5a). In the Oribi Gorge Suite, Natal and Spektakel Suite, Namaqualand, the two least deformed of the three areas, a primary igneous flow fabric, formed by sub-parallel alignment of tabular feldspar phenocrysts, can be seen locally in low-strain zones in some plutons. Elsewhere, a weak to strong regional fabric is developed, giving a pronounced gneissic foliation, especially around, and parallel to, pluton margins where augen gneisses predominate. In Natal, pluton cores may contain low-strain zones devoid of a tectonic fabric, though many are deformed by later ductile, transcurrent shears which produced extensive, west-trending, sub-vertical augen gneiss and mylonite belts. In Kirwanveggen, the intrusions have been extensively transected by low angle thrust shear zones such that in some areas contacts of the bodies are seen as gradational ultramylonites grading through blasto-mylonites into augen gneisses to virtually undeformed low strain zones.

3. Petrography

The K-feldspar: plagioclase ratio of the megacrystic feldspars is variable, so that within single plutons granitic (charnockitic), granodioritic (enderbite) with increasing plagioclase, monzonite/quartz monzonite (mangerite/mangeronorite) with decreasing quartz, varieties may be recognised. Carlsbad twins are common in K-feldspar and combination Carlsbad-Albite twins are common in plagioclase. Perthitic and antiperthitic textures are common in K-feldspar and plagioclase respectively providing evidence of sub-solidus exsolution during cooling from high temperature conditions.

The general ferromagnesian mineralogy in the less deformed and/or retrogressed varieties includes brownish-green hornblende (~5%), reddish-brown biotite (0–5%; locally symplectically intergrown with quartz), weakly pleochroic orthopyroxene ($En_{15\text{-}58}$; 5–15%) ± pale-green clinopyroxene (0–5%), partially altered fayalite ($Fo_{5\text{-}8}$, 0–5%) and late garnet (up to ~5%; commonly in garnet/quartz symplectite). Accessory minerals include sulphides, ilmenite, zircon, apatite, allanite and graphite. Apatite, ilmenite and zircon commonly occur within the interstitial ferromagnesian minerals. Rarely, fayalitic olivine grains are locally mantled by orthopyroxene (Fig. 5d) suggesting the reaction fayalite + quartz → orthopyroxene. Garnet is common in non-charnockitic plutons in Natal and Kirwanveggen where it commonly has a symplectitic texture, being intergrown with quartz. In Kirwanveggen the garnet-quartz symplectites are clearly derived from the reaction of Opx + Pl → Grt + Qtz ± Cpx and Hbl + Pl → Grt + Qtz. Garnet is absent from the Munster Suite which is also characterised by significant clinopyroxene.

4. Major and trace-element geochemistry

Whole-rock geochemical data from Namaqualand are from Thomas *et al.* (1996) and Von Backstrom (1964); the Natal data are from Thomas (1988), Grantham (1984), Mendonidis and Grantham (1989) and Eglington *et al.* (1986) and the data from Kirwanveggen (WDML) are shown in Table 1. Within individual plutons, major and trace element distributions show strong linear trends on variation diagrams suggesting fractional crystallisation has played a significant role in the evolution of the bodies. The rocks have high K_2O, Na_2O, FeO and P_2O_5 compared to average granitoids with comparable silica contents. The high FeO/(FeO+MgO) ratios are typical of tholeiitic suites (*e.g.* Irvine and Barager, 1971; Jensen, 1976) (Figs. 6a and b). Kilpatrick and Ellis (1992) reported both tholeiitic and calc-alkaline C-type magmas. Most of the samples are tholeiitic in character although the Munster Suite is calc-alkaline (Figs. 6a and b) being characterised by higher Mg/Mg+Fe ratios which may explain why garnet is not

(a)

(b)

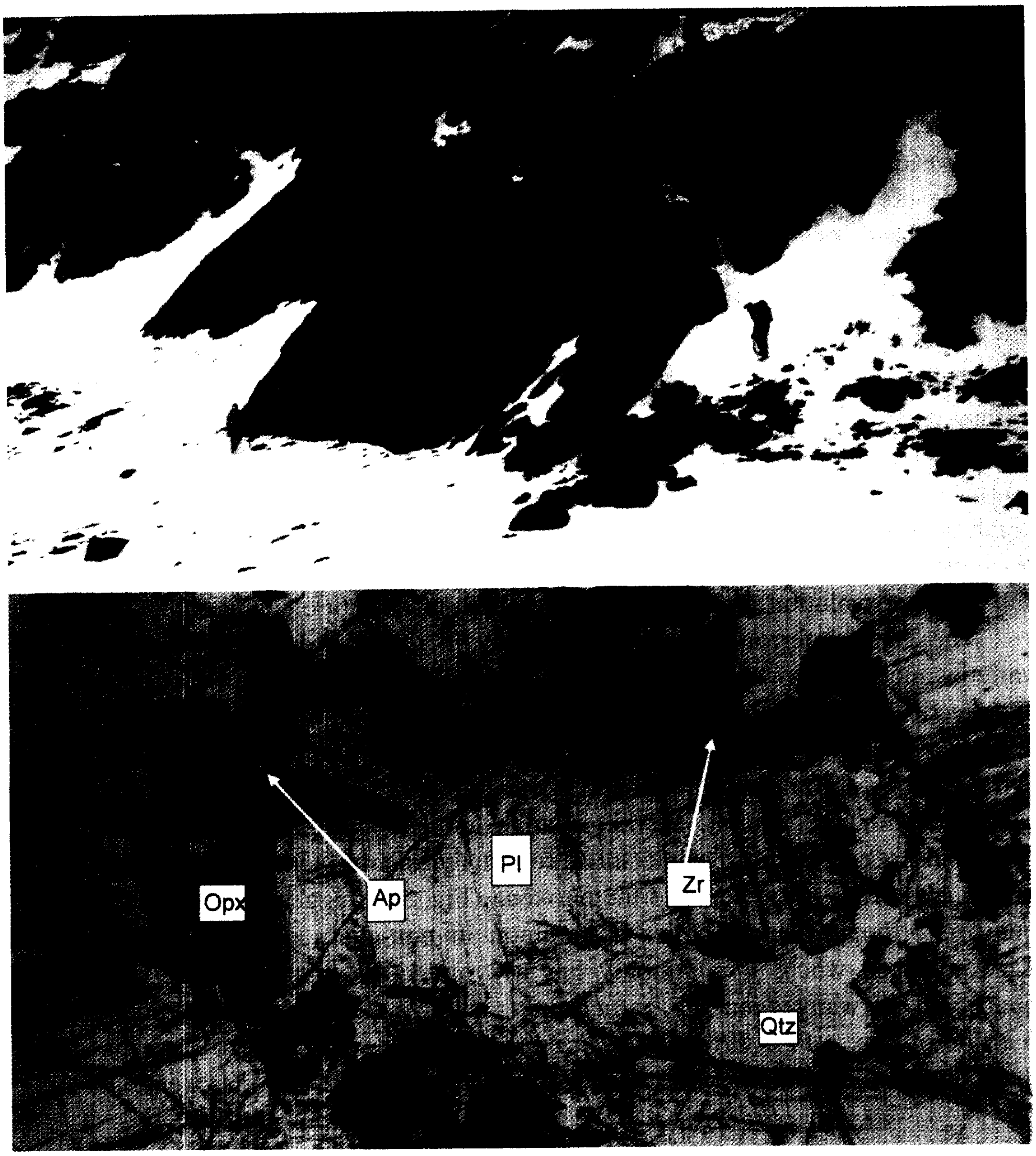
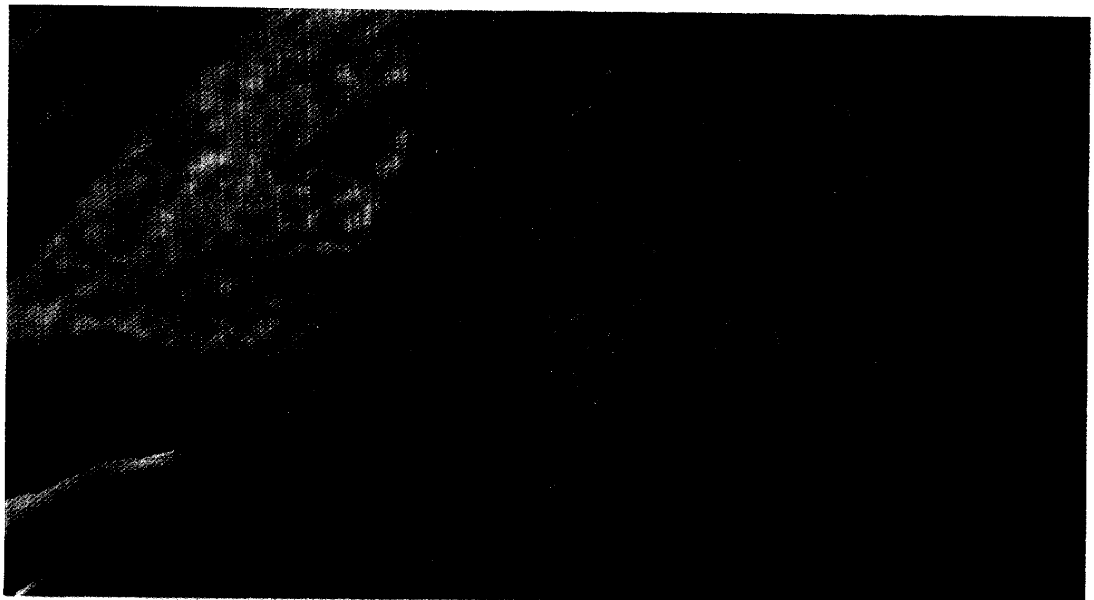


Fig. 5. (a) Dark undeformed charnockitic patch enclosed in foliated non-charnockitic gneiss in the Kirwanveggen Megacrystic Orthogneiss at Neumeyerskarvet, WDML, Antarctica.
(b) Photomicrograph from the Port Edward Pluton of the Oribi Gorge Suite in Natal showing the intercumulate nature of the ferromagnesian mineralogy which itself is poikilitic with inclusions of zircon and apatite. Field of view is 20 mm.

recognised in these rocks. (Na_2O + K_2O)/CaO ratios, TiO_2 and P_2O_5 contents are high. The rocks plot dominantly in the post-collision, late orogenic to syn-collisional fields of the R1-R2 diagram of Batchelor and Bowden (1985) with some of the Antarctic samples plotting in the pre-plate collisional field (Fig. 6c).

The high TiO_2, P_2O_5 and Zr contents in these rocks are consistent with high temperature anhydrous origins as indicated by the solubility experiments performed by Watson and Harrison (1983, Zr) and Harrison and Watson (1984, P) and Green and

(c)



(d)

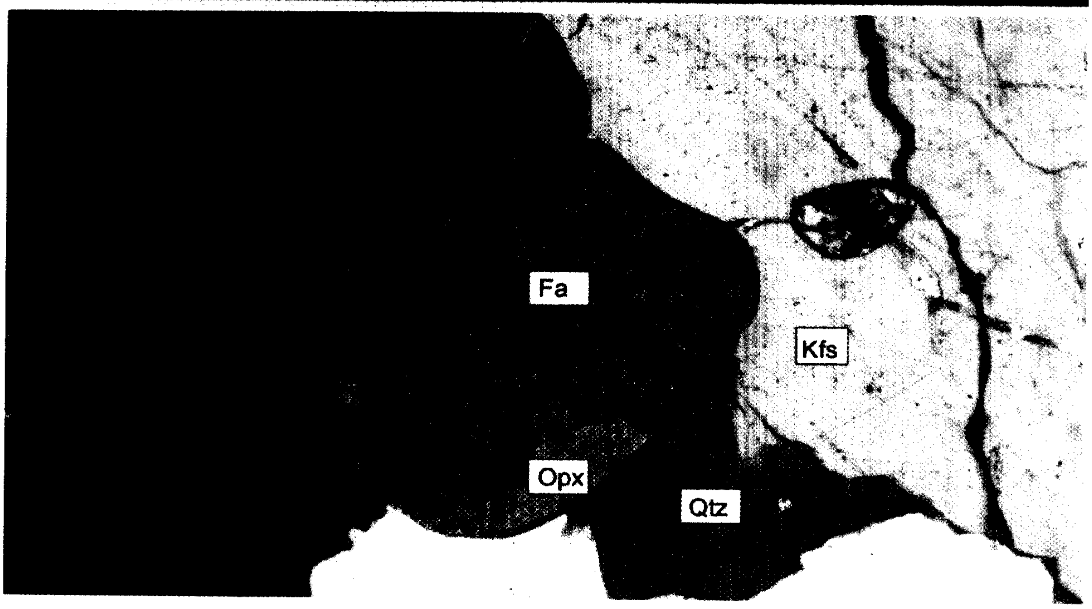


Fig. 5. (c) Rapakivi texture in the Kirwanveggen Megacrystic Orthogneiss at Neumeyerskarvet, WDML, Antarctica.
(d) Orthopyroxene partially mantling fayalite in the Oribi Gorge Pluton of the Oribi Gorge Suite, Natal. Field of view is 5 mm.

Pearson (1986, Ti). Figures 7a and b show the temperatures calculated from the P_2O_5 and Zr contents of the samples assuming that all the P is partitioned into apatite and all the Zr into zircon. Although there are some spurious points, possibly resulting from local crystal accumulation during fractionation or due to xenocrystic inheritence, the data are remarkably consistent suggesting temperatures of ~900°–1100°C for most samples including the many non-orthopyroxene-bearing varieties. These temperatures are also consistent with the TiO_2 contents (Fig. 7c) which suggests that temperatures ranged from ~1050°C to ~850°C based on the TiO_2 saturation data presented by Green and Pearson (1986) for their experiments at ~7.5 kb. An interesting aspect of these data is that all the

Table 1a. Geochemical data from the Kirwanveggan Megacrystic Orthogneiss Complex from Skappelnabben (SKAP), Enden (END), Hallgrynskarvet and Stignabben (HALLG).

SAMPLE NO	AG93-55	AG93-56	AG93-57	AG93-74	AG93-75	AG93-76	AG93-77	AG93-81	AG93-82	AG93-83	AG93-84	AG93-87	AG93-88	AG93-89
LOCALITY	SKAP	SKAP	SKAP	END	END	END	END	HALLG	HALLG	HALLG	HALLG	HALLG	HALLG	HALLG
SiO_2	70.68	75.38	65.02	69.55	59.11	63.99	72.09	62.60	62.10	58.35	59.61	72.03	71.50	65.96
TiO_2	0.36	0.18	0.48	0.45	1.28	0.89	0.27	1.59	1.50	1.85	1.77	0.29	0.32	0.52
Al_2O_3	14.16	13.05	15.76	13.99	15.89	15.70	13.12	12.79	14.21	14.99	15.10	13.02	13.94	15.70
Fe_2O_3	3.03	0.18	3.89	4.10	9.68	4.95	3.69	8.75	7.61	9.02	8.50	3.61	3.23	4.85
MnO	0.05	0.01	0.07	0.08	0.17	0.11	0.08	0.14	0.13	0.15	0.15	0.06	0.05	0.09
MgO	0.53	0.30	1.60	0.54	1.29	1.37	0.23	1.95	1.84	2.35	2.11	0.30	0.36	0.36
CaO	1.56	1.23	3.24	2.17	4.56	2.06	1.42	3.82	3.70	4.71	4.05	1.39	1.51	2.00
Na_2O	3.55	3.70	4.49	2.75	3.61	4.27	3.13	2.83	3.42	3.41	3.37	2.83	3.43	3.85
K_2O	5.36	4.05	3.93	5.67	2.92	4.45	5.29	3.97	4.18	3.63	3.89	5.61	5.35	5.96
P_2O_5	0.10	0.05	0.15	0.15	0.47	0.33	0.05	0.71	0.57	0.75	0.70	0.08	0.09	0.09
TOTAL	99.38	98.13	98.63	99.45	98.98	98.12	99.37	99.15	99.26	99.21	99.25	99.22	99.78	99.38
Rb	149	115	99	113	59	89	111	100	107	91	84	191	95	117
Sr	207	1663	424	283	433	151	169	263	321	457	411	138	158	191
Th	12	7	14	13	4	5	22	4	4	4	4	32	4	23
Zr	262	83	161	473	902	539	406	686	496	584	534	378	328	799
Y	31	13	16	67	88	79	102	113	77	82	80	55	31	60
Nb	9	9	11	17	35	27	32	36	27	26	27	21	14	21
Ba	1696	583	1402	3108	3173	2005	1995	1452	1726	2230	2111	1483	1517	2040
Sc	6	7	12	6	22	10	14	18	16	16	21	7	6	18
V	30	11	64	39	57	30	7	85	88	125	99	10	14	20
Cu	22	11	24	26	47	25	23	45	38	45	46	20	17	26
Ni	4	3	12	3	6	5	5	12	16	15	16	3	3	3
Zn	49	23	48	55	163	85	92	121	103	115	123	70	59	89
Ga	18	13	19	21	27	16	18	21	24	23	27	26	15	23

Table 1b. *Geochemical data from the Kirwanveggan Megacrystic Orthogneiss Complex from Hallgrynskarvet and Stignabben (HALLG), Mjöllföyke (MJOL), and Neumeyerskarvet (NEUM).*

SAMPLE NO LOCALITY	AG93-90 HALLG	AG93-91 HALLG	AG93-94 HALLG	AG93-40 MJOLL	AG93-41 MJOLL	AG93-42 MJOLL	AG93-43 MJOLL	AG93-44 MJOLL	AG93-46 MJOLL	AG93-47 MJOLL	NMG92-5 NEUM	NMG92-18 NEUM
SiO_2	69.52	72.28	68.23	73.01	67.70	68.64	69.23	72.55	71.65	74.84	67.48	64.83
TiO_2	0.50	0.40	0.95	0.18	0.68	0.61	0.59	0.41	0.28	0.27	0.83	1.25
Al_2O_3	13.44	12.48	12.87	13.25	14.10	14.13	14.02	13.30	13.39	12.08	14.82	13.98
Fe_2O_3	5.44	4.57	5.56	2.26	4.60	4.55	4.13	2.92	2.98	2.38	4.73	7.13
MnO	0.09	0.08	0.08	0.04	0.07	0.09	0.05	0.04	0.04	0.03	0.07	0.10
MgO	0.37	0.32	1.07	0.35	0.94	0.76	0.66	0.43	0.31	0.32	1.22	1.54
CaO	1.71	1.46	2.34	1.33	2.43	2.26	1.85	1.46	1.52	1.14	2.26	3.08
Na_2O	3.44	3.20	3.33	3.80	3.75	3.67	3.55	3.68	3.22	2.74	2.88	3.01
K_2O	4.87	5.16	4.70	4.45	4.23	4.37	4.49	4.55	5.53	5.58	5.32	4.13
P_2O_5	0.09	0.10	0.34	0.10	0.25	0.24	0.21	0.14	0.09	0.06	0.32	0.49
TOTAL	99.47	100.05	99.47	98.77	98.75	99.32	98.78	99.48	99.01	99.44	99.93	99.54
Rb	86	85	112	136	130	112	137	125	109	111	195	93
Sr	137	125	192	103	251	255	247	155	181	163	231	310
Th	10	7	4	9	18	14	17	15	17	20	15	0
Zr	871	698	498	159	413	431	341	234	348	335	365	428
Y	59	45	85	25	99	68	73	75	40	32	26	48
Nb	16	14	27	10	26	15	16	18	14	12	17	22
Ba	1714	1645	1202	660	1549	1643	1665	897	1674	1573	1468	1656
Sc	9	7	12	10	11	7	9	7	7	7	12	16
V	15	10	54	19	45	30	32	26	17	12	59	68
Cu	26	22	28	16	27	27	24	18	21	15	5	14
Ni	6	4	8	3	8	12	6	5	3	3	7	7
Zn	121	108	76	42	80	77	68	53	57	43	96	120
Ga	24	20	17	16	21	19	18	19	18	16		
La					106.63	87.46	117.31					58.34
Ce					166.74	179.23	177.49					137.31
Pr					25.26	21.86	27.34					13.11
Nd					85.29	76.29	91.77					67.66
Sm					15.86	15.17	16.26					14.11
Eu					2.29	2.37	2.14					2.37
Gd					13.29	13.43	13.43					11.43
Dy					15.03	13.56	12.97					9.77
Ho					3.11	2.6	2.54					1.8
Er					10.17	7.37	7.8					5.06
Yb					8.91	5.26	6.51					3.63

Table 1c. Geochemical data from the Kirwanveggan Megacrystic Orthogneiss Complex from Neumeyerskarvet (NEUM). Those samples which have a C as part of the sample number are charnockitic (i.e. contain orthopyroxene).

SAMPLE NO	NMG92-19C	NMG92-34	NMG92-10	NMG92-14	NMG92-16C	NMG92-17C	NMG92-19C	NMG92-36	NMG92-35	NMG92-45	NMG92-46
LOCALITY	NEUM	NEUM	NEUM	NEUM	NEUM	NEUM	NEUM	NEUM	NEUM	NEUM	NEUM
SiO_2	65.67	64.64	70.43	62.88	62.74	61.83	65.62	58.76	66.49	72.76	73.53
TiO_2	1.16	1.30	0.57	1.24	1.13	1.32	1.27	0.90	1.16	0.38	0.32
Al_2O_3	14.02	14.94	13.72	15.22	15.80	15.59	14.15	18.04	14.55	13.02	12.56
Fe_2O_3	6.53	7.12	3.52	7.12	7.04	7.35	6.50	6.44	5.88	2.84	2.27
MnO	0.09	0.14	0.05	0.13	0.09	0.11	0.09	0.16	0.07	0.08	0.04
MgO	1.32	1.51	0.43	1.16	1.09	1.27	1.15	1.46	1.12	0.14	0.13
CaO	3.00	2.86	2.10	3.25	3.42	3.48	3.00	3.86	2.63	1.21	1.37
Na_2O	2.85	3.24	3.86	4.32	4.45	4.29	3.70	5.93	4.33	3.29	3.22
K_2O	4.64	3.81	5.02	4.14	4.24	4.16	4.51	3.45	3.67	5.82	5.20
P_2O_5	0.42	0.55	0.16	0.48	0.46	0.49	0.43	0.31	0.45	0.09	0.08
TOTAL	99.70	100.11	99.86	99.94	100.46	99.89	100.42	99.31	100.35	99.63	98.72
Rb	100	123	90	84	86	72	97	68	126	132	115
Sr	316	308	266	359	382	396	320	616	268	228	171
Th	nd	nd	nd	nd	nd	8	nd	nd	nd	nd	nd
Zr	415	358	300	499	486	540	404	340	387	290	238
Y	45	33	17	35	36	35	43	49	30	20	14
Nb	18	37	5	24	21	25	21	14	20	6	9
Ba	1817	1645	1770	2155	2179	2265	1809	2705	1474	1551	1327
Sc	20	20	6	12	11	14	15	13	16	6	6
V	64	70	39	68	80	87	69	43	62	20	15
Cu	14	20	0	16	15	15	11	11	15	4	4
Ni	5	5	5	10	6	4	10	4	9	6	8
Zn	109	139	56	133	137	146	123	124	109	35	45
La				40.93		48.96	46.14				
Ce				85.22		100.01	112.17				
Pr				12.59		13.92	11.26				
Nd				57.48		61.79	59.77				
Sm				11.81		111.84	12.97				
Eu				3.08		2.83	2.31				
Gd				8.86		8.78	10.74				
Dy				6.9		6.2	9.49				
Ho				1.26		1.18	1.74				
Er				3.75		3	5.14				
Yb				2.74		2.36	3.49				

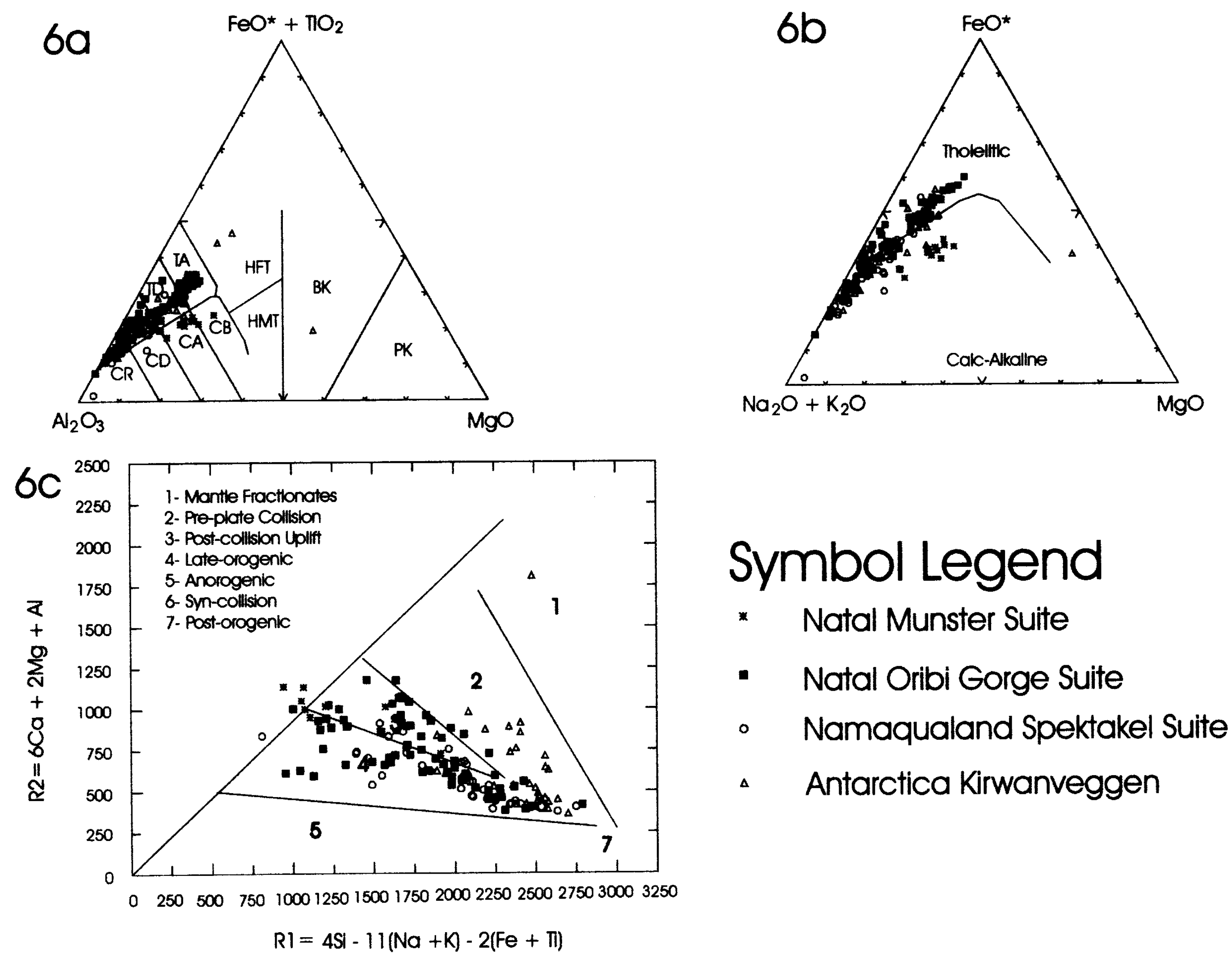


Fig. 6. *(a) Jensen cation diagram (Jensen, 1976) and (b) AFM diagram after Irvine and Barager (1971) showing the dominantly tholeiitic nature (except the Munster Suite) of the rocks and (c) R1-R2 discrimination diagram after Batchelor and Bowden (1985) showing the samples plotting in the pre-plate collision field (Kirwanveggen) and syn-collision, post-collision uplift and late-orogenic fields (Natal, Namaqualand).*

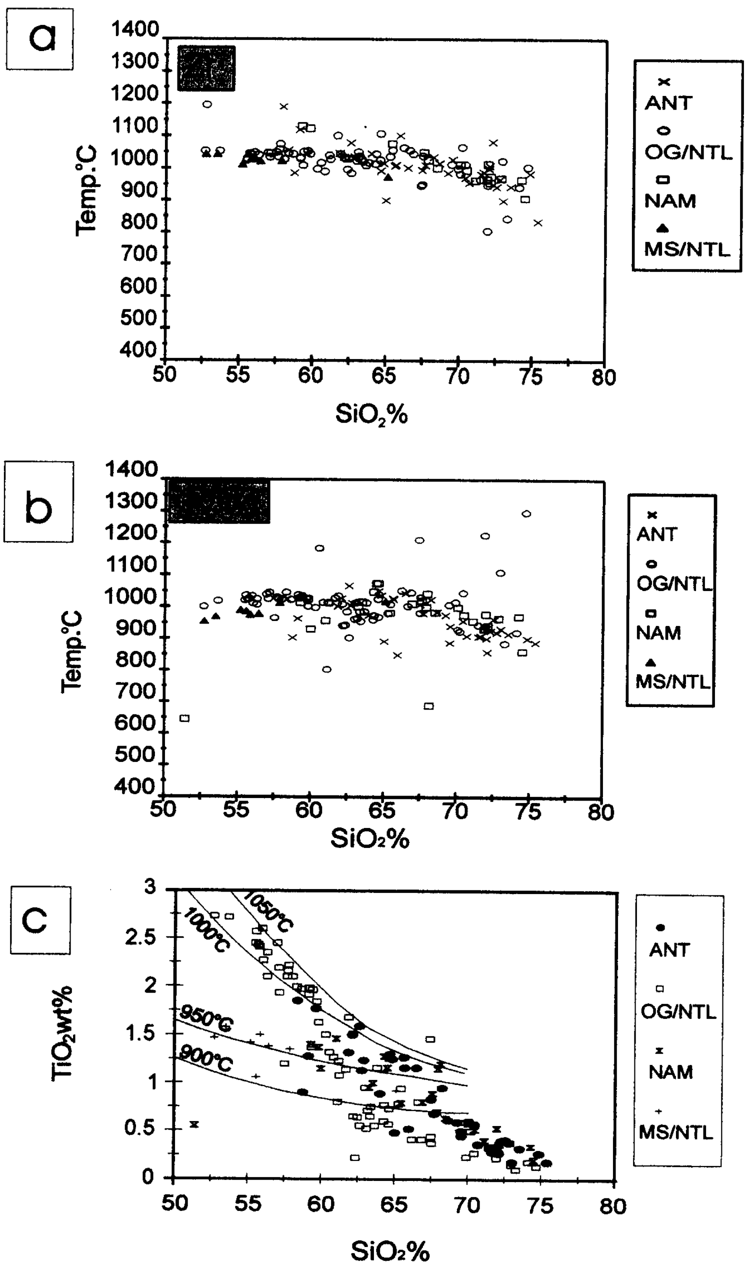


Fig. 7. Temperatures calculated from saturation surface thermometers for Zr vs SiO_2 (a) after Watson and Harrison (1983) and for P_2O_5 vs SiO_2 (b) after Harrison and Watson (1984) and comparison with TiO_2 vs SiO_2 (c) with isotherms from solubility data from Green and Pearson (1986). The saturation surface thermometry assumes all Zr and P are partitioned into zircon and apatite respectively.

curves show gentle decreases of temperature with increasing SiO_2 which is what one may have expected in a fractionating intrusion. It is remarkable that these consistent data are derived from plutons thousands of kilometers apart suggesting that they have probably originated from a common process.

Samples from all three areas mostly show A-type, within plate- and rapakivi-granite geochemical characteristics (Whalen *et al.*, 1987; Pearce *et al.*, 1984; Haapala and Ramo,

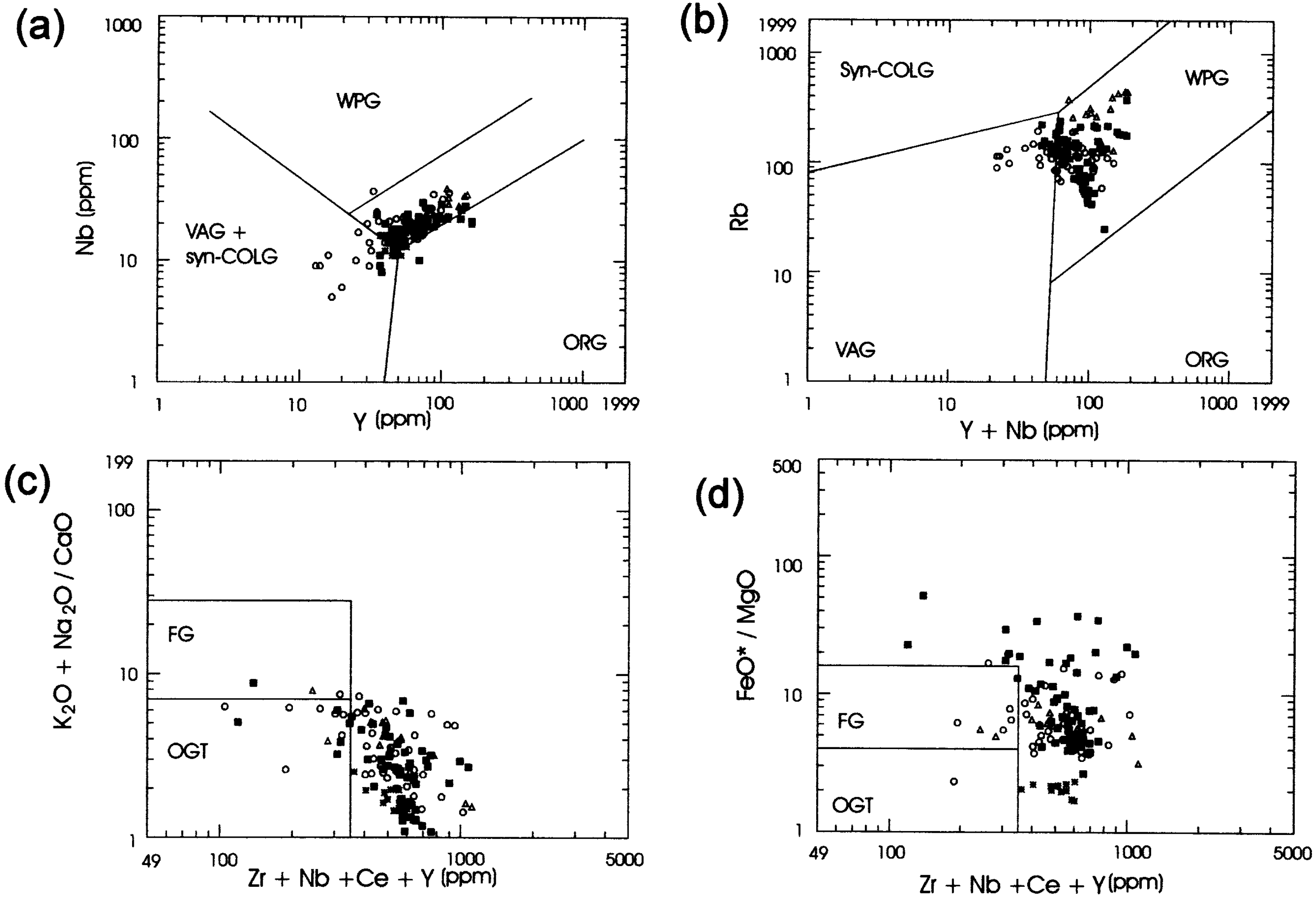


Fig. 8. *(a, b) Granitoid discrimination diagrams after Pearce et al. (1984) and (c, d) Whalen et al. (1987) showing the within-plate characteristics and A-type natures of most samples from all the areas (symbols for different areas the same as for Fig. 6).*

1992; Ramo and Haapala, 1996) (Figs. 8a, b, c and d) (Eglington *et al.*, 1986; Thomas, 1988). The lack of complete conformity to the A-type discrimination diagrams of Whalen *et al.* (1987) can partially be ascribed to the fact that REE data are only available for some of the samples with most samples still having sufficient contents of other trace elements to plot in the A-type field. The lack of complete conformity to the discrimination diagrams of Pearce *et al.* (1984) can partially be ascribed to retrogressive hydration facilitating mobility of some of the trace elements. This is evident in the data from Kirwanveggen where all the anhydrous charnockitic samples from Neumeyerskarvet plot in the within-plate field whereas the hydrated garnet-hornblende varieties plot mostly in the volcanic-arc granitoid field. All samples have high values of the HFS elements Nb, Y, Zr, Zn and Ba. Chromium and Ni are low whereas V is high.

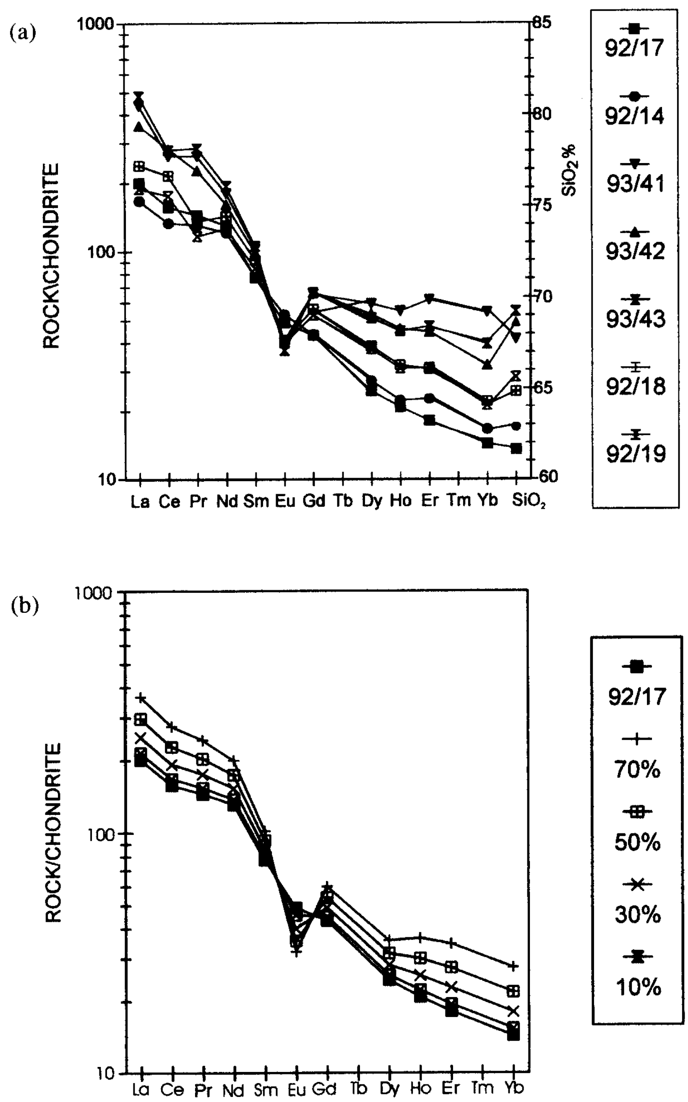


Fig. 9. (a) REE profiles of data from Kirwanveggen Megacrystic Orthogneisses, (b) Equilibrium fractionation model of the REE data based on parameters described in Table 2.

Table 2. Table showing the mineral fractions and partition coefficients for the REE used in the equilibrium fractionation model shown in Fig. 9b. The partition coefficients were taken from a compilation of data in Rollinson (1993). Mineral abbreviations after Kretz (1983).

	Fraction	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Qtz	0.3	0.015	0.014	0.015	0.016	0.014	0.056	0.016	0.017	0.015	0.015	0.015	0.016	0.17
Kfs	0.3	0.08	0.04	0.06	0.035	0.023	2.5	0.011	0.025	0.05	0.01	0.006	0.04	0.02
Pl	0.3	0.38	0.26	0.27	0.2	0.14	2.2	0.2	0.2	0.1	0.1	0.084	0.08	0.08
Opx	0.09	0.78	0.93	0.8	1.25	1.6	0.825	1	1.85	1.8	0.9	0.65	0.7	0.86
Ap	0.01	14.5	21	25	32	46	25	44	40	34	27	23	18	15.4

Available REE data (Table 1) from Kirwanveggen are characterised by steep LREE enriched patterns with strongly developed negative Eu anomalies (Fig. 9). Four of the samples are characterised by relatively large negative europium anomalies samples 93/41, 93/42/, 93/43, 92/18 and 92/19) whereas two samples (samples 92/17 and 92/14) show negligible negative europium anomalies. The latter two are characterised by lower SiO_2 contents in general whereas the former group have higher SiO_2 contents. The latter group is also characterised by lower HREE and LREE contents whereas the former group have enriched LREE contents and flat HREE patterns. Samples taken at Neumeyerskarvet are characterised by higher LREE and HREE and stronger Eu anomalies than those from Mjöllföyke (Table 1). The samples from Neumeyerskarvet include two charnockites and two non-charnockites. Figure 9a shows that there does not appear to be any difference between the charnockitic and non-charnockitic samples suggesting that the redistribution of Y+Nb described above does not appear to have affected the REE to any discernable degree.

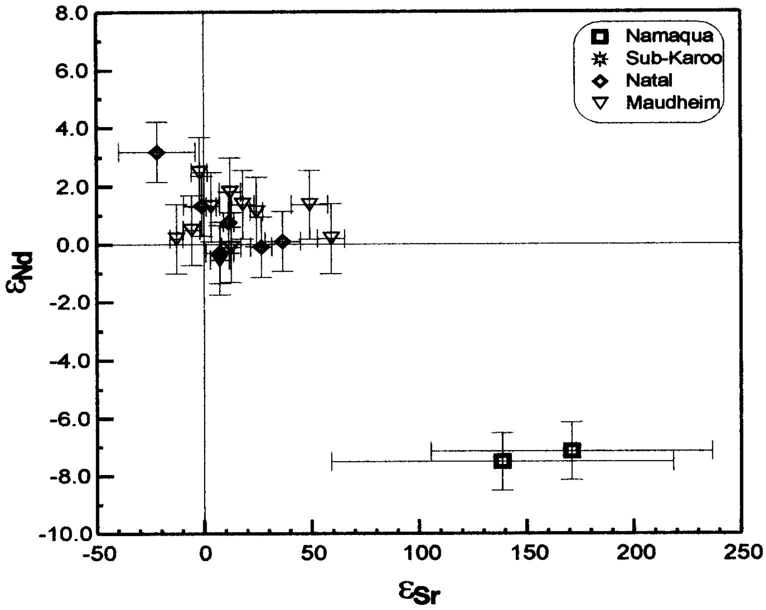
Equilibrium crystallisation modelling of the change in magma composition using the mineral proportions and partition co-efficients shown in Table 2 yields the chondrite-normalised patterns shown in Fig. 9b. The starting composition used for this modelling is that of sample 92/17 which has low SiO_2 and virtually no Eu anomaly possibly suggesting that the source rocks had no feldspar in its residue and had not experienced significant feldspar fractionation.

The REE variations seen in Figs. 9a and b suggest that the distributions are controlled by fractionation with the development of the negative europium anomaly being related to feldspar fractionation. The increasing HREE and LREE enrichment with increasing SiO_2 would arise from partitioning of HREE and LREE into the liquid with greater fractions of crystallisation.

5. Geochronology, thermochronology and isotope data

The available Sr and Nd isotopic data from the magmatic A-type granites and charnockites from Natal suggest a dominantly juvenile origin (Eglington *et al.*, 1986, 1989) (Fig. 10a). The Spektakel Suite in the Springbok area of Namaqualand shows an older crustal contribution (Clifford *et al.*, 1995; Robb *et al.*, 1997, 1999) (Fig. 10a) whereas elsewhere juvenile origins are suggested from the Sm/Nd data (Ashwal *et al.*, 1997). Arndt *et al.* (1991) also found juvenile Sm/Nd ($\epsilon_{Nd(1100\ Ma)} = +2.2$) signatures for their samples from Heimefrontfjella as did Harris (1999) for his samples from Kirwanveggen. Figure 10 shows unpublished $\epsilon_{Nd}/\epsilon_{Sr}$ data for the Kirwanveggen Megacrystic Orthogneiss compared with published data from Natal, Namaqualand and

(a)



(b)

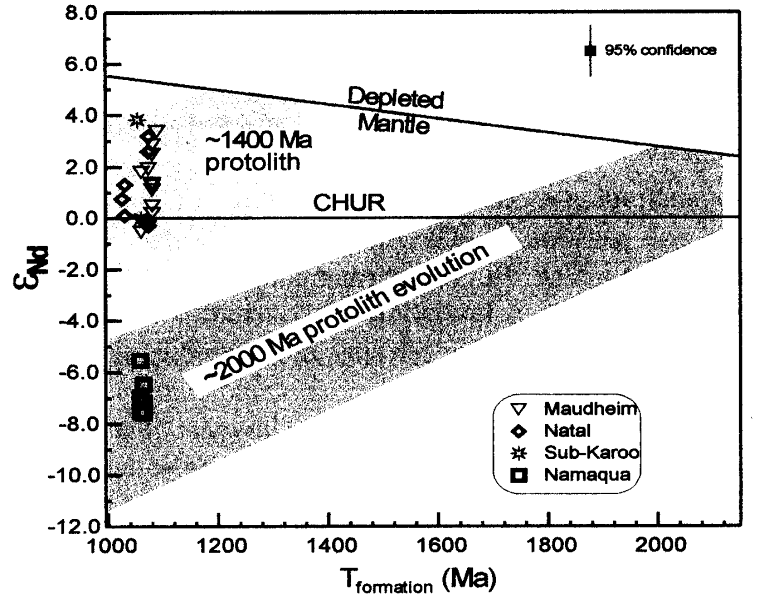


Fig. 10. (a) Plot of ε_{Nd} relative to ε_{Sr} for A-type granitoids from the Namaqua-Natal Belt and Maudheim Province (Eglington and Armstrong, 2000; Eglington et al., 1989; Arndt et al., 1991; Clifford et al., 1995; Moyes and Harris, 1996; Harris, 1999) . (b) Plot of formation age relative to ε_{Nd} for A-type grantoids from the Namaqua-Natal Belt and Maudheim Province relative to the Proterozoic crustal evolution in these regions (Thomas et al., 2000; Eglington and Armstrong, 2000; Eglington et al., 1989; Arndt et al., 1991; Clifford et al., 1995; Storey et al., 1994; Moyes and Harris, 1996; Krynauw and Jackson, 1996; Wareham et al., 1998; Cornell et al., 1986; Reid, 1997; Harris, 1999).

Antarctica (Clifford *et al.*, 1995; Robb *et al.*, 1999; Eglington and Armstrong, 2000; Harris, 1999) with the new data from Kirwanveggen being tabulated in Table 3. Figure 10b shows the ϵ_{Nd} *vs* $T_{formation}$ ages for comparison and it is evident that the data from Natal and Maudheim Provinces are juvenile, possibly derived from protoliths ~1400 Ma

Table 3. Rb/Sr and Sm/Nd isotopic data from the Kirwanveggen Megacrystic Orthogneiss at Neumeyerskarvet.

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	1 sigma	$^{87}Sr/^{86}Sr$	Precision	1 sigma	Sm(ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	1 sigma	$^{143}Nd/^{144}Nd$	Precision	1 sigma
92/14	76.08	363.20	0.60646	0.80 %	0.714481	0.000016	0.01 %	10.79	51.56	0.12650	0.60 %	0.51219	0.000063	0.0060
92/17	84.56	395.30	0.61917	0.80 %	0.712055	0.000017	0.01 %	11.94	56.45	0.12786	0.60 %	0.51215	0.000025	0.0060
92/18	95.19	307.00	0.89792	0.80 %	0.717116	0.000015	0.01 %	14.74	70.21	0.12691	0.60 %	0.51226	0.000011	0.0060
92/19	101.60	310.00	0.94916	0.80 %	0.717650	0.000014	0.01 %	14.11	64.25	0.13275	0.60 %	0.51220	0.000038	0.0060
92/34	133.20	302.70	1.27500	0.80 %	0.722565	0.000014	0.01 %	12.75	62.45	0.00000	0.60 %	0.00000	0.000000	0.0060
92/36	71.87	603.30	0.34471	0.80 %	0.708950	0.000015	0.01 %	9.72	44.40	0.13231	0.60 %	0.51224	0.000009	0.0060

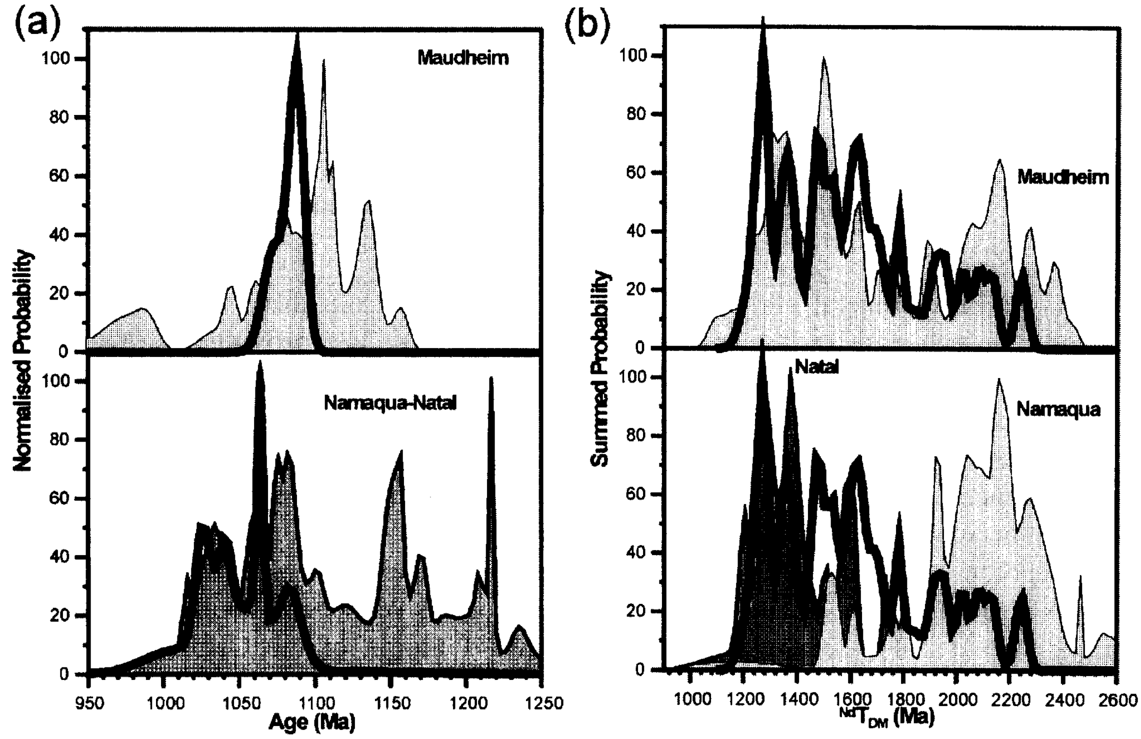


Fig. 11. (a) Normalised probability distribution of dates for A-type granitoids from the Namaqua-Natal Belt and Maudheim Province (thick black line) relative to the distribution of dates for all lithologies from these Mesoproterozoic Provinces (data from Eglington and Armstrong, 2000; Eglington et al., 1989; Arndt et al., 1991; Clifford et al., 1995; Robb et al., 1999; Storey et al., 1994; Gose et al., 1997; Moyes and Harris, 1996; Krynauw and Jackson, 1996; Barton, 1983a, b; Barton and Burger, 1983). (b) Plot of normalised probability distribution of model depleted mantle dates for A-type granitoids from the Namaqua-Natal Belt and Maudheim Province (thick black lines) relative to fields for the Proterozoic crustal evolution in these regions (Thomas et al., 2000; Eglington and Armstrong, 2000; Eglington et al., 1989; Arndt et al., 1991; Clifford et al., 1995; Storey et al., 1994; Moyes and Harris, 1996; Krynauw and Jackson, 1996; Wareham et al., 1998; Cornell et al., 1986; Reid, 1997; Harris, 1999).

old whereas those samples from the Springbok area in Namaqualand suggest protolith ages of > ~2000 Ma (Fig. 10b).

Figure 11b (right) shows a plot of normalised probability distribution of model depleted mantle dates for A-type granitoids from the Namaqua-Natal Belt and Maudheim

Province (thick black lines) relative to fields for the Proterozoic crustal evolution in these regions. The data show a range of T_{DM} ages from ~2700 Ma to ~1000 Ma with the highest probabilities being recorded for ages < ~1650 Ma indicating that the mantle extraction of magma related to these intrusions occurred after this date.

U/Pb zircon geochronological data from the intrusions range in age from ~1090–1030 Ma (Thomas *et al.*, 1993; Jackson and Armstrong, 1997; Harris, 1999; Robb *et al.*, 1999; Eglington *et al.*, 2000) (Fig. 11a). The intrusions in Namaqualand and Natal range mostly from 1030–1060 Ma (Robb *et al.*, 1999; Ashwal *et al.*, 1997; Clifford *et al.*, 1995) whereas the limited data from Antarctica suggest ages of ~1080–1095 (Arndt *et al.*, 1991; Jackson and Armstrong, 1997; Harris, 1999). Similar A-type intrusions in Mozambique have yielded a SHRIMP U/Pb zircon age of ~1107 Ma (Miller *et al.*, 2001). These authors suggested that the ages of the A-type intrusions extending from Natal to Mozambique possibly suggest diachronous emplacement deceasing in age from north to south.

6. Mineral compositions and thermobarometry

6.1. Introduction

Only limited mineral composition data are available from these intrusions. Direct and indirect evidence of temperatures of emplacement are provided by Opx-Cpx thermometry from some of the intrusions (Van der Kerkhof and Grantham, 1999; Mendonidis and Grantham, 1989) as well as the high TiO_2, P_2O_5 and Zr contents described above (Mineral abbreviations after Kretz, 1983). Direct pressure estimates of emplacement are not possible from the available data however retrogressive cooling reactions in some intrusions and their thermal aureoles suggest wide ranges of sub-solidus cooling environments from 3–4 kb in Namaqualand (Waters, 1986) to ~12 kb in Kirwanveggen, Dronning Maud Land. In Natal retrogressive isobaric-cooling reactions in charnockitic aureoles adjacent to the Port Edward Pluton of the Oribi Gorge Suite suggest pressures of ~5 kb (Van der Kerkhof and Grantham, 1999).

6.2. Thermometry

Mineral compositional data provide support for high temperatures of genesis with two pyroxene thermometry from the Port Edward Pluton in Natal indicating core temperatures of >900 ℃ (Van der Kerkhof and Grantham, 1999) whereas Mendonidis and Grantham (1989) calculated temperatures of ~1000°C from pyroxenes (Opx=$En_{62\text{-}64}$, Cpx=$En_{\sim 39\text{-}41}$) from the Munster Suite. Some intrusions (Oribi Gorge pluton, Natal) contain fayalite which is partially replaced by orthopyroxene (Fig. 5d). Thermobarometry on fayalite coexisting with orthopyroxene and quartz in the Oribi Gorge Pluton in Natal suggests that the cooling reaction of Fa + Qtz → Fs took place at 4.8–6 kb at the temperature of 800–1000°C using the program TWEEQU (Berman, 1991a) (Fig. 12a). The orthopyroxene and olivine analyses on which this estimate is based are shown in Table 4a.

At Neumeyerskarvet, Kirwanveggen, mineral reactions useful for constraining the high grade subsolidus *P-T* conditions in the Kirwanveggen Megacrystic Orthogneiss Complex include:-

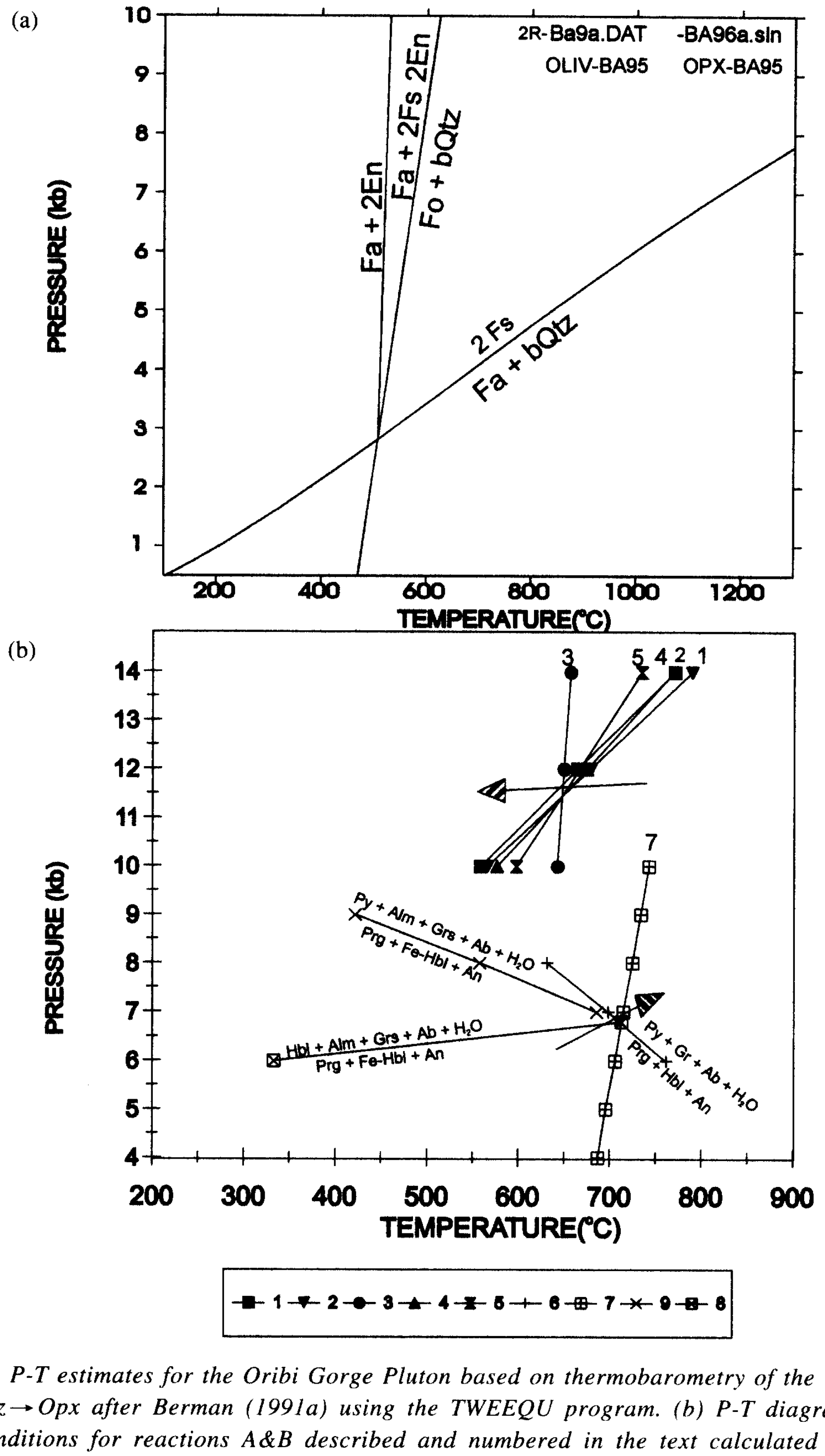


Fig. 12. (a) P-T estimates for the Oribi Gorge Pluton based on thermobarometry of the reaction of Fa+ Qtz→Opx after Berman (1991a) using the TWEEQU program. (b) P-T diagram showing the conditions for reactions A&B described and numbered in the text calculated for the various end members from Neumeyerskarvet, Kirwanveggen using appropriate solution parameters and THERMOCALC (Powell and Holland, 1990).

$$\text{Opx} + \text{Pl} \rightarrow \text{Grt} + \text{Qtz} + \text{Cpx}, \quad \text{(A)}$$

and

Table 4a. Mineral compositions from the Kirwanveggen Megacrystic Orthogneiss used for reaction A.

	Cpx	Cpx	Cpx	Grt	Grt	Grt	Grt	Opx	Opx	Opx	Pl	Pl	Pl
SiO_2	51.76	51.58	51.68	37.84	37.36	37.31	37.31	49.07	49.50	49.62	65.88	62.63	61.13
Al_2O_3	2.61	2.68	2.67	21.23	21.22	21.25	21.25	1.05	0.86	0.86	22.57	23.56	23.48
FeO	17.73	17.52	17.72	34.98	35.15	35.00	35.00	37.13	36.40	36.64	0.19	1.40	0.92
MnO	0.11	0.16						0.23	0.29	0.24			
MgO	7.92	7.92	7.78	4.65	4.58	4.61	4.61	9.44	9.70	9.24		0.43	
CaO	19.22	19.08	19.22	0.49	0.44	0.45	0.45	1.09	1.43	0.70	4.01	6.01	6.00
Na_2O	1.10	0.91	1.05					0.69	0.50	0.45	8.35	7.27	7.00
K_2O	0.18	0.15	0.19					0.14	0.11	0.19	0.33	0.45	0.44
TiO_2	0.23	0.19	0.15					0.00	0.00	0.14			
TOTAL	100.86	100.19	100.46	99.19	98.75	98.62	98.62	98.84	98.79	98.08	101.33	101.75	98.97
Si	1.98	1.98	1.98	3.03	3.01	3.01	3.01	2.00	2.01	2.03	2.86	2.75	2.75
Al	0.12	0.12	0.12	2.00	2.02	2.02	2.02	0.05	0.04	0.04	1.15	1.22	1.24
Fe	0.57	0.56	0.57	2.34	2.37	2.36	2.36	1.27	1.24	1.25	0.01	0.05	0.04
Mn		0.01						0.01	0.01	0.01			
Mg	0.45	0.45	0.45	0.56	0.55	0.55	0.55	0.57	0.59	0.56		0.03	
Ca	0.79	0.79	0.79	0.04	0.04	0.04	0.04	0.05	0.06	0.03	0.19	0.28	0.29
Na	0.08	0.07	0.08					0.05	0.04	0.04	0.70	0.62	0.61
K	0.01	0.01	0.01					0.01	0.01	0.01	0.02	0.03	0.03
Ti	0.01	0.01											
TOTAL	4.00	3.99	4.00	7.97	7.98	7.98	7.98	4.01	3.99	3.97	4.93	4.97	4.95
No. O	6	6	6	12	12	12	12	6	6	6	8	8	8

$$\text{Hbl} + \text{Pl} \rightarrow \text{Grt} + \text{Qtz} + H_2O. \quad \text{(B)}$$

Various reaction equilibria can be written involving reaction A, recognised in the charnockitic patches which appear to have survived as low strain zones (Fig. 5a) and have not been completely hydrated during retrogression and subsequent deformation. These reaction equilibria are numbered below and correspond to the various reactions shown in Fig. 12b below.

$$\text{Ab} \rightarrow \text{Jd (solid solution in cpx)} + \text{Qtz}, \quad (1)$$
$$\text{An} + \text{Fs} \rightarrow \text{Hd} + \text{Alm} + \text{Qtz}, \quad (2)$$
$$\text{Fs} + 2\text{Di} \longleftrightarrow \text{En} + 2\ \text{Hd}, \quad (3)$$
$$2\text{An} + \text{En} + 3\text{Fs} \rightarrow 2\text{Di} + 2\text{Alm} + 2\text{Qtz}, \quad (4)$$
$$\text{An} + 2\text{En} + 3\text{Hd} \rightarrow 4\text{Di} + \text{Alm} + \text{Qtz}. \quad (5)$$

The *P–T* conditions of the reactions were calculated using the computer program THERMOCALC (Powell and Holland, 1988, 1990) using appropriate solution models (amphibole from Kohn and Spear, 1989, 1990; garnet from Berman, 1991b; orthopyroxene from Aranovich and Kosyakova (1986) ; and feldspar from Fuhrman and Lindsley, 1988) for the various minerals which occur as solid solutions and the analysed data for garnet, orthopyroxene, feldspar and hornblende shown in Table 4b.

Figure 12b shows that these reactions intersect at temperatures of between 640°C and 660°C and pressures of 11–12 kb. Reactions 1, 2, 4 and 5 are net transfer reactions which will cease before reaction 3 which essentially involves the exchange of Fe and Mg between garnet and clinopyroxene. Reaction 3 therefore probably represents a closure temperature at which the diffusion of Fe and Mg ceased. Application of the garnet-clinopyroxene thermometers of Ellis and Green (1979) and Pattison and Newton (1989) and the garnet-orthopyroxene thermometer of Harley (1984) yield temperatures of ~750°C, ~975°C and 800°C respectively. If these estimates of temperature are correct they suggest that pressures may have been higher.

Various reaction equilibria can be written involving the minerals defining reaction B. Reaction B is recognised in the foliated non-charnockitic portions of the Kirwanveggen Megacrystic Orthogneiss Complex at Neumeyerskarvet. These reaction equilibria are numbered below and correspond to the various reactions shown in Fig. 12b above. The reaction directions are written as indicated in figure and in the list below to conform to the textural relationships (except reaction 7, a cation exchange reaction which is not visible).

$$15Prg + 9Hbl + 36An \rightarrow 32Py + 28Grs + 15Ab + 24H_2O, \quad (6)$$

	Hbl	Hbl	Hbl	Hbl	Grt	Grt	Grt	Pl	Pl	Pl	Pl
SiO_2	40.28	40.63	40.81	42.1	37.120	36.7	36.79	62.79	63.48	63.38	62.21
Al_2O_3	10.89	11.05	10.69	10.32	20.660	20.75	20.71	24.49	24	24.07	24.4
Fe_2O_3	0	0	0	0	0.000	0	0	0	0	0	0
FeO	23.12	23.03	23.74	22.94	31.630	31.66	31.89	0	0	0	0
MnO	0.15	0.16	0	0	1.000	1.04	0.93	0	0	0	0
MgO	5.89	6.19	5.88	6.42	1.720	1.83	1.39	0	0	0	0
CaO	11.13	11.08	11.06	11.57	7.140	7.48	7.36	5.37	5.1	5.13	5.52
Na_2O	1.45	1.59	1.87	1.58	0.000	0	0	7.36	7.3	6.88	7.53
K_2O	1.6	1.56	1.57	1.42	0.000	0	0	0.25	0.22	0.23	0.24
TiO_2	2.16	2.17	2.03	1.65	0.000	0	0	0	0	0	0
TOTAL	96.67	97.46	97.65	98	99.270	99.46	99.07	100.26	100.1	99.69	99.9
Si	6.36	6.353	6.391	6.52	3.00	2.972	2.991	2.761	2.789	2.791	2.751
Al	2.027	2.037	1.974	1.884	1.97	1.981	1.985	1.27	1.243	1.25	1.272
Fe	3.053	3.012	3.109	2.971	2.14	2.144	2.168				
Mn	0.02	0.021	0	0	0.06	0.071	0.064				
Mg	1.386	1.442	1.372	1.482	0.20	0.221	0.168				
Ca	1.883	1.856	1.856	1.92	0.61	0.649	0.641	0.253	0.24	0.242	0.262
Na	0.444	0.482	0.568	0.474				0.628	0.622	0.588	0.646
K	0.322	0.311	0.314	0.281				0.014	0.012	0.013	0.014
Ti	0.257	0.255	0.239	0.192							
TOTAL	15.752	15.769	15.823	15.724	8.01	8.038	8.017	4.925	4.907	4.884	4.943
No. O	23	23	23	23	12	12	12	8	8	8	8
SUMFM	13.103	13.12	13.086	13.049							
Fe2/Fe2+Mg	0.688	0.676	0.694	0.667							

Table 4c. Fayalite and orthopyroxene compositions from the Oribi Gorge Suite.

	Opx	Opx	Opx		Fa	Fa	Fa
SiO_2	45.01	45.04	45.89		29.58	29.89	29.34
Al_2O_3	0.37	0.37	0.3				
FeO	48.25	48.11	48.4		68.27	68.11	67.33
MnO	0.93	1.13	1.02		1.26	1.13	1.25
MgO	4.26	4.22	4.33		1.88	1.83	1.82
CaO	0.79	0.77	0.58				
TiO_2	0.08	0.11					
TOTAL	99.69	99.75	100.52		100.99	100.96	99.74
Si	1.919	1.919	1.939	Si	0.985	0.993	0.988
Al	0.019	0.019	0.015	Fe	1.901	1.892	1.897
Ti	0.003	0.004		Mn	0.036	0.032	0.036
Fe3	0.139	0.136	0.107	Mg	0.093	0.091	0.091
Fe2	1.58	1.59	1.603				
Mn	0.034	0.041	0.037				
Mg	0.271	0.268	0.273				
Ca	0.036	0.035	0.026				
Sum_cat	4.001	4.012	4	Cations	3.015	3.008	3.012
No. O	6	6	6		4	4	4

$$3Hbl + 4Alm \leftrightarrow 3Hbl\ (ferro) + 4Py, \qquad (7)$$
$$15Prg + 24Hbl\ (ferro) + 36An \rightarrow 15Hbl + 32Alm + 28Grs + 14Ab + 24H_2O, \qquad (8)$$
$$15Prg + 9Hbl\ (ferro) + 36An \rightarrow 20Py + 12Alm + 28Grs + 15Ab + 24H_2O. \qquad (9)$$

The garnet hornblende thermometer of Graham and Powell (1984) yields a temperature of ~620°C. Reactions 6, 8 and 9 are typically dehydration reactions requiring a thermal input or pressure increase. Reactions 6, 7, 8 and 9 intersect at 6.8 kb and 713°C. A significant difference between reactions A and B is that the garnets produced are relatively grossular poor and grossular rich respectively (Table 4b and c).

The pressure difference suggested between reactions A and B is significant. It is not possible to determine whether these two reactions occurred at similar times or whether reaction A occurred during cooling after emplacement of the Kirwanveggen Megacrystic Orthogneiss Complex and reaction B after the intense deformation which foliated and retrogressed most of the Kirwanveggen Megacrystic Orthogneiss Complex at Neumeyerskarvet had ceased. The latter possibility is preferred because of the different P conditions suggested by the assemblages produced by reactions A and B. Possible support for this interpretation are the hornblende $^{40}Ar/^{39}Ar$, Rb/Sr biotite–whole-rock age and Sm/Nd garnet whole rock ages of ~500–600 Ma obtained by Harris (1999) on samples from the Kirwanveggen Megacrystic Orthogneiss at Neumeyerskarvet, WDML, Antarctica. These data suggest therefore (1) a shallow isobaric cooling (IBC) trajectory after emplacement resulting in reaction A which is typical of IBC reactions (Harley, 1989) followed by (2) increasing pressure or heating resulting in the dehydration reactions recognised in B. It is possible that these reactions were separated by considerable time with reaction A occurring relatively soon after cooling and reaction B being a reflection of Pan Africa heating which has been recognised as being responsible for resetting the Rb/Sr and Sm/Nd isotope systematics in Sverdrupfjella, at least on a mineral scale (Moyes, 1993; Moyes *et al.*, 1993; Grantham *et al.*, 1995).

The pressures suggested by the isobaric cooling curves recognised in the aureoles to the intrusions as well as some of the cooling reactions within the intrusions suggest that pressures/depths of emplacement of these bodies vary. In the case of the intrusion at Neumeyerskarvet, emplacement appears to have been at levels normally ascribed to the base of the crust *i.e.* ~10 kb or 30 km in contrast to the 3–4 kb levels suggested by Waters (1986) in Namaqualand.

7. Discussion and conclusions

The intrusive suites described above are all characterised by the following common features:

- Presence of orthopyroxene at least in some of their exposures.
- Megacrystic/porphyritic textures with interstitial ferromagnesian and accessory mineralogy.
- High Zr, P and Ti which require high temperatures for dissolution at the levels of concentration seen.
- A-type and within plate granite chemistry.
- Similar age.

- Wide range in chemistry with SiO_2 varying from ~50–75%, the lower values being typical of basaltic magmas.

The first three of these a criteria above are typical of high temperature, low X_{H_2O} magmas, suggesting temperatures >850°C, particularly the textures (Whitney, 1975; Naney and Swanson, 1980) and the chemical characteristics. Consequently, it is probable that orthopyroxene was probably more prevalent in these intrusions but has suffered subsequent retrogression to garnet and/or biotite/hornblende depending on the fluid regime during retrogression. With regard to the latter aspect, the fluid inclusions of these intrusions has received little attention. Van der Kerkhof and Grantham (1999) showed that the Port Edward Pluton was characterised by dense CO_2 + N_2 inclusions, also consistent with high temperature anhydrous emplacement of those rocks. The experimental study of Naney and Swanson (1980) suggests that with X_{H_2O}>~4 wt% in a granodioritic magma, the first phase on the liquidus would be hornblende whereas with X_{H_2O}<~4 wt% feldspar is the first phase to crystallise, therefore supporting the interpreted low X_{H_2O} nature of these rocks.

Differences between the intrusions revolve around the isotopic nature of their sources with regard to juvenile derivation (Antarctica and Natal) or whether significant contributions from older crust are recognised (*i.e.* most of the available data from Namaqualand). These data partially contradict the within-plate chemistry signature suggested by the intrusions because it might be expected that within plate granites would be expected to have significant contributions from crustal material.

Questions to be considered are whether it is possible to generate the isotopic signatures and chemical compositions of the magmas from a single broad process. From this perspective one can draw the following conclusions:

- It is not possible to generate the juvenile signatures observed in Natal and Antarctica from the melting of older crustal material.
- It is unlikely that partial melting of presumably heterogeneous **crustal** material over such a wide area (Namaqualand to Antarctica) could generate magmas of such uniform characteristics.
- The high REE and high field strength element contents, which characterise these rocks, are more likely to arise from residual concentration in a fractionating melt rather than arising from crustal partial melting. During partial melting their general incompatibility in most common rock forming minerals (except Eu in feldspar) implies enrichment related to low fractions of melting associted with low melting temperatures. With greater fractions of melting, partial melt models predict declining concentrations of these trace elements in the magma. In contrast, fractionation models require increasing concentration of such elements in the residual magma because of their general lack of compatibility in the fractionating mineral assemblage. Consequently high degrees of partial melting of crustal material, which might be expected from the high temperatures suggested by thermometry, will not produce rocks with these trace element compositions.
- The least evolved compositions recognised in the these A-type charnockitic intrusions verge on the field of basalts ie SiO_2 contents ~52%. Partial melting of crustal material, albeit from the lower depleted lower crust, is unlikely to yield magmas basaltic in composition but is more likely to yield magma compositions similar to the more

intermediate, average values for the lower crust.

It is therefore suggested that a more plausible genesis for these magmas is that of intrusion of partially fractionated, mantle derived, basaltic magma into lower to middle crustal chambers arising from crustal extension. Further fractionation, complicated by assimilation and contamination at the levels of emplacement would provide the range and consistency of chemical variation seen in these rocks. Fractional crystallisation could also result in the relatively concentrated levels of Nb + Y and Rb which are used to characterise the within-plate chemistry of these intrusions. The fluid composition of such intrusions is also likely to evolve with dehydration reactions in the high temperature aureoles of the intrusions (Van der Kerkhof and Grantham, 1999) contributing to increasing X_{H_2O} in the magmas with progressive fractionation.

8. Suggestions for future fields of study

Currently available data suggest that the rocks in Namaqualand are anomalous in comparison with those from Natal and Maudheim. A contributory factor to this is that no comprehensive studies have been conducted. For example whole-rock, major and trace element data are not available for the Spektakel Suite samples which have been studied isotopically (Clifford *et al.*, 1995; Robb *et al.*, 1997, 1999; Ashwal *et al.*, 1997). Similarly, those Spektakel Suite samples which have analysed for major and trace element contents, have not been studied for Rb/Sr and Sm/Nd isotope characteristics (Thomas *et al.*, 1996; Von Backstrom, 1964). Consequently future studies aimed at gaining a comprehensive understanding of these rocks should involve combined isotopic and major and trace element compositions in Namaqualand to resolve the apparent anomalies recognised there. The apparent crustal contributions to the Namaqua rocks may be a localised phenomena in the Springbok area of Namaqualand where Robb *et al.* (1999) have shown the existence of older crustal material within the Namaqua Metamorphic Province. Ashwal *et al.* (1997) reported T_{CHUR} ages of ~1200 Ma for Spektakel Suite rocks at Steenkampskraal in southern Namaqualand implying juvenile sources in that area in contrast to the rocks from the Springbok area.

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