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Charnockite composition in relation to the tectonic evolution of East Antarctica

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Abstract

Charnockitic suites in central Dronning Maud Land (DML), Mac.Robertson Land (MRL), and the Bunger Hills area are compositionally varied and probably include both mantle and lower-crustal components. In this paper we present new geological and geochemical data on the DML charnockitic rocks, and compare their geochemistry with that of charnockitic rocks from several other Antarctic high-grade terranes, particularly MRL and the Bunger Hills. These areas have different geological histories and one of the main aims of this study is to investigate possible links between charnockite composition and the tectonic history of their host terranes. Antarctic charnockitic rocks form two distinct compositional groups. 510 Ma DML charnockites are relatively alkalic and ferroan, with high K_2O, Zr, Ga, Fe/Mg, and Ga/Al, and very low MgO, characteristic of A-type (alkaline, commonly anorogenic) granitoids. The more mafic DML rocks, at least, were derived by fractionation of a relatively alkaline high-P–Ti ferrogabbro parent magma. Most other early Palaeozoic charnockitic rocks in Antarctica are of similar composition. In contrast, MRL (c. 980 Ma) and Bunger Hills (c. 1170 Ma) charnockites are mainly calc-alkalic or calcic and magnesian, and the associated mafic components are tholeiitic. MRL and Bunger Hills charnockites are late-orogenic, whereas DML charnockites are post-orogenic, and appear to have been emplaced after post-collision extension and decompression. These two mineralogically and geochemically distinct charnockite groups may thus reflect a compositional trend in an evolving orogen, either accretional or collisional, respectively.

Keywords: Charnockite; Neoproterozoic; Pan-African; East Antarctica

1. Introduction

Charnockitic rocks (orthopyroxene granitoids, s.l., including monzogabbro to quartz syenite and granite, Le Maitre, 2002) constitute a prominent rock type throughout much of East Antarctica and, indeed, in Precambrian high-grade metamorphic terranes world-wide. In Antarctica, such rocks were mapped by Craddock (1972) in central Dronning Maud Land (Muhlig Hofmann Mountains and Wohlthat Massif), the Yamato Mountains, Enderby Land, Mac.Robertson Land (Northern Prince Charles Mountains, Mawson Coast), Queen Mary Coast, Bunger Hills, Windmill Islands, and a few other localities as far east as the Adelie Coast. Isotopic studies have shown that Antarctic charnockites were emplaced in at least three distinct episodes: late Archaean (e.g., Enderby Land, c. 3000 Ma: Sheraton et al., 1987), late Mesoproterozoic to early Neoproterozoic (e.g., Bunger Hills, 1170–1150 Ma: Sheraton et al., 1992; Mac.Robertson Land, 980–950 Ma: Young and Black, 1991; Kinny et al., 1997), and late Neoproterozoic to early Palaeozoic (central Dronning Maud Land, c. 600 Ma: Jacobs et al., 1998; 510 Ma: Mikhalsky et al., 1997, Ravindra and Pandit, 2000; Mirnyy Station: c. 500 Ma: Ravich et al., 1968, McQueen et al., 1972).

The nature and origin of charnockite and its tectonic significance have been subjects of debate since the earliest investigations. Charnockite formation was commonly regarded as a manifestation of the cratonisation of the East Antarctic shield, or of its subsequent tectonic re-activation during the Proterozoic and early Palaeozoic (Ravich and Soloviev, 1966), and charnockites considered as entirely intracrustal anorogenic rocks (Ravich, 1972; Grikurov, 1980). Later workers suggested an

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orogenic origin for many charnockites, which may have crystallised from either predominantly crustal or mantle-derived melts (e.g., Kilpatrick and Ellis, 1992; Sheraton et al., 1992, 1996).

The East Antarctic Shield is composed of relatively small Archaean cratons (Vestfold Hills block, Enderby Land block, Southern Prince Charles Mountains, etc., Black et al., 1992) enclosed in an extensive Proterozoic mobile belt (Kamenev, 1991; Yoshida, 1994; Fitzsimons, 2000). Charnockitic rocks are known from both Archaean (e.g., Sheraton et al., 1987) and Proterozoic terrains (e.g., Tingey, 1991). The rocks described here occur within the Proterozoic mobile belt. The tectonic peak occurred in the Bunger Hills at about 1190 Ma (Sheraton et al., 1992), in Mac.Robertson Land at about 1000 Ma (Tingey, 1991), and in Dronning Maud Land at 570–530 Ma (Jacobs et al., 1998). Many charnockite plutons are essentially undeformed, and are considered to be post-tectonic (e.g., Dronning Maud Land), whereas others (e.g., Mac.Robertson Land, Bunger Hills) show ductile deformation, mainly within marginal zones, and are considered to be syn- to late-tectonic (Young and Ellis, 1991; Kilpatrick and Ellis, 1992; Sheraton et al., 1992). However, it is noteworthy that charnockite emplacement in those areas for which adequate isotopic age data are available appears to have post-dated the main deformation phase(s) and metamorphic peak by about 20 to 60 Ma. Charnockite emplacement may thus characterise the later stages of an orogenic cycle, although the orogens may be of different origins.

In this paper we present new geological and geochemical data on central Dronning Maud Land (DML) charnockitic rocks, obtained by KH in 1991–1992, EVM in 1991–1992, and the GeoMaud 1995–1996 expedition, and compare their geochemistry with that of charnockitic rocks from several other Antarctic high-grade terranes, particularly Mac.Robertson Land (MRL) and the Bunger Hills, for which much geochemical and isotopic data are published elsewhere. These areas have different geological histories and one of the main aims of this study is to investigate possible links between charnockite composition and the tectonic history of their host terranes. Although source composition and magmatic history are clearly of primary importance in determining charnockite composition, some compositional features may be related to the tectonic environment, and could thus provide a key for the distinction of different charnockite types in Antarctica and elsewhere.

2. Early Palaeozoic charnockitic rocks of central Dronning Maud Land

2.1. Geological features

Charnockitic rocks form large plutons of up to 4000 km^2 which dominate the geological structure of central DML (Fig. 1) (Klimov et al., 1964; Hussain, 1989; Joshi et al., 1991; Rama Rao et al., 1995; Paech, 1997; Roland, 2004; Markl and Henjes-Kunst, 2004). Contacts with country rocks are only rarely exposed, but are clearly discordant and are not significantly deformed. The polymetamorphic basement rocks consist predominantly of metasediments (including abundant calcareous metamorphic rocks in some areas) and plutonic orthogneiss, which are mainly of Mesoproterozoic age (Jacobs et al., 1998), although a complex sequence of late Neoproterozoic to early Palaeozoic tectonothermal events (see below) has

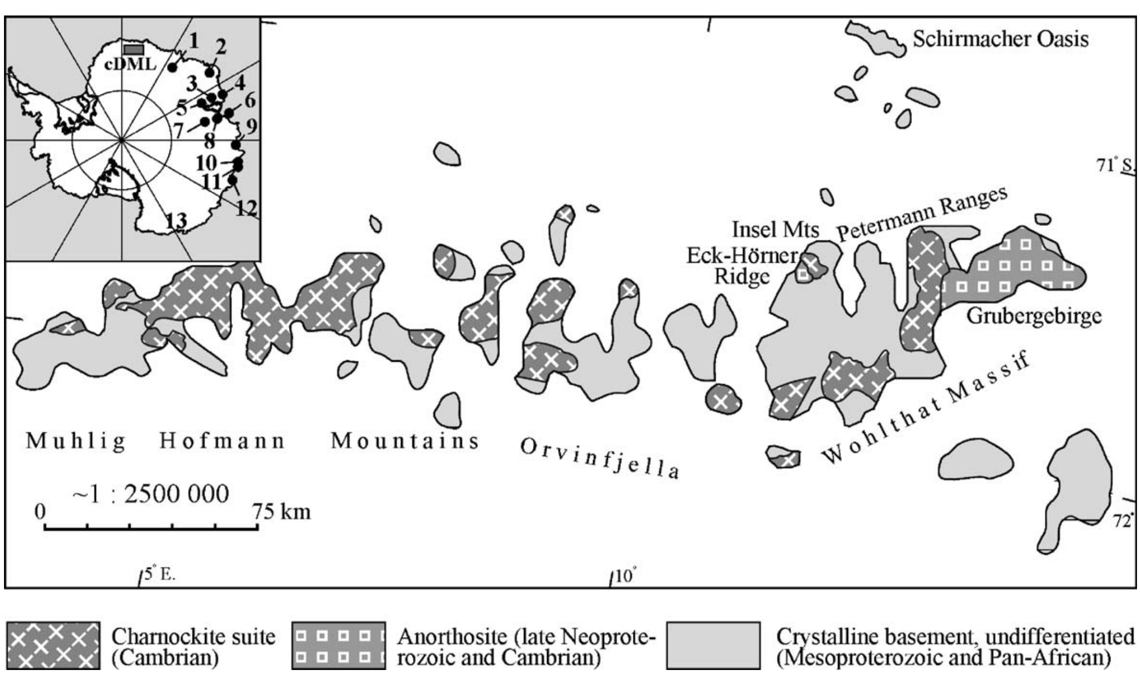

Fig. 1. Charnockitic rocks and anorthosite occurrences in the central Dronning Maud Land. Figures in the inset indicate: 1 — the Yamato Mountains, 2 — Enderby Land, 3 — Mac.Robertson Land, 4 — Mawson Coast, 5 — the Prince Charles Mountains, 6 — Prydz Bay, 7 — the Grove Mountains, 8 — Princess Elizabeth Land, 9 — Queen Mary Coast, Mirnyy Station, 10 — David Island, 11 — the Bunger Hills, 12 — the Windmill Islands, 13 — Adelie Coast.

been recorded (Jacobs et al., 1998). Estimated crystallisation conditions for charnockitic rocks are 4.8±0.3 kbar and 925–940 °C for a less evolved (lower Fe) Cpx–Opx–Qtz-bearing sample, and 855–875 °C for the most evolved (higher Fe) Cpx–Ol–Qtz-bearing sample (Markl and Henjes-Kunst, 2004). These authors concluded that the decrease in equilibrium temperature was a reflection of the fractional crystallization of the parent melt.

The largest pluton, Lodochnikov Massif of Ravich and Soloviev (1966), crops out in the Muhlig Hofmann Mountains and western Orvinfjella (Fig. 1), and is composed mainly of coarse-grained two pyroxene-bearing granitic rocks and biotite–amphibole granitic rocks (ranging from quartz monzodiorite to granite). Plutons in the Wohlthat Massif consist of predominant granite and subordinate monzodiorite, monzonite, monzosyenite, and associated ferrogabbro and ferromonzogabbro (Joshi and Pant, 1995). In the former area two intrusive phases of charnockitic rocks with cross-cutting relationships occur. The early phase is composed of relatively smaller-grained predominantly monzodioritic rocks, while the later phase is composed of coarse-grained syenitic rocks. In the eastern Petermann Ranges (Grubergebirge) charnockitic rocks are spatially associated with voluminous anorthosite.

A structurally and compositionally complex pluton, which crops out in the southwestern Insel Mountains and eastern Eck-Hörner Ridge (hereafter called the Insel Massif), is the main subject of the present study. It has given a U–Pb zircon age of c. 510–505 Ma (Mikhalsky et al., 1997), and includes at least two magmatic phases. The eastern and northern parts of the massif consist mainly of an older suite of coarse-grained porphyritic fayalite–clinopyroxene–amphibole±orthopyroxene monzonite, quartz monzonite, syenite, and minor granite (termed *syenite group*). These are homogeneous coarse-grained leucocratic (colour index M=5–10) rocks. Contacts with the country rocks are poorly exposed, but in a few localities fine-grained rocks of similar composition form the contact "chilled margin" which is about 20–30 m thick and grades inwards into the typical coarse-grained textural variant. Mafic phases have Fe-rich compositions: clinopyroxene ($Ca_{40-46}Mg_{7-12}Fe_{46-49}$), olivine ($Fo_{2.5-5}$), biotite (*mg*, atomic $100Mg/(Fe^{2+}+Mg)$= 5–10, TiO_2 up to 4%, F 1.62%), ferro-pargasitic hornblende (*mg*=8–13, TiO_2 1.5–2%), and rare orthopyroxene ($Ca_{1-7}Mg_{14-17}Fe_{76-85}$). Representative chemical analyses of the rock-forming minerals are presented in Table 1. The syenite also contains rare mafic pyroxene–ilmenite–magnetite–apatite 'layers' up to 25 cm thick of apparent cumulus origin. Relatively

Table 1
Representative mineral compositions of the central DML charnockitic rocks and associated gabbroid

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sample ID	37642-15		37642-10	37656-4	37642-10	37642-15	37656-4	37656-17		132 zh	51	37664-7	37657-10	37642-15
Group	S	S	S	MD	S	S	MD	MD	MD	LM	S	LG	LG	S
Mineral	Ol	Ol	Ol	Ol	Cpx	Cpx	Cpx	Opx	Lamella	Opx	Opx	Opx	Opx	Hbl
SiO_2	31.17	30.78	29.44	28.93	47.76	47.75	47.74	46.96	49.53	47.92	47.45	47.06	49.17	40.97
TiO_2	0.17	0.02	–	0.02	0.15	0.02	0.20	0.32	0.20	0.14	0.21	0.02	0.05	0.24
Al_2O_3	–	0.14	0.16	0.10	1.37	0.85	0.53	0.70	1.56	0.15	1.07	0.80	1.26	11.34
Cr_2O_3	–	–	0.08	–	0.08	–	–	–	–	–	–	–	–	–
Fe_2O_3	–	–	–	–	–	–	–	–	–	2.07	2.05	–	–	–
FeO	65.46	63.65	67.14	69.13	25.82	27.31	26.93	37.82	17.59	39.77	43.51	36.88	31.98	31.46
MnO	1.62	1.63	0.88	1.23	0.17	0.42	0.50	0.64	0.01	0.67	0.94	0.72	0.39	0.18
NiO	–	–	0.10	–	0.08	–	–	–	–	–	–	–	–	–
MgO	0.93	1.86	1.91	1.11	3.36	2.32	2.77	10.69	8.64	4.82	3.93	12.11	15.04	1.85
CaO	0.14	0.08	0.09	0.16	18.86	18.63	20.01	0.98	21.69	3.16	0.03	1.20	1.63	10.54
Na_2O	0.51	0.95	0.18	–	0.55	0.02	1.64	1.13	–	–	–	1.40	0.10	2.61
K_2O	–	–	0.02	–	0.01	0.09	–	–	–	–	–	–	–	1.38
Total	100.00	99.11	99.99	100.68	98.22	97.41	100.32	99.24	99.22	98.7	99.19	100.19	99.62	100.57
Oxygens	4	4	4	4	6	6	6	6	6	6	6	6	6	23
Si	1.033	1.024	0.987	0.975	1.965	1.993	1.951	1.931	1.943	2.021	2.009	1.912	1.941	6.442
Al (IV)	–	–	0.006	0.004	0.035	0.007	1.951	0.034	0.057	–	–	0.038	0.059	1.558
Al (VI)	–	0.005	–	–	0.031	0.035	0.026	–	0.015	0.007	0.053	–	–	0.544
Ti	0.004	0.001	–	0.001	0.005	0.001	0.006	0.010	0.006	0.004	0.007	0.001	0.001	0.028
Cr	–	–	0.002	–	0.003	–		–	–	–	–	–	–	–
Fe^{+2}	1.814	1.771	1.882	1.947	0.888	0.953	0.920	1.310	0.577	1.468	1.606	1.253	1.0556	4.137
Mn	0.045	0.046	0.025	0.035	0.006	0.015	0.017	0.022	–	0.024	0.034	0.025	0.013	0.024
Ni	–	–	0.003	–	0.003	–	–	–	–	–	–	–	–	–
Mg	0.046	0.092	0.095	0.056	0.206	0.144	0.169	0.655	0.505	0.303	0.248	0.733	0.885	0.434
Ca	0.005	0.003	0.003	0.006	0.831	0.833	0.876	0.043	0.912	0.143	0.001	0.052	0.069	1.776
Na	0.033	0.061	0.012	–	0.044	0.002	0.130	0.090	–	–	–	0.110	0.008	0.796
K	–	–	0.001	–	0.001	0.005	–	–	–	–	–	–	–	0.277
Total	2.980	3.003	3.015	3.023	4.018	3.988	4.095	4.087	4.015	3.971	3.958	4.124	4.032	16.015

S — syenite group, Insel Massif; MD — monzodiorite group, Insel Massif; LG — layered gabbro series, the Eck-Hörner Ridge; LM — Lodochnikov Massif (Muhlig-Hofmann Mountains). Mineral phase chemical compositions were obtained with a wave-detector equipped electron microscope at BGR (Hannover) (1–9, 12–14) or by wet chemistry on mineral separates (10, 11; Ravich and Soloviev, 1966).

Table 2
Representative analyses of the charnockitic rocks from the Insel Massif, Mac.Robertson Land, and the Bunger Hills

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Area	Insel Massif										MRL (nPCM)		Bunger Hills			David Island
Sample ID	41049-1a	41049-2	KH42-15	KH41-7	37642-10	KH26-9	KH18-1	KH18-3	KH8-12	37637-3	69280308	71280109	86285850	86286276	86285817	86286033
Lithology	Monzodiorite fine-grained	Monzonite	Qtz monzonite	Qtz monzodiorite	Qtz monzonite (chilled margin)	Syenite	Qtz monzonite	Qtz syenite	Granite	Ferrogabbro	Hbl–Bt–Opx granite	Opx granite	Bt–Cpx–Opx Qtz gabbro	Cpx–Opx granite	Bt–Hbl–Opx Qtz monzonite	Opx–Bt–Hbl syenite
Group	MD	MD	MD	MD	S	S	S	S	S	Dyke	Low-Si	High-Si	Gabbro–granite	Gabbro–granite	Monzodiorite	
SiO_2	52.23	63.75	58.30	60.71	61.46	61.55	62.39	65.77	70.99	42.80	60.40	74.68	54.80	60.70	57.10	60.10
TiO_2	1.94	0.69	0.93	1.09	1.09	0.41	0.78	0.55	0.50	6.08	2.04	0.09	1.19	1.70	1.65	0.67
Al_2O_3	13.44	16.62	15.54	13.89	15.47	17.61	16.13	16.05	13.63	12.15	14.51	13.56	15.74	14.06	14.86	18.63
Fe_2O_3	3.98	2.09	1.90	4.29	0.57	2.02	2.79	1.65	1.63	20.49tot	1.82	0.33	1.88	1.92	2.72	1.45
FeO	13.89	4.03	7.09	7.37	8.29	2.68	4.47	3.74	2.19		7.10	0.44	8.14	6.94	9.16	3.46
MnO	0.22	0.07	0.13	0.20	0.11	0.09	0.11	0.08	0.04	0.25	0.14	0.01	0.20	0.15	0.24	0.09
MgO	1.20	0.28	0.40	0.41	0.41	0.18	0.46	0.27	0.42	5.02	1.30	0.30	5.11	1.91	1.32	0.62
CaO	5.88	3.51	4.12	4.40	3.96	2.54	3.81	2.95	1.95	8.04	5.01	1.36	7.60	5.41	4.74	3.27
Na_2O	1.64	3.24	3.07	2.83	3.30	3.33	3.31	3.30	3.10	2.19	2.50	2.69	2.06	2.63	2.79	4.61
K_2O	3.67	5.57	5.55	4.37	4.72	7.24	5.12	5.63	5.27	0.66	3.26	5.70	1.67	3.03	3.71	5.65
P_2O_5	0.81	0.20	0.29	0.30	0.45	0.11	0.23	0.15	0.15	2.08	0.70	0.03	0.23	0.45	0.92	0.20
H_2O			0.56	0.58		0.45	0.62	0.43	0.67	0.15	1.39	0.58	1.48	0.76	0.96	0.67
LOI	0.66	0.33			0.57											
Sum	99.53	100.80	97.88	100.44	100.40	98.21	100.22	100.57	100.54	99.91	100.17	99.77	100.10	99.66	100.17	99.42
V	9	6	6	3		7	16	14	20	224	53	5	170	126	33	8.0
Cr	108	157	bdl	bdl		bdl	bdl	bdl	bdl	40	6	3	95	17	bdl	bdl
Ni	12.0	24.0	2.0	2.0		1.3	2.0	1.4	1.4	18.0	3	4	23	8	bdl	bdl
Cu	1667	31	bdl	bdl						11	26	8	22	14	18	2
Zn	275	101	193	250		97	150	121	120	243	154	10	105	105	125	99
Ga	23	26	27.1	26		28	28.5	28	29	16	20	12	20	19	21	26
Rb	57	105	96	84	110	147	117	124	282	4	113	185	45	70	48	106
Sr	448	105	500	350	414	440	396	363	132	641	333	132	322	262	414	649
Y	87	29	46	54	103	19	51	43	20	60	45	8	27	56	49	35
Zr	617	295	1146	1805	1524	815	768	773	292	303	715	95	165	328	608	838
Nb	85	35	34	54	77	22	30	26	20	67	48	2	7	16	61	33
Ba	2390	2808	3541	2089	1483	4116	2325	2257	511	797	1520	1148	726	1454	1946	3680
La	71	37	50	62		24	55	55	131	74	127	55	34	48	50	301
Ce	168	79	113	156		50	130	125	259	123	286	96	70	101	104	516
Pr	23	10	15	21		6	17	15	30		30					
Nd	106	44	65	94		29	67	61	108		129	32	29	48	54	182
Sm	22.61	8.97	13.70	20.00		6.00	14.00	12.60	19.00		20.70					
Eu	6.1	5.9	7.3	5.5		6.8	4.2	4.6	1.7		3.59					
Gd	20.74	7.94	13.00	17.70		5.90	12.00	11.70	12.00							
Tb	2.90	1.06	1.71	2.50		0.73	1.85	1.59	1.40		1.89					
Dy	16.08	5.55	8.80	12.45		4.04	10.30	8.79	5.90							
Ho	3.22	1.10	1.43	2.14		0.76	1.90	1.60	0.88							
Er	8.15	2.68	4.30	6.10		1.90	5.10	4.23	1.85							
Tm	1.10	0.36	0.50	0.84		0.26	0.72	0.57	0.24							
Yb	6.90	2.30	3.30	5.50		1.60	4.30	3.30	1.20		3.17					
Lu	1.07	0.35	0.49	0.86		0.24	0.65	0.45	0.16		0.47					
Pb	13.8	19.2	18.5	18		21	23	23	34		35	68	12	17	12	55.0
Th	1.7	1.6	2.9	2.4		1.1	4.4	5.7	106.0		17.5	51.0	1.0	1.0	0.0	39.0
U	0.6	0.6	0.8	0.9		0.3	1.0	1.2	5.5	4.0	0.8	1.0	0.0	0.0	0.0	2.0

MD — monzodiorite group. S — syenite group. Analyses (major and trace elements, respectively) 1, 2 — by wet chemistry and ICP-MS; 3, 4, 6–10 — by XRF (except FeO by wet chemistry); 5 — by wet chemistry and XRF; 11–16 — by XRF for major (FeO was detected volumetrically) and trace elements, except Cr, Ni, Cu, Zn — by atomic absorption spectrophotometry, and REE, Th, U — by instrumental neutron activation. bdl — below determination level.

melanocratic (M = 10–25) amphibole–clinopyroxene (Ca_{38-44} $Mg_{9-10}Fe_{47-52}$) ± olivine (Fo_{3-4}) monzodiorite and quartz monzodiorite to quartz monzonite (*monzodiorite group*) probably form a distinct magmatic suite, which crops out in the central part of Eck-Hörner Ridge. Fine-grained monzodiorite in the contact zone, rare leucocratic syenite–granite blocks (xenoliths?) within monzodiorite, and a few monzodiorite veins and dykes within syenite group rocks all provide evidence that the monzodiorite group is the younger. However, the field evidence was not fully convincing, and some of these features may reflect cumulus processes. In some localities both groups contain abundant xenogenic blocks of country rocks (most Eck-Hörner Ridge), while in others such xenoliths are lacking (SW Insel Mountains). Granitic (s.s.) rocks occur as relatively small and rare isolated bodies, which may represent late-stage injections.

The western part of Eck-Hörner Ridge is composed of layered gabbroic rocks (the exposed section is about 200 m thick), and overlying massive (spotted) or layered anorthosite. The gabbroic rocks comprise 1–10 m thick layers of orthopyroxenite, websterite, anorthosite, orthopyroxene-bearing monzonite, and nelsonite (essentially ilmenite–apatite–titanite rock). The relationships of the gabbroic rocks to the monzodiorite group charnockites were not clear in the field, but the former appear to grade into monzodiorite and may represent cumulates. Anorthosite contains gabbroic xenoliths up to 20 m across. Thus, anorthosite appears to post-date the c.510 Ma charnockite intrusion, which is consistent with U–Pb zircon data (c. 505 Ma, conventional U–Pb zircon data, Mikhalsky et al., 1997), but by only a short time interval, so that they are roughly co-eval. The Eck-Hörner anorthosite is cut by thick (up to 20 m) potassium feldspar-rich pegmatite veins (locally beryl-bearing), and contains 50 m wide pegmatite bodies. The pegmatite veins are subhorizontal or gently dipping, and cut both layered gabbroic rocks and monzodiorite; similar, but much thinner, veins occur within the syenite group rocks. We suggest that the pegmatites represent late-magmatic segregations within the anorthosite. Anorthosite and layered gabbroic rocks are cut by a few mafic dykes up to 15 m thick which thin upwards.

2.2. Geochemistry

Major elements were determined by wet chemistry or XRF, trace elements by XRF or ICP-MS, and REE by INAA at the GeoForschungsZentrum (Potsdam). Representative analyses of rocks from the Insel Massif are given in Table 2.

The various Insel Massif charnockitic rocks (monzodiorite to granite, with quartz monzonite being the most common rock type: Fig. 2) define more or less linear trends on most major element plots (Fig. 3). Trace element variations and ratios are also generally similar, albeit with considerable scatter, suggesting a broadly co-genetic origin. All the analysed rocks have relatively high (though varied) Al_2O_3 and HFSE (Y, Zr, Nb, Ti, and P), and very low MgO and *mg* (8–25). Hussain (1989), Joshi et al. (1991), and Rama Rao et al. (1995) reported even

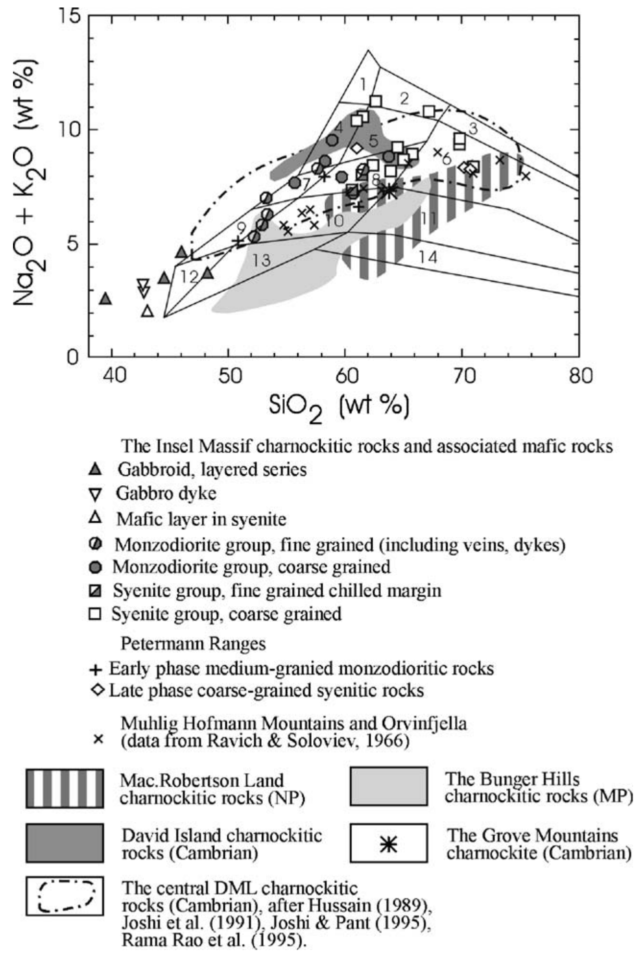

Fig. 2. Total alkalis–SiO_2 (TAS) diagram. Field numbers after Middlemost (1985): 1 — alkaline syenite; 2 — alkaline quartz syenite; 3 — alkaline granite; 4 — syenite; 5 — quartz syenite; 6 — granite; 7 — monzonite; 8 — quartz monzonite; 9 — monzodiorite; 10 — quartz monzodiorite; 11 — granodiorite; 12 — diorite and gabbro; 13 — quartz diorite; 14 — tonalite.

less magnesian (*mg* < 5) granitic rocks from the Petermann Ranges. Monzodiorite group rocks have higher MgO, CaO, P_2O_5 and FeO_{tot}, but lower SiO_2 (52–63%) than those of the syenite group (61–72% SiO_2). The former are higher in Sr, Zr, and Nb, and lower in Rb, Pb, and Th. Together the monzodiorite and syenite groups cover a wide range of SiO_2 contents, with no compositional gaps. Moreover, the composition of the chilled margin of the syenite intrusion is quite similar to that of many monzodiorite group rocks. Some leucocratic rocks have K_2O contents as high as 7–8% and plot within the alkaline syenite field on Fig. 2, whereas other rocks with similar SiO_2 contents (60–65%) contain 4–6% K_2O. The K_2O/Na_2O ratio is within the range 0.99–2.75 (average 1.83), with the syenite group rocks having somewhat higher K_2O/Na_2O (1.4–2.7) than monzodiorite group rocks (1.0–2.3). The aluminium saturation index ($ASI = Al_2O_3/(CaO - 1.67P_2O_5 + Na_2O + K_2O)$, molecular; Frost et al., 2001) is generally low. All rocks are metaluminous, with most monzodiorite group samples having ASI = 0.82–0.92 and syenite group samples 0.91–0.99.

In terms of modified alkali–lime index ($MALI = Na_2O + K_2O - CaO$, wt.%, Frost et al., 2001), charnockitic rocks from

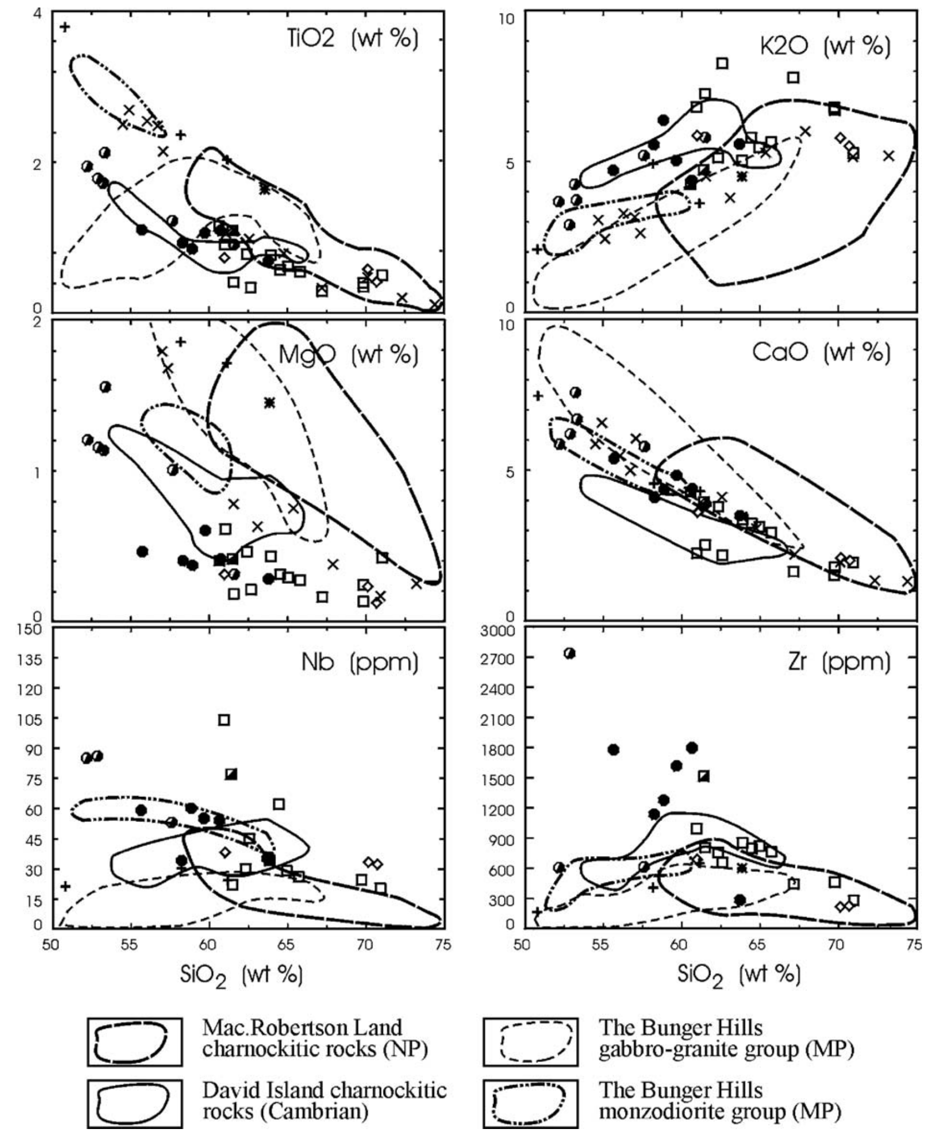

Fig. 3. Selected major and trace element vs. SiO_2 plots showing compositions of the DML charnockitic rocks and the ranges of MRL, the Bunger Hills and David Island charnockitic rocks. Symbols as in Fig. 2.

Insel Massif are alkali-calcic to alkalic (Fig. 4). In terms of Fe-number ($Fe^* = FeO^{tot}/(FeO^{tot} + MgO)$, wt.%, Frost et al., 2001), they are strongly ferroan ($Fe^* > 0.85$; Fig. 5). On a normative Ab–An–Or plot (Fig. 6) most rocks fall within the granite and adamellite fields (after Barker, 1979) and only a few within the granodiorite field. No rocks are tonalitic or trondhjemitic in terms of this diagram. In terms of the charnockite classification recently proposed by Rajesh and Santosh (2004), the Insel Massif charnockitic rocks have distinct compositional differences from both their intermediate (dominantly calc-alkalic and ferroan to magnesian, low K_2O/Na_2O, relatively melanocratic) and felsic (dominantly alkali-calcic and ferroan, high K_2O/Na_2O) charnockites. Thus, the monzodiorite group rocks tend to have higher MALI (Fig. 4) and have much higher Fe* (Fig. 5) than the intermediate charnockite of Rajesh and Santosh (2004); the syenite group rocks tend to have higher MALI and possibly Fe* than both intermediate and felsic charnockites, and some have lower SiO_2 than the latter. Mafic dykes are composed of plagioclase, orthopyroxene and Ti-magnetite; they are slightly alkaline (Fig. 2) and extremely rich in FeO^{tot} (20–30%), P_2O_5 (4–6%), and TiO_2 (1.2–2.1%).

Least-squares mixing calculations (using mineral compositions measured by microprobe) for major components were carried out to test possible fractionation of ferrogabbro to quartz syenite. The composition of a ferrogabbro dyke (41048-9) as the parent magma would produce a liquid similar to fine-grained monzodiorite (41049-1a, presumably a chilled margin) by fractionation of orthopyroxene, clinopyroxene, ilmenite, magnetite, and lesser amounts of plagioclase and apatite. The monzodiorite 41049-1a as a parent would produce a composition similar to a fine-grained syenite (chilled margin 37642-10) by fractionation of clinopyroxene, plagioclase, magnetite, and minor ilmenite, apatite, and possibly orthopyroxene. However, the sums of squares of the residuals were quite large (6.0 and 4.6, respectively), showing that fractionation alone could not have produced the observed compositional variations. In contrast,

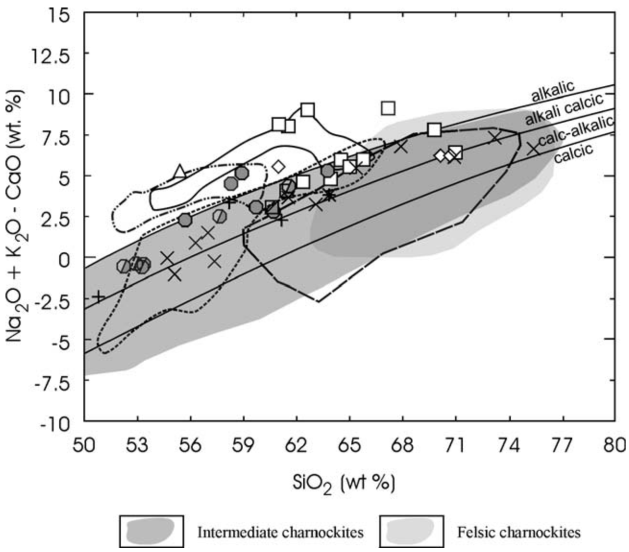

Fig. 4. Na_2O+K_2O-CaO (MALI) vs. SiO_2 (wt.%) plot showing compositions of the DML charnockitic rocks and the ranges of MRL, the Bunger Hills and David Island rocks. Symbols as in Fig. 2. Contours as in Fig. 3. Shaded areas are intermediate and felsic charnockites from Rajesh and Santosh (2004). MALI fields from Frost et al. (2001).

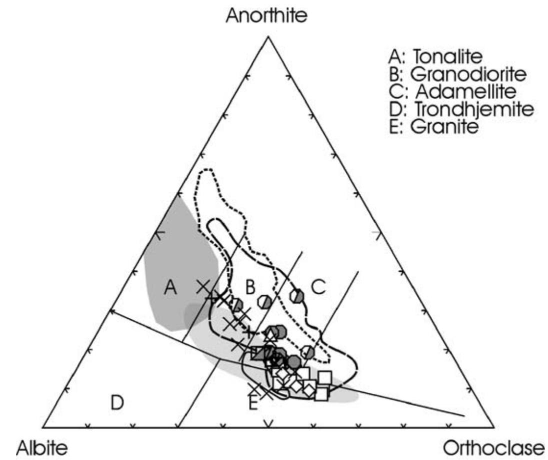

Fig. 6. Normative Ab–Or–An diagram. Granitoid fields after Barker (1979). Symbols and fields as in Figs. 2, 3 and 4.

fractionation of clinopyroxene (2%), olivine (6%), plagioclase (11%), ilmenite (1.3%), and apatite (0.9%) from this syenite (37642-10) would quite accurately (sum of squares = 0.6) reproduce the composition of a coarse-grained quartz syenite (KH18-3) from the inner zone of the pluton. Amphibole was not included in the mass-balance calculations as it was probably not a major primary magmatic phase and is not present in cumulus gabbro layers.

The presence of pyroxene–ilmenite–magnetite–apatite± plagioclase cumulates, which comprise a significant part of the layered gabbroic series, provides support for the proposed fractionation model. The syenite also contains rare mafic layers of similar composition. However, clinopyroxene is much less common than would be predicted from the mixing calculations, so that other factors must also have been involved. Nevertheless, crystal fractionation probably played an important petrogenetic role, and compositional variations within the syenite group can be fairly well modelled by such a process. The source of the charnockites might therefore be ferrogabbro magma similar to the analysed dyke, which is distinctive in being exceptionally Fe-rich and slightly alkaline.

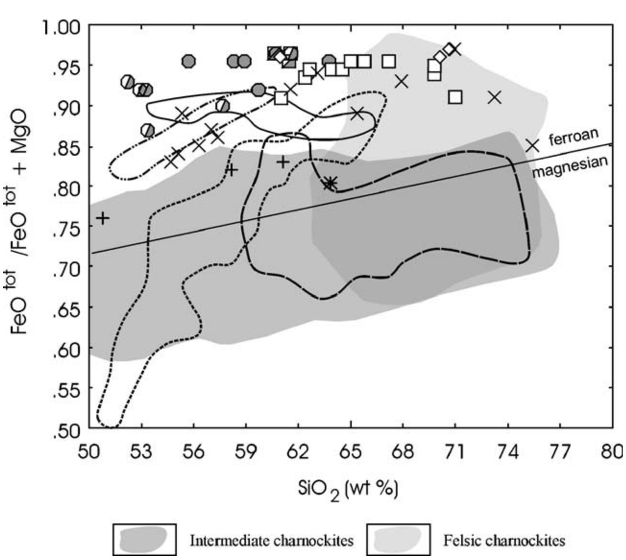

Fig. 5. $FeO^{tot}/FeO^{tot}+MgO$ (Fe*) vs. SiO_2 (wt.%) plot (Frost et al., 2001) showing compositions of the DML charnockitic rocks and the ranges of MRL, the Bunger Hills and David Island rocks. Symbols as in Fig. 2. Contours as in Fig. 3. Shaded areas are intermediate and felsic charnockites from Rajesh and Santosh (2004).

It is noteworthy that the chilled margin of the pluton (a syenite group rock) is compositionally quite similar to many monzodiorite group rocks (Figs. 2–3). However, monzodiorite group rocks tend to have higher K/Rb and somewhat lower Ti/P than the syenite group, and there is little correlation between *mg* value and SiO_2 (plot not presented), suggesting that not all these rocks are strictly co-magmatic, and that other factors, such as a range of source and/or parent magmas and perhaps different degrees of melting, were clearly involved. On an AFM plot (Fig. 7) they apparently form a tholeiitic trend, although there may be a compositional gap between the gabbroic and charnockitic groups.

Spidergram patterns of most syenite group rocks are highly fractionated, with large negative Sr, P, and Ti anomalies, relatively small Nb anomalies, and positive Zr anomalies (Fig. 8). However, one sample of syenitic composition (KH26-9) is much less fractionated, having no significant Nb, Ta, or Sr anomalies. In contrast, two granitic (s.s.) samples show particularly irregular patterns (except for smaller Zr anomalies), which, together with strong Ba depletion, suggest more extensive crystal fractionation. Their much higher Th, U, and Th/U (20–28) than the other syenite group rocks (average Th/U ratio of 4 samples is 4.4) might reflect the mobility of these elements in volatile-rich fluids. The spidergram patterns of the granites appear to be more consistent with extensive fractional crystallisation of a ‘syenitic’ parent magma than derivation from a distinct source region, and much of the compositional variations of the syenitic rocks may well be due

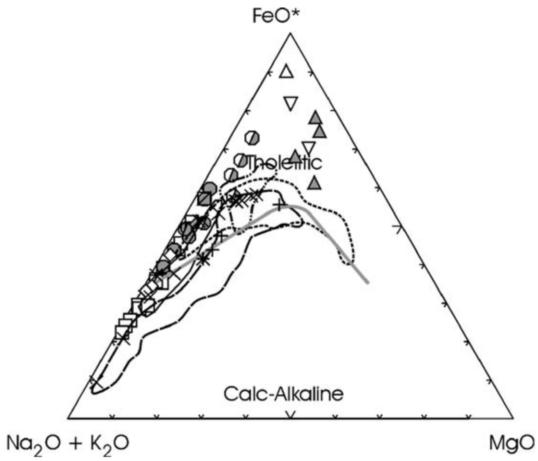

Fig. 7. Total alkalis–total Fe–MgO (AFM) diagram showing compositions of the DML charnockitic rocks and the ranges of MRL, the Bunger Hills, and David Island rocks. Symbols and fields as in Figs. 2 and 3. Tholeiitic–calc-alkaline divider line after Irvine and Baragar (1971).

to such a process. The monzodiorite group shows generally similar, but somewhat less fractionated, patterns to the syenite group rocks, consistent with derivation from broadly similar source(s).

REE patterns (Fig. 9) are mostly smooth and only moderately fractionated ($(La/Yb)_n$ 7–11), generally with no significant Eu anomaly, but the two granites have highly

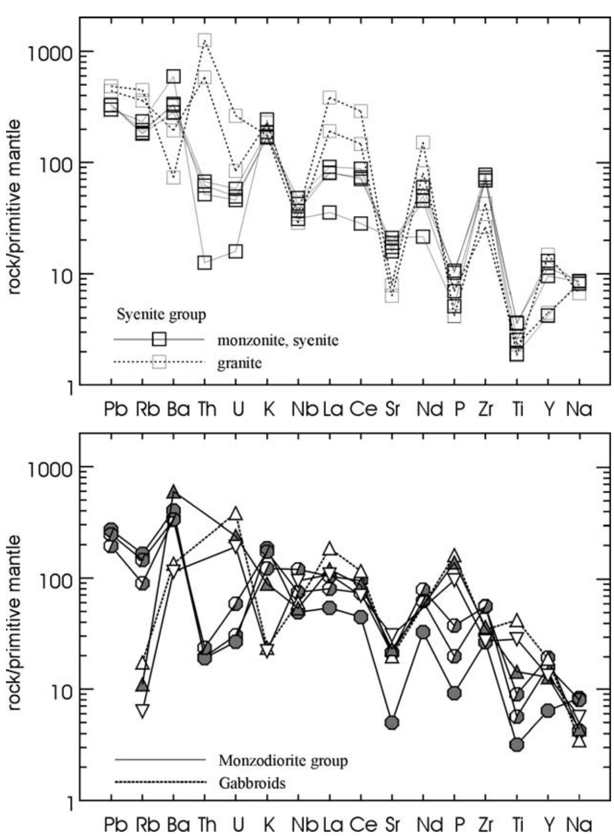

Fig. 8. Primitive mantle-normalized incompatible-element abundances diagrams for the Insel Massif charnockitic and spatially associated rocks. Symbols as in Fig. 2. Normalization values from Sun and McDonough (1989).

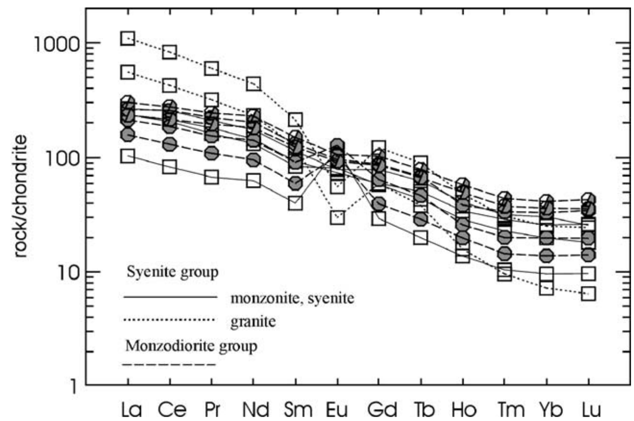

Fig. 9. Chondrite-normalized REE abundances diagram for the Insel Massif charnockitic rocks. Symbols as in Fig. 2. Normalization values from Sun and McDonough (1989).

fractionated patterns ($(La/Yb)_n$ 44, 78) with negative Eu (and Sr) anomalies. These features suggest at least some variation in source composition for the syenitic group, and probably somewhat different histories of magmatic evolution and/or crystallisation.

We analysed 6 charnockitic rocks (5 syenite group and one monzodiorite group sample), and 5 anorthosites for Rb–Sr isotopes, and 3 charnockitic rocks for the Sm–Nd isotopes (Table 3). Three charnockites from the Eck-Hörner Ridge, where country rock rafts are abundant, have very high $^{87}Sr/^{86}Sr$, and plot well above the reference line defined by the other data points (Fig. 10). These rocks are relatively depleted in Sr, so that metasomatic interaction with rafts of metamorphic rocks, which are abundant in this part of the massif, resulting in increased $^{87}Sr/^{86}Sr$, may have occurred. The other three charnockitic rocks were collected from other part of the massif (SW Insel Mountains), where country rock xenoliths are lacking. These three charnockitic rocks and three of five anorthosites plot along a five-point reference line (514 ± 59 Ma, $Sr_i = 0.7071 \pm 0.0013$) reported by Ravindra and Pandit (2000) from the Insel Massif. The other two anorthosites are relatively depleted in Sr and enriched in Rb, their somewhat elevated $^{87}Sr/^{86}Sr$ suggesting a crustal component. A reference line drawn through 11 points (including the five samples of Ravindra and Pandit, 2000) yields an age of 523 ± 22 Ma ($Sr_i = 0.7069 \pm 0.0013$) which is in quite good agreement with the U–Pb zircon age of ca 510–505 Ma reported by Mikhalsky et al. (1997). It is important to note that these charnockitic rocks and anorthosites plot on the same isochron, implying a broadly co-genetic origin, or, at least, similar sources. A mantle source would seem more likely than a crustal one, although the relationships between anorthosite and charnockite are not fully understood.

Sm–Nd isotopic compositions of the Insel Massif charnockites ranges widely ($T_{DM} = 1010–1643$ Ma; $\varepsilon_{Nd}(T) = -2.32 – +4.34$). The highest $\varepsilon_{Nd}(T)$ value obtained for the contact (chilled margin) syenite group rock.

Insel Massif charnockitic rocks have a wide compositional range, but nevertheless consistently demonstrate many features in common with those of some granitoids (A-type of Collins et al., 1982; Whalen et al., 1987), such as high $Na_2O + K_2O$, Zr,

Table 3
Rb–Sr and Sm–Nd isotope data for the Insel Massif charnockitic rocks and the Eck-Hörner Ridge anorthosites

N	Sample ID	Lithology	[Rb]	[Sr]	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{8}6Sr$	2σ	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ
1	41049-6	Syenite group, chilled margin	108.2	195.4	1.60357	0.749241	26	0.14221	0.512678	11
2	37620-1	Syenite group	67.13	42.61	4.61204	0.759412	16	0.13647	0.512318	9
3	41049-2	Monzodiorite group	41.2	34.56	3.45243	0.748271	24	0.12056	0.512442	10
4	KH18-1	Syenite group	121.1	395.2	0.88710	0.713891	23			
5	KH18-2	Syenite group	122.9	340.9	1.04370	0.715060	15			
6	KH18-3	Syenite group	126.6	368.4	0.99490	0.714616	30			
7	KH29-4	Anorthosite	14.97	1475	0.02938	0.706826	26			
8	KH29-2	Anorthosite	25.31	1353	0.05394	0.706941	20			
9	KH48-10	Anorthosite	57.5	1184	0.14060	0.707672	23			
10	KH48-03	Anorthosite	139.3	916.5	0.44000	0.711557	25			
11	KH48A-12	Anorthosite	142.8	865	0.47790	0.711831	22			

Ns 1–3 analysed in the Institute of Precambrian Geology and Geochronology (St Petersburg, Russia), analyst B. Beliatsky; Ns 4–11 analysed in the Geoforschungszentrum (Potsdam, Germany), analyst H. Gerstenberger.

Nb, Y, Zn, Fe/Mg, and Ga/Al. They fall well outside the fields of M, I, and S-type granitoids on the discrimination diagrams of Whalen et al. (1987) (not presented), and could thus be classified as A-type rocks (Jacobs and Thomas, 2002; Roland, 2004), although CaO and Sr are less depleted than in typical A-types. The Insel Massif charnockites are commonly rich in amphibole and biotite, which in many cases completely replace primary orthopyroxene, and rock textures indicate early crystallisation of minor amphibole. The abundance of such hydrous phases reflects relatively high volatile (H_2O, F, etc.) activity, which appears to be a significant factor in generation of many granitic magmas, including A-types (Collins et al., 1982; Whalen et al., 1987; Keppler, 1993).

Many of the compositional features of the Insel Massif charnockites could theoretically be explained by high-temperature partial melting of an essentially anhydrous granulite-facies source which had previously been depleted by extraction of near-minimum calc-alkaline magmas (Collins et al., 1982; Whalen et al., 1987). Accessory minerals such as zircon are more soluble in high-temperature melts (Watson and Harrison, 1983), which would produce high HFSE concentrations. However, in view of the relatively low-SiO_2 compositions (monzonite–quartz syenite) of most Insel Massif rocks, any lower-crustal source region would need to have been of quite mafic composition. Mafic lower crustal rocks were proposed by Rajesh and Santosh (2004) as the source of charnockites of southern India, through partial melting under a range of water activities.

Another plausible model is the generation of charnockitic magma through extensive crystal fractionation of a mantle-derived melt. The Sm–Nd isotopic compositions of the Insel Massif charnockitic rocks (high $\varepsilon_{Nd}(T)$ up to +4.34 for the chilled margin syenite group rock), suggest a mantle source. The relatively low initial $^{87}Sr/^{86}Sr$ (Sr_i) ratio (0.7069) is consistent with such an origin. The compositional trends (e.g., AFM, Fig. 7) are consistent with fractionation of a mafic parent magma, which was probably Fe-rich, taking into account the composition of spatially associated mafic dykes. The occurrence of cumulus layers within the syenite group rocks, high P_2O_5 (up to 1.5%) and Zr (up to 2700 ppm) abundances in some more mafic (monzodiorite group) rocks, and the progressive decrease in crystallization temperature (Markl and Henjes-Kunst, 2004) support a significant role for crystal fractionation, and thus involvement of mantle, rather than lower crustal, source(s). The prominent negative Sr anomalies of most (but not all) samples are consistent with extensive fractional crystallisation of mantle-derived magma, although melting of a (relatively mafic) lower-crustal source with residual plagioclase would produce similar patterns. The granite samples show evidence for even greater degrees of fractionation.

The origin of the extreme Fe-enrichment (or, more strictly, MgO depletion), which characterises alkaline granitic magmas, is unclear. Although important, fractionation alone seems an inadequate explanation, particularly as there is commonly only a poor correlation between SiO_2 and *mg* (cf., Sheraton et al., 1992), and even the least-evolved rocks have low MgO (Fig. 2). Separation of a highly magnesian phase or phases must have occurred at some stage of their evolution, but whether this took place in the mantle or lower crust is uncertain. Both source composition and fluid activities are likely to have been important (Frost et al., 2001). The nature and composition of the source region(s) are thus difficult to decipher. It is possible

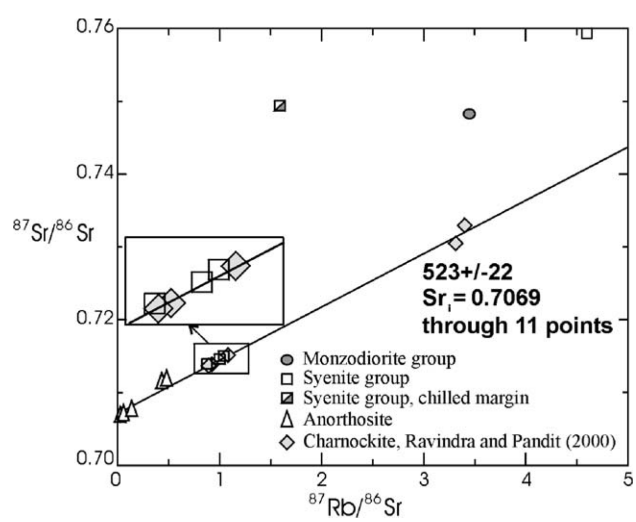

Fig. 10. Rb–Sr isochron diagram for the Insel Massif charnockitic rocks and anorthosites.

that the Insel Massif syenitic rocks represent mixtures of mantle-derived mafic magma and a more felsic crustal component. Indeed, many A-type granites may represent mixtures of mantle and crust-derived components, with either being predominant in particular cases (Eby, 1990; Kerr and Fryer, 1993). That the Insel Massif charnockitic rocks may also include a significant crustal component is evident from the isotopic data (Sr_i 0.75–0.76, Table 4). A similar origin was proposed by Zhao et al. (1995) for c. 520 Ma clinopyroxene± orthopyroxene-bearing syenites from the Yamato Mountains of eastern DML and by Sheraton et al. (1996) for 984±12 Ma syenitic rocks from Mount Collins (MRL). We therefore consider it is likely that at least some of the Insel Massif charnockites were derived from mantle melts, and that fractionation played an important role in their petrogenesis. However, derivation from the lower crustal sources may not be excluded assuming the crust was relatively young.

Charnockitic rocks from other plutons in the central DML (Muhlig Hofmann Mountains, Orvinfjella and Petermann Ranges) have basically similar chemical compositions to the Insel massif rocks, which is best reflected in high Fe* values (Fig. 5). However, a group of predominantly monzodioritic rocks some of which represent an earlier magmatic phase have somewhat lower Na, K, Nb, Zr, Fe* and higher MgO, TiO_2. These rocks may represent more primitive, less fractionated magma batches or derivates from somewhat different sources.

Table 4
A comparison of major geological and geochemical features of the charnockitic rocks from different areas of East Antarctica

	Central Dronning Maud Land	Mac. Robertson Land	The Bunger Hills (gabbro–granite)	David Island
Major lithologies	Monzodiorite, Qtz monzonite, syenite	Qtz monzonite, granodiorite, granite	Qtz monzogabbro, minor Qtz monzonite, granite	Qtz monzonite, syenite, granite
Age	510–505 Ma[1]	980 Ma[2]	1170 Ma[3]	515 Ma[3]
Preceding high-grade metamorphic age	570–530 Ma[4]	1000 Ma[5]	1190 Ma[3]	Event not known
P–T evolution path	Decompression	Isobaric cooling	Isobaric cooling	Not determined
Pluton deformation	None	Strong	Strong	None
Associated basic rocks	High-Fe–Ti, mildly alkaline gabbroids, anorthosite	Not known	Tholeiitic gabbro	Not known
SiO_2	58.3–70.1	58.9–73.8	52.6–66.7	54.00–65.70
K_2O	3.0–8.0	1.5–6.5	0.8–5.6	4.50–6.70
Zr	300–2000	120–870	220–600	520–1080
Nb	20–104	2–43	4–30	25–51
10^4 Ga/Al	2.9–4.7	1.7–2.9	2.0–2.8	2.2–3.2
Ce/Y	1.8–2.9	2.4–18.2	1.6–3.0	4.5–26.3
ASI	0.79–1.04	0.82–1.13	0.82–0.98	0.86–0.96
$(La/Yb)_N$	6.6–12.0; 78.0	13.4–28.7	6.8–16.7	20.0–137
Sr_i	0.7074–0.7075; 0.7259–0.7376	0.7063–0.7334[2,7,8]	0.7091–0.7144[6]	0.7111–0.7122[3,6]
ε_i^{Nd}	−2.3–+4.3	−11.1–−0.2[2,7,8]	−9.4[6]	−13.1; −14.4[3,6]
Fe*	0.80–0.95	0.50–0.75	0.50–0.90	0.87–0.92
mg (Hbl)	8–13	25–53	26–39	No data
mg (Cpx)	13–16	no data	37–67	22–27
mg (Opx)	10–35	35–45	20–56	15–19

$Fe^*=FeO^{tot}/FeO^{tot}+MgO$, wt.%; $mg=100Mg/(Mg+Fe^2)$. MC — Mawson Coast.
Age and isotopic data sources: [1]Mikhalsky et al. (1997), [2]Kinny et al. (1997), [3]Sheraton et al. (1996), [4]Jacobs et al. (1998), [5]Tingey (1991), [6]Sheraton et al. (1993), [7]Zhao et al. (1997), [8]Young et al. (1997).

3. Neoproterozoic charnockites of Mac.Robertson Land

3.1. Geological features

Orthopyroxene-bearing granitoids are also widespread in Mac.Robertson Land (MRL: Fig. 1), particularly in the Mawson Coast and Northern Prince Charles Mountains (NPCM) where they cut mainly late Mesoproterozoic (c. 1000 Ma) granulite-facies metamorphic rocks (Young and Black, 1991; Young and Ellis, 1991; Kilpatrick and Ellis, 1992; Sheraton et al., 1996; Zhao et al., 1997). In Princess Elizabeth Land early Palaeozoic granitic rocks are quite common (Sheraton et al., 1996), but how many of them are charnockites is not clear. However, charnockitic rocks are reported from the regions further east, in the Mirnyy Station area, at David Island, the Bunger Hills and Windmill Islands.

A typical example of a charnockite pluton is the Loewe Massif–White Massif batholith, which crops out over an area of about 300 km^2 in the NPCM, and has given an ion-microprobe U–Pb zircon age of 980±21 Ma (Kinny et al., 1997). It is compositionally varied and has large-scale compositional layering. It generally has deformed contacts, is cut by mafic granulite dykes, and contains lenses of mafic granulite which probably also represent deformed dykes. The most melanocratic rocks comprise quartz monzonite or quartz monzodiorite, containing reddish-brown biotite (*mg* 63–66; up to 4%), greenish-brown potassian ferroan pargasitic hornblende (*mg* 49–53; 2–4%), orthopyroxene ($Ca_2Mg_{42-45}Fe_{53-56}$; 4–6%), quartz, andesine antiperthite (An_{34-42}), orthoclase perthite, and minor clinopyroxene, ilmenite, magnetite, apatite, and zircon (mineral composition from Sheraton et al., 1996). Granite (s.s., grading into granodiorite) is more abundant, and contains biotite (*mg* 50–52; up to 1%), orthopyroxene ($Ca_{0.5}Mg_{40}Fe_{59}$; 1–4%), and more sodic plagioclase (oligoclase–sodic andesine), but little or no hornblende or clinopyroxene. The rocks are locally foliated and partly recrystallised to granoblastic interlobate textures, and orthopyroxene is commonly partly replaced by biotite or iddingsite. Biotite and amphibole in this batholith are relatively F-rich (1.67–3.44% and 0.84–1.82%, respectively). Some intrusions have slightly more Fe-rich mafic minerals (e.g., orthopyroxene *mg* 35, biotite *mg* 28–30, hornblende *mg* 25–28), but much less so than those in Insel Massif charnockites. Garnet is present in some intrusions.

3.2. Geochemistry

In terms of a granite classification of Frost et al. (2001), most MRL charnockitic rocks are magnesian (Fe* 0.65–0.85 for most samples, Fig. 5), and have highly variable MALI, with most rocks being calc-alkalic or alkali-calcic, with a few calcic (Fig. 4). They cover a wide range of SiO_2 compositions (60–75%), although less so than Insel Massif charnockitic rocks (Fig. 2). As compared with the latter, the MRL rocks are generally poorer in alkali components. On a normative Ab–An–Or diagram (Fig. 6) these rocks mostly plot within the granodiorite–granite fields (Barker, 1979) and only a few in the tonalite field. The rocks are mostly metaluminous (ASI < 1.0) with some rocks slightly peraluminous (ASI up to 1.04), but a few high-SiO_2 rocks have ASI up to 1.14. Thus, the MRL rocks have generally somewhat higher ASI than the Insel Massif charnockitic rocks.

Sheraton et al. (1996) recognised two charnockite groups in the NPCM: low-SiO_2 (58.9–62.1%) and high-SiO_2 (66.2–74.0%). The former group includes quartz monzonite and relatively melanocratic granite (s.s.), whereas the latter group comprises orthopyroxene granite and minor granodiorite. The co-eval Mawson Coast charnockites also have a wide compositional range with similar chemical features, apart from somewhat lower Na_2O, Ba, and Sr, and higher MgO (Young and Ellis, 1991). All the analysed MRL charnockites (Sheraton, 1982; Sheraton et al., 1996; Zhao et al., 1997; Young et al., 1997) form generally coherent trends on most major and trace-element plots, and differ from Insel Massif charnockites most notably in their higher MgO, CaO, and lower K_2O (Fig. 3). MRL charnockites lack the Or-rich, Qtz-poor compositions of those from Insel Massif. Certain trace element ratios are also quite different (e.g., 10,000 Ga / Al 1.7–2.9; Nb / La 0.15–0.48; Rb / Ba 0.06–0.30). The K_2O/Na_2O ratio ranges from 0.74 to 2.00 (average 1.65), with the low-SiO_2 rocks being less potassic (average $K_2O/Na_2O = 1.14$) than the high-SiO_2 rocks ($K_2O/Na_2O = 1.78$). Isotopic ratios range widely: Sr_i 0.7063–0.7100 (NPCM) and 0.7076–0.7334 (Mawson Coast); $\varepsilon_{Nd}(T)$ -59.9–-2.9 (NPCM) and -11.1– -4.0 (Mawson Coast) (Zhao et al., 1997; Young et al., 1997).

In terms of the charnockite classification of Rajesh and Santosh (2004), the MRL charnockitic rocks appear to have many features in common with both their intermediate and felsic charnockites. The low-SiO_2 group is more akin to the former, but is somewhat more potassic; the high-SiO_2 group is generally more magnesian than the felsic charnockites. On an AFM diagram, the MRL charnockitic rocks define a continuous calc-alkaline trend (Fig. 7).

Spidergrams for the low-SiO_2 group show significant negative Nb, Sr, P, and Ti anomalies and little or no Y depletion (Fig. 11); high-SiO_2 granites have larger Nb, P, and Ti anomalies, but Sr anomalies are similar or even smaller and most samples are Y-depleted. Sheraton et al. (1996) suggested that the relatively mafic low-SiO_2 group originated by fractionation of mantle-derived parent magma, although this may have tended towards an intermediate (e.g., monzodioritic), rather than mafic, composition (cf. Stern and Hanson, 1991). If so, their marked negative Sr anomalies would imply significant feldspar fractionation. Another model was proposed by Zhao et al. (1997), who suggested that the charnockitic rocks of the NPCM were generated by high-temperature, water-deficient, decompression melting of dehydrated, Nb-depleted, but not melt-depleted granulitic lower crust during post-collision thermal relaxation and uplift. These authors also assumed mixing of subducted sediments with upper mantle material via metasomatism during previous crust formation events. However, partial melting of mafic to intermediate granulite-facies crustal rocks (Young and Ellis, 1991; Kilpatrick and Ellis, 1992; Zhao et al., 1997) would require a very large, and possibly unrealistic, heat input, as relatively ‘dry’ melting is implied.

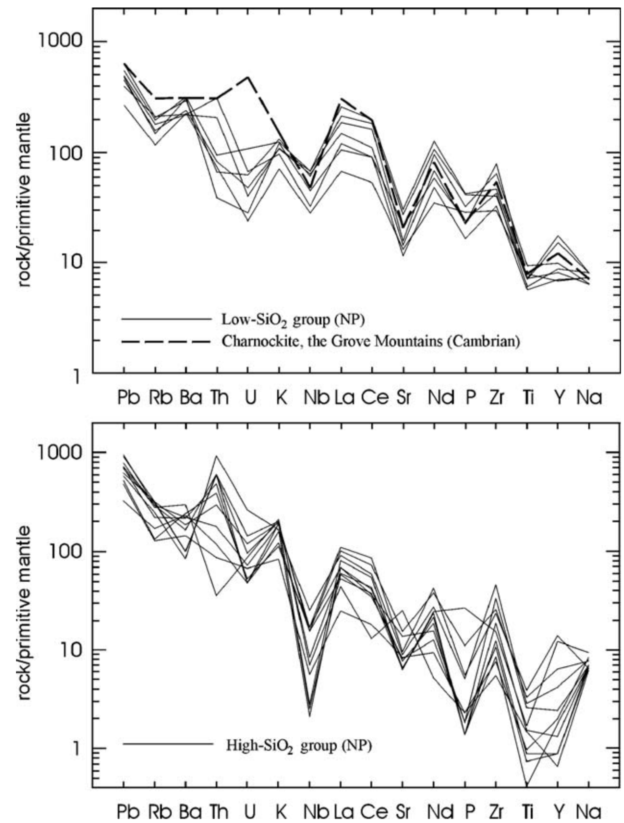

Fig. 11. Primitive mantle-normalized incompatible-element abundances diagrams for the MRL charnockitic rocks and the Grove Mountains charnockite. Normalization values from Sun and McDonough (1989).

Sheraton et al. (1996) suggested that the high-SiO_2 rocks represent a distinct magma type, produced by high-degree, high-temperature melting of dry intermediate to felsic lower crustal rocks, with variations in the amount of residual garnet. Although they plot on similar trends on most variation diagrams, it is unlikely that the high-SiO_2 charnockites could have been derived by fractionation of low-SiO_2 magma, because their *mg* values are similar and their Sr (and Eu) anomalies are no larger (and in some cases are smaller: Fig. 11), precluding feldspar-dominated fractionation. Moreover, their Y depletion could only be explained by major clinopyroxene and/or hornblende fractionation, which is inconsistent with the relatively small change in ASI. Similar compositional features of the Mawson Charnockite on the Mawson Coast of MRL were taken by Young et al. (1997) to imply melting of thickened crust in an Andean or Himalayan-type plate margin. These authors distinguished a specific low-Ti charnockitic group with geochemical features transitional between "normal" high-Ti charnockites and calc-alkaline granitoids, which was attributed to variations of melting temperature. Kilpatrick and Ellis (1992) pointed out that the very high-temperatures (~1000 °C) required to produce such charnockitic magmas can be attained in granulite terranes, although a major heat input, such as emplacement of mantle-derived magma near the base of the crust, would clearly be necessary.

Sheraton et al. (1996) proposed that the two MRL charnockite groups may represent parts of a continuum from a largely mantle-derived mafic-intermediate end member to a predominantly crust-derived felsic one. Nevertheless, relatively evolved Sr_i and $\varepsilon_{Nd}(T)$ imply significant crustal components in both low-SiO_2 and high-SiO_2 granitoids (Zhao et al., 1997). Similarly, all subgroups of the Mawson Charnockite have evolved isotopic compositions (Young and Ellis, 1991; Young et al., 1997).

4. Mesoproterozoic and Cambrian charnockites of the Bunger Bills area

4.1. Geological features

A compositionally diverse (gabbro–granite), locally deformed group of charnockitic plutons intrude 1190 ± 15 Ma granulite-facies metamorphic rocks in the Bunger Hills area of Wilkes Land (Fig. 1) (Klimov et al., 1964; Sheraton et al., 1993, 1995). The largest pluton extends over an area of at least 300 km^2, and most are composed of orthopyroxene-bearing quartz gabbro, monzogabbro, quartz monzodiorite, quartz monzonite, and granite (gabbro–granite group). These rocks gave an age of 1170 ± 4 Ma. Most rocks contain biotite–hornblende–clinopyroxene–orthopyroxene as rock-forming minerals. Quartz monzogabbro forms a geochemically coherent suite with associated gabbro and quartz gabbro, and is therefore considered to have been derived by fractionation of tholeiitic mafic magma (Sheraton et al., 1992). Minerals (Sheraton et al., 1992) in the most evolved rocks (granite) are relatively Fe-rich (orthopyroxene *mg* 20–34, clinopyroxene *mg* 45, hornblende *mg* 26–39, biotite *mg* 27), but still markedly less so than Insel Massif charnockites. A compositionally distinct pluton of hornblende–clinopyroxene–orthopyroxene quartz monzodiorite and quartz monzonite (monzodiorite group) gave a younger age (1151 ± 4 Ma, Sheraton et al., 1992).

Alkaline felsic rocks (two-pyroxene–hornblende or biotite–hornblende syenite, quartz monzonite, granite) form a large (more than 120 km^2) pluton on David Island (west of Denman Glacier). These rocks were dated at 516 ± 1.5 Ma (Sheraton et al., 1992). Poikilitic aggregates of hornblende + quartz ± biotite are present in some rocks, suggesting replacement of primary pyroxene. The accessory minerals (apatite, zircon, allanite, chevkinite or perrierite) are notably abundant.

4.2. Geochemistry

These rocks have a wide compositional range (Figs. 2–3), generally overlapping with those of MRL charnockitic rocks, but differing in having much higher proportions of mafic and intermediate compositions and fewer felsic (SiO_2 > 63%) rocks. All rocks are metaluminous (ASI 0.80–0.96).

The gabbro–granite group rocks are calc-alkalic to alkali-calcic and ferroan to magnesian in terms of the classification of Frost et al. (2001), and have ASI mostly in the range 0.80–0.96 (excluding quartz gabbro) and K_2O/Na_2O 0.80–2.85. In both the TAS (Fig. 2) and SiO_2 vs. Fe* (Fig. 5) diagrams these rocks form coherent trends which were attributed by Sheraton et al. (1992) to extensive crystal fractionation. The monzodiorite group rocks are mainly alkalic and ferroan, with ASI 0.83–0.93 and K_2O/Na_2O 0.93–1.72. They are distinctive in having, for a given SiO_2 content, higher TiO_2, FeO, K_2O, P_2O_5, Zr, Nb, and Y, and lower MgO and CaO than the gabbro–granite group (Sheraton et al., 1992). The gabbro–granite group can probably be correlated with the intermediate charnockite type of Rajesh and Santosh (2004), but the monzodiorite group differs in its much higher MALI and Fe* (mostly 0.55–0.85) (Figs. 4–5).

On a normative Ab–An–Or diagram (Fig. 6) the more siliceous charnockitic rocks (monzonite to granite) plot mostly within the granodiorite–granite fields (after Barker, 1979), whereas the more mafic rocks (quartz gabbro, monzogabbro) plot within the tonalite and granodiorite fields. On an AFM diagram (Fig. 7), most Bunger Hills rocks form a transitional calc-alkaline to tholeiitic trend, but with far less pronounced Fe-enrichment than the Insel Massif charnockitic rocks.

Spidergrams of the gabbro–granite group rocks are generally similar (Fig. 12), although absolute abundances of most elements increase with fractionation (Sheraton et al., 1992). Most rocks are enriched in LILE and LREE, have prominent negative Nb and Sr anomalies, Th and U troughs, and somewhat elevated Zr. It has long been considered that negative Nb anomalies are characteristic of subduction-related magmatism, and that metasomatic enrichment of the subcontinental lithosphere in LILE and LREE, ultimately derived by partial melting or dehydration of subducted oceanic crust (with sedimentary component), could produce the required Nb-poor source (e.g., Sun and McDonough, 1989, and references therein). Metasomatic enrichment is indicated by relatively high Sr_i = 0.7091–0.7144, and low $\varepsilon_{Nd}(T)$ of −9.4 (Sheraton et al., 1992, 1993). Even the more felsic rocks of the Bunger Hills plutons (orthopyroxene-bearing quartz monzonite and granite) have very similar trace-element characteristics, suggesting a predominantly mantle origin.

The monzodiorite group rocks were apparently derived from a much more Nb-rich source as indicated by the absence of significant Nb anomalies on the spidergrams (Fig. 7). These rocks have lower degrees of LILE enrichment, more primitive Sr_i (0.7074–0.7082) and $\varepsilon_{Nd}(T)$ (−3.5), and higher MALI, and Fe* (0.80–0.90), which imply derivation from a quite different source. The Nb-rich compositions of these rocks may indicate involvement of a source similar to that of ocean-island basalts (OIB) (Sheraton et al., 1992, 1995).

The c. 515 Ma syenitic to granitic rocks of David Island are chemically quite different from the Bunger Hills plutons. Compared to the latter, they have higher Al_2O_3, Na_2O, K_2O, LREE, and many LILE and HFSE abundances, but lower FeO,

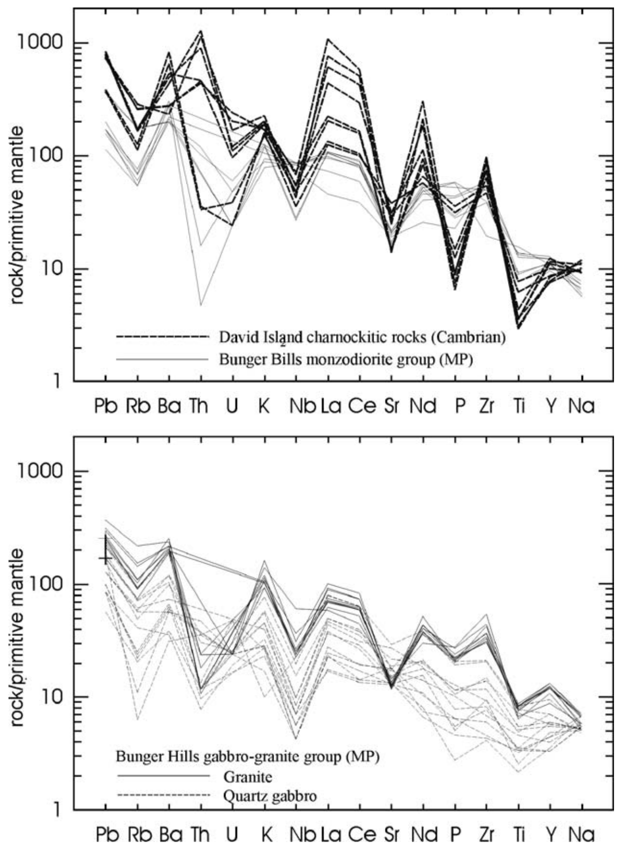

Fig. 12. Primitive mantle-normalized incompatible-element abundances diagrams for the Bunger Hills and David Island charnockitic rocks. Normalization values from Sun and McDonough (1989).

MgO, CaO, P_2O_5, Cr, Ni, V, and Cu. In terms of the classification of Frost et al. (2001), these rocks are highly alkalic (Fig. 4), ferroan (Fe* > 0.85, Fig. 5), and metaluminous (ASI 0.86–0.96). David Island rocks have very high Ba (1600–5700 ppm) and LREE (Ce up to 1020 ppm); K_2O/Na_2O is 1.2–1.7, 10 000 Ga/Al 2.2–3.2, Nb/La 0.06–0.37, Rb/Ba 0.01–0.11, and Rb/Sr 0.10–0.62.

The highly irregular spidergrams (Fig. 12) and highly fractionated REE patterns of the David Island pluton are consistent with fractionation of clinopyroxene, orthopyroxene, plagioclase, and potassium feldspar, with involvement of apatite and a Ti-oxide phase (Sheraton et al., 1992). However, these authors concluded that the considerable compositional scatter precludes fractionation being the only process involved, and different degrees of melting were probably an important factor. Some of these rocks (monzonites) were suggested to have originated from a presumed mantle-derived melt, while others (syenite–granite) may have a more significant crustal component. The isotopic compositions of these rocks are rather "evolved": $Sr_i = 0.7111–0.7122$ and $\varepsilon_{Nd}(T) = -13$–$-14$. However, it is unclear whether these features reflect crustal or long-term enriched mantle composition. Thus derivation of these rocks by melting of lower-crustal rocks, fractionation of enriched mantle melts, or both, are equally plausible.

The gabbro–granite intrusives of the Bunger Hills have broadly similar geochemical features to the MRL charnockites, albeit with a much higher proportion of mafic-intermediate compositions, reflected in largely overlapping fields in most variation and discrimination plots (Figs. 2–6). In contrast, the monzodioritic group and the syenitic rocks of David Island have many features in common with the Insel Massif charnockitic rocks (high Fe*, LILE, HFSE, low mineral phase *mg*). The irregular (strongly fractionated) spidergram patterns of the David Island rocks are very similar to those of Insel Massif charnockites. However, the David Island rocks differ in having considerably higher LREE, reflecting higher accessory phase abundances.

5. Tectonic setting

The DML, MRL, and Bunger Hills area charnockite suites all comprise a wide range of lithologies and compositions. Although many element abundances are similar, there are systematic differences, particularly in less siliceous rocks. The MRL and most Bunger Hills rocks (gabbro–granite) are of "calc-magnesian" type (a term suggested by Frost et al., 2001 to describe calc-alkaline or I-type granites), whereas Insel Massif (DML) charnockites are alkalic and ferroan, and have many geochemical features in common with those of alkaline (A-type) granitoids: notably high K_2O, Zr, Ga, Fe*, and Ga/Al, and very low MgO, implying derivation from quite different parent melts. David Island intrusives have broadly similar chemical features to the DML rocks, as has the quartz monzodioritic to quartz monzonitic suite from the Bunger Hills, although the latter has some transitional features between the DML and Bunger Hills gabbro–granite plutons (e.g., Fe*, HFSE). On the other hand, the lower-K, higher-Mg early phase monzodioritic rocks from the DML (apart from the Insel Massif) have geochemical features transitional between the Insel Massif and the MRL–Bunger Hills charnockitic rocks.

The major compositional differences between the two distinct charnockite groups are well shown by the discrimination diagrams (not presented) of Pearce et al. (1984a,b), Batchelor and Bowden (1985), Whalen et al. (1987), Maniar and Piccoli (1989) on which the DML charnockites generally plot in "A-type" fields, whereas MRL and most Bunger Hills rocks are more akin to "orogenic" types. The latter group comprises the more typical orthopyroxene-rich charnockitic rocks, including the Indian examples described by Rajesh and Santosh (2004). The applicability of trace element compositions to tectonic environments is debatable, and Frost et al. (2001) postulated that the trace element compositions of granitoids are functions of the source and crystallization history of the melt rather than of tectonic setting. However, while the observed major differences in the trace element compositions of Antarctic charnockitic rocks must partly reflect differences in source composition and/or crystallization history, they may also, to some extent, reflect the nature and evolutionary history of the host tectonic terrane in which appropriate source rocks were formed.

To what extent, then, can these compositional features be related to the tectonic environment during emplacement? In this connection, it is important to decipher the main geological features of the tectonic terranes under study. Central DML is generally regarded as a late Neoproterozoic to early Palaeozoic ('Pan-African') continental collision zone (e.g., Paech, 1997; Jacobs et al., 1998), which experienced extensive crustal thickening and subsequent decompression (Piazolo and Markl, 1999; Harley, 2003). The protolith crustal residence ages as evidenced by Sm–Nd two-stage model ages (T_{DM2}) are 1700–1000 Ma (Jacobs et al., 1998; EVM, unpublished data). The crystallisation ages of metamorphosed volcanic rocks and syn-tectonic granites were determined at c. 1130 and 1080 Ma, respectively, contemporaneous with high-grade metamorphic zircon growth (Jacobs et al., 1998). These late Mesoproterozoic rocks have relatively high initial ε_{Nd} values (−4–+7), suggesting that their magmatic precursors represent variable mixtures of primitive mantle-derived and continental crustal components generated within a mature island arc; however, the geochemical features indicate a significant proportion of within-crust melts (Mikhalsky and Jacobs, 2004). Mafic metamorphic rocks are not abundant and form rare, relatively thin (not exceeding 200–300 m) members, which may be volcanic piles or subvolcanic intrusions, or form part of layered bimodal suite (Paech, 1997; EVM, unpublished data). Ultramafic rocks which might represent ophiolite complexes and lithologies which might be attributed to a subduction-related environment are generally lacking, although small mafic/ultramafic boudins within felsic gneiss in the Schirmacher Oasis may be very tentatively considered as ophiolites. Thus, juvenile material of this age is apparently not abundant in central DML and this terrane probably represents a collisional, rather than an accretional, orogen (e.g., Fitzsimons, 2000; Jacobs and Thomas, 2004). It probably underwent major thermal reworking in the late Mesoproterozoic, resulting in crustal anatexis and granite emplacement, which strongly modified bulk compositions, but key isotopic features were retained. In late Neoproterozoic–early Palaeozoic times the area was affected by major tectonic and thermal processes which resulted in high-grade metamorphism, pervasive ductile deformation, and granite emplacement at 570–515 Ma (Jacobs et al., 1998), with the main charnockitic rocks emplacement event dated at c. 510 Ma (Mikhalsky et al., 1997). Late Neoproterozoic (570–550 Ma; Jacobs et al., 1998) metamorphism occurred at 800–850 °C and 8 kbar, followed by cooling and decompression to 650° and 3–4 kbar (Piazolo and Markl, 1999; Harley, 2003) at 530–515 Ma (Jacobs et al., 1998). The late Neoproterozoic granitoids cannot be distinguished from the Grenville-age igneous rocks either in isotopic (Jacobs et al., 1998) or chemical composition (Mikhalsky and Jacobs, 2004). Other late Neoproterozoic to early Palaeozoic rock types are apparently lacking from this area, so that a collisional nature for this orogen seems most likely.

The tectonic environment in DML during charnockite emplacement may have been dominated by transcurrent shearing (Jacobs and Thomas, 2002), possibly associated with rifting, which followed continental collision in conjugated parts of Gondwana (central and northern Africa, Madagascar: Rogers et al., 1995). The DML charnockites may thus have been emplaced into thinner crust, following post-collision extension. Whether these rocks should be regarded as 'anorogenic,' as opposed to 'post-orogenic,' is debatable, but they clearly have compositional affinities to ferroan plutonic rocks which are common in extensional environments (Frost et al., 2001). The presence of anorthosites suggests comparisons with the AMCG (anorthosite–mangerite–charnockite–granite) suite typical of Proterozoic anorogenic magmatism.

Other parts of the East Antarctic Precambrian mobile belt, as exemplified by MRL and the Bunger Hills area, exhibit different geological histories. Sm–Nd T_{DM2} model ages are mostly in the range 2200–1500 Ma in MRL (Mikhalsky et al., 2001b, and references therein), and 2300–1600 Ma (with a few Archaean ages) in the Bunger Hills area (Fitzsimons, 2003, and references therein). Most rocks are metasediments or within-crust anatectic granitoids, but in some areas subduction-related metamorphic rocks, including Mesoproterozoic (c. 1300 Ma) metavolcanic rocks, are abundant and form piles up to 3000 m thick (Mikhalsky et al., 1996). Mafic and ultramafic rocks are locally common, but in many cases, their origin remains unclear. However, at least in the NPCM, volcanic/magmatic arc and active margin settings have been advocated (Munksgaard et al., 1992; Mikhalsky et al., 2001b, and references therein). Thus, the Grenville-age orogens may include significant proportions of juvenile crustal material, and an accretionary origin may be suggested for at least part of this terrane.

The MRL charnockites were considered by Sheraton et al. (1996) and Mikhalsky et al. (2001b) to have been emplaced into overthickened crust in a late Mesoproterozoic continental collision zone during the waning stages of metamorphism, i.e., they are late-orogenic. Mafic underplating may well have been an important factor, as a source of both heat and parent magmas. Granulite-facies peak metamorphic conditions were attained at c. 1000 Ma (Tingey, 1991) and the waning stages of tectonic activity were dated at c. 940 Ma (Boger et al., 2000). Peak P–T conditions were 700–850 °C and 5–8 kbar, with poorly constrained, but probably distinct, subsequent P–T evolutionary paths at different localities (Mikhalsky et al., 2001b, and references therein; Harley, 2003, and references therein). Some areas appear to have undergone post-peak near-isobaric cooling, although others probably experienced significant decompression. In the NPCM near-isobaric cooling paths were documented by Fitzsimons and Harley (1992), Hand et al. (1994), and Harley (2003). Thus, there is little direct evidence for a collisional tectonic setting involving major crustal thickening in MRL. Nevertheless, the global-scale late Mesoproterozoic (Grenvillean) event appears to have been related to assembly of the Rodinia supercontinent (Unrug, 1996; Powell, 1998), and therefore certainly involved extensive continental collision in at least parts of what is now East Antarctica. The MRL Grenville-age rock associations include a large proportion of juvenile (mantle-derived) material, and MRL may therefore represent a largely accretional, rather than a collisional, orogen. The MRL charnockites can reasonably be classified as late-orogenic.

Regional high-grade metamorphism in the Bunger Hills was probably an earlier phase of the same global event. Most Proterozoic orthogneisses were considered by Sheraton et al. (1993) as representing new continental crust derived by partial melting of a mafic source, possibly subducted oceanic crust. The charnockitic rocks appear to have been emplaced under similar P–T conditions to the peak of metamorphism, although significant uplift occurred soon after this (Sheraton et al., 1995). Late-orogenic charnockite emplacement in a collision zone bordering essentially accretional orogen is therefore likely.

The effects of late Neoproterozoic–early Palaeozoic tectonothermal activity varies widely in MRL and Princess Elizabeth Land. In some areas (e.g., Mawson Escarpment of MRL, and the Prydz Bay Coast and Grove Mountains of Princess Elizabeth Land) granulite-facies metamorphism, deformation, and alkalic granite emplacement occurred at c. 550–500 Ma (Fitzsimons, 2003, and references therein). In other areas, relatively weak thermal overprinting and some pegmatite vein emplacement have been recorded (e.g., NPCM, Manton et al., 1992). Alkaline mafic dykes of this age are known in the Bunger Hills area (Sheraton et al., 1992). The nature of the late Neoproterozoic–early Palaeozoic orogen in the MRL–Princess Elizabeth Land area remains obscure. Fitzsimons (1996) and Carson et al. (1997) tentatively ascribed metamorphism in the Prydz Bay Coast to collision at a convergent plate margin, followed by extensional exhumation as the orogen collapsed. Boger et al. (2001) argued for an early Palaeozoic suture zone in the southern PCM, and correlated it with the high-grade metamorphic belt in the Prydz Bay Coast. In his excellent review of Proterozoic provinces of southern Australia and Antarctica, Fitzsimons (2003) noted that late Neoproterozoic to early Palaeozoic activity in the PCM may be interpreted as the marginal influence of tectonism focused further east (Princess Elizabeth Land to Denman Glacier in the Bunger Hills area). It is noteworthy that, as in DML, no juvenile crustal additions of this age are known from any of these areas. However, in spite of widespread granite occurrences, charnockites of this age are known from only a few localities (Grove Mountains, Mikhalsky et al., 2001a; Mirnyy Station, Klimov et al., 1964), although this may partly reflect insufficient sampling or the poor exposure in much of the area.

6. Discussion and conclusions

In spite of the many similarities in the compositions of charnockitic rocks in the three areas of study, there are also striking differences. The main geological and geochemical features of these rocks are summarised in Table 4. Of the three areas discussed in this paper, only the MRL intrusives include a large proportion of orthopyroxene-bearing granite, and could be said to be “typical” charnockites. The Bunger Hills rocks are predominantly mafic to intermediate, albeit with some granite (s.s.), while the DML charnockites include a large proportion of potassium-rich, relatively alkaline rocks. The latter are also associated with mafic rocks, although these are of an unusual high-Fe–Ti character, and anorthosites. They contain abundant amphibole and biotite, which in many places completely replace primary orthopyroxene. Fayalite, rather than orthopyroxene, occurs in the more Fe-rich rocks. Many geochemical features (high HFSE, LILE, Fe*, Ga/Al, very low MgO) of the DML charnockitic rocks are very different from those of MRL and most Bunger Hills charnockites. However, monzodioritic rocks of the Bunger Hills and David Island intrusives are comparable to the DML rocks in many respects, and the latter are of similar age (c. 515 Ma and c. 510 Ma, respectively). 500 Ma charnockitic rocks in the Mirnyy area are also basically akin to the DML rocks, although only major component compositions are available (Ravich et al., 1968). These rocks are mainly coarse-grained orthopyroxene-bearing granodiorite to subordinate monzodiorite with similar SiO_2 in the range 64–70%, TiO_2 up to 1.15%, Na_2O+K_2O 7–9%, Fe* = 0.86–0.92, although K_2O is lower (2.3–3.4)%. It should be noted that Mesoproterozoic (c. 1200 Ma, Tingey, 1991) charnockites from the Windmill Islands have major and trace elements compositions (Kilpatrick and Ellis, 1992) similar to the MRL/Bunger Hills charnockitic rocks: Fe* = 0.81–0.87, Ga/Al 2.1–2.7, Zr ≤ 300 ppm, Nb ≤ 20 ppm.

It was generally accepted that charnockites represent intrusions of water-undersaturated magma into dry granulite-facies crust (e.g., Martingole, 1979). Several models have been proposed for magmatic charnockite genesis. Those include: in situ dry anatexis during granulite metamorphism, which may be enhanced by CO_2-fluxing (e.g., Newton, 1992), residua after removal of granitic melts or cumulative origin (e.g., Emslie, 1991), partial melting of ‘dry’ granulitic sources at elevated temperatures after first-stage melt extraction (Sheraton, 1982), crystal fractionation of lithospheric mantle-derived mafic magmas (Sheraton et al., 1992), dehydration partial melting of Ti-enriched underplates (Kilpatrick and Ellis, 1992), and partial melting of amphibole-bearing mafic lower crust under varying water activities which cause variations in bulk charnockite composition (Rajesh and Santosh, 2004).

A mantle origin for the Bunger Hills charnockitic rocks was advocated by Sheraton et al. (1992), who noted their very close genetic association with gabbroic rocks which precludes them representing entirely crustal melts. The MRL charnockites probably include a major felsic, likely crustal-derived, component (Zhao et al., 1997), in addition to a significant mantle component (Sheraton et al., 1992). The DML charnockitic rocks were probably derived by fractionation of mafic mantle-derived melt, which may be indicated by high $\varepsilon_{Nd}(T)$ and a close spatial and likely genetic association with mafic rocks and anorthosites. However, derivation of DML charnockitic rocks from mafic lower crust, or at least its involvement via mixing, cannot be ruled out. Given that the crust in central DML is relatively young (T_{DM} < 1700 Ma), such a component would evolve to similar, apparently primitive isotopic composition.

Frost et al. (2001) suggested that ferroan granitic rocks originated from relatively anhydrous, reduced basaltic source rocks, either by fractionation of a mantle-derived melt or by partial melting of a lower crustal source. Many experimental studies have shown that partial melts are enriched in K_2O (higher Or/Ab) with decreasing water activity or decreasing pressure (Ebadi and Johannes, 1991; Beard et al., 1994). Superficially, such a model does not appear to be consistent with the DML charnockitic rocks being water-saturated, rather than undersaturated. However, water saturation might have resulted from progressive crystallisation in a closed system, even though the source melting conditions were relatively anhydrous. CO_2 and halogens might have been equally important in charnockite petrogenesis. Experimental work has shown that increased amounts of CO_2 increase the normative orthoclase content of the melt (e.g., Kaszumba and Wendlandt, 2000). CO_2-rich melt is also enriched in Zr and some other trace elements (e.g., Eggler, 1987). Similarly, Collins et al. (1982) and Keppler (1993) showed that halogens, particularly F, may be responsible for the elevated HFSE abundances in some granitic rocks. The halogens could have been derived by breakdown of F- and Cl-rich amphibole and biotite during melting, or may have come from a mafic underplate.

Rajesh and Santosh (2004) proposed that intrusion of relatively anhydrous basalts resulted in dehydration melting of the lower crust and production of intermediate charnockites (trondhjemites to tonalites), whereas intrusion of hydrous basalts would produce felsic charnockites (granodiorites to granites). However, only some of the Antarctic charnockitic rocks (MRL, Bunger Hills gabbro–granite group) described in this paper have similar compositional features to the intermediate and felsic charnockites of Rajesh and Santosh (2004). Others (DML, Bunger Hills monzodiorite group, David Island) have quite different compositions, being more potassic, alkalic and ferroan. Thus, it seems most unlikely that a single petrogenetic model can be applied to all charnockitic rocks.

Clearly a number of factors were important in charnockite petrogenesis, including a variety of source rocks and magmatic processes. It is noteworthy that the Insel Massif (DML) and David Island rocks exhibit strong enrichment in Fe (as well as K and some HFSE: e.g., Zr, Nb), in contrast to MRL and most Bunger Hills charnockitoids. These two major charnockitic groups (DML/David Island, and MRL/Bunger Hills) appear to roughly correspond with the two granitic rock types distinguished by Frost et al. (2001) — 'ferroan' and 'magnesian.' These authors deduced that ferroan granitoids were derived from relatively anhydrous, reduced magmas and source regions, whereas magnesian granitoids reflect relatively hydrous, oxidized magmas and source regions. Thus, the ferroan DML/David Island rocks might have been derived from relatively anhydrous, reduced source regions, possibly with elevated CO_2 and halogen activity, and the MRL/Bunger Hills rocks from more hydrous (lower CO_2/H_2O) source regions. These source regions may have been either enriched mantle or lower crust, but we favour a predominantly mantle origin, at least for the suites closely associated with mafic rocks. However, the mantle sources for the two charnockite types were apparently quite different, with a more Nb-rich (OIB-like) end-member being more likely for the ferroan DML type, and a Nb-poor source for the magnesian MRL/Bunger Hills type. Moreover, the former is associated with relatively alkaline high-P–Ti ferrogabbro, and the latter with tholeiitic gabbro. Intermediate or mixed sources may well have been involved, as evidenced by elevated Nb and smaller Nb anomalies of low-SiO_2 MRL rocks. Interaction of mantle-derived magmas with crustal material is indicated by the isotopic data (high Sr_i in many rocks). The essential triggering process for charnockitic magmatism in all these areas was probably regional-scale underplating at the base of the crust following regional decompression.

It is difficult to say from the available data whether this major distinction was a result of magma generation in fundamentally different tectonic environments, reflects a compositional trend in an evolving orogenic belt, or is entirely determined by the composition of the source regions and conditions of melting. In all three major areas, the charnockitic rocks were emplaced during the waning stages of granulite-facies metamorphism, or relatively shortly after that event. Charnockite emplacement occurred at least 20 Ma after the peak of high-grade metamorphism and deformation in all these areas. The 1151 Ma monzodiorite group of the Bunger Hills are about 20 Ma younger than the other charnockitic rocks in that area, that is about 40 Ma younger than the peak of tectonic activity. Moreover, it is possible that the dated Insel Massif (DML) rocks may post-date the metamorphic peak by an even longer time (up to 60 Ma), but much more precise age data will be necessary to prove this. The presence of early magmatic higher-Mg, lower-K monzodioritic phase in the Petermann Ranges point to possible evolution of melt composition with time. Albeit undated, these rocks are clearly of late Neoproterozoic–early Cambrian age, as they post-date main metamorphic/deformation events in the area. While the MRL and most Bunger Hills charnockitic rocks are late-tectonic, the Insel Massif and other DML charnockitic rocks appear to have formed after post-collisional extension, and the David Island rocks are apparently post-tectonic or anorogenic and roughly co-eval with alkaline mafic dykes.

The exact natures of the late Mesoproterozoic–early Neoproterozoic and late Neoproterozoic–Cambrian (Pan-African) events in Antarctica are not well understood, but both appear to have been related to continental assembly, of Rodinia and Gondwana, respectively (Unrug, 1996; Powell, 1998). There is some evidence, albeit far from conclusive, that the Proterozoic MRL and Bunger Hills charnockites may have formed in essentially accretional orogens, and the Cambrian DML charnockites in a collisional orogen. Thus, it is possible that the compositionally and mineralogically distinct charnockite types may, to some extent, correspond to different tectonic settings. Frost et al. (2001) pointed out that magnesian granitoids are more characteristic of subduction-related terranes (e.g., island-arcs and accretional terranes), whereas ferroan granitoids are more common in extensional (e.g., post-collisional) environments.

Hence, it seems likely that both the tectonic setting and timing of magma generation in an orogenic event, as well as the more obvious factors of source composition, conditions of melting, and magmatic history, were important in charnockite petrogenesis. Of course, the two charnockite types we have described may well represent end-members, and 'transitional' types may well exist. The Bunger Hills monzodiorite group may well be an example. Granitoids, partly orthopyroxene-bearing, are common in wide areas of the Pan-African mobile belt in East Antarctica (Rajesh et al., 1996), including DML, the Amery Ice Shelf area (c. 500 Ma; Sheraton et al., 1996), Grove Mountains (504 ± 2 Ma; Mikhalsky et al., 2001a), David Island (516 ± 2 Ma; Sheraton et al., 1992), and Mirnyy (502 ± 24 Ma; Ravich et al., 1968; McQueen et al., 1972). Most of these early Palaeozoic rocks are of alkalic-ferroan character (DML-type), except the 504 Ma charnockitic rocks from the Grove Mountains which are compositionally similar to the calc-magnesian MRL/Bunger Hills charnockites (Mikhalsky et al., 2001a). The Grove Mountains rocks are also thought to be late-orogenic (Zhao et al., 2000). This may provide indirect evidence for accretionary origin of the late Neoproterozoic–early Palaeozoic orogen in the Grove Mountains as suggested by Fitzsimons (1996), Carson et al. (1997), Boger et al. (2001). This terrain may include a "hydrous" (newly accreted) source component, rather than being of entirely "anhydrous" (reworked) composition.

The alkali-ferroan charnockitic rocks of David Island are located in an area which may represent the southward continuation in Antarctica of a major Neoproterozoic to early Palaeozoic suture zone (Fitzsimons, 2003). The collisional nature of this suture would thus be consistent with the composition of these charnockites. It must be noted that David Island is located in the region of the Bunger Hills and this may argue against the importance of geological prehistory of the host terrane. However, David Island is situated about 60 km westward the Bunger Hills, and in the opposite side of the Denman Glacier–Scott Glacier system which may be a major crustal boundary as suggested by Fitzsimons (2003).

Further work in Antarctica and elsewhere is needed to clarify the exact tectonic and temporal relationships of these compositionally distinct types of charnockite. In particular, precise age-dating (ion-microprobe), combined with detailed structural and metamorphic (P–T) studies, will be required to determine the timing and conditions of charnockite emplacement during tectonothermal events. Only then will it become clear if charnockite composition is indeed related to tectonic setting, as we favour at present stage of study, as well as reflecting the different stages of an orogenic cycle and the source composition and subsequent magmatic history.

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