

THE ORIGIN OF ARCHAEOAN GNEISSES IN THE FYFE HILLS REGION, ENDERBY LAND; FIELD OCCURRENCE, PETROGRAPHY AND GEOCHEMISTRY

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ABSTRACT

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Granulite and amphibolite facies gneisses at Fyfe Hills in Enderby Land, East Antarctica, form part of an early Archaean (c. 3.8 Ga) terrain termed the Napier Complex. The gneissic sequence at Fyfe Hills is composed of both supracrustal and intrusive rocks. The oldest lithological association, the Layered Gneissic Series, is defined by interlayered felsic and basic metavolcanics and metasediments derived from psammitic, pelitic, ferruginous and calcareous precursors. Felsic gneisses in the Layered Gneissic Series have low Y/Ce, low Ga/Al and are low in incompatible elements and, therefore, correspond to Sheraton and Black's depleted granulites. The Layered Gneissic Series has been intruded by ultrabasic rocks and by subconcordant sheets of charnockite, enderbite and pyroxene granulite which form the Massive Gneissic Series. The 'undepleted' felsic gneisses of the Massive Gneissic Series probably derive from crustal anatexis associated with granulite facies metamorphism of the Napier Complex. Dehydration during this unusually high grade metamorphism was achieved by the removal of partial melts, rather than by 'CO₂-flushing', as metamorphism occurred either during vapour-absent conditions or, if vapour was present, then the composition of the vapour phase was internally buffered. Anatectic pegmatites generated during granulite facies metamorphism differ little in chemistry from the felsic granulites from which they derive. Chemical modification accompanied rehydration during waning granulite facies metamorphism and during the development of retrograde shear zones, the latter are associated with a magmatic episode in which numerous pegmatites were intruded into the Napier Complex.

INTRODUCTION

The Fyfe Hills–Khmara Bay region forms part of an Archaean granulite facies terrain in Enderby Land, East Antarctica (Fig. 1). Nd–Sm (isochron) Rb–Sr (isochron) and Pb–U (zircon) studies indicate that the Fyfe Hills gneisses have a crustal history extending back to 3.3–3.8 Ga (Grew and Manton, 1979; DePaolo et al., 1982; Black and James, 1983; Black et al., 1983a; McCulloch and Black, 1984) while ion-microprobe studies of zircons

a alkaline dykes

▨ amphibolite-grade RSZ's

Ad Amundsen dykes

Kd Khmara dykes

Massive Gneissic Series

M quartz-feldspar-pyroxene gneiss

Mp pyroxene-plagioclase gneiss

Layered Gneissic Series

Li meta-igneous (dominantly)

Ls metasedimentary (dominantly)

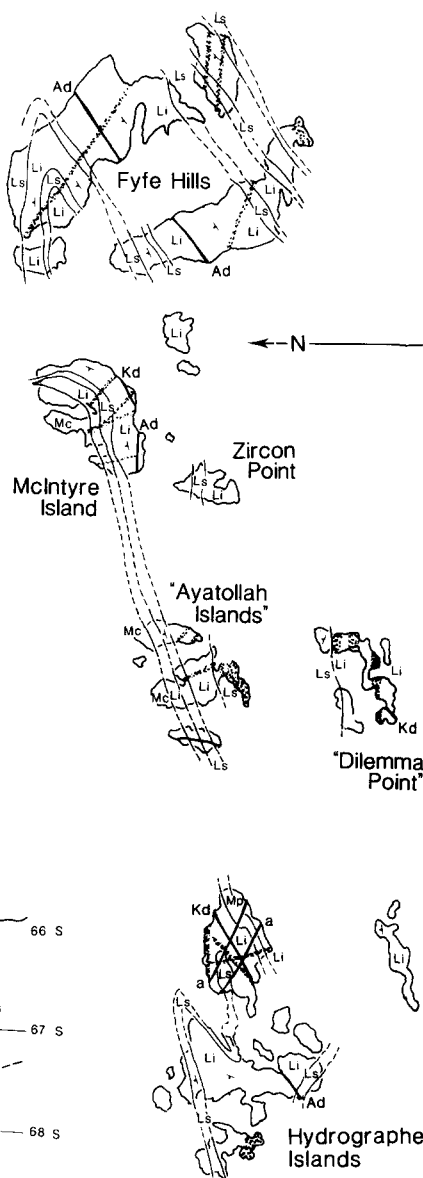
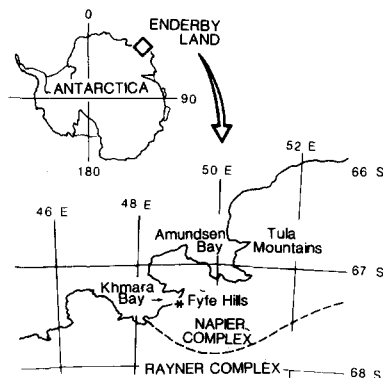


Fig. 1. Geology of the Fyfe Hills-Khmara Bay region. Inset shows the extent of the Napier and Rayner Complexes (after Ravich and Kamenev, 1975; Grikurov et al., 1976; Sheraton et al., 1980). Official names have been used for geographic features wherever appropriate; unofficial names are placed in inverted commas.

in meta-igneous gneisses from Fyfe Hills also suggest these rocks may be as old as 3.8 Ga (Compston and Williams, 1982, Black and James, 1983). These studies indicate that the Fyfe Hills gneisses represent a fragment of the early Archaean crust. Owing to their excellent exposure, the Fyfe

Hills gneisses provide a unique opportunity for investigation of early Archaean lithological associations. In this contribution we describe the field occurrence, petrography and geochemistry of these gneisses. In particular, we attempt to elucidate the relationships between the individual lithological components and the relationship between crust-forming processes, deformation and metamorphism of this ancient gneiss terrain. This research is based on field work during the 1979/80 ANARE expedition to Enderby Land as part of a research program complementing regional based tectonic and geochronologic investigations by other Australian geologists (e.g., Black et al., 1983a,b).

The Fyfe Hills gneisses comprise both metasedimentary and meta-igneous rocks (Sobotovich et al., 1976; Kamenev, 1982; DePaolo et al., 1982, Black et al., 1983a). As with many Archaean gneissic terrains (cf. Bridgwater et al., 1978), the relationship between these two dominant gneiss types is by no means clear in the Fyfe Hills region. To establish appropriate models for the evolution of Archaean gneissic terrains it is necessary to integrate the results of diverse techniques including field studies, petrology, geochemistry and isotope systematics. The work presented below is based largely on the interpretation of field relationships and geochemistry (see also Sandiford and Wilson, 1984). A thorough evaluation of the conclusions presented herein will necessarily involve detailed isotopic work, which is beyond the scope of the present study. It is hoped that the framework presented may provide a basis for more rigorous interpretation of the data generated by independent geochronologic investigations (e.g., DePaolo et al., 1982; Black et al., 1983a, b).

Sandiford and Wilson (1984) presented evidence for five deformation events (D_1 – D_5) and four associated metamorphic events (M_1 – M_4) in the Fyfe Hills region. These events, which are summarised in Table I, provide a relative chronology against which the timing of the major crust-forming events in the Fyfe Hills region have been evaluated.

THE REGIONAL SETTING OF FYFE HILLS

Fyfe Hills lies near the western margin of the Napier Complex, a granulite facies terrain which outcrops over some 50 000 km² in central and western Enderby Land (Fig. 1). The Napier Complex was metamorphosed and effectively stabilised during the Archaean (Sheraton et al., 1980; James and Black, 1981; Grew, 1982a). It is bounded along its continental margin by the Rayner Complex (Fig. 1) which consists of granulite and amphibolite facies gneisses derived, in part, from late Proterozoic reactivation of much older, possibly Napier Complex rocks (Grew, 1978; Sheraton et al., 1980). This bipartite subdivision of the crystalline basement of Enderby Land is supported by isotopic (Grew, 1978) and petrologic (Ellis, 1983) evidence, and by the fact that the Napier Complex contains abundant mafic dykes including the largely unmetamorphosed Amundsen dykes of mid–late

TABLE I

Lithological components of the Fyfe Hills—Khmara Bay region, Enderby Land, East Antarctica. The relative stratigraphic age of individual components is indicated with the youngest components highest in the table

Rock types	Deformation events	Metamorphic events	Isotope data	
			Age	Source
sapphirine gneisses				
garnet—feldspar gneisses				
meta-ironstones			3.3	—3.8 Ga 4,5,6,7
calc-silicates				
quartz—feldspar—pyroxene gneisses ('depleted')				
pyroxene—plagioclase gneisses				
Ultramafic gneisses				
quartz—feldspar—pyroxene gneisses ('undepleted')				
pyroxene—plagioclase-gneisses			2.5	—3.1 Ga 4,5
Granulite pegmatites	D1 recumbent folding	M1 pyroxene-granulite metamorphism (900°C, 8–10 kbar)	2.5	—3.1 Ga 3,4,5,8
	D2 reclined folding	M2 hornblende granulite metamorphism (640°C, 6–8 kbar)	2.35–2.5	Ga 1,5
	D3 upright folding	(intruded at 5–9 kbar)	1.0	—1.4 Ga 1
		M3 amphibolite grade metamorphism (650°C, 5–8 kbar)	0.5	—1.0 Ga 2,9
Amundsen dykes	D4 retrograde shearing 'schists'	M4 amphibolite grade metamorphism (650°C, 3–7 kbar)	0.5	Ga 2
	D5 retrograde shearing 'mylonites'			
Late pegmatites				

TABLE I (continued)

Alkaline dykes

0.49 Ga 10

The structural and metamorphic events have been described by Sandiford and Wilson (1984) and Sandiford (1985a,b).

Geochronologic data are from:

- (1) Sheraton and Black (1981).
- (2) Grew and Manton (1979).
- (3) Grew et al. (1982).
- (4) DePaolo et al. (1982).
- (5) Black et al. (1983a).
- (6) McCulloch and Black (1984).
- (7) Compston and Williams (1982).
- (8) Sheraton and Black (1983).
- (9) Black et al. (1983b).
- (10) Black and James (1983).

Proterozoic age (Sheraton and Black, 1981). In contrast, the Rayner Complex contains no unmetamorphosed basic dykes, although possible equivalents of the Amundsen dykes occur as highly deformed relics at a number of localities (Sheraton et al., 1980).

The Napier Complex has been subdivided into two series (Grikurov et al., 1976): (1) the predominantly orthogneissic Raggatt Series; and (2) the predominantly paragneissic Tula Series. The two series are interlayered on a regional scale (James and Black, 1981). Three possibilities exist for this interlayering: (1) deposition in a composite volcano-sedimentary succession; (2) tectonic interleaving of an older basement complex with its supracrustal cover succession; or (3) emplacement of younger intrusive sheet-like bodies into an older supracrustal succession. Soviet geologists have regarded the Raggatt Series as the fundamental basement in the Napier Complex (Grikurov et al., 1976). In contrast, James and Black (1981) suggested that the intimate interlayering of the Tula and Raggatt Series in the Amundsen Bay region is the result of interleaving and argued, by analogy with other Archaean gneissic terrains such as West Greenland, that the supracrustal Tula series may well be older than the interleaved orthogneisses of the Raggatt Series. However, no previous isotopic and field studies have unequivocally established the relative ages of the two series. Thus, the nature of the relationship between the meta-igneous and meta-sedimentary sequences remains one of the fundamental problems of Enderby Land geology and is one of the principal questions addressed in this paper.

ANALYTICAL TECHNIQUES

All major and trace elements were determined on a Siemens X-ray fluorescence spectrometer at the Department of Geology, University of Melbourne. Rock samples in excess of 0.5 kg were crushed in soft steel and agate and fused with lithium meta-borate (Haukka and Thomas, 1977). Major element accuracy for standard granitic and basaltic rocks is estimated to be less than $\pm 2\%$ while trace element detection limits are: 1 ppm for Sc and Ga; 3 ppm for Co and Y; 6 ppm for V, Ni, Zn, Sr, Rb, Nd, Ce and Cu; 11 ppm for Cr and Ba; 14 ppm for Zr; and 20 ppm for Cl.

LITHOLOGICAL COMPONENTS OF THE GNEISSIC SEQUENCE; PETROGRAPHY AND GEOCHEMISTRY

The Fyfe Hills-Khmara Bay region consists predominantly of granulite facies gneisses. These gneisses are locally retrogressed to amphibolite facies schists and mylonites in discrete retrograde shear zones (RSZ's) which comprise 10% of the mapped area (Figs. 1 and 2). A number of generations of mantle-derived dyke rock are recognised in the Fyfe Hills region (Sandiford and Wilson, 1983; Table I), including the doleritic Amundsen dykes (Sheraton and Black, 1981). The Amundsen dykes retain igneous textures

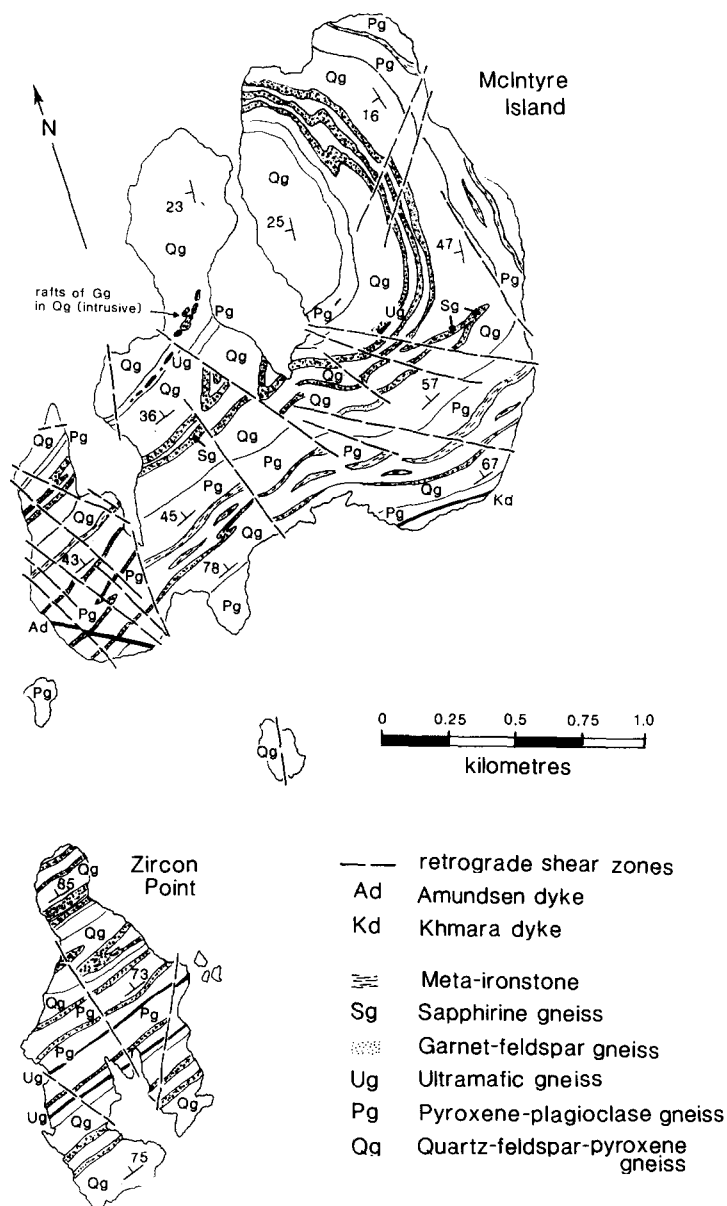


Fig. 2. Geology of McIntyre Island, Khmara Bay.

where they intrude granulite facies gneisses but are deformed and metamorphosed within the RSZ's. Thus, the Fyfe Hills region occurs within a zone which exceeds 30 km in width (that is, the width of the mapped area, Fig. 1) characterised by extensive late Proterozoic or early Palaeozoic reactivation of the Napier Complex.

The granulite facies gneisses define a lithologic sequence with an exposed thickness of approximately 3 km. All gneisses exhibit the effects of a pervasive recumbent deformation event (D_1) and all contain assemblages and textures indicative of equilibration during unusually high grade granulite facies metamorphism (M_1). Seven petrographically and chemically distinct groups of gneisses have been recognised. These gneisses are interlayered on both the mesoscopic and macroscopic scales throughout the Fyfe Hills region and include (Table I): (1) quartz—feldspar—pyroxene gneisses; (2) pyroxene—plagioclase gneisses; (3) ultramafic gneisses; (4) sapphirine gneisses; (5) garnet—feldspar gneisses; (6) meta-ironstones; and (7) calc-silicate gneisses. The quartz—feldspar—pyroxene, pyroxene—plagioclase, and ultramafic gneisses correspond to the pyroxene—quartz—feldspar gneiss group of Sheraton et al. (1980), and are distinctly meta-igneous in character. The garnet—feldspar gneisses include the pelitic metasediments and the garnet—quartz—feldspar group of Sheraton et al. (1980), and together with the calc-silicate gneisses and the meta-ironstones have metasedimentary compositions. The sapphirine gneisses are most probably derived from hydrothermally altered protoliths.

Quartz—feldspar—pyroxene gneisses (QFPG's)

The QFPG group includes green, brown or rusty coloured, medium grained (2–6 mm) hetero-granoblastic charnockites and enderbites (Tilley, 1936). QFPG's form approximately 60% of total outcrop and occur either as massive units exceeding 50 m in thickness or as 0.3–10 m thick layers (Fig. 3). A weak to moderately developed gneissic layering is defined by the preferred dimensional elongation of component minerals, and by variation in the colour index and grain size. The feldspar is either mesoperthite (charnockite) or antiperthitic plagioclase (enderbite). Pyroxenes are typically hypersthene and salite. Ilmenite, magnetite, rutile, zircon and apatite are common accessory phases. Typical M_1 assemblages include:

mesoperthite—quartz—hypersthene—ilmenite—apatite—zircon

antiperthite—quartz—hypersthene—salite—ilmenite

The QFPG's (analyses 1 and 2, Table II; analyses 1 and 2, Table III) are distinctively igneous in character (low molecular Al_2O_3/Na_2O+K_2O+CaO) and, as such, are similar to the diopside normative QFPG's elsewhere in the Napier Complex (Sheraton and Black, 1983). QFPG's typically contain SiO_2 in excess of 69 wt.%, with less acidic varieties (analysis 2, Table II) forming <5% of the gneissic sequence. The QFPG's have alkali contents very similar to LeMaitre's (1976) average granodiorite (Table IV), and thus, contrary to DePaolo et al. (1982), do not appear to be systematically depleted in alkalis. Relative depletion of Rb may be indicated by the high K/Rb ratios which average 450 (cf. Heier and Billings, 1972). Compared with typical granitoid rocks the QFPG's have low Al_2O_3 contents, a feature common to many Archaean granitic gneisses (Glikson, 1979). Apart from

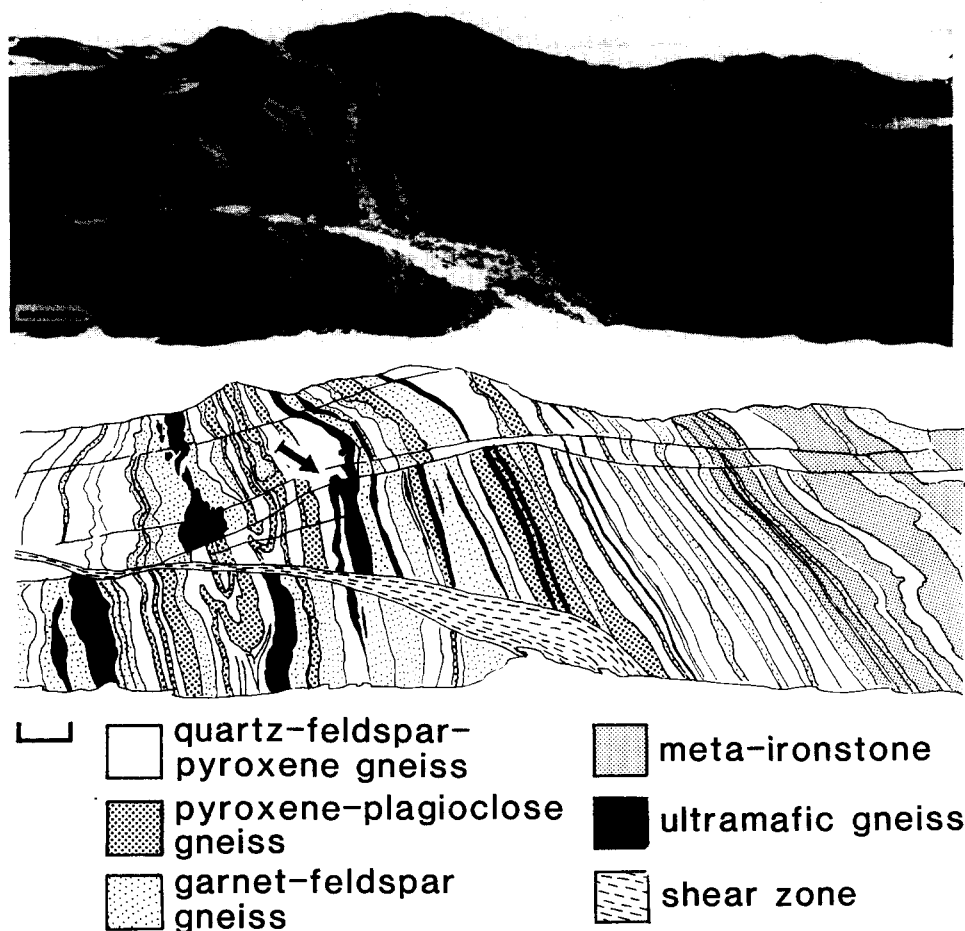


Fig. 3. Typical gneissic sequence in the Layered Gneissic Series at Ayatollah Island. The interlayering of these gneisses is believed to reflect the primary compositional variation in a supracrustal sequence, with subsequent intrusion of ultramafic sills indicated by local discordant contacts (arrowed). The bar scale in the foreground of the oblique section is 5 m long.

Rb, most trace element abundances are comparable with typical granitoid rocks (Wedepohl, 1969). The QFPG's are therefore believed to be derived from igneous rocks with the primary compositional variation ranging from granite through to tonalite. Two distinct suites of QFPG occur in the Fyfe Hills region corresponding to Sheraton and Black's (1983) 'depleted' (low Y/Ce, Ga/Al, incompatible elements) and 'undepleted' suites, respectively (Table V).

The QFPG's are bleached pale grey in the RSZ's where hornblende, biotite, sphene and garnet have formed at the expense of the primary Fe—Mg and Fe—Ti phases, and microcline at the expense of orthoclase.

TABLE II

XRF determinations of major elements and selected trace elements of gneisses of the Layered Gneissic Series, from Fyfe Hills and Khmara Bay.

Analysis	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO ₂	71.70	62.61	51.13	48.10	43.71	56.58	48.48	40.75	51.22	40.67	60.43	57.23	76.31	48.75	32.02	46.89
TiO ₂	0.50	1.07	1.05	1.43	2.26	1.53	0.11	1.07	0.26	0.39	0.98	0.89	0.09	0.33	0.76	1.01
Al ₂ O ₃	13.31	14.84	14.04	14.02	13.68	13.67	20.74	7.20	2.06	23.14	23.85	15.18	12.95	1.39	6.91	12.76
Fe ₂ O ₃	3.10	7.61	12.28	14.80	16.63	12.30	7.20	18.47	13.59	3.74	3.48	7.90	44.57	44.57	31.54	12.52
MnO	0.02	nd	0.05	0.14	0.20	0.03	0.11	0.18	nd	nd	0.02	0.03	0.01	0.12	16.87	0.95
MgO	0.69	3.47	6.82	7.48	8.64	4.66	11.11	27.02	18.77	28.43	4.03	9.89	0.38	2.47	3.13	5.23
CaO	3.07	5.56	9.70	11.10	11.27	6.35	10.15	3.69	12.17	1.62	0.45	0.73	0.71	0.92	9.10	19.78
Na ₂ O	3.17	2.99	2.89	1.43	0.95	2.29	1.33	0.44	0.51	0.15	1.29	3.13	2.06	0.10	0.27	1.39
K ₂ O	2.78	0.53	0.51	0.37	0.19	1.66	0.26	1.33	0.21	0.63	3.18	2.57	6.61	0.06	0.03	0.18
P ₂ O ₅	0.11	0.19	0.18	0.20	0.40	0.33	0.03	0.27	0.03	0.13	0.03	0.26	0.03	0.11	0.09	0.16
SO ₃	0.04	0.29	0.17	0.19	0.22	0.31	0.02	0.16	0.13	0.11	0.02	0.02	0.01	0.05	0.07	0.03
LOI	0.21	0.15	-0.08	-0.16	0.56	-0.11	na	-0.72	0.11	0.46	0.28	0.27	0.27	1.35	-0.66	-0.22
Total	98.70	99.33	98.72	99.10	99.19	99.60	99.57	97.35	99.00	99.67	98.04	98.10	99.87	100.2	100.1	100.7
Rb	52	3	5	9	6	72	6	56	12	38	61	120	94	14	30	9
Sr	136	165	117	138	116	128	68	29	58	59	38	42	59	14	14	271
Ba	886	219	158	200	43	618	20	103	61	18	465	342	612	11	2564	136
Zn	34	94	98	93	79	76	50	137	80	20	39	7	6	34	90	85
Y	31	17	46	28	35	29	6	34	15	105	69	121	25	9	39	30
Ce	86	30	55	55	47	46	na	86	49	897	136	281	141	nd	89	116
Nd	361	13	31	25	25	23	na	41	32	301	38	106	48	nd	47	39
Zr	361	179	137	100	156	321	13	150	35	479	147	452	24	7	51	125
V	28	152	192	307	386	228	71	154	7	131	256	32	10	nd	172	200
Cr	4	43	331	310	348	118	642	4589	2129	15	553	nd	9	nd	249	199
K/Rb	444	1468	848	342	263	191	359	197	145	138	432	177	584	35	8	166

Analyses 28-II, 28-III, and 28-V from DePaolo et al. (1982) are also included. All Fe determined as Fe₂O₃. Sample numbers are Melbourne University Geology Department Museum numbers.

1. Average of six quartz-feldspar-pyroxene gneisses.
2. Intermediate quartz-feldspar-pyroxene gneiss, McIntyre Island (R25597).
3. Average of four 'basaltic' pyroxene-feldspar gneisses (without secondary garnet).
4. Average of three pyroxene-feldspar gneisses with secondary garnet.
5. Average of three hornblende 'schists', Ahatollah Island.
6. Average of two hornblende 'mylonites', Hydrographer Island.
7. Average of three leucocratic gneisses (including major elements of 28-II and 28-III from DePaolo et al., 1982).
8. Peridotitic ultramafic gneiss, McIntyre Island (R25664).
9. Pyroxenitic ultramafic gneiss, Hydrographer Island (R25839A).
10. Sapphirine gneiss, Mount Novogodnaya (R31169).
11. Average of three Cr-rich garnet-feldspar gneisses, McIntyre Island.
12. Cr-poor garnet-feldspar gneiss, McIntyre Island (R25643).
13. Cr-poor felsic gneiss (interlayered with Cr-rich garnet-feldspar gneisses), McIntyre Island (R25641A).
14. Average of three meta-ironstones (including major elements of 28-V from DePaolo et al., 1982).
15. Mn-Ba rich meta-ironstone, Mount Novogodnaya (R31122).
16. Calc-silicate, Mount Novogodnaya (R31136).

nd: not detected; na: not analysed.

TABLE III

XRF determinations of major elements and selected trace elements for intrusive rocks, including the gneisses of the Massive Gneissic Series (MGS), from Fyfe Hills, Khmara Bay and Amundsen Bay

Analysis	1	2	3	4	5	6	7
SiO ₂	72.06	71.15	52.38	50.46	74.20	74.39	61.37
TiO ₂	0.18	1.08	1.08	1.84	0.15	0.12	1.07
Al ₂ O ₃	13.92	12.18	12.86	13.99	14.38	13.17	10.52
Fe ₂ O ₃	1.21	6.21	10.30	13.52	0.52	2.02	8.25
MnO	0.02	0.02	0.04	0.01	nd	0.02	0.12
MgO	0.55	0.90	4.83	6.24	0.22	0.52	4.42
CaO	3.54	3.12	7.10	8.77	2.48	0.90	4.69
Na ₂ O	3.17	2.93	3.10	2.43	3.56	3.79	0.96
K ₂ O	2.36	2.54	0.80	0.53	3.53	4.65	7.52
P ₂ O ₅	0.02	0.19	0.16	0.40	0.05	0.03	1.31
SO ₃	0.01	0.06	0.08	0.34	0.02	0.05	0.25
LOI	0.01	0.06	-0.62	-0.40	0.30	0.48	1.01
Total	100.5	97.50	98.87	98.30	99.41	100.1	100.4
Rb	36	54	9	13	53	147	176
Sr	200	111	113	154	105	103	801
Ba	802	1110	295	353	856	645	6417
Ga	7	21	22	38	1	17	20
Cu	2	26	14	50	nd	11	39
Zn	17	56	150	90	17	26	110
Sc	2	16	31	22	2	4	16
Y	12	48	74	38	25	14	64
Ce	52	73	84	65	200	na	na
Zr	104	921	300	169	17	103	909
V	13	45	139	291	9	10	92
Cr	2	7	458	160	nd	14	130
Ni	38	25	30	143	nd	31	97
Cl	86	250	312	na	241	109	375

All Fe determined as Fe₂O₃. LGS: Layered Gneissic Series.

1. Average of two 'depleted' QFPG, LGS (R31131; R31132).
2. Average of two 'undepleted' QFPG, MGS (R25384A, R25555).
3. Pyroxene-plagioclase gneiss from a dyke within R25384A, MGS, McIntyre Island (R25384B).
4. Pyroxene-plagioclase gneiss, MGS, Hydrographer Island (R25878).
5. Granulite facies pegmatite, Zircon Point (R31035).
6. Average of six 'late' pegmatites and granitic dykes from RSZ.
7. Average of three alkaline dykes, Khmara Bay.

Pyroxene-plagioclase gneisses (PPG's)

The PPG (or mafic granulite) group comprises dark, green to brown, medium grained granoblastic gneisses of basic to intermediate composition.

TABLE IV

Average analyses for (1) granodiorite (Le Maitre, 1976), (2) tholeiite (Le Maitre, 1976), (3) norite (Le Maitre, 1976), and (4) shale (Wedepohl, 1971)

	1	2	3	4
SiO ₂	66.09	49.58	50.44	58.9
TiO ₂	0.54	1.98	1.00	0.78
Al ₂ O ₃	15.73	14.79	16.28	16.7
Fe ₂ O ₃	4.41	12.32	10.42	6.9
MnO	0.08	0.18	0.14	0.09
MgO	1.74	7.30	8.73	2.6
CaO	3.83	10.36	9.41	2.2
Na ₂ O	3.75	2.37	2.26	1.6
K ₂ O	2.73	0.43	0.70	3.6
P ₂ O ₅	0.18	0.24	0.15	0.16
Total	99.08	99.54	99.53	93.5
K/Rb	270	270	230	213

K/Rb ratios are from Heier and Billings (1972) for analyses (1)–(3) and Wedepohl (1971) for analysis (4).

TABLE V

Felsic granulites from the Napier Complex: a comparison of the Fyfe Hills QFPG's with Sheraton and Black's (1983) 'depleted' and 'undepleted' suites, indicated by the asterisk

Rock type	'Depleted suite'			'Undepleted suite'		
	Ba/Sr	Al/Ga	Ce/Y	Ba/Sr	Al/Ga	Ce/Y
Average tonalite*	1.92	4900	4.4	4.24	3900	2.2
Average trondhjemitite*				6.00	3500	2.4
Average granodiorite*	3.52	4900	6.3	6.00	3500	2.4
Average granite*	8.27	5800	21.0	17.1	4100	6.4
Proclamation granite*				14.9	3500	1.5
Layered Gneissic Series						
R31131	2.16	12600	3.0			
R31134	7.48	6000	5.2			
Massive Gneissic Series						
R25384A				4.17	3100	1.6
R25555				18.1	2900	1.4
Granulite pegmatite						
R31035	8.12	7600	8.0			

PPG's comprise 15–20% of the total outcrop, occurring either as massive layers (often in excess of 50 m thick) or, more typically, as 1–5 m thick layers and boudins (Fig. 3). Characteristic M_1 assemblages are:

hypersthene—salite—andesine/labradorite—ilmenite

hypersthene—bytownite

Quartz, ilmenite, magnetite, apatite, and zircon are common accessory phases. PPG's have mineralogical compositions plotting in Streickeisen's (1973) gabbro, gabbro—norite and norite fields (as well as their quartz bearing equivalents). True anorthosites are restricted to net-vein material (Fig. 4A) generated during the boudinage of ultramafic gneisses (Sandiford and Wilson, 1984). The majority of the PPG's have basaltic compositions (analysis 3, Table II). Indeed, apart from the somewhat low Rb, K_2O and Al_2O_3 , the composition of these gneisses is remarkably similar to unaltered

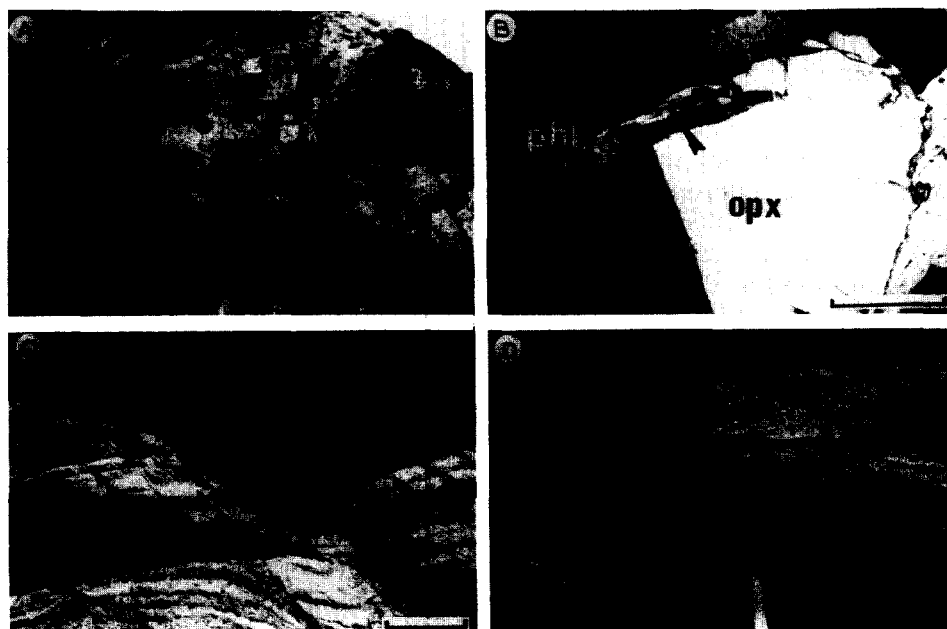


Fig. 4. (a) Leuco-norite with layering defined by darker, cumulus-like, bronzite rich ultramafic gneisses. Anorthosite forms net veins in boudinaged bronzite pods (bottom left). Hydrographer Island. Bar scale is 3 m. (B) Phlogopite flakes (phl) have grown along grain boundaries (arrowed), replacing the primary granulite facies enstatite (opx) in ultramafic gneiss. Bar scale is 2 mm long. (C) Contact between raft of garnet—feldspar gneiss (light coloured) of the Layered Gneissic Series and charnockitic gneiss (dark coloured) of the Massive Gneissic Series. The truncation of the gneissic layering within the raft, and embayment of its margin by the charnockitic gneiss suggest an intrusive origin. McIntyre Island. Hammer handle is 0.25 m long. (D) Pyroxene—plagioclase gneiss (dyke) occurring in the charnockite figured in 3B. The dyke contains F_1 folds indicating emplacement of the Massive Gneissic Series prior to D_1 (Sandiford and Wilson, 1984). Analyses 2 and 3, Table III, of charnockitic and pyroxene—plagioclase gneiss, respectively, are from this locality.

tholeiitic basalts (Table IV), and thus provides substantial evidence for an igneous origin.

Leuconoritic PPG's outcrop in podiform bodies up to 20 m across. An internal layering defined by cumulus-like orthopyroxene rich zones (Fig. 4A) suggests an intrusive origin for these rocks, however, intrusive contacts have not been observed (possibly because they have been obscured by subsequent deformation). Furthermore, as noted by DePaolo et al. (1982), the leuco-norites (analysis 7, Table II) have somewhat higher Mg/Fe (total) and Al_2O_3 and much lower alkali contents than norites with comparable SiO_2 and CaO (Table IV). The origin of the leuconorites therefore remains obscure.

Garnet, hornblende, cummingtonite, tremolite, biotite, sphene, scapolite and calcite occur in the partially retrogressed PPG's that grade into amphibolites and biotite schists in the RSZ's.

Ultramafic gneisses (UG's)

The UG group consists of variously coloured, generally dark, medium to coarse grained granoblastic pyroxenites and lherzolites. UG's comprise less than 3% of the outcrop and occur either as concordant layers less than 10 m thick or as boudins (Fig. 3). Major components are orthopyroxene (hypersthene—enstatite), clinopyroxene (diopside—salite/augite) and olivine; ilmenite, magnetite, Ti-hornblende and Cr-spinel occur in accessory amounts. Plagioclase is restricted to olivine-free assemblages, while garnet occurs only as exsolution products within or between orthopyroxene. Typical M_1 assemblages are:

bronzite—forsterite—diopside—Ti-hornblende—Cr-spinel—ilmenite
bronzite—diopside—andesine/labradorite—ilmenite
diopside—bytownite

Phlogopite is abundant in UG's, often occurring as large centimetre-sized crystals. Invariably this phlogopite isolates optically continuous fragments of orthopyroxene, suggesting it is of retrogressive origin, possibly formed as a result of the release of hydrous fluids during crystallisation of M_1 anatectic melts (auto-retrogression).

The UG's (analyses 8 and 9, Table II) have, compared with typical igneous precursors (cf. Heier and Billings, 1972), comparatively low K/Rb ratios (average 165) suggesting that there has been little or no redistribution of K and/or Rb during metamorphism. However, as most Rb is likely to be in phlogopite, which is regarded as a retrogressive product, the UG's may have formerly been depleted in Rb. Pyroxenitic UG's tend to occur as boudins. In contrast, the peridotitic and lherzolic varieties occur typically as sub-concordant layers and locally preserve intrusive contacts (Fig. 3). The intrusion of all UG's in the Fyfe Hills region predates D_1 . However, both Ravich and Kamenev (1975) and Sheraton et al. (1980) recorded similar gneisses which postdate early folding (F_1) elsewhere in the Napier Complex.

Thin reaction zones between UG's and bounding gneisses are typical (Fig. 5). The UG's are altered to hornblendites and phlogopite bearing serpentinites within the RSZ's with clinohumite occurring in partially retrogressed UG's.

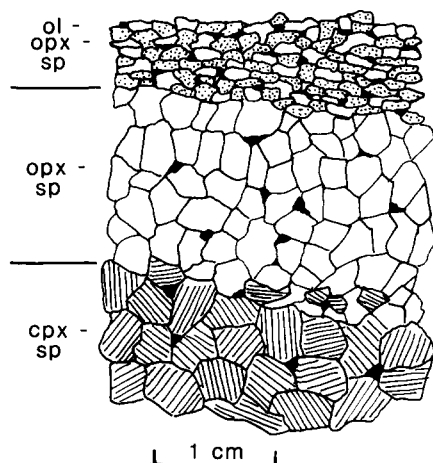


Fig. 5. Orthopyroxene-spinel reaction zones at the margin of olivine bearing ultramafic gneiss. The high variance of reaction zones bounding ultramafic gneisses imply a high grade origin.

Sapphirine gneisses (SG's)

Sapphirine rich ultramafic gneisses form a minor component of the sequence (<1%), occurring as pods up to 3 m long typically within felsic hosts (Fig. 2). Sapphirine constitutes more than 50% of these gneisses. Enstatite, phlogopite and sillimanite may form significant components, while garnet, spinel, corundum, rutile, zircon, monazite and plagioclase occur as accessory phases. Typical assemblages are:

sapphirine-bronzite/enstatite-sillimanite spinel

sapphirine-garnet-plagioclase-corundum

bronzite-sapphirine-garnet

Greater than 90% of the bulk chemistry of the SG's is accounted for by subequal proportions of SiO_2 , MgO and Al_2O_3 , with Fe_2O_3 (total Fe), CaO and K_2O forming the only other significant constituents (analysis 10, Table II). As such, they do not correspond to typical igneous (LeMaitre, 1976) or sedimentary (Mason, 1966) rock types. They are unusually enriched in Zr, Y, Ce and Nd, and depleted in Cr (Fig. 6). The composition of these SG's as well as SG's from elsewhere in the Napier Complex (Sheraton, 1980; Grew, 1983) and from other granulite terrains (Vallance, 1967; Wilson, 1971; Warren, 1979; Windrum, 1983), is approximated by mixtures of Mg-chlorite, quartz and/or sericite and haematite. Therefore, the Fyfe Hills SG's probably formed from chlorite-rich precursors. Such chloritic rocks presum-

ably result from the hydrothermal alteration of volcanogenic sequences (Wilson, 1971). The low Cr-content of the SG's suggests a felsic volcanic protolith (Wilson, 1971). The extremely high concentrations of Ce, Nd and Y are most unusual for rocks of any origin (Herrmann, 1970). There is, however, evidence that REE's are mobile in the hydrothermal environment (Kerrick and Fryer, 1979), and thus are potentially capable of concentration in hydrothermally altered rocks.

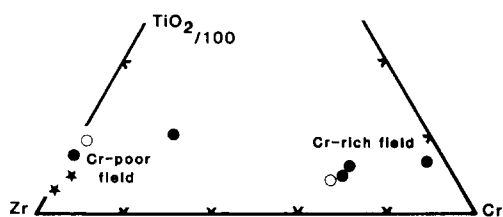


Fig. 6. $\text{TiO}_2/100\text{:Zr:Cr}$ plot for garnet-feldspar (solid circles) and sapphirine (stars) gneisses. Sheraton's (1980) average Cr-poor and Cr-rich meta-pelites are indicated by open circles.

Garnet-feldspar gneisses (GFG's)

The GFG's are pink to rusty orange, medium to coarse grained (3–6 mm) hetero-granoblastic, per-aluminous gneisses which typically, although not always, contain significant garnet and/or feldspar (and are distinguished from SG's by more silicic bulk compositions). They form approximately 10% of the outcrop and occur as laterally extensive units which only occasionally exceed 10 m in thickness (Fig. 3). At McIntyre and Hydrographer Islands, isolated blocks of GFG, interpreted as rafts (see below), occur within massive QFPG (Fig. 4C). GFG's are commonly migmatitic, and are composed dominantly of feldspar and/or garnet, but locally contain abundant quartz, sapphirine, sillimanite, orthopyroxene and phlogopite, as well as accessory corundum, spinel, ilmenite, rutile, magnetite, zircon, monazite, graphite and/or sulphide. Typical M_1 assemblages include:

mesoperthite-garnet-spinel-sillimanite-quartz-rutile
 mesoperthite-orthopyroxene-sillimanite-rutile-quartz
 mesoperthite-garnet-orthopyroxene-sapphirine-quartz-rutile
 mesoperthite-garnet-sapphirine-sillimanite-quartz
 plagioclase-garnet-orthopyroxene-quartz-rutile
 plagioclase-garnet-sapphirine-sillimanite-quartz
 plagioclase-orthopyroxene-sillimanite-quartz-rutile

Phlogopite is abundant in GFG's and, as with phlogopite in the UG's, is regarded as a product of retrograde hydration (Sandiford, 1985a). In contrast with the Amundsen Bay and Tula Mountains exposures of the Napier Complex (Ellis et al., 1980; Grew, 1982b), osumilite does not appear to be a component of the Fyfe Hills aluminous gneisses, possibly due to higher

operative metamorphic pressures stabilising the assemblage mesoperthite—sapphirine—quartz—hypersthene (Sandiford, 1985a).

The GFG's are similar to per-aluminous (corundum normative) gneisses elsewhere in the Napier Complex (Sheraton, 1980; Sheraton and Black, 1983), and have compositions consistent with derivation from clastic sedimentary precursors ranging in composition from pelites to psammites (analyses 11, 12 and 13, Table II). A metasedimentary origin is compatible with the occurrence of GFG's in association with meta-ironstones and calc-silicate gneisses, however, conclusive proof of a sedimentary origin is absent as no unambiguous sedimentary structures have been recognised. It is possible, therefore, that some Napier Complex GFG's are meta-igneous (Sheraton and Black, 1983). The sapphirine bearing GFG's are unusually magnesian compared with typical sedimentary rocks with otherwise similar chemistry (Table IV), presumably due to source enrichment in ultramafic and mafic igneous rocks (Sheraton, 1980).

As first recognised by Sheraton (1980), two distinct GFG groups occur in the Napier Complex, characterised by significant differences in Cr, V, Ni and Zn (Fig. 6). Both groups occur as laterally extensive horizons and are interlayered (see analyses 11, 12 and 13, Table II, which come from adjacent 10 cm thick horizons). Sheraton (1980) suggested that Cr-poor metapelites may have formed by the hydrothermal alteration of volcanogenic protoliths rather than by sedimentary processes, and thus may be related to the SG's which are also Cr-poor (Fig. 5). However, the differing modes of occurrence and the different bulk compositions of the Cr-poor GFG's and the SG's suggest different origins. Interlayered Cr-rich (> 500 ppm Cr) and Cr-poor (< 10 ppm Cr) GFG's have distinct mineralogical assemblages. Whereas, the Cr-rich GFG's contain abundant garnet and in some cases sapphirine and spinel, the Cr-poor GFG's contain neither sapphirine nor spinel and only minor garnet. We suggest, therefore, that Cr, V, Ni and Zn were redistributed on a centimetre-scale during the crystallisation of M_1 assemblages. While some Cr-poor GFG's have major element chemistry comparable to the Cr-rich variants (analyses 12, Table II), others are distinctly more felsic (analysis 13, Table II) and possibly represent partial melts generated during M_1 .

M_1 assemblages in GFG's are replaced by kyanite, gedrite, staurolite, biotite, cordierite, white mica (muscovite and fuchsite) and/or fibrolite (in addition to garnet and feldspar) in the RSZ's (Sandiford, 1985b).

Meta-ironstones (MI's)

Quartz—magnetite—pyroxene rocks occur as thin (< 3 m), often tectonically disrupted layers. They form a minor ($< 3\%$), sporadically distributed component of the gneissic sequence (Fig. 2). They frequently preserve evidence for the former existence of metamorphic sub-calcic ferroaugite and pigeonite (Sandiford, 1985a). They consist almost entirely of Fe_2O_3

(total Fe) and SiO₂ (analysis 14, Table II). Somewhat different bulk compositions, containing unusually high Ba and Mn, occur in a gneiss containing magnetite, spessartine, Mn-hedenbergite and hyalophane (55% celsian end member) from Mount Novogodnaya (analysis 15, Table II). Reported Ba—Mn associations, including examples from high grade terrains (Plimer and Lovering, 1983), occur typically in metasedimentary successions associated with exhalite-related base metal mineralisation. The Ba—Mn association at Fyfe Hills, therefore, probably results from exhalative processes, and provides support for arguments that other components of the gneissic sequence may derive from hydrothermally altered protoliths.

Calc-silicate gneisses (CSG's)

Isolated pods and layers of CSG have been identified at Mount Novogodnaya, Fyfe Hills and Ayatollah and Hydrographer Islands. The most common CSG paragenesis is diopside—plagioclase—scapolite. Grossular, often with a significant spessartine component, is common, especially in manganeseiferous CSG's. At Ayatollah Island, a small zoned pod 2 m in diameter occurring within GFG contains the phases diopside, grossular, calcite, plagioclase, wollastonite and scapolite, with secondary hornblende, sphene and clinozoisite; and includes, amongst others, the primary assemblage wollastonite—quartz—calcite. Diopside—plagioclase—scapolite CSG's superficially resemble metagabbros (see Black et al., 1983). However, their high CaO and MnO and low Cr contents (analysis 16, Table II), favour a metasedimentary rather than meta-igneous origin, (typical gabbro's contain 0.12 wt.% MnO and 9.5 wt.% CaO (LeMaitre, 1976) compared with the Fyfe Hills CSG values of 0.95 and 19.78 wt.%, respectively).

THE NATURE OF THE COMPOSITIONAL LAYERING

A striking feature of the gneissic sequence is its pronounced layering (Fig. 3) developed on all scales from 0.01 m to greater than 50 m. This layering has two principal components: (1) a layering defined by the bulk compositional variations in the gneissic pile; and (2) a metamorphic foliation defined by the distribution and preferred orientation of metamorphic minerals in individual compositional layers. The metamorphic foliation developed primarily as a result of deformation (Sandiford and Wilson, 1984) and is not discussed further herein. As all seven gneiss types exhibit assemblages and textures equilibrated during M₁, the lithologic sequence defined by the mutual interlayering of these gneisses (Fig. 3) represents the syn-metamorphic 'stratigraphy'. The interpretation of the nature of the layering is therefore critical to any evaluation of the pre-metamorphic history of the gneisses. It is, however, emphasized that flattening during subsequent deformation events has undoubtedly rotated many pre-existing discordances into parallelism (Black et al., 1983a; Sandiford and Wilson,

1984), and necessitates caution in the interpretation of the pre-deformational history of this compositional layering.

Systematic variations in the nature of the compositional layering allow for the distinction of two series in the Fyfe Hills region, termed the Layered Gneissic Series and the Massive Gneissic Series, respectively (Sandiford and Wilson, 1983). The preservation, albeit rarely, of discordant intrusive contacts between the two series, and the restriction of intrusive ultramafics to the Layered Gneissic Series suggests that the gneissic sequence results from the intrusion of the Massive Gneissic Series into the pre-existing Layered Gneissic Series. The validity of the distinction between the two series is strongly supported by the fact that QFPG's in the Layered Gneissic Series (analysis 1, Table III), which correspond to Sheraton and Black's (1983) depleted suite (Table V), are chemically distinct from the intrusive QFPG's in the Massive Gneissic Series (analysis 2, Table III), which correspond to Sheraton and Black's (1983) undepleted suite (Table V).

The Layered Gneissic Series

The Layered Gneissic Series comprises 60–70% of the sequence (Fig. 1), and is characterised by a pronounced layered compositional heterogeneity (Fig. 3). Individual units are rarely more than 10 m thick and are generally 0.5–3 m thick. All gneissic types are present in the Layered Gneissic Series while GFG's, SG's, CSG's, MI's and UG's are almost entirely confined to it. QFPG's and PPG's frequently occur as < 0.5 m thick, laterally persistent interlayers totally enclosed within the metasedimentary gneisses. The lateral persistence of such compositional layers is generally greater than outcrop sections (although local tectonic disruption is common) and individual units of the Layered Gneissic Sequence are readily traced from one island or nunatak to the next. This lateral persistence of thinly layered sequences including rock types of undoubted supracrustal origin, suggests that the Layered Gneissic Series is derived from a supracrustal sequence (albeit substantially modified by tectonic processes). It is suggested that most, if not all, of the PPG and QFPG in the Layered Gneissic Series is volcanic in origin, although an intrusive origin cannot be unequivocally discounted.

The Massive Gneissic Series

The Massive Gneissic Series is characterised by massive compositionally homogeneous units of intermediate to acidic QFPG (mostly charnockite but also enderbite) and, more rarely, PPG. These units characteristically exceed 50 m in thickness. Lherzolite and peridotite, which occur as intrusive sills within the Layered Gneissic Series, have not been observed in the Massive Gneissic Series. Lateral continuity of individual units has not been established beyond the scale of individual outcrops, although it is possible that charnockites on McIntyre and Ayatollah Islands form a continuous unit (Fig. 1).

The contacts between the Massive and Layered Gneissic Series are invariably concordant. However, at McIntyre Island and Hydrographer Islands, discordant contacts have been recognised between blocks of GFG, which presumably form relics of the Layered Gneissic Series, and charnockite (analysis 1, Table III) of the Massive Gneissic Series (Figs. 2 and 4C). These embayed contacts show no evidence of strain localisation and, as such, cannot result from the tectonic interleaving of different units, or from the boudinage of the GFG within the QFPG. An intrusive origin is therefore favoured. Further evidence for an intrusive origin is provided by the fact that peridotitic and lherzolitic UG's occur only in the Layered Gneissic Series, as this suggests that intrusion of the UG's preceded the emplacement of the Massive Gneissic Series (Table I).

A metasomatic or charnockitisation origin (cf. Janardhan et al., 1979; Friend, 1981) for the discordances between the GFG and the charnockites is regarded as untenable because: (1) no nebulitic development of charnockite has been observed within GFG; (2) discordant or replacement-type contacts between charnockites and GFG are very rare despite many kilometres of concordant contacts; (3) compositional zoning in either the GFG blocks or the surrounding charnockite is not well developed (Fig. 4C); and (4) variable compositional types, including PPG's, appear (on the basis that they postdate emplacement of the UG's) to be included in the Massive Gneissic Series.

Compositional variations exhibited by QFPG's (analyses 1 and 2, Table III) can best be explained by magmatic hypotheses (Sheraton and Black, 1983). QFPG's in the Massive Gneissic Series (analysis 2, Table III) are enriched in incompatible elements and in Fe_2O_3 (total Fe) with respect to comparable rocks of the Layered Gneissic Series and correspond to Sheraton and Black's (1983) "undepleted" suite which are characterised by normal (for granitic rocks) trace element abundances. In particular these intrusive gneisses do not show the extreme Y contents of the Layered Gneissic Series QFPG's (Table V). Sheraton and Black (1983) argued that the 'depleted' felsic gneisses in the Napier Complex, which define a calc-alkaline trend and which show strong LREE enrichment (as indicated by high Ce/Y, Table V), represent new continental crust derived from a garnet-bearing mafic source, and proposed a two-stage model for the origin of depleted QFPG's similar to current models for the origin of calc-alkaline rocks at modern convergent margins (cf. Tarney and Windley, 1977). In contrast, the undepleted intrusive QFPG's define a Fe-enriched trend (Sheraton and Black, 1983) and almost certainly derive from melting of crustal rocks. PPG's in the Massive Gneissic Series (analyses 3 and 4, Table IV) also tend to be enriched in incompatible elements with respect to the average composition of PPG's in the Fyfe Hills region (analysis 3, Table III). However, as all analysed intrusive PPG's contain secondary garnet, incompatible element enrichment may be due to chemical modification during subsequent metamorphism (see below).

At McIntyre Island, the intrusive charnockite contains thin dykes of basaltic composition (Fig. 4D). As these PPG interlayers contain D_1 folds (Fig. 4D), their emplacement, and that of the charnockite, must predate the M_1 and D_1 (Table I; Sandiford and Wilson, 1984). Charnockites in the Amundsen Bay region of the Napier Complex, which are otherwise similar to the charnockites of the Massive Gneissic Series described herein, were intruded during D_1 (A.C. Griffin, personal communication, 1980), while 'un-depleted' felsic gneisses at Proclamation Island are regarded by Sheraton and Black (1983) as syn- D_1 . Thus, while the emplacement of charnockite at McIntyre Island preceded the D_1 event, the magmatic episode responsible for its origin appears to have been, at least on the regional scale, broadly coeval with D_1 throughout the Napier Complex.

METAMORPHISM, PEGMATITE GENESIS AND THE GEOCHEMISTRY OF THE GRANULITES

The formation of anhydrous assemblages is a fundamental problem in the interpretation of the metamorphic and geochemical evolution of granulite terrains and has been the subject of considerable discussion (Fyfe, 1973; Tarney, 1976; Tarney and Windley, 1977; Newton et al., 1980). Two models for dehydration have been advocated: (1) the residual model in which dehydration results from the removal of H_2O -saturated granitic melts (Fyfe, 1973); and (2) the 'CO₂-flushing' model in which dehydration results from the dilution of H_2O in another species such as CO₂ (Newton et al., 1980). The principal constraints on models for dehydration of granulite terrains have largely been based on geochemical arguments. The effects of metamorphism on the bulk composition of the Fyfe Hills granulites and their retrogressed equivalents is described below to provide a basis for the interpretation of dehydration mechanisms (Table I).

The Fyfe Hills gneisses have undergone polyphase metamorphism (Table I). Unusually high grade conditions attained during the M_1 granulite facies metamorphism are indicated by the occurrence of mesoperthite-sapphirine-quartz in metasediments on McIntyre Island; an assemblage which, to our knowledge, has not been recorded from other terrains. Sandiford (1985a) estimated peak M_1 temperatures of about 900°C and pressures in the range 8–10 kbars. Subsequent metamorphism occurred during somewhat lower grade granulite conditions (M_2) and during amphibolite facies conditions (M_3 and M_4) (Sandiford, 1985a,b).

The seven gneiss groups form an extremely diverse chemical suite. Many of the gneisses have compositions similar to typical igneous and sedimentary rocks. Thus the principal control on compositional variation appears to be the primary rock forming process and the prograde granulite facies (M_1) event is believed to have had little effect on the major element chemistry of these gneisses. There is, however, evidence for redistribution of some trace elements during M_1 although, apart from the pervasive dehydration, these

effects are localised to restricted rock types. Unusually high K/Rb ratios (Fig. 7A) are exhibited by the QFPG's (average 444), PPG's (average 846) and GFG's (average 413), but not by the UG's (average 165), SG's (average 147) and MI's (average 7) (cf. Heier and Billings, 1972). K/Rb have been observed to increase dramatically at the amphibolite/granulite transition (Tarney, 1976), and thus we attribute the unusually high K/Rb ratios of some of the Fyfe Hills granulites to processes attendant with granulite facies metamorphism.

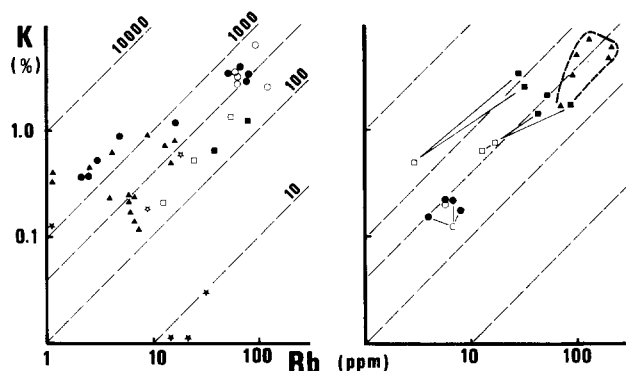


Fig. 7. K/Rb plot, Fyfe Hills/Khmara Bay gneisses. (A) Granulite facies gneisses; quartz—feldspar—pyroxene gneiss (solid circles); pyroxene—feldspar gneiss (triangle); ultramafic gneiss (open square); sapphirine gneiss (open star); garnet—feldspar gneiss (open circle); meta-ironstone (solid star); calc-silicate (solid square). (B) Selected granulite facies gneisses (open symbols) and their retrogressed equivalents (solid symbols). Circles are retrogressive 'schists', squares are retrogressive 'mylonites'. Related suites are connected by tie lines. The field defined by the late pegmatites is indicated by the heavy broken line. The K and Rb chemistry of the retrogressive mylonites is consistent with derivation from mixtures of gneiss and pegmatite.

The higher K/Rb ratios in felsic gneisses as compared with UG's, SG's and MI's may reflect the role of partial melting in the modification of the trace element chemistry of the felsic gneisses, a process for which there is evidence in the form of localised migmatite development, especially in GFGs. However, Sheraton and Black (1983) considered that partial melting was unlikely to have significantly affected the Napier Complex gneisses and argue that Rb was removed via a mantle-derived CO_2 rich fluid. This suggestion is apparently supported by the Ba/Sr ratios of the QFPG's in the Fyfe Hills region (average 6.5) which are equivalent with values from typical lower grade felsic rocks (cf. Tarney and Windley, 1977). Wholesale anatexis is predicted to result in a dramatic lowering of the restite Ba/Sr because K_d melt/restite is known to be higher for Ba than Sr (Tarney and Windley, 1977). However, discordant pegmatites assumed to have formed from anatexis during granulite facies metamorphism (Fig. 8A) differ little in trace element chemistry from the felsic gneisses from which they are believed to have been derived (analysis 5, Tables III and V). Importantly, the

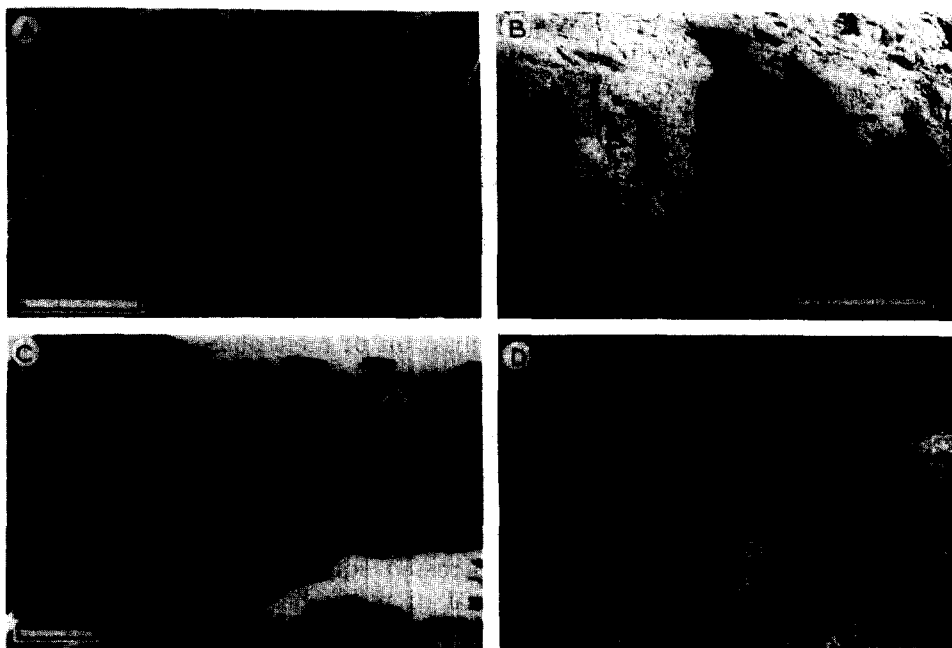


Fig. 8. (A) Sillimanite bearing early pegmatite forms an irregular discordant dyke in the hinge region of F_2 folds in garnet-feldspar gneiss. Christmas Point. The gneissic layering is highlighted by striped lines. Bar scale is 0.5 m. (B) Late pegmatite showing resorbed contacts with amphibolites, retrogressed after pyroxene-plagioclase gneisses, and quartz-biotite schists, retrogressed after quartz-feldspar-pyroxene gneiss. Transposition Point. Bar scale is 2 m. (C) Dark coloured Amundsen dyke displaced by retrogressive 'schist' zone (in the foreground) and 'mylonite' zone and associated pegmatite (in the middle distance). Christmas Point. Bar scale is 5 m. (D) Dark coloured alkaline dyke cross-cutting mylonitized, microcline rich, late pegmatite (light coloured). Hydrographer Island.

Ba/Sr, K/Rb and Ce/Y ratios in such pegmatites are not significantly different from the 'depleted' felsic gneisses. If these pegmatites are taken to represent the composition of melt generated during granulite facies metamorphism, the removal of this melt from the metamorphic pile would apparently have had little effect on the trace element geochemistry of the residual felsic gneisses. Thus, it is not at all clear how wholesale anatexis might have affected the geochemical signature of the Fyfe Hills gneisses.

DePaolo et al. (1982) recorded anomalously low U concentrations in QFPG's and PPG's from Mount Novogodnaya, a feature common to many granulites, including QFPG's throughout the Napier Complex (Sheraton and Black, 1983), and almost certainly a result of granulite facies metamorphism (Heier, 1973). Local metasomatic effects during M_1 are suggested by the correlation between Cr content and mineral assemblages in GFG's from McIntyre Island (analyses 11, 12 and 13, Table II), as well as by the evidence for reaction zoning coeval with the development of high variance

M₁ assemblages between UG's and other rock types (Fig. 5).

Significant chemical changes can be correlated with a number of episodes of retrograde hydration. These effects are observed in zones of: (1) secondary garnet and hornblende growth during waning granulite facies metamorphism (the M₂ event of Sandiford and Wilson, 1983); and (2) amphibolite grade metamorphism in the RSZ's (M₃ and M₄). M₂ garnet growth and the coeval growth of biotite and hornblende in PPG's appears to have accompanied depletion of SiO₂ (by up to 5 wt.%), Na₂O and K₂O, enrichment of FeO, V and possibly TiO₂ (analysis 4, Table II). The retrograde fluid necessary for the rehydration of the pyroxene assemblages during this event may have been released during the crystallisation of melt phases during cooling following M₁ (Sandiford and Wilson, 1984).

Two distinct types of RSZ occur in the Fyfe Hills region, termed 'schist' zones (which contain M₃ assemblages) and 'mylonite' zones (which contain M₄ assemblages), respectively (Sandiford and Wilson, 1984; Sandiford, 1985b). In addition to rehydration, the 'schists' are depleted in SiO₂ and CaO, enriched in Na₂O and Fe₂O₃ and show no substantial change in K or Rb contents, compared with unretrogressed equivalents (analysis 5, Table II; Fig. 7B); features which are typical of many basement complex retrograde zones (Beach, 1976; Etheridge and Cooper, 1981). In contrast, the 'mylonites' are enriched in SiO₂, K₂O, Rb and, to some degree, Ba (analysis 6, Table II, Fig. 7B) compared to non-retrogressed equivalents. These unusual chemical changes are attributed to the infiltration of a retrograde fluid equilibrated with the numerous pegmatites intruded at this time (Fig. 8B–D). The RSZ pegmatites (analysis 6, Table III) are readily distinguished from the granulite facies pegmatites by coexisting K-feldspar and plagioclase, and by biotite and/or muscovite. Accessory phases include garnet, kyanite, sillimanite, dumourtierite, chrysoberyl, beryl and tourmaline (Grew, 1981). These pegmatites locally assimilate the bounding gneiss (Fig. 8B), while more frequently they show abruptly discordant contacts (Fig. 8C). They are frequently deformed (Fig. 8D) and a progression from pegmatite through to mylonite has been documented (Sandiford and Wilson, 1984). In the extreme case of mylonitisation, where there is little remaining microstructural evidence of pegmatite, the chemical signature of the pegmatite is apparent as enrichment of the mylonite in Si, K, Ba and Rb (analysis 6, Table III). The K/Rb ratio of the pegmatites is distinctly lower than the granulites. The K/Rb ratio of the mylonites is intermediate between the pegmatites and the granulites (Fig. 7B).

DISCUSSION

The lithological components of the gneissic sequence at Fyfe Hills are characteristic of the Napier Complex (Sheraton et al., 1980). Particularly distinctive of the Napier Complex is the occurrence of: (1) multiple generations of mafic dykes, including unmetamorphosed Amundsen dykes; (2)

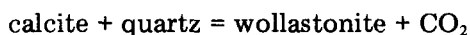
a sequence consisting of units of massive 'orthogneiss' interlayered with supracrustal successions metamorphosed in the granulite facies; and (3) sapphirine-quartz gneisses in unusually magnesian metapelitic compositions. The recognition of supracrustal gneisses at Fyfe Hills negates arguments that this sequence derives from a (metasomatically altered) intermediate intrusive complex (Sobotovich et al., 1976; Kamenev, 1982); and casts doubt on the validity of the Tula/Raggatt series subdivision of the Napier Complex (Grikurov et al., 1976) in the Fyfe Hills region. The occurrence of calcareous metasediments at Fyfe Hills is unusual, as these rock types are rare in the Napier Complex (the only previous record of calc-silicates is from Forefinger Point (E.S. Grew, personal communication, 1980) some 40 km west of Fyfe Hills). Calc-silicates have, however, been recorded from a number of localities in the Rayner Complex in western Enderby Land (Sheraton et al., 1980) and, in light of the contention that the Rayner Complex consists of reworked Napier Complex gneisses (Sheraton et al., 1980), their occurrence at Fyfe Hills is not altogether unexpected.

The composite nature of the gneissic sequence at Fyfe Hills is believed to result from the intrusion of magma as subconcordant sheets (the Massive Gneissic Series) into a preexisting supracrustal sequence (the Layered Gneissic Series). The Layered Gneissic Series is believed to have been deposited in an active volcanic environment characterised by: (1) contemporaneous eruption of acid through to basic volcanics, possibly of bimodal character; (2) immature clastic sediments derived from a provenance enriched in mafics; (3) chemical sediments including Ba-Mn-Fe rocks; and (4) local hydrothermal alteration to chlorite. Some components of the Layered Gneissic Sequence, such as meta-ironstones, invite comparison with the more familiar Archaean sedimentary deposits of the greenstone belts. However, ultramafic volcanics corresponding to the komatiites are absent, and thus such a comparison is tenuous (Viljoen and Viljoen, 1969). No pre-Layered Gneissic Series basement has been identified in the Fyfe Hills region. Indeed, as the 'depleted' QFPG's in the Layered Gneissic Series may represent new crustal material derived from subduction-related processes (Sheraton and Black, 1983), the Layered Gneissic Series may have been ensimatic.

While field evidence in the Fyfe Hills region remains equivocal, relationships between intrusive charnockites and structures elsewhere in the Napier Complex (A.C. Griffin, personal communication, 1980; Sheraton and Black, 1983) suggest that the Massive Gneissic Series was emplaced during granulite facies metamorphism. This interpretation is consistent with near isobaric cooling from peak conditions (cf. England and Richardson, 1977; Wells, 1980) following granulite facies metamorphism in the Napier Complex (Ellis, 1980; Harley, 1983; Sandiford and Wilson, 1983; Sandiford, 1985a). Input of mantle derived magmas, such as the PPG's of the Massive Gneissic Series, into the lower crust at this time would have generated the conditions required for widespread crustal anatexis. Indeed, it is likely that the 'undepleted' QFPG's of the Massive Gneissic Series formed in such

a regime (Sheraton and Black, 1983). The buoyant rise of these felsic melts may account for the deep burial of supracrustal rocks during this granulite facies event (Sandiford, 1985a).

Most aspects of the distinctive 'depleted' character of the Fyfe Hills granulites have been attributed to the nature of the primary melts (Sheraton and Black, 1983); an interpretation proposed for depleted granulites in other terrains (Tarney and Windley, 1977; Tarney et al., 1979; Weaver and Tarney, 1980). However, the selective depletion of LIL elements in these same rocks is generally regarded as the result of metamorphic processes. It has been fashionable to explain such depletions by appealing to a dehydration process involving the influx of volatile species capable of selectively mobilising LIL elements (Heier, 1973; Tarney and Windley, 1977; Newton et al., 1980). The volatile species most favoured is CO_2 derived from the mantle or lower crust. In contrast, Pride and Muecke (1980) suggested that metamorphic depletions in granulites are consistent with their being the residue of melting events. In the residue model for granulite genesis (Fyfe, 1973) the principal mechanism of dehydration is the removal of anatectic melts. Support for a residual model in preference to a ' CO_2 -flushing' model is provided by evidence that granulite metamorphism occurred under vapour absent conditions or, if vapour was present, then the composition of the vapour phase was internally buffered. Such evidence precludes ' CO_2 -flushing' which, as with all examples of infiltration metasomatism, requires an externally buffered fluid phase. The critical evidence is provided by a wollastonite—calcite—quartz assemblage (Fig. 9). Exceptionally high temperatures are required for the equilibrium relation (Valley and Essene, 1980):



at $P_{\text{CO}_2} = 8\text{--}10$ kbar (equivalent to the lithostatic pressure operative during metamorphism of the Fyfe Hills granulites; Sandiford, 1985a), temperatures which are higher than are generally considered reasonable for crustal metamorphism because they exceed the temperatures required for wholesale melting of felsic granulites at $P_{\text{CO}_2} = P_{\text{total}}$ (Wendlandt, 1981). At lower temperatures, P_{CO_2} in equilibrium with calcite, wollastonite and quartz must be much less than P_{total} . The occurrence of Ca-mesoperthite in adjacent felsic granulites requires $P_{\text{H}_2\text{O}} \leq 0.5$ kbar and temperatures in excess of 900–950°C (Sheraton et al., 1980). Since high grade metamorphic fluids are likely to be composed essentially of mixtures of CO_2 and H_2O , the local variations in P_{CO_2} and $P_{\text{H}_2\text{O}}$ imply that either $P_{\text{CO}_2} + P_{\text{H}_2\text{O}} \ll P_{\text{total}}$ giving rise to vapour-absent conditions (Grew, 1984) or that, if vapour was present, then the composition of the vapour phase was internally buffered (Powell, 1983). The low variance assemblages diagnostic of the Fyfe Hills granulites are also indicative of internal buffering of fluid compositions, and suggest that silicate liquid may have been present during metamorphism (Powell, 1983). Dehydration during such a regime is most likely to have occurred by removal of the silicate liquid. The occurrence of granulite facies pegmatites

(analysis 10, Table III) testifies to the existence of a melt phase during the granulite facies event. The principal arguments against dehydration by removal of melt relate to the geochemical signature of the granulites. However, our comparisons of the chemistry of anatectic melts with felsic granulites at Fyfe Hills show that it is not at all clear how large scale melting might have effected the chemical signature of the residual granulites, if indeed it would have any effect at all.

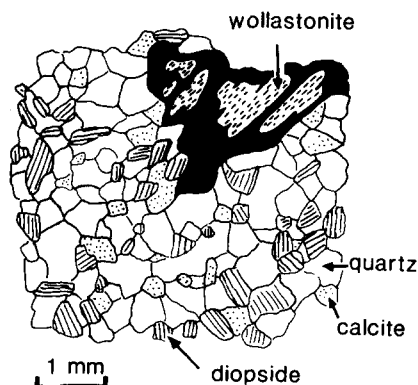


Fig. 9. Calcite—wollastonite—quartz—diopside assemblage, Ayatollah Island. Wollastonite porphyroblast is partially retrogressed.

Rehydration of the gneissic sequence, during the formation of RSZ's in the late Proterozoic and/or early Palaeozoic marked a period of extensive reactivation, which is correlated with the deformation and metamorphism of the Rayner Complex in other parts of Enderby Land (Sheraton et al., 1980). Indeed, the contention that the Rayner Complex consists partly of reworked Napier Complex gneisses is supported by the occurrence of numerous late Proterozoic RSZ's in the Fyfe Hills region (the age of these zones is constrained by the age of the Amundsen dykes (1190 ± 200 Ma) and the alkaline dykes (490 Ma), respectively (Black and James, 1983). The field relationships in the Fyfe Hills region suggest that the boundary between the two complexes is transitional, extending over a zone in excess of 30 km wide (compare with James and Black (1981), Fig. 1, which shows an abrupt boundary passing directly through the Fyfe Hills).

The origin of the retrograde fluid and the associated pegmatites during the formation of the RSZ's is problematical as the Napier Complex is believed to have been effectively anhydrous prior to this retrogression (Sheraton et al., 1980). The source of the retrograde fluid must, therefore, be exotic to the Napier Complex. The enrichment of some of the RSZ's (that is the 'mylonite' zones) in Si, K, Rb, B and, to a lesser extent, Ba is atypical of retrograde zones in basement complexes (Beach, 1976; Etheridge and Cooper, 1981). Many aspects of the chemistry of the 'mylonite' zones approximate granulite plus pegmatite (Fig. 7B). Therefore rehydration of

the Fyfe Hills granulites is believed to have been achieved by intrusion of these pegmatites (Sandiford, 1985b). Wet-melting in crustal levels beneath Fyfe Hills implies deep-crustal penetration of the retrograde fluid. Such deep level rehydration is most likely to have been achieved by thrusting of hydrous crust beneath the Fyfe Hills granulites (Sandiford, 1985b). Such thrusting accounts for the simultaneous rehydration and excavation of the granulite facies gneisses (Sandiford, 1985b). The final stages of RSZ activity in the Fyfe Hills region were marked by the intrusion of a suite of intermediate alkaline dykes (Sandiford and Wilson, 1983; analysis 7, Table III; Fig. 8D). These dykes are anomalous in that their TiO_2 contents are much lower than typical 'cratonic' alkaline dykes, but are similar to typical 'orogenic' alkaline dykes (Venturelli and Battastini, 1979). Orogenic alkaline rocks are typically intruded soon after crustal thickening and the emplacement of low-Ti alkaline dykes at the cessation of the RSZ activity may be indicative of gross continental thickening of Enderby Land at this time.

CONCLUSIONS

(1) The Archaean gneisses at Fyfe Hills consist of an older supracrustal component (the Layered Gneissic Series), deposited in a volcanic environment, which has subsequently been invaded by subconcordant intrusive sheets of felsic and mafic granulite (the Massive Gneissic Series). We have found no evidence for a metasomatic origin of charnockites at Fyfe Hills.

(2) The age of the Massive Gneissic Series is unknown but, by analogy with relationships exposed elsewhere in the Napier Complex, is believed to be broadly coeval with granulite facies metamorphism; an event which has been variously dated at 3.1 Ga (Black et al., 1983) and 2.5 Ga (DePaolo et al., 1982; Grew et al., 1982), and suggests that granulite facies metamorphism in the Napier Complex was accompanied by extensive accretion of both mantle and crustal melts.

(3) The predominance of supracrustal rocks at Fyfe Hills suggests that the Tula and Raggatt series subdivision of the Napier Complex, as originally defined by Grikurov et al. (1976), and as applied to the Fyfe Hills region by Sobotovich et al. (1976), is inadequate. Detailed investigations of contact relationships between dominantly metasedimentary and dominantly metaigneous sequences are required elsewhere in the Napier Complex before the significance of this subdivision can be properly evaluated.

(4) The close approximation of many of the Fyfe Hills granulite facies gneisses to typical protolith compositions suggests that the granulite facies metamorphism did not substantially affect the distribution of major and most trace elements. Evidence for internal buffering of vapour phases suggests that extraction of partial melt phases during this event was the primary dehydration mechanism. Substantial chemical modification has occurred during secondary garnet growth during waning granulite facies metamorphism in the late Archaean, and during late Proterozoic/early

Palaeozoic retrogression associated with the development of retrograde shear zones.

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