Aegerine–augite bearing meta-leucogabbros in the Gascoyne Complex

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Abstract

Numerous small occurrences of metamorphosed leucogabbro, quartz gabbro, and anorthosite outcrop within foliated porphyritic biotite monzogranite in the central Gascoyne Complex. These abstruse mafic rocks contain aegerine–augite, along with abundant titanite, allanite, zircon, and xenotime. The meta-leucogabbros differ from Proterozoic massif-type anorthosites, including alkaline varieties, based on their whole-rock chemistry and the composition of associated granites. The Gascoyne Complex meta-leucogabbros most likely represent a fractionated mafic–ultramafic intrusion, or intrusions, subsequently dismembered during regional deformation and metamorphism. The unusual composition of these rocks may be due to a mildly alkaline parent magma.

KEYWORDS: anorthosite, geochemistry, Paleoproterozoic, Western Australia, Gascoyne Complex, Capricorn Orogen

Introduction

Anorthosites are igneous rocks consisting of at least 90% plagioclase that can be categorized into six basic types: Archean (calcic) anorthosites, Proterozoic (massif-type) anorthosites, anorthosites in layered intrusions, anorthosites of oceanic settings, anorthosite inclusions in other rocks, and extraterrestrial anorthosites (Ashwal, 1993). Probably the most enigmatic are the massif-type anorthosites, which typically consist of large plutonic masses, with only minor associated mafic and ultramafic rock (Ashwal, 1993). Some anorthosites, such as those of the '…Aïr complex, Niger are associated with Paleozoic syenite–granite ring complexes, and may be unique' (Ashwal, 1993, p. 3).

A unit of 'alkaline anorthositic gneiss' in the Gascoyne Complex was described briefly, and partial whole-rock analyses presented for three samples by Williams et al. (1983). These rocks are largely confined to a southeasterly trending belt about 85 km long and about 10 km wide in the central part of the complex (Fig. 1). The rocks are dominated by plagioclase ($An_{10–30}$), but are unusual in that they contain a 'green clinopyroxene', in addition to abundant titanite (up to 5%), and allanite, zircon, and xenotime. These alkaline anorthositic gneisses were thought to be coeval with 'early stage gneissic' granites.

Several anorthositic gneiss occurrences from part of the central Gascoyne Complex are described here. They comprise metamorphosed leucogabbro, quartz gabbro, and minor anorthosite, and are referred to collectively as meta-leucogabbros.

Geological setting and field descriptions

The Gascoyne Complex comprises Paleoproterozoic granitic rocks and medium- to high-grade metasedimentary rocks (Williams, 1986). Extensive U–Pb zircon sensitive high-resolution ion microprobe (SHRIMP) geochronological studies show that the complex was primarily shaped by three orogenic events involving crustal formation and reworking; the 2005–1960 Ma Glenburgh Orogeny, the 1830–1780 Ma Capricorn Orogeny, and the 1680–1620 Ma Mangaroon Orogeny (Sheppard et al., 2005).

The meta-leucogabbros commonly form concentrations 2–10 km^2 in areal extent, although the largest of the individual bodies is only about 0.3 km^2. Williams et al. (1983) noted that the meta-leucogabbros always form elongate bodies that are closely associated with large masses of foliated, coarsely porphyritic biotite monzogranite. There are no minerals in the monzogranite indicative of alkaline affinity. Williams et al. (1983) placed the monzogranite into their 'early stage gneissic' granites, but a preliminary U–Pb SHRIMP date of c. 1660 Ma (Geological Survey of Western Australia (GSWA), unpublished data) shows that it is younger than their 'late stage' granites that make up the bulk of the Minnie Creek batholith to the north, which has been dated at c. 1790 Ma (GSWA, in prep.).

The meta-leucogabbros outcrop as knolls or low ridges, and are

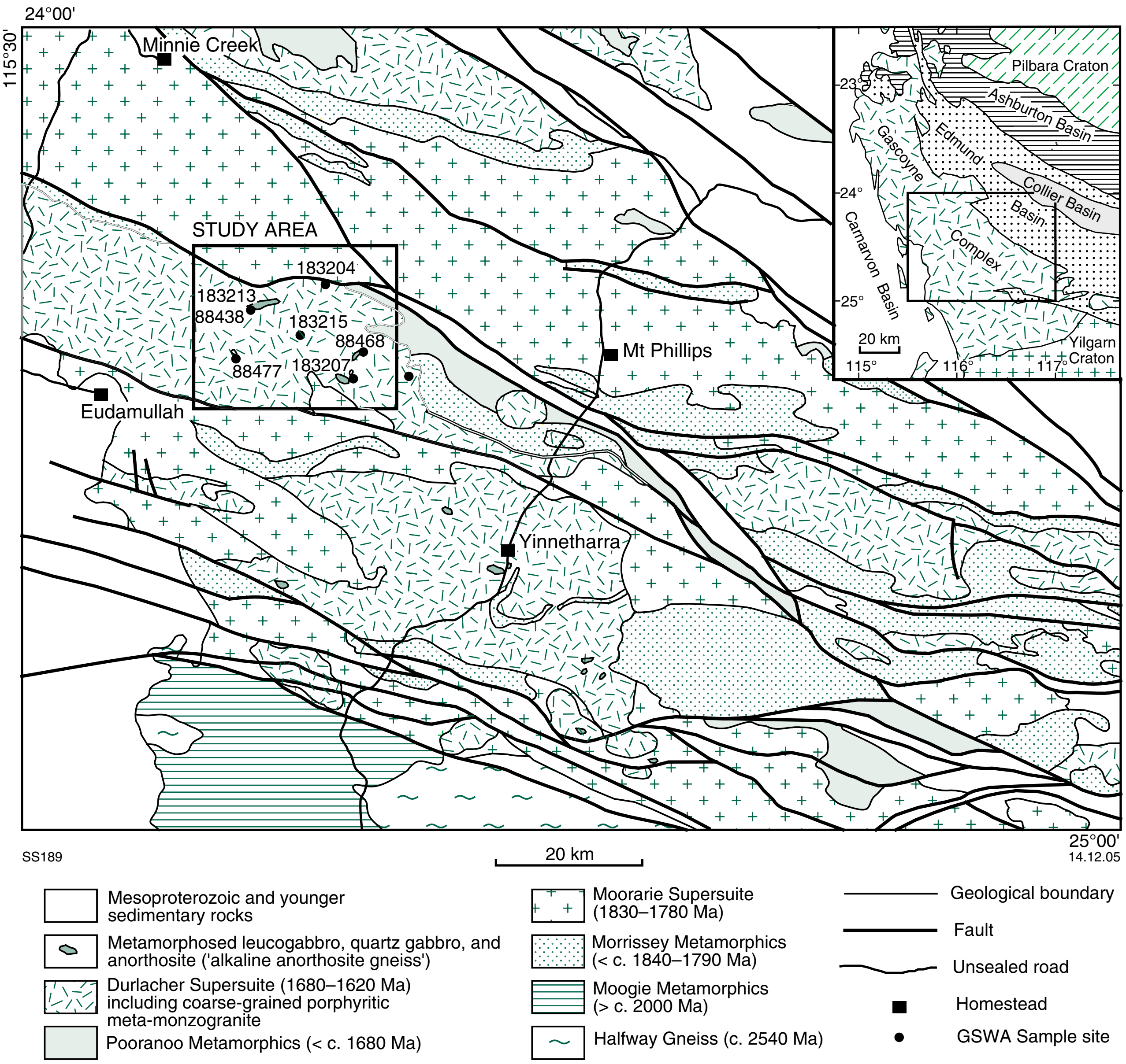

Figure 1. Sketch map of the Gascoyne Complex showing distribution of meta-leucogabbros. Inset shows outline of the Gascoyne Complex and location of the Mount Phillips 1:250 000 map sheet area. Box in main map shows study area, along with GSWA sample numbers in Table 1

commonly difficult to distinguish from the surrounding monzogranite. The meta-leucogabbros, and surrounding monzogranite, were metamorphosed at amphibolite-facies conditions, and all have the same moderate to strong tectonic foliation or L-tectonite fabric. Contacts between the meta-leucogabbros and monzogranite are typically tectonic. However, at one relatively low-strain locality 5.5 km northwest of New Well (MGA Zone 50, 392922E 7297584N), field relationships suggest that the meta-leucogabbros are older than the monzogranite; monzogranite apophyses in meta-leucogabbro are finer grained and less porphyritic than the monzogranite away from the contact, and the margins of the meta-leucogabbros are altered to epidote, whereas the adjacent monzogranite is fresh.

The meta-leucogabbros are medium to coarse grained (Fig. 2), and range from leucogabbro through quartz gabbro (all with 10–25% pyroxene or amphibole), to anorthosite (>90% plagioclase) in minor segregations. Plagioclase phenocrysts are preserved in places (Fig. 2a). Locally, the rocks contain magnetite crystals 5–10 mm in diameter. The meta-leucogabbros commonly have a weak centimetre-scale compositional layering, defined by variations in the proportion of plagioclase to the mafic silicates and oxides. A subtle compositional layering on the scale of a few metres is also present in some exposures.

a)

b)

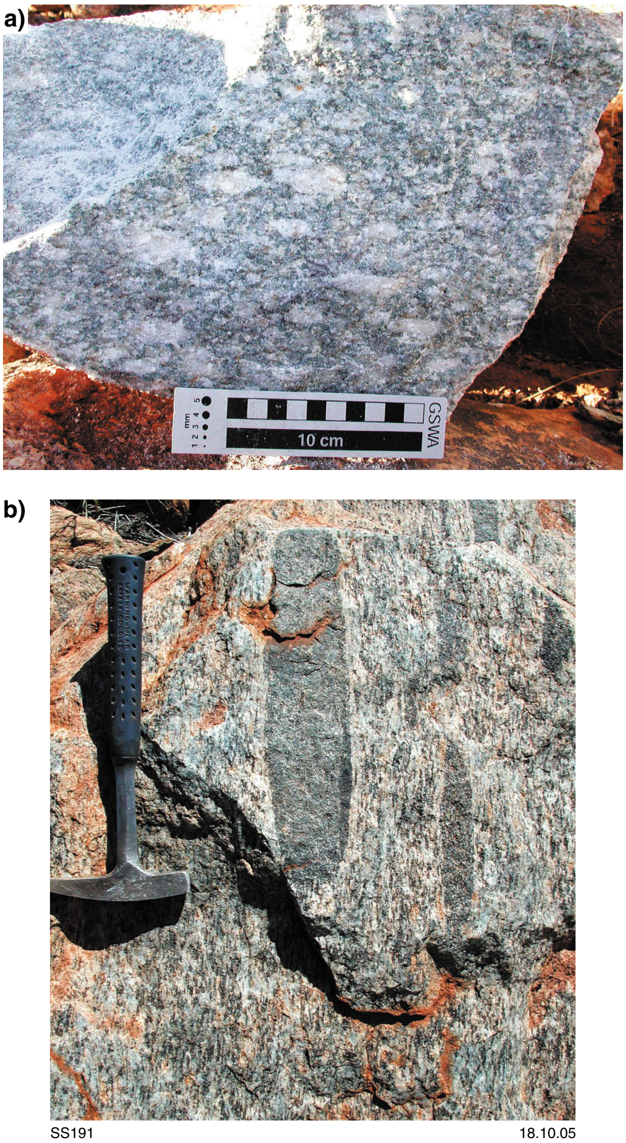

Figure 2. a) Schistose, coarsely porphyritic meta-leucogabbro with pale green aegerine–augite (MGA Zone 50, 381621E 7307421 N); b) Coarse-grained meta-leucogabbro with inclusions of amphibolite and meta-quartz diorite (MGA Zone 50, 393379E 7299597N). All rock types have a well-developed L-tectonite fabric. Hammer is 33 cm long

Meta-leucogabbro locally contains elongate inclusions of amphibolite and fine- to medium-grained metamorphosed quartz diorite (Fig. 2b). At one locality about 20 km east-northeast of Eudamullah Homestead (MGA Zone 50, 377686E 7299747N), metamorphosed leucogabbro and anorthosite, along with minor amphibolite and coarse-grained hornblendite, define a horizon about 3–4 m thick within metasedimentary schist and gneissic medium-grained monzogranite. The metamorphosed leucogabbro and anorthosite contain a centimetre- to decimetre-scale crude banding defined by layers and lenses rich in hornblende. About 200 m to the north, a foliated anorthosite layer about 10 m thick (with locally abundant epidote), is bordered by a thin band of amphibolite.

Petrography

The meta-leucogabbros comprise plagioclase (oligoclase to andesine), subordinate aegerine–augite or amphibole, and lesser amounts of quartz (5–12%), epidote, titanite, and allanite. Other minerals present include grossular, titanomagnetite, zircon, and apatite. Accessory allanite and zircon are present even in samples of amphibolite (metamorphosed gabbro).

Most of the meta-leucogabbros have an anhedral granular or granoblastic texture, but some samples (e.g. GSWA 183213) contain remnants of a subhedral granular igneous texture. In rocks with a granoblastic texture, aegerine–augite has straight grain boundaries with epidote and fine-grained titanite, and sharp boundaries with plagioclase. In some samples aegerine–augite forms oikocrysts with small inclusions of hornblende, quartz, and plagioclase. Amphibole ranges from hornblende to a sodic hornblende with deep bluish-green pleochroism. Epidote, titanite, and grossular may form fine-grained clots up to 10 mm in diameter with blebby quartz inclusions. Titanite, which constitutes about 1–5% of the rocks, forms idioblastic 1–2 mm long crystals with blebby inclusions of quartz, as well as fine-grained xenoblastic crystals. Allanite is typically partly or wholly altered and is mantled by epidote or, less commonly, titanite. Titanomagnetite has straight grain boundaries adjacent to titanite and allanite.

Whole-rock chemistry

Five leucogabbro and three associated monzogranite samples were analysed at Geoscience Australia for major and trace element compositions (Table 1). Analytical procedures are outlined in Morris and Pirajno (2005).

The meta-leucogabbros from the Gascyone Complex are characterized by high SiO_2 (60–66 wt%) relative to most anorthosites (48–54 wt%; tables 3.5 and 4.2, Ashwal, 1993), as well as much lower Sr, Ba (Fig. 3a), and Al_2O_3 contents. The Gascoyne rocks are distinguished from other

Table 1. Whole-rock analyses of leucogabbros and spatially associated biotite monzogranite

Sample ID	*183213*	*183207*	*88438*	*88468*	*88477*	*183204*	*183215*	*183216*
	Leucogabbro					*Monzogranite*		
				Oxides (wt%)				
SiO_2	59.94	63.18	60.89	60.17	65.73	70.22	67.16	68.19
TiO_2	1.21	1.10	1.18	1.37	0.40	0.48	0.74	0.41
Al_2O_3	18.47	15.28	17.88	17.49	19.04	13.65	13.95	14.93
Fe_2O_3	0.53	3.23	0.60	1.44	2.45	1.09	2.01	1.42
FeO	0.89	1.19	0.92	1.58	0.59	1.88	2.31	2.47
MnO	0.02	0.06	0.03	0.03	0.05	0.08	0.11	0.13
MgO	2.18	1.01	2.33	2.25	0.06	0.66	1.00	1.27
CaO	9.87	8.53	9.93	6.60	4.08	1.99	2.60	3.35
Na_2O	5.69	4.93	5.48	7.40	7.14	2.34	2.09	2.94
K_2O	0.15	0.33	0.13	0.28	0.18	5.65	5.58	3.64
P_2O_5	0.35	0.31	0.33	0.41	0.21	0.14	0.21	0.15
MLOI	0.45	0.55	0.05	0.66	-0.09	1.41	1.73	0.60
SO_3	0.02	0.02	0.03	0.02	0.03	0.02	0.03	0.02
O-S	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.01
Rest	0.19	0.19	0.20	0.20	0.11	0.23	0.27	0.24
Total	**100.06**	**100.07**	**100.07**	**100.09**	**100.03**	**100.06**	**100.06**	**100.03**
				Trace elements (ppm)				
As	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	0.5
Ba	102	40	102	41	2.7	853	1 031	982
Be	9.8	3.2	7.9	9.2	0.2	3.0	3.3	4.0
Cr	22	19	26	21	30	10	10	28
Cs	0.18	0.09	0.11	0.10	0.23	4.00	5.19	16.83
Cu	-1	-1	-1	-1	-1	3	10	11
F	812	876	764	1 307	308	1 672	2 354	1 302
Ga	12.0	19.2	13.6	16.0	16.8	14.4	16.1	15.4
Hf	10.8	11.5	11.1	11.3	4.1	5.3	7.4	4.6
Mo	0.6	0.5	0.7	0.2	0.2	0.5	1.2	1.0
Nb	28.3	25.3	27.1	27.7	19.0	16.7	20.4	11.0
Ni	6	3	6	7	-2	-2	3	4
Pb	10.6	16.9	12.7	11.3	9.0	43.0	45.0	28.0
Rb	1.9	3.1	2.0	1.9	2.7	244.3	257.5	149.4
Sb	3.0	7.5	1.4	0.3	0.3	2.7	2.4	9.2
Sc	21	18	22	23	18	10	13	9
Sn	5.2	5.8	5.4	6.2	8.2	4.2	4.4	3.7
Sr	386.4	350.3	352.5	249.9	244.7	108.5	143.3	254
Ta	1.8	1.6	2.0	2.1	1.5	1.0	1.4	1.1
Th	37.0	50.2	55.6	52.5	25.2	53.1	42.9	22.2
U	2.83	4.56	2.78	4.78	4.62	2.06	3.25	3.91
V	90	132	80	138	86	33	60	46
Y	48	48.8	48.9	52.8	27	34	44	21
Zn	4	11	6	12	4	34	51	47
Zr	350	332	334	351	108	190	234	161
La	91.55	101.50	116.60	130.30	38.07	86.07	71.92	41.77
Ce	169.9	189.0	222.9	262.4	92.5	149.2	137.9	77.8
Pr	19.50	21.61	25.28	27.40	8.73	18.04	16.17	8.39
Nd	76.12	87.54	98.77	104.40	32.09	68.66	62.91	31.87
Sm	13.72	14.94	16.66	17.96	5.51	11.75	11.30	5.51
Eu	2.118	2.624	2.482	3.072	1.435	1.608	1.861	1.314
Gd	11.14	12.61	12.63	14.37	4.37	8.23	8.55	4.11
Tb	1.62	1.76	1.78	2.05	0.81	1.13	1.26	0.59
Dy	9.93	10.73	10.29	11.94	4.98	5.87	7.31	3.44
Ho	1.88	2.03	1.95	2.22	0.83	1.06	1.40	0.65
Er	5.43	5.71	5.65	6.52	2.15	3.00	4.17	2.01
Yb	4.62	4.97	4.88	5.29	1.43	2.50	3.83	1.98
Lu	0.65	0.67	0.69	0.73	0.17	0.35	0.55	0.29
Na_2O/K_2O	39.2	14.8	41.2	26.0	39.9	0.4	0.4	0.8
La/Nb	3.2	4.0	4.3	4.7	2.0	5.2	3.5	3.8
Nb/Th	0.76	0.50	0.49	0.53	0.75	0.31	0.48	0.50

183213 metamorphosed leucocratic quartz gabbro or quartz diorite: oligoclase(An_{27}) –aegerine augite–quartz–titanite–allanite–hornblende
183207 metamorphosed leucogabbro: plagioclase–quartz–aegerine augite–epidote–titanite–grossular–allanite–hornblende–titanomagnetite
88438 metamorphosed quartz gabbro: labradorite (An_{55})–clinopyroxene–quartz–epidote–titanite–allanite
88468 metamorphosed quartz diorite or quartz gabbro: plagioclase–?sodic hornblende–quartz–titanite–allanite–epidote
88477 metamorphosed leucogabbro: plagioclase–quartz–titanomagnetite–titanite–allanite–apatite–zircon–garnet
183204 weakly schistose, coarse-grained porphyritic biotite monzogranite
183215 massive, coarse-grained porphyritic biotite monzogranite
183216 schistose, medium-grained porphyritic biotite monzogranite

meta-leucogabbros by their extremely high Na_2O/K_2O values (15–42 vs <7 for other leucogabbros and anorthosites in Fig. 3a), primarily due to their very low K_2O contents (Table 1). However, what really sets the Gascoyne meta-leucogabbros apart from other anorthosites and leucogabbros are their high Hf, Nb, Ta, Th, U, Y, and Zr abundances (Fig. 3a). The trace element abundances, particularly for the rare earth elements (REE), Zr, Hf, and Y, are similar to ocean island basalts (Fig. 3a). Nevertheless, there are some important differences, particularly the presence of negative Nb–Ta anomalies for the Gascoyne rocks (Fig. 3a).

The high REE abundances, and lack of a positive Eu anomaly on chondrite-normalized plots for the Gascoyne Complex meta-leucogabbros contrasts with anorthosites and most other leucogabbros (Fig. 3b), including anorthosite and leucogabbro from the Ofoud anorthosite of the Aïr region in Niger, which are associated with alkaline syenite and granite (Demaiffe et al., 1991). Figure 3 shows that the Gascoyne Complex rocks have similar trace element and REE patterns to some leucogabbros and anorthosites from the Panzhihua intrusion of southwest China (Zhou et al., 2005), although the latter usually have lower absolute abundances.

Discussion

Plagioclase in the Gascoyne meta-leucogabbros is much more sodic than in most other anorthosites (Ashwal, 1993), but the presence of epidote, titanite, and grossular in many samples suggests that the plagioclase may have recrystallized to a more sodic variety during regional metamorphism. The presence of aegerine–augite in the meta-leucogabbros makes them unique amongst anorthosites. The aegerine–augite appears to be in equilibrium with plagioclase, epidote, and fine-grained titanite, indicating it formed before or during regional metamorphism.

In igneous rocks aegerine–augite is essentially a crystallization product

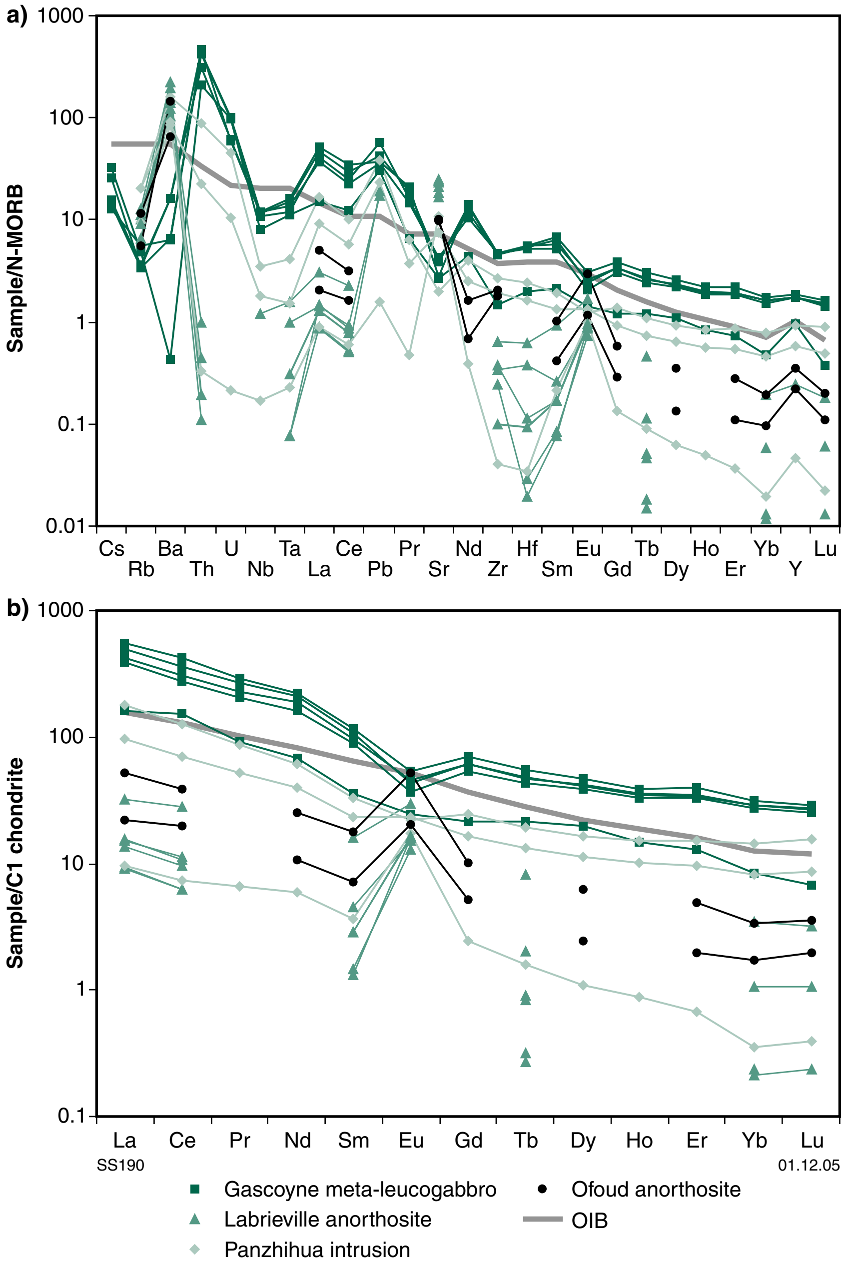

*Figure 3. **Compositions of meta-leucogabbros from the Gascoyne Complex compared with anorthosites and leucogabbros from a massif-type anorthosite (Labrieville, analyses 35, 106, 89 and 218: Owens and Dymek, 2001), a layered mafic–ultramafic intrusion (Panzhihua intrusion, analyses Lj-15, Lj-29 and Lj-40: Zhou et al., 2005), and the Ofoud anorthosite in the Aïr region of Niger (analyses OF2.2 and OF100b: Demaiffe et al., 1991). Also shown is the average ocean island basalt of Sun and McDonough (1989). Normalizing values for N-MORB in (a) and chondrite in (b) are from Sun and McDonough (1989)***

of alkaline magmas. Although there are alkaline massif-type anorthosites (e.g. Roseland and Labrieville), they lack aegerine–augite, and they have much higher K_2O contents (1.0–3.2 wt%, Herz, 1968; Owens and Dymek, 2001) than the Gascoyne meta-leucogabbros. Furthermore, most massif-type anorthosites have an areal extent of hundreds to thousands of square kilometres, and, in the associated granites, the mafic silicates '…are dominated by pyroxenes and/or olivines…' (Ashwal, 1993). Anorthosites associated with alkaline rocks of the Aïr region also do not resemble the Gascoyne meta-leucogabbros, as Aïr region anorthosites contain olivine and clinopyroxene as the main mafic silicates (Demaiffe et al., 1991).

Aegerine–augite is uncommon in metamorphic rocks, being largely restricted either to rocks that have been metasomatized before metamorphism, or to metamorphosed alkaline igneous protoliths (Deer et al., 1997). The low K_2O (and Ba) contents and extreme Na_2O/K_2O values of the Gascoyne meta-leucogabbros could be related to metasomatic alteration. It is also conceivable that the high Zr, Y, Nb, Hf, Ta, and REE contents in the meta-leucogabbros are related to alteration by a F-rich hydrothermal fluid, but this is unlikely given that the F values of the meta-leucogabbros (<1300 ppm) are lower than many igneous rocks in the Gascoyne Complex (Geological Survey of Western Australia, unpublished data).

The association of metamorphosed leucogabbro with amphibolite and hornblendite at some localities, suggests that the meta-leucogabbros may belong to the fractionated parts of a dismembered mafic–ultramafic intrusion (or intrusions). The chemistry of Gascoyne Complex meta-leucogabbros most resembles leucogabbro from the fractionated Panzhihua intrusion from southwest China, which is part of the Late Permian Emeishan Large Igneous Province. The mafic rocks in this province are interpreted to be derived from an enriched lithospheric component, similar to the source for ocean island basalt (see Zhou et al., 2005). Gabbros in the Panzhihua intrusion have positive Ti anomalies, and lack negative Nb and Ta anomalies, consistent with this interpretation. However, anorthosites in the intrusion, like the meta-leucogabbros in the Gascoyne Complex, have negative Nb–Ta (Fig. 3a) and Ti anomalies. Similarly, meta-leucogabbros in the Gascoyne Complex may have been derived from fractionation of a mildly alkaline basaltic magma.

References

ASHWAL, L. D., 1993, Anorthosites: Berlin, Springer-Verlag, 422p.

DEER, W. A., HOWIE, R. A., and ZUSSMAN, J., 1997, Single-Chain Silicates: London, The Geological Society, Volume 2A, 668p.

DEMAIFFE, D., MOREAU, C., BROWN, W. L., and WEIS, D., 1991, Geochemical and isotopic (Sr, Nd and Pb) evidence on the origin of the anorthosite-bearing anorogenic complexes of the Aïr Province, Niger: Earth and Planetary Science Letters, v. 105, p. 28–46.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, in prep., Western Capricorn Orogen (July 2005 update), 1:100 000 Geological Information Series.

HERZ, N., 1968, The Roseland alkalic anorthosite massif, Virginia, *in* Origin of anorthosite and related rocks *edited by* Y. W. ISACHSEN: New York State Museum and Science Service, Memoir 18, p. 357–367.

MORRIS, P. A., and PIRAJNO, F., 2005, Mesoproterozoic sill complexes in the Bangemall Supergroup, Western Australia: geology, geochemistry, and mineralization potential: Western Australia Geological Survey, Report 99, 75p.

OWENS, B. E., and DYMEK, R. F., 2001, Petrogenesis of the Labrieville Alkalic Anorthosite Massif, Grenville Province, Quebec: J. Petrology, v. 42, p. 1519–1546.

SHEPPARD, S., OCCHIPINTI, S. A., and NELSON, D. R., 2005, Intracontinental reworking in the Capricorn Orogen, Western Australia: the 1680–1620 Ma Mangaroon Orogeny: Australian Journal of Earth Sciences, v. 52, p. 443–460.

SUN, S.-S., and McDONOUGH, W. F., 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle compositions and processes, *in* Magmatism in the Ocean Basins *edited by* A. D. SAUNDERS and M. J. NORRY: Geological Society, London, Special Publication 42, p. 313–345.

WILLIAMS, S. J., 1986, Geology of the Gascoyne Province, Western Australia: Western Australia Geological Survey, Report 15, 85p.

WILLIAMS, S. J., WILLIAMS, I. R., CHIN, R. J., MUHLING, P. C., and HOCKING, R. M., 1983, Mount Phillips W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 29p.

ZHOU, M.-F., ROBINSON, P. T., LESHER, C. M., KEAYS, R. R., ZHANG, C.-J., and MALPAS, J., 2005, Geochemistry, petrogenesis and metallogenesis of the Panzhihua gabbroic layered intrusion and associated Fe–Ti–V oxide deposits, Sichuan Province, SW China: Journal of Petrology, p. 2253–2280.