The geochemistry of the Yule Granitoid Complex, East Pilbara Granite–Greenstone Terrane; evidence for early felsic crust

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Abstract

The middle- to late-Archaean Yule Granitoid Complex lies in the westernmost part of the East Pilbara Granite–Greenstone Terrane, and is dominated by commonly potassic, felsic, calc-alkaline granitoids, with Sr-depleted, Y-undepleted compositions, and mostly with moderate to large negative Eu anomalies. These characteristics all indicate that felsic crust was a significant component of the source. Typical Archaean tonalite–trondhjemite–granodiorite (TTG) series are not found, even amongst the very oldest (>3.4 Ga) granites. The most TTG-like granitoids are post-3270 to 2930 Ma in age, confined to the westernmost part of the complex, and share some similarities with granites found in the West Pilbara Granite–Greenstone Terrane. An abundance of post-2950 Ma granite also contrasts the Yule Granitoid Complex with complexes in the eastern part of the East Pilbara Granite–Greenstone Terrane, where such rocks are uncommon. This feature, and the presence of the c. 2945 Ma Mungaroona Granodiorite (high-Mg diorite suite) in the western part of the Yule Granitoid Complex, is probably related to the tectonic development of the adjacent Central Pilbara Tectonic Zone.

KEYWORDS: Archaean, Pilbara Craton, Yule Granitoid Complex, geochemistry

The Yule Granitoid Complex lies in the westernmost part of the East Pilbara Granite–Greenstone Terrane (Fig. 1), and is the largest outcropping granitoid complex of the Pilbara Craton. Recent studies have shown that the complex contains an extremely diverse range of rock types and has a long magmatic history of 600 million years or more. Geological and geochemical data, presented here, relating to the northern half of the exposed Yule Granitoid Complex show that recycling of early felsic crust is a major feature of the evolution of this complex. Consequently, the suggestion that old Archaean granitoid bodies are dominated by rocks of the tonalite–trondhjemite–granodiorite (TTG) series (Martin, 1994) is not always the case.

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Regional geology

The granite–greenstone terrain of the Pilbara Craton is subdivided into the East and West Pilbara Granite–Greenstone Terranes, which are separated by the northeasterly trending Central Pilbara Tectonic Zone (Fig. 1; Hickman, 1999). The East Pilbara Granite–Greenstone Terrane consists of large ovoid granitoid–gneiss complexes partially surrounded by belts of volcanic and sedimentary rocks (greenstones). The majority of the greenstones accumulated periodically between c. 3600 to 3240 Ma, whereas significant felsic magmatism occurred episodically from c. 3660 to 2850 Ma (Nelson et al., 1999). The Central Pilbara Tectonic Zone is dominated by clastic rocks of the 3000–2950 Ma Mallina Basin that obscure the boundary between the East and West Pilbara Granite–Greenstone Terranes. The Central Pilbara Tectonic Zone was intruded by a mantle-derived high-Mg diorite suite and alkaline rocks at c. 2950 Ma, and voluminous felsic granites at c. 2935 Ma (Smithies and Champion, 1999, 2000). These granites intruded both the eastern margin of the Central Pilbara Tectonic Zone and the East Pilbara Granite–Greenstone Terrane, but decrease in both age and volume away from the contact between those two terranes. Consequently, while the majority of granites in the eastern half of the East Pilbara Granite–Greenstone Terrane are older than c. 3240 Ma, a volumetrically significant, and locally dominant, component of the Yule, Carlindi, and Pippingarra Granitoid Complexes in the western part of the terrane were intruded between c. 2945 and 2930 Ma. Younger (c. 2850 Ma) two-mica granites are also more abundant within these western complexes.

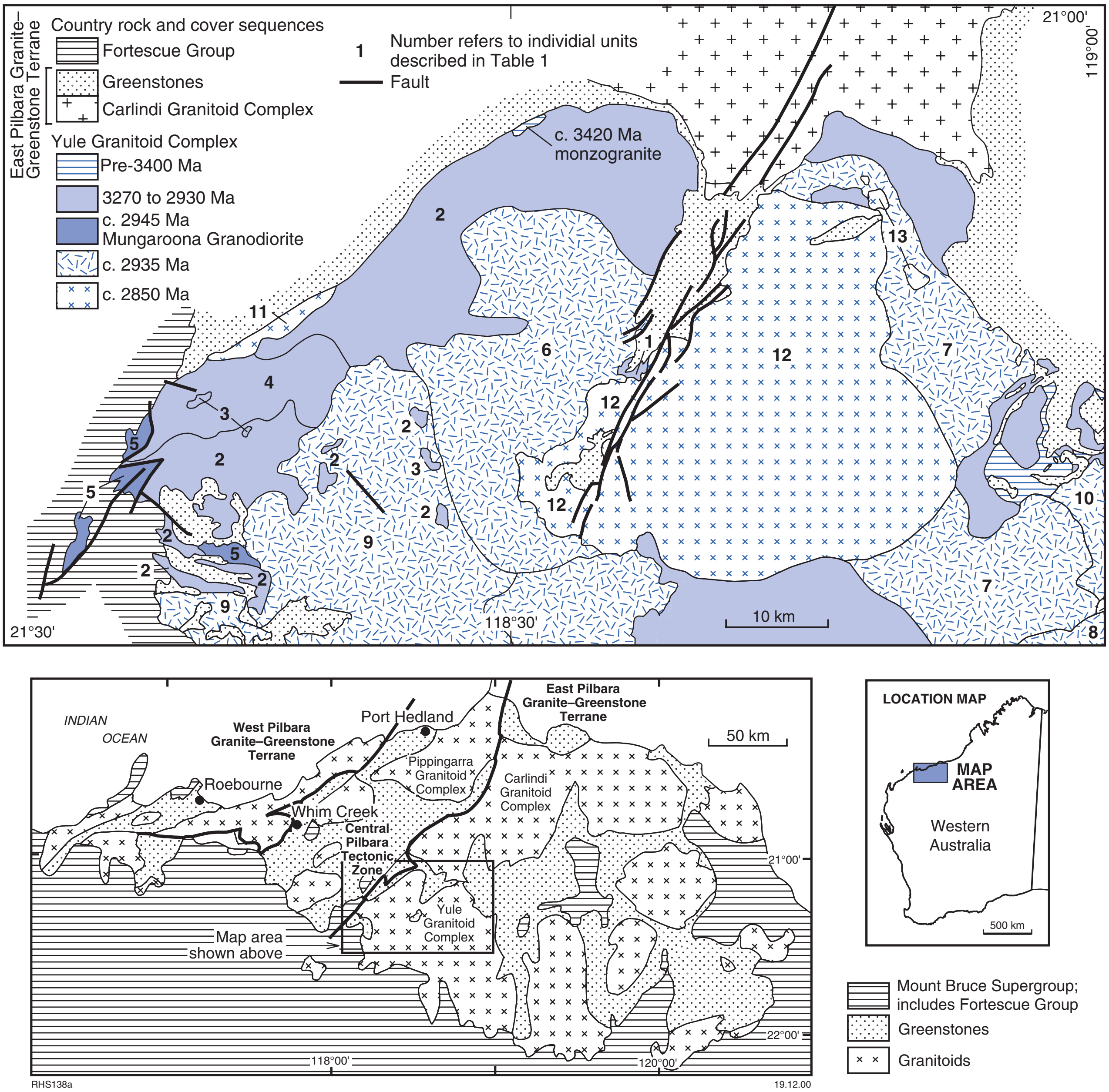

Figure 1. Distribution of granitoid units in the Yule Granitoid Complex: 1) Siffleetes Granodiorite; 2) Cheearra Monzogranite; 3) Yallingarrintha Tonalite; 4) Yandeearra Granodiorite; 5) Mungaroona Granodiorite; 6) Mungarinya Monzogranite; 7) Pincunah Monzogranite; 8) Abydos Monzogranite; 9) Powdar Monzogranite; 10) Woodstock Monzogranite; 11) Pilbara Creek Monzogranite; 12) Numbana Monzogranite; 13) Gillam Monzogranite

Geology of the Yule Granitoid Complex

Figure 1 shows the geology of the northern part of the Yule Granitoid Complex. At least 18 distinct granite phases have been mapped and many of these can be further subdivided. The emplacement age of six phases has been determined by SHRIMP U–Pb (zircon) geochronology (Van Kranendonk, 1998; Nelson et al., 1999; Nelson, 2000), whereas Nd-isotopic data place age constraints on a further three phases (Champion and Smithies, unpublished data). The age ranges of the remaining phases have been inferred primarily on contact relationships and to a lesser extent on geophysical, petrographic, and structural data. When used as the sole criterion, it was noted that neither geochemistry nor structural data provide a reliable basis for identifying individual age groups.

The oldest known intrusive phases are found at, or near, contacts with greenstone belts and include c. 3420 Ma monzogranite, the c. 3470 Ma Petroglyph Gneiss (Van Kranendonk, 1998), and other unnamed gneisses in the northeastern part of the complex. The c. 3240 Ma Kavir Granodiorite

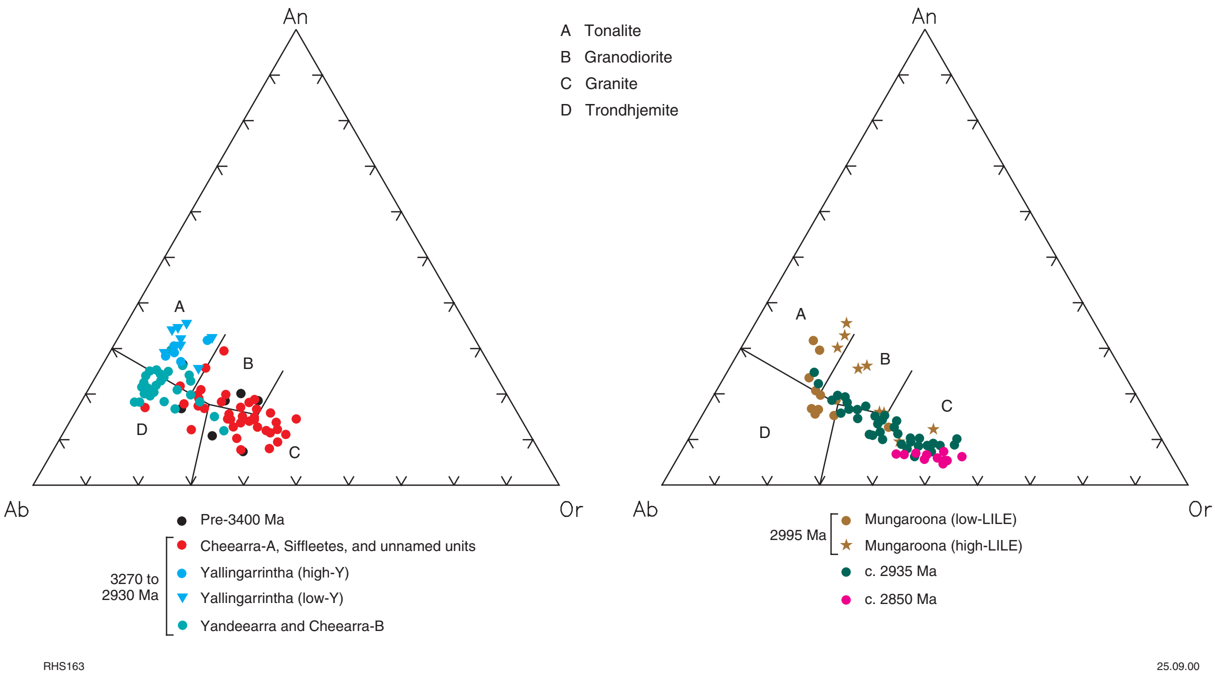

Figure 2. Normative An–Ab–Or classification diagram (Barker, 1979) for granitoids of the Yule Granitoid Complex

(Van Kranendonk, 1998) in the northeast, and the 3270 to 2945 Ma (and ?older) rocks in the western and northern parts of the complex are either in contact with the oldest phases or with the greenstones. Rocks in the southern part of the WODGINA* sheet are also probably between 3450 and 2945 Ma in age, and contain abundant greenstone enclaves, indicating that these are also marginal phases of the complex. Granites younger than c. 2945 Ma appear to form about 80% of the outcrop within the complex.

Geology and geochemistry

The granitoids of the northern part of the Yule Granitoid Complex span the range from tonalite and trondhjemite through to granite (Fig. 2). However, the great majority are calc-alkaline and monzogranitic, with the younger granites (post-2940 Ma) commonly lying at the more evolved end of this compositional range (Table 1, Fig. 2). The geochemistry of the rocks is described in terms of five groups that are defined on a basis of both age and composition. These groups include pre-3400 Ma, 3270–2930 Ma, c. 2945 Ma, c. 2935 Ma, and c. 2850 Ma granitoids (Table 1).

Old (pre-3400 Ma) granites

This is the volumetrically smallest group of granites, and the few available geochemical data are mostly from the northeastern margin of the complex. Many of the rocks are gneissic granite, locally migmatitic, commonly with biotite-rich bands, pegmatite, and granite dykes. Compositionally, they are granodiorites to granites (65–75% SiO_2) characterized by calc-alkaline chemistry, with low Al_2O_3 (13.4 – 15.8%) and moderate to high K_2O (1.6 – 4.1%). All are Sr-depleted and Y-undepleted (Fig. 3). Samples are mostly LREE†-enriched, with moderate negative Eu anomalies (Fig. 4). Two samples with biotite-rich bands have elevated HREE and Y (100 and 180 ppm), higher K_2O, and lower LREE, possibly resulting from accumulation of biotite and accessory phases.

3270 to 2930 Ma granitoids

This group comprises medium to small plutons, some of which are clearly composite (e.g. the Cheearra Monzogranite). Many contain dykes, pods, or plutons that are either known or inferred to have intruded at 2935 or 2850 Ma. This group includes tonalite and trondhjemite, as well as granodiorite and granite (Fig. 2). They are moderate- to high-K (1 – 4.7%), Sr-depleted, Y-undepleted, LREE-enriched granitoids, mostly with moderate negative Eu anomalies (Figs 3 and 4). A porphyry phase of the Cheearra Monzogranite shares similar features, but is even more strongly depleted in Sr (and has lower Al_2O_3), with correspondingly higher Y.

The Yallingarrintha Tonalite is distinct. Compared with the other rocks of this age group, it is more mafic (61–66% SiO_2), with lower TiO_2, MgO, P_2O_5, Ba, Sr, and LREE, (Fig. 3) and has low to moderate K_2O (1.1 – 2.0%) with moderate Na_2O (3.9 – 5.0%). Two subgroups are evident, with one having significantly higher Y (70–100 ppm versus 10–35 ppm), HREE, and Nb, lower La/Lu, and much larger negative Eu anomalies (Fig. 4)

* Capitalized names refer to standard 1:100 000 map sheets.

† REE = rare earth elements, including light REE (LREE) and heavy REE (HREE).

Table 1. Simplified geochemical features of granitoid units and geochemical subgroups in the Yule Granitoid Complex

Unit	*Location (number in Fig. 1)*	*SiO_2 (wt%)*	*K_2O (wt%)*	*Na_2O/K_2O*	*Eu[(a)] anomaly*	*Y (ppm)*
Pre-3400 Ma						
all units	–	66–75	1.6 – 4.1	1.5–1.0	MO (to L)	15–40
3270–2930 Ma						
unnamed units	–	73–74	4.6 – 4.7	0.7 – 0.5	MO	11
Siffleetes	1	71–72	2.5 – 4.2	1.8 – 1.2	nd	nd
Cheearra-A	2	66–74	2.0 – 4.2	2.2 – 0.7	MI to L	15–40
Cheearra-B	2	68–73	1.1 – 1.8	4.5 – 2.5	MO to L	15–50
Cheearra-C	2	67–74	1.8 – 4.6	2.0 – 0.8	N to L	7–32
Cheearra-D	2	70–74	3.2 – 4.0	1.1 – 0.8	L	35–68
Yallingarrintha (high-Y)	3	61–66	1.2 – 2.0	3.8 – 2.1	MO	72–100
Yallingarrintha (low-Y)	3	61–66	1.1 – 2.0	4.0 – 2.0	MI to P	10–37
Yandeearra	4	70–74	0.9 – 3.0	5.0 – 1.5	N to Mo	18–37
c. 2945 Ma						
Mungaroona (high-LILE)	5	54–69	1.8 – 4.7	2.0 – 0.8	MI	18–35
Mungaroona (low-LILE)	5	66–72	1.3 – 2.8	3.0 – 1.6	MI	5–26
c. 2935 Ma						
Mungarinya	6	68–74	1.8 – 5.8	1.7 – 0.5	MO to L	10–78
Pincunah	7	66–74	2.4 – 4.6	1.8 – 0.8	MO to L	10–35
Abydos	8	69.5	3.3	1.1	L	97
Powdar	9	71–74	3.4 – 5.2	1.0 – 0.6	MO to L	20–35
Woodstock	10	72–75	4.4 – 4.5	0.9 – 0.8	MO to L	9–48
c. 2850 Ma						
Pilbara Creek	11	73.5	4.5	0.9	VL	67
Numbana	12	73–76	4.6 – 5.6	0.9 – 0.5	VL	50–60
unnamed pods	–	73–75	5.1 – 5.6	0.7 – 0.6	L to VL	12–25
Gillam	13	74–75	5.1 – 5.5	0.7 – 0.6	L to VL	35–50

NOTE: (a) Size of Eu anomaly based on ratio of actual Eu value to expected value if no anomaly: positive anomaly (P) >1, no anomaly (N) = 1, minimal anomaly (MI) <1 to 0.8, moderate anomaly (MO) <0.8 to 0.5, large anomaly (L) <0.5 to 0.2, very large anomaly (VL) <0.2
nd = no data

coupled with higher and commonly constant Eu than the other. The reasons for the subgroups are not clear, particularly given the similar compositional trends. Both subgroups are Sr-depleted and Y-undepleted (Fig. 3).

The Yandeearra Granodiorite is also distinctive. Compared with the other rocks of this age group, this felsic unit (70–74% SiO_2) has low K_2O, Rb, and Sr; moderate to low Th, LREE, HREE, and Y; moderate to high CaO and Na_2O; and is typically Sr-depleted and Y-undepleted, with moderate negative Eu anomalies (Figs 3 and 4). However, it does include a Y-depleted subgroup that has no, or very minimal, negative Eu anomalies. Samples from this subgroup lie towards the mafic end of the group, but have lower Eu contents, suggesting a complex relationship between the two subgroups. Some samples of the Cheearra Monzogranite (foliated, porphyritic, and injection migmatite phases) also appear to have many similarities with the Yandeearra Granodiorite. Together, they form a group that has some similarities with the Archaean tonalite–trondhjemite–granodiorite series (see below).

2945 Ma Mungaroona Granodiorite

The Mungaroona Granodiorite ranges from diorite, through tonalite and granodiorite, to granite (Fig. 2). Two geochemical subgroups are present; a high-LILE* and a low-LILE subgroup. Compared with the low-LILE subgroup, the high-LILE subgroup has high K_2O, Ba, Rb, Pb, Th, and U, and is strongly LREE-enriched (La 250–450 times chondrite), with unfractionated HREE, and no or minimal negative Eu anomalies (Figs 3 and 4), despite its more mafic composition (<55 to 70% SiO_2). The mafic end-members of the high-LILE subgroup (<62% SiO_2) have high MgO (4–5%), Mg#† (50–60), Ni (60–90 ppm) and Cr (120–200 ppm), which, coupled with the elevated LILE contents, clearly indicate that the subgroup belongs to the high-Mg diorite suite of the nearby Central Pilbara Tectonic Zone (Smithies and Champion, 1999, 2000). The low-LILE subgroup (>70 to 66% SiO_2), is moderately LREE enriched (La 60–130 times chondrite), and also has minimal to slight negative Eu anomalies (Fig. 4). Although this subgroup shares many similarities with the c. 2935 Ma granites, their lower TiO_2 and lack of significant Eu anomalies suggest that they are more like the rocks of the high-LILE subgroup of the Mungaroona Granodiorite, to which they are probably related.

2935 Ma granites

This group comprises small to large plutons (up to 300 km²) of mainly granodiorites to granites (Fig. 2). All have calc-alkaline

* LILE = large ion lithophile element
† $Mg^{\#} = Mg^{2+}/(Mg^{2+} + Fe_{Total}) \times 100$ with Fe_{Total} as Fe^{2+}

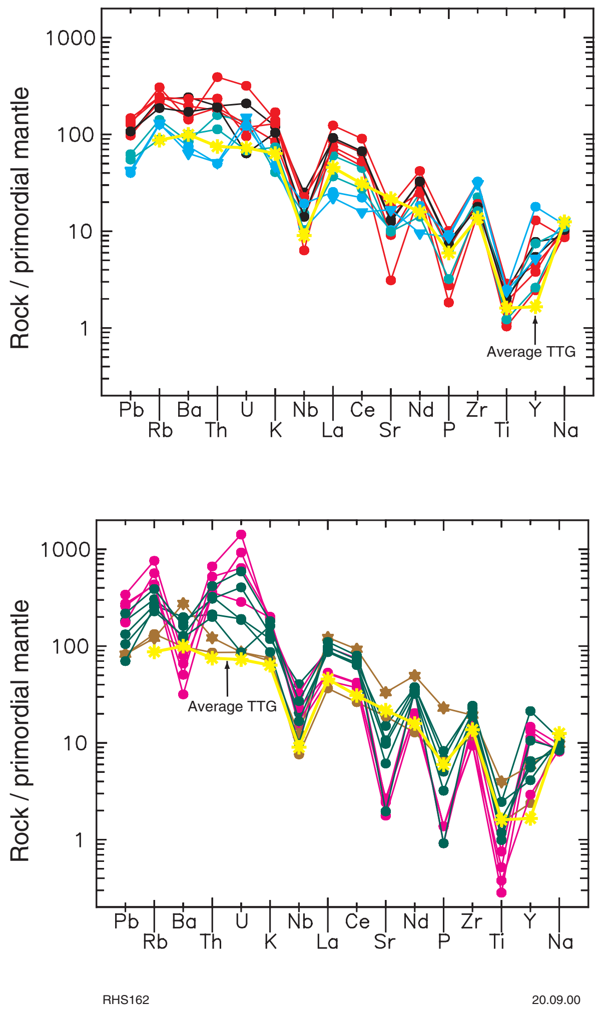

Figure 3. Primordial mantle-normalized multi-element variation diagrams showing the compositional variation of selected granitoids of the Yule Granitoid Complex. The average TTG composition from Martin (1994) is also shown. Normalizing values are from Sun and McDonough (1989). The legend for this figure is the same as Figure 2

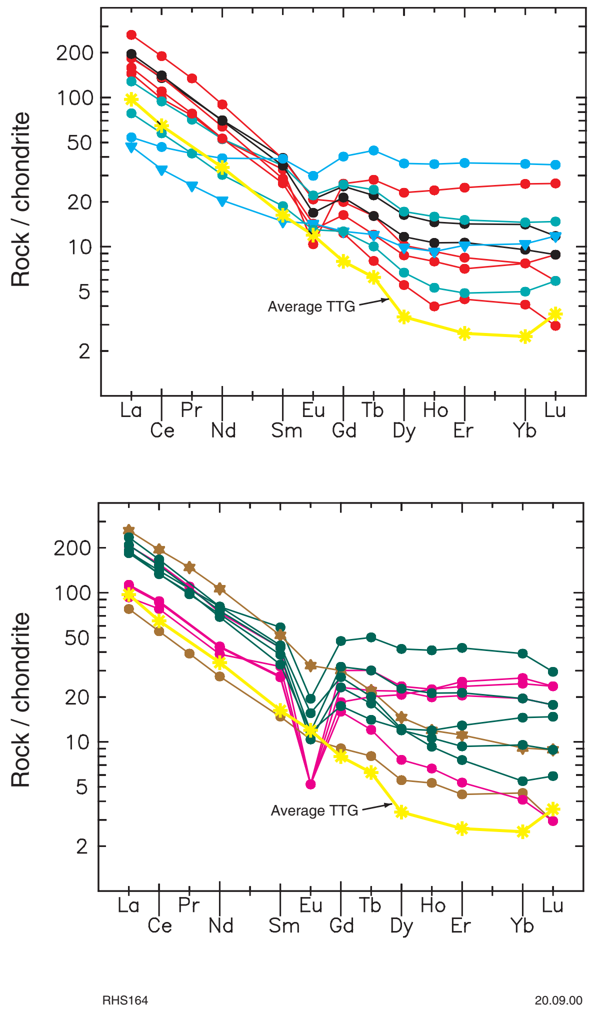

Figure 4. Chondrite-normalized rare earth element diagrams showing the compositional variation of selected granitoids of the Yule Granitoid Complex. The average TTG composition from Martin (1994) is also shown. Normalizing values are from Nakamura (1974) and Evensen et al. (1978). The legend for this figure is the same as Figure 2

characteristics, with moderate to high LILEs, and are Sr-depleted and Y-undepleted, LREE-enriched, and have moderate negative Eu anomalies (Table 1). The compositional range and trends for most elements are similar for all units, with increasing K_2O, Rb, Rb/Sr, Pb, Th, U, and K_2O/Na_2O, and decreasing Al_2O_3, Na_2O, Sr, Zn, Sc, Cr, and Ni, as silica content increases. The greatest variation between units is for the HREE and Y (Table 1, Figs 3 and 4). These rocks show extensive overlap with most of the 3270–2930 Ma granitoids, including the Siffleetes Granodiorite and the foliated, gneissic, and injection migmatite phases of the Cheearra Monzogranite.

2850 Ma granites

This group includes small pods (<1 to 10 km^2) to very large bodies (~ 400 km^2) emplaced as sheets. It also includes common to abundant pegmatites, and granite dykes intruding other granites and greenstones. The units are commonly massive and nonmagnetic, with biotite and muscovite and occasional garnet. They are typically granites (Fig. 2) that are silica rich (>73% SiO_2), with high LILE, and moderate to large negative Eu anomalies (Figs 3 and 4) and are clearly depleted in Sr and undepleted in Y. Moderate to high Rb, Rb/Sr, Rb/Ba, Ca/Sr, and K_2O/Na_2O, and low K/Rb ratios are most consistent with crystal fractionation, but could also reflect small degrees of partial melting.

Petrogenesis and discussion

Despite the range of ages (c. 3420–2850 Ma) within the northern part of the Yule Granitoid Complex, the majority of rocks share some geochemical characteristics; they have a fairly narrow silica range (66–76% SiO_2), are calc-alkaline, have moderate to high K, are Sr-depleted and Y-undepleted, and have mostly moderate to large negative Eu anomalies (Figs 3 and 4). Champion and Smithies (1998,

1999) noted that such characteristics are typical of post-3000 Ma granites in the East Pilbara Granite–Greenstone Terrane, and indicate a source that included a significant proportion of felsic crust that partially melted at low to moderate crustal pressures within the stability field of plagioclase. Such rocks also form the older (>3400–2945 Ma) parts of the Yule Granitoid Complex, indicating that a felsic crustal source must have existed before c. 3400 Ma. This is inconsistent with the notion that the majority of middle Archaean and older granitoids worldwide belong to the TTG series (Martin, 1994). More particularly, it contrasts markedly with the granitoid complexes in the eastern part of the terrane, where pre-3000 Ma, and particularly pre-3400 Ma, calc-alkaline rocks are uncommon, but where rocks showing TTG-like compositions are abundant (Champion and Smithies, 1998).

The petrogenesis of TTGs contrasts with that of calc-alkaline rocks, with the high Al_2O_3 and Na_2O, low to moderate K_2O and LILE, and Sr-undepleted and Y-depleted compositions of the former (Fig. 3) requiring high pressure (>10 kb) melting of a mafic (basaltic) source (Martin, 1994). The only pre-2945 Ma rocks from the Yule Granitoid Complex that bear any resemblance to TTGs are all from the western part of the complex, and include the Yandeearra Granodiorite, parts of the Cheearra Monzogranite, and, possibly, the Yallingarrintha Tonalite (Fig. 3). Even these differ from typical TTGs, in having commonly Sr-depleted and Y-undepleted compositions, and moderate negative Eu anomalies that are indicative of derivation at only moderate crustal pressures. This aspect, coupled with their inferred ages (post-3270–2930 Ma, Table 1), makes them most similar to TTG-like granitoids of the West Pilbara Granite–Greenstone Terrane (Smithies and Champion, 1998), and may indicate a link between the two terranes.

The other relatively mafic unit in the northern Yule Granitoid Complex is the 2945 Ma Mungaroona Granodiorite. This unit has composition features that suggest mantle derivation, and is also confined to the western part of the complex. Its distinctive chemistry indicates that it forms part of the high-Mg diorite suite that Smithies and Champion (2000) described from the adjacent Central Pilbara Tectonic Zone.
Rocks of this suite combine very mafic compositions with very high LILE and LREE and require a subduction-enriched source (Smithies and Champion, 2000).

The overwhelming abundance of post-2950 Ma granite contrasts the Yule Granitoid Complex with complexes in the eastern part of the East Pilbara Granite–Greenstone Terrane, where such rocks are uncommon. This feature, and the presence of the c. 2945 Ma Mungaroona Granodiorite (high-Mg diorite suite) in the western part of the Yule Granitoid Complex, is probably related to the tectonic development of the adjacent Central Pilbara Tectonic Zone.

Rocks of the 2945 Ma high-Mg diorite suite are concentrated within the Central Pilbara Tectonic Zone (Smithies and Champion, 2000), and Smithies and Champion (1999) argued that the thermal event responsible for the c. 2930 Ma granites was directly related to generation and emplacement of the earlier mantle-derived high-Mg diorite suite.

The 2850 Ma granites are present across the Eastern Pilbara Granite–Greenstone Terrane, but are significantly more abundant in the Yule Granitoid Complex (and the Carlindi and Pippingarra Granitoid Complexes to the north). However, they do not continue westwards into the Central Pilbara Tectonic Zone or Western Pilbara Granite–Greenstone Terrane (Smithies and Champion, 1998). The significance of these rocks and their distribution is not yet understood.

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