Geochemistry of the Corunna Downs Granitoid Complex, East Pilbara Granite–Greenstone Terrane, Western Australia

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Abstract

About 80% of the Archaean Corunna Downs Granitoid Complex in the East Pilbara Granite–Greenstone Terrane consists of c. 3315 Ma monzogranites. The monzogranites are typically highly fractionated, K rich, Al poor, and have trace element compositions consistent with remelting of an older tonalitic–trondhjemitic–granodioritic (TTG) crust at a mid-crustal level. The remaining 20% of the complex comprises tonalites, trondhjemites, and granodiorites. Some of these granitoids are as old as c. 3400 Ma, but the majority are similar in age to the monzogranites. The tonalites, trondhjemites, and granodiorites have high Y and Yb, and low Sr and Al_2O_3 concentrations compared to classic Archaean TTGs, which are thought to form through high-pressure melting of hydrated mafic crust. In contrast to TTGs, the tonalitic, trondhjemitic, and granodioritic rocks of the complex have a low-pressure, mid- to lower-crustal, amphibolite source that was garnet free and probably also had residual plagioclase. It is proposed that at the same time as mid-crustal melting of TTG occurred to form the monzogranites, melting of an associated mafic intraplate formed the tonalites, trondhjemites, and granodiorites.

KEYWORDS: Archaean, Pilbara Craton, Corunna Downs Granitoid Complex, tonalite, trondhjemite, granodiorite, granite.

Introduction

Rocks of the Archaean tonalite–trondhjemite–granodiorite (TTG) series formed by melting of hydrous mafic crust at high pressure (e.g. Rapp et al., 1991). Although it is still widely accepted that most Archaean granite–greenstones are dominated by TTG (e.g. Condie, 1981; Windley, 1995), some late Archaean terrains (e.g. the Yilgarn Craton) are clearly dominated by K-rich granitoid rocks that are derived through remelting of older felsic (TTG-dominated) crust (Sylvester, 1994; Champion and Sheraton, 1997; Champion and Smithies, 2000). The evidence so far from the granitoid complexes of the Pilbara Craton is that the amount of TTG preserved is very small, and that these complexes are dominated by K-rich granitoids (Collins, 1993; Champion and Smithies 1999, 2000). This observation is important because it implies that a much greater degree of crustal reworking has occurred in the Pilbara Craton than is required by TTG-dominated crust. Here we discuss the geology and geochemistry of the Corunna Downs Granitoid Complex (CDGC) in the southeastern part of the East Pilbara Granite–Greenstone Terrane (EPGGT; Fig. 1). This complex is unusual for the Pilbara Craton because it lacks rocks of the classic Archaean TTG series (Rapp et al., 1999), although it does contain tonalite, trondhjemite, and granodiorite (Fig. 2). This study is based largely on geochemical analyses of about 200 samples that were collected in the early 1980s (Davy, 1988) and have recently been reanalysed by Geoscience Australia (formerly Australian Geological Survey Organisation).

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Geological setting

The CDGC has an elliptical and domal shape with a long axis of about 50 km, and is surrounded by greenstone belts (Figs 1 and 2). The greenstones comprise dominantly greenschist-facies volcanic rocks of the Warrawoona Group, which is dated between c. 3480 and 3325 Ma, and lesser amounts of metamorphosed sedimentary rocks, and ultramafic, mafic, felsic, and intrusive rocks (Bagas and Van Kranendonk, in prep.). This succession is unconformably overlain by the c. 3310 Ma Budjan Creek Formation, which in turn is unconformably overlain by the dominantly clastic rocks of the Gorge Creek Group dated at younger than 3235 Ma. The entire volcano-sedimentary succession dips and youngs away from the CDGC, and all granite–greenstone contacts are intrusive.

Several generations of granitic magmatism have been documented from granitoid complexes of the EPGGT (Hickman, 1983). Major magmatic age ranges include 3470–3410, 3330–3100, 3000–2930, and c. 2850–2830 Ma (Champion and

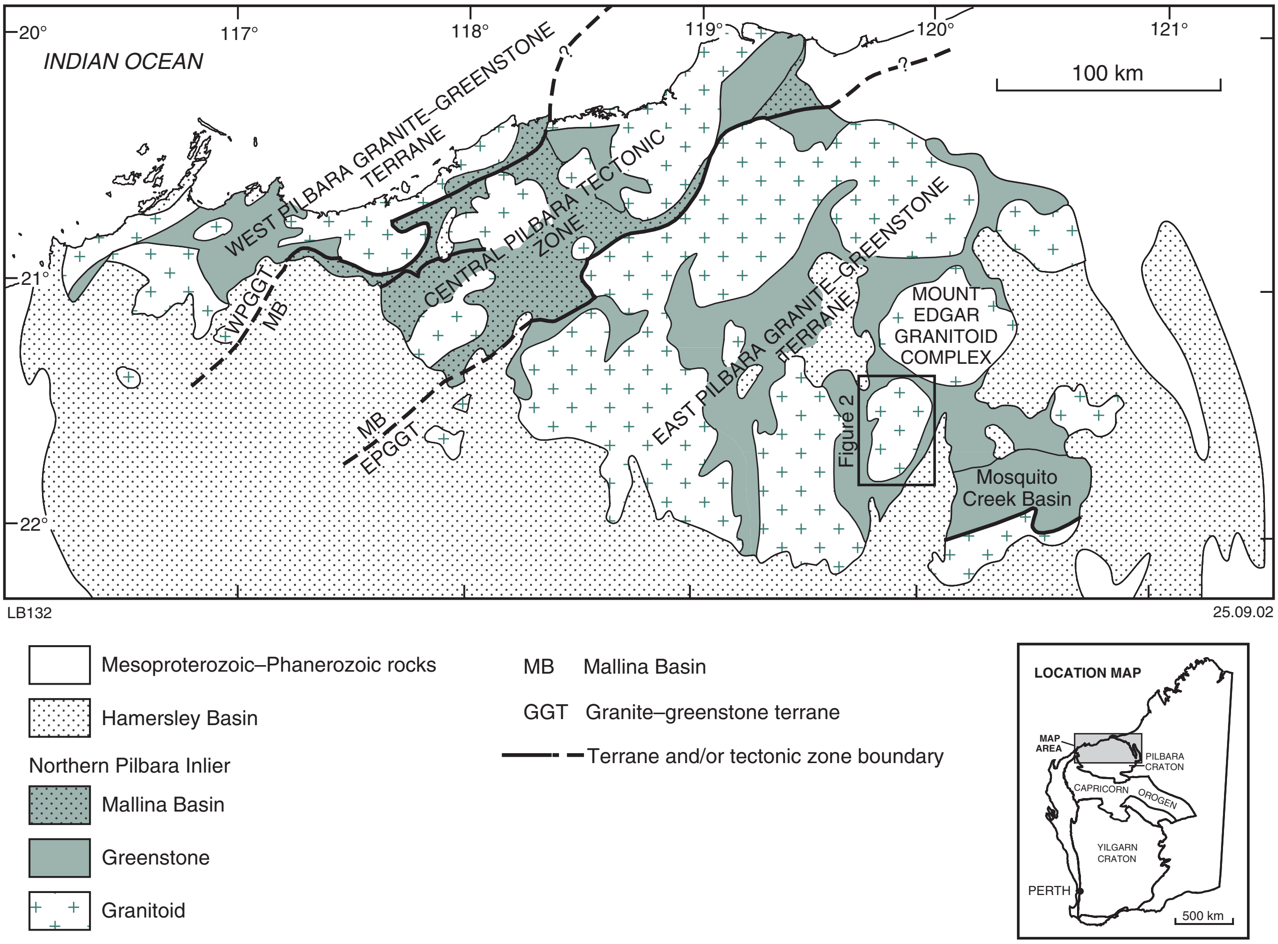

Figure 1. Location of the Corunna Downs Granitoid Complex and distribution of granitoids

Smithies, 1999). The older period of magmatism (3470–3410 Ma) included locally significant TTG magmatism representing high-pressure melting of a mafic source (Champion and Smithies, 1999). Younger TTG-type rocks are present in the West Pilbara Granite–Greenstone Terrane and Central Pilbara Tectonic Zone (Fig. 1; Champion and Smithies, 1999, 2000), but are rare in the EPGGT. Most magmatism after c. 3400 Ma represents remelting of older crust, including TTG older than 3400 Ma, to produce moderate- to high-K monzogranite (Champion and Smithies, 1999).

In contrast to most other granitoid complexes of the EPGGT, most granitoids in the CDGC fall within a narrow intrusive age range of around 3317 to 3307 Ma (Nelson, 2001, 2002, in prep.), including the 3315 Ma Boobina Porphyry (Barley and Pickard, 1999). These rocks were emplaced contemporaneously with felsic volcanic rocks in the surrounding greenstone belts, including the c. 3325 Ma Wyman Formation and felsic lithic tuff in the c. 3308 Ma Budjan Creek Formation (Nelson, 2001).

Geology of the Corunna Downs Granitoid Complex

The Corunna Downs Granitoid Complex can be subdivided into the following readily mappable units (Fig. 2).

Nandingarra Granodiorite

The Nandingarra Granodiorite (Bagas and Van Kranendonk, in prep.; *AgOna**) forms an elliptical body of fine- to coarse-grained, equigranular, biotite granodiorite, with lesser amounts of tonalite and monzogranite. Rocks along the eastern margin of the body show a more restricted compositional range from tonalite to granodiorite, and contain hornblende as an additional mafic mineral. The eastern edge of the Nandingarra Granodiorite contains biotite tonalite to granodiorite with minor microcline.

Sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon ages of c. 3427–3408, 3313 ± 3, and 3300 ± 3 Ma from tonalites (Nelson, 2002) indicate that the Nandingarra Granodiorite is a composite body that includes older components.

Tonalite

Fine- to medium-grained tonalite (*AgOt*), containing minor amounts of hornblende and microcline, is

* Codes refer to units shown on the SPLIT ROCK 1:100 000 geological series map (Bagas and Van Kranendonk, 2002).

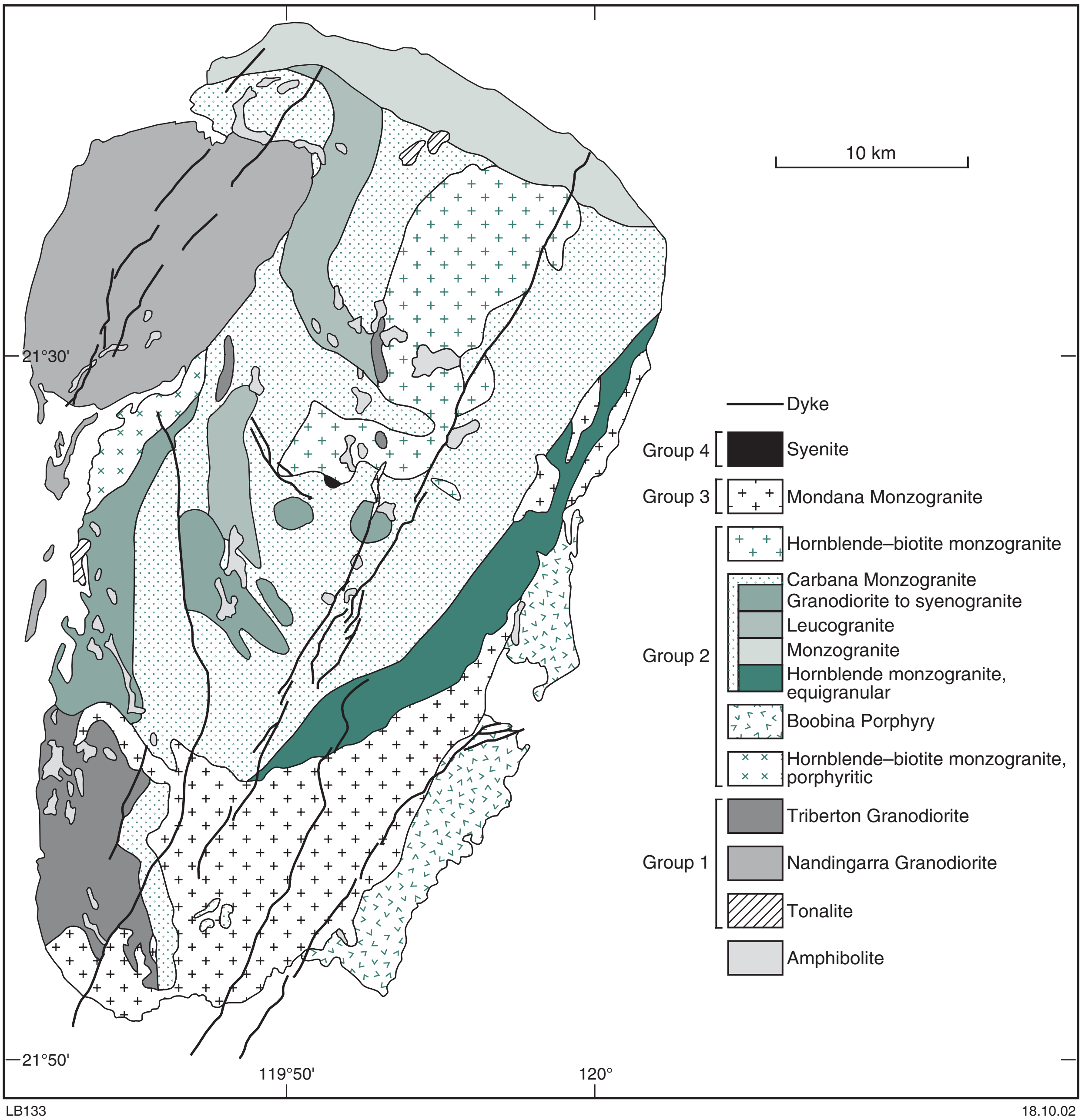

Figure 2. Geology of the Corunna Downs Granitoid Complex

exposed near the western and northern edges of the Carbana Monzogranite (Fig. 2).

Triberton Granodiorite

The Triberton Granodiorite (Bagas and Van Kranendonk, 2002; *Ag*o*tr*) is a porphyritic, medium- to coarse-grained, biotite–hornblende granodiorite with minor medium-grained tonalite and porphyritic monzogranite containing abundant mafic xenoliths.

Carbana Monzogranite

The Carbana Monzogranite was previously called the 'Carbana Pool Adamellite' by Hickman and Lipple (1978). The redefined Carbana Monzogranite now includes the granitic rocks forming most of the northern two-thirds of the CDGC. The Carbana Monzogranite includes fine- to coarse-grained, plagioclase-phyric biotite monzogranite to granodiorite (*Ag*o*ca*) with minor pegmatitic dykes, as well as fine- to medium-grained, equigranular to slightly porphyritic, hornblende monzogranite. The Carbana Monzogranite commonly contains abundant mafic xenoliths that were probably derived from the Warrawoona Group.

Four samples of the Carbana Monzogranite give SHRIMP U–Pb zircon ages of 3313 ± 9 and 3317 ± 2 Ma (Barley and Pickard, 1999), and 3315 ± 6 and 3314 ± 4 Ma (Nelson, in prep.). The monzogranite is locally intruded by hornblende-bearing monzogranite (*Ag*o*mh*) with a SHRIMP U–Pb zircon age of 3307 ± 4 Ma (Nelson, 2000).

Boobina Porphyry

The Boobina Porphyry (*AgObo*), originally defined by Lipple (1975), is a hornblende-bearing, quartz–feldspar porphyry with a glassy pink to purple matrix, which has intruded the Warrawoona Group along the eastern margin of the CDGC (Fig. 2). The Boobina Porphyry hosts a number of copper-mineralized quartz veins and has a SHRIMP U–Pb zircon age of 3315 ± 4 Ma (Barley and Pickard, 1999).

Mondana Monzogranite

The Mondana Monzogranite (*AgOmo*) was originally defined as the 'Mondana Adamellite' by Hickman and Lipple (1978), and is now known to have a smaller areal extent (Fig. 2). The monzogranite has intruded both the Triberton Granodiorite and the Boobina Porphyry in the southeastern part of the CDGC, and extends as a series of narrow bodies along the northeastern margin of the complex. The monzogranite is fine to medium grained and leucocratic, and includes abundant quartz-rich aplite dykes.

Syenite

A small and isolated outcrop of fine- to medium-grained, equigranular to porphyritic syenite (*AgOs*) in the centre of the Carbana Monzogranite (Fig. 2) consists of microcline, euhedral plagioclase commonly altered to epidote–sericite–albite–carbonate, relic biotite altered to chlorite, and less than 10% quartz. This syenite has not yet been dated.

Geochemistry

The samples collected by Davy (1988) included low-silica, mafic-xenocrystic granodiorite from the Nandingarra Granodiorite, mafic hornfels, and samples of dolerite dykes. These samples were considered to be contaminated or xenolithic and have been excluded from this study.

Selected trace element concentrations plotted against SiO_2 content (Fig. 3) for granitoids of the CDGC show a decrease in Na_2O with increasing K_2O and SiO_2 in contrast to a typical tonalite trend, which has increasing Na_2O with increasing SiO_2. The K–Na–Ca plot of Defant and Drummond (1993) also shows that the granitoids of the complex do not have typical TTG trends (Fig. 4). Most of the granitoids in the complex fall in the high-K calc-alkaline field of Le Maître (1989; Fig. 2). The tonalitic, trondhjemitic, and granodioritic rocks fall in the medium-K field and comprise about 20% of the analysed sample suite and a similar proportion of the outcrop area of the CDGC.

The rocks of the CDGC can be broadly subdivided into four groups that show progressively higher K_2O/Na_2O values (Fig. 3):

- Group 1 includes medium-K rocks with high Na_2O and Al_2O_3 and low K_2O/Na_2O (Fig. 3), which includes the Nandingarra Granodiorite, Triberton Granodiorite, and an unnamed tonalite from the northern part of the complex. This group commonly has the highest Mg# (Mg number*), which is typically between 35 and 43 (Fig. 5). This group also has notably lower SiO_2 than Groups 2 and 3.
- Group 2 includes high-K rocks with higher K_2O/Na_2O and lower Al_2O_3 than Group 1 rocks, and includes various granitoids of the Carbana Monzogranite, Boobina Porphyry, and the unnamed bodies of hornblende monzogranite.
- Group 3 includes highly leucocratic high-K rocks that commonly have higher SiO_2 and K_2O/Na_2O than Group 1 and 2 rocks, and the lowest Al_2O_3, CaO, MgO, and Fe_2O_3. These compositions are consistent with these rocks representing highly fractionated examples of Group 2. However, rocks of Group 3 form discrete intrusions, including the voluminous Mondana Monzogranite in the southwest of the CDGC.
- Group 4 is the syenite to quartz syenite that forms an isolated outcrop in the centre of the complex (Fig. 2). The syenite has higher total alkalies and Al_2O_3 and lower SiO_2 compared to rocks of the other groups.

Although rocks from Groups 1 and 2 partially overlap in terms of major element composition (Fig. 3), distinct trends for Y versus K_2O (Fig. 6) indicate that these two groups cannot be cogenetic. The highly fractionated Mondana Monzogranite (Group 3) has significantly higher Y, Rb, and Th concentrations and lower Sr concentrations than rocks of Group 2 for a given silica content. The combined major and trace element geochemistry of the CDGC granitoids suggests that compositional trends from Groups 1 to 2 and 3 commonly reflect progressively more fractionated compositions, whereas rocks of Group 1 are not directly related to rocks of Groups 2 and 3 genetically.

Average chondrite-normalized rare earth element (REE) patterns for the four groups in the CDGC are shown in Figure 7. The rocks exhibit strongly fractionated light REE (LREE) patterns with high La/Gd values, but nearly constant normalized heavy REE (HREE) concentrations. The tonalitic, trondhjemitic, and granodioritic rocks of Group 1 have a small negative Eu anomaly, whereas Group 2 shows a moderately negative Eu anomaly. Group 3 (Mondana Monzogranite) and Group 4 (syenite) have large negative Eu anomalies. Group 3 differs from Group 4 in having less variation in the LREE patterns. The REE pattern for rocks in Groups 2 and 3 are very similar to those of post-3300 Ma monzogranites in other parts of the East Pilbara Granite–Greenstone Terrane (Champion and Smithies, 2000).

Archaean TTG suites are typically characterized by a large silica range with an average SiO_2 content of about 70 wt % (Barker and Arth, 1976; Barker, 1979). They are sodic, with moderate K_2O and high Na_2O/K_2O (>1). They also are typically aluminous rocks (Al_2O_3 >15 wt % at 70% SiO_2), with high Sr and Ba (both >500 ppm), are LREE enriched (e.g. La/Yb >30), and HREE depleted (e.g. Yb<0.5 ppm) (Barker and Arth, 1976; Barker, 1979; Martin, 1994, 1999). Using these criteria, none of the rocks of the voluminous CDGC conform to a classic Archaean TTG suite. Most notably, even the tonalitic, trondhjemitic, and granodioritic rocks of Group 1 are too low in Al_2O_3 and too rich in Y (and HREE; see Figs 3 and 7). This supports the suggestions that the majority of true

* Mg # = 100×Mg/(Mg+ΣFe^{2+})

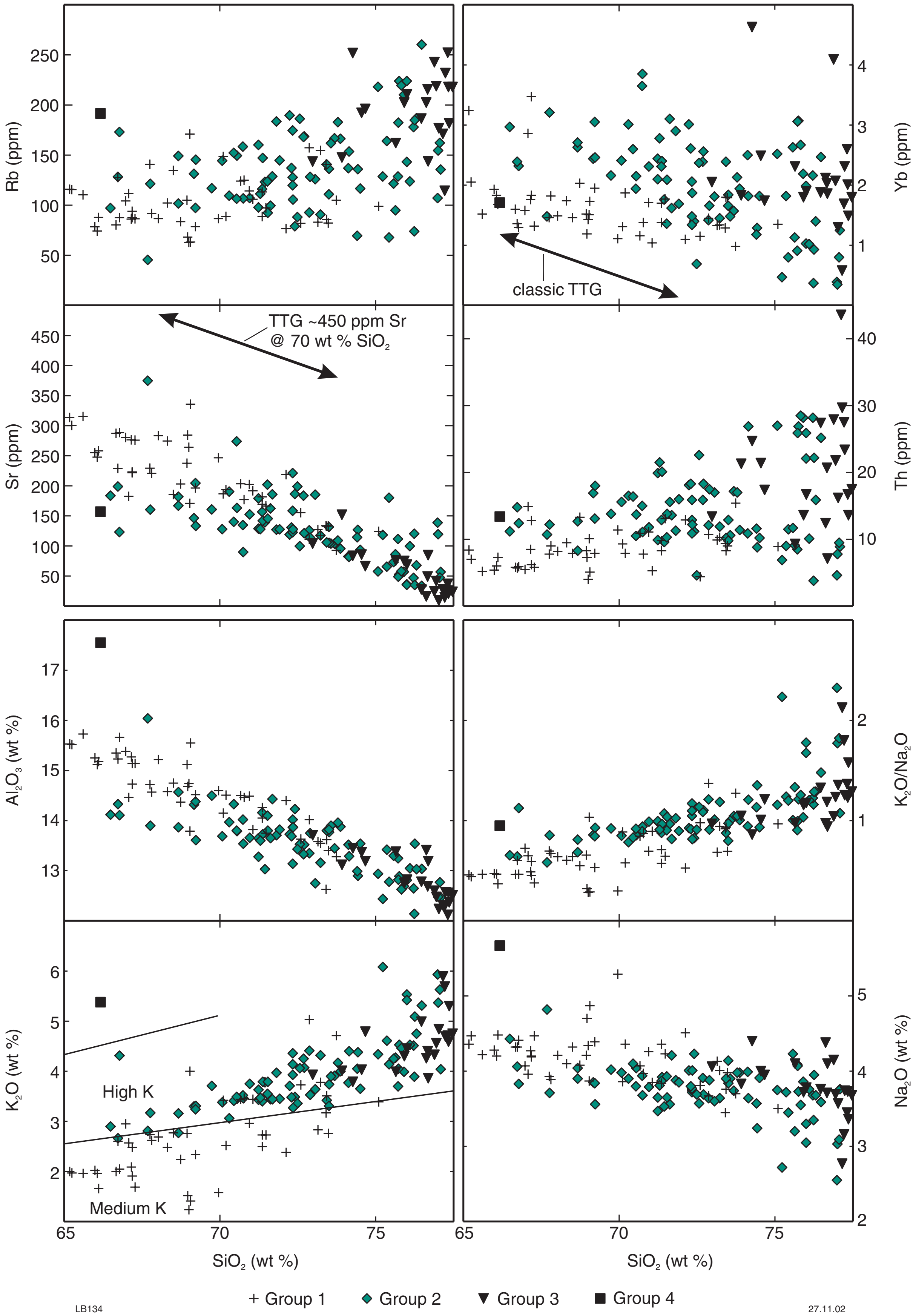

Figure 3. Harker (1909) variation diagrams showing the four major subdivisions of granitoids from the Corunna Downs Granitoid Complex

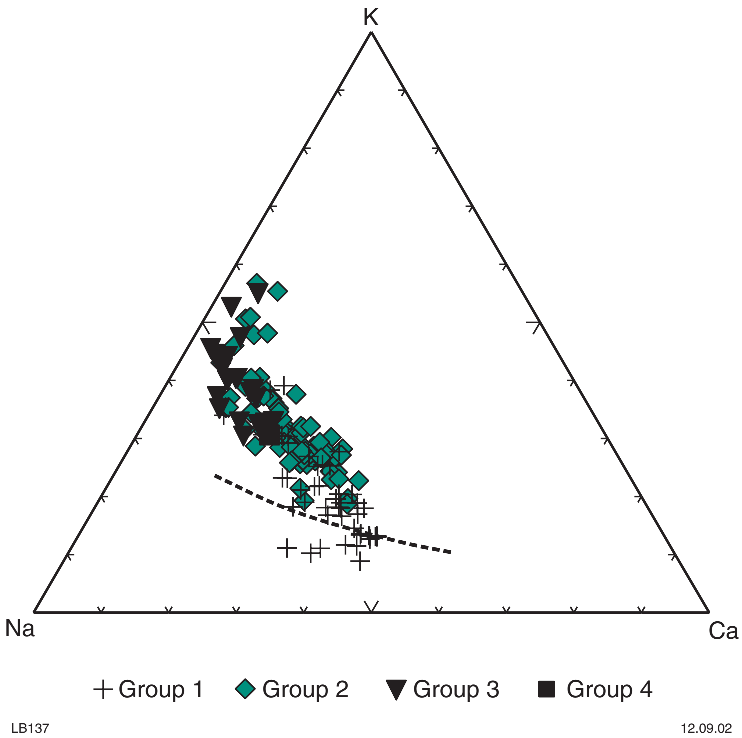

Figure 4. Ternary Ca–Na–K diagram of Archaean tonalite–trondhjemite–granodiorite. The dashed curve represents the trend of Defant and Drummond (1993)

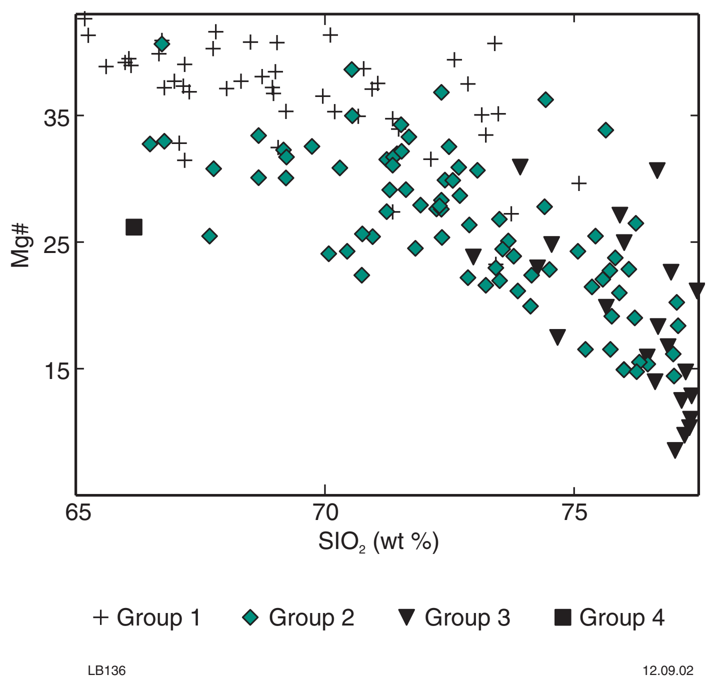

Figure 5. Plot of Mg# versus SiO_2 for the granitoid rocks in the Corunna Downs Granitoid Complex

TTGs in the Pilbara Craton are restricted to the older (>3440 Ma) rocks of the granitic complexes of the East Pilbara Granite–Greenstone Terrane, and that extensive recycling of old TTG to produce voluminous high-K magmatism was not restricted to the late Archaean (i.e. post-2800 Ma; Champion and Smithies, 1999).

Petrogenesis

A large proportion of the rocks of the CDGC (Groups 2–4) have compositions very similar to many (mostly post-3.3 Ga) high-K monzogranites throughout the Pilbara Craton (Champion and Smithies, 2000). These high-K monzogranites have a fairly narrow silica range (66–76%), are calc-alkaline, Sr depleted, and Y undepleted, and have mostly moderate to large negative Eu anomalies (Champion and Smithies, 1999, 2000). Such characteristics are thought to result from remelting of older TTG (Champion and Smithies, 1999, 2000). The tonalitic, trondhjemitic, and granodioritic rocks (Group 1) comprise 20% of the CDGC, but cannot be explained by the same process because they require a more mafic source.

Experimental results show that tonalitic to low- to medium-K granodioritic melts can be generated by low degrees of partial melting (<10%) of mafic crust at 8–16 kbar (e.g. Rapp et al., 1991). Melting in the presence of garnet leads to melts with high La/Yb values and very low Y and HREE concentrations (e.g. Sen and Dunn, 1994), whereas an absence of plagioclase in the residual assemblage results in melts with high Eu and Sr concentration (i.e. with no normalized negative Sr or Eu anomalies). Thus, the compositions of typical Archaean TTG are interpreted to reflect melting of mafic crust at pressures too high for plagioclase to be stable, but high enough to stabilize garnet in the residue (e.g. Martin, 1994).

Most rocks of the CDGC have high La/Yb values, but they also have low Gd/Yb values (flat middle to HREE normalized patterns) and high Y and Yb. These patterns contrast with those of classic Archaean TTG and indicate that garnet was probably not stable during melting of the source. The negative Eu anomalies in most of the rocks of the CDGC, including the tonalites, trondhjemites, and granodiorites of Group 1, also suggest that plagioclase was a residual mineral, or that the magmas underwent significant fractionation of plagioclase, or both. This is also indicated by the low Sr concentrations of these rocks compared with those of TTG at similar silica contents (Fig. 3). The geochemistry of the rocks of the CDGC reflects a hornblende- and plagioclase-bearing source and possibly also some fractionation of those minerals. The source must have melted at pressures lower than the garnet stability field (i.e. <10 kbar; Wyllie et al., 1997), and thus at higher crustal levels (~35–40 km) than was typical of the TTG series.

Available geochronology data suggest that the majority of the monzogranitic rocks of the CDGC were derived over the same period (~3320–3310 Ma). At least some tonalites, trondhjemites, and granodiorites are also of this age. A 3313–3300 Ma age for the Nandingarra Granodiorite suggests that it intruded the surrounding monzogranite; however, an age of c. 3427 Ma from a single tonalite indicates an additional older component.

We invoke a two-step process for the formation of the CDGC. First, high-pressure melting of young mafic lower crust produced TTG magmas (such as those presently exposed in the Shaw Granitoid Complex; Bickle et al., 1993). The thermal anomaly was also associated with basaltic magmatism that formed a mid-crustal intraplate. A second thermal event at c. 3.3 Ga then caused widespread crustal melting at a depth of 35–40 km. This event involved the re-melting of the older TTG to produce the monzogranites of the CDGC, whereas re-melting of the mafic intraplate produced the tonalitic to granodioritic rocks of the complex.

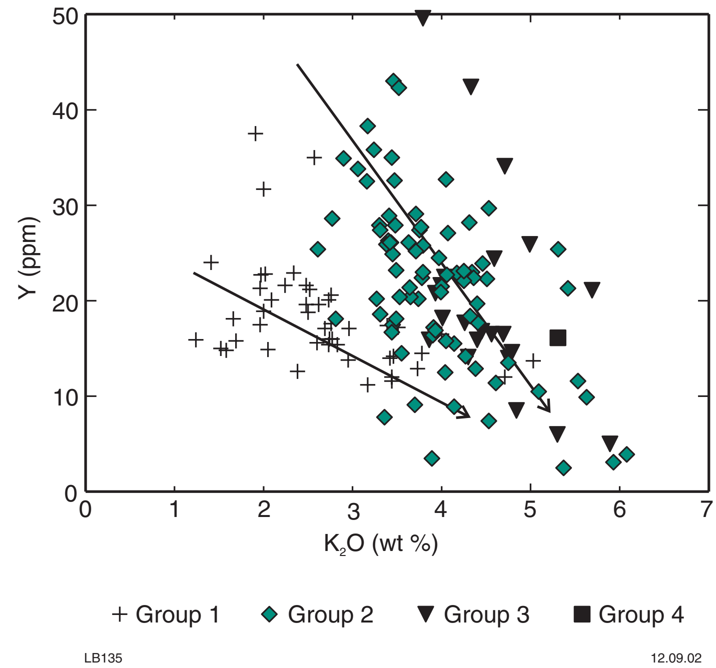

Figure 6. Compositional variation diagram for the four main groups in the Corunna Downs Granitoid Complex showing trends for Group 1 and Groups 2–4

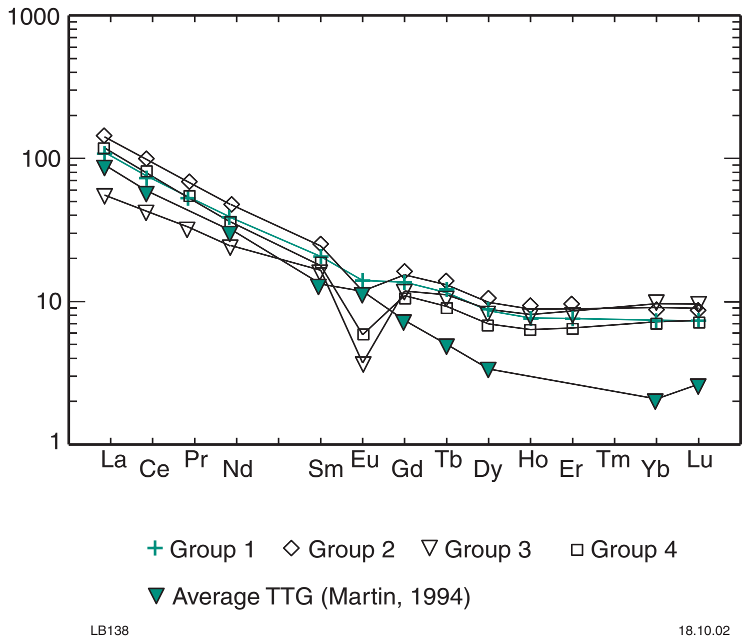

Figure 7. Average chondrite-normalized rare earth element patterns for the various rocks in the Corunna Downs Granitoid Complex. Also shown is the average tonalite–trondjhemite–granodiorite composition from Martin (1994)

References

BAGAS, L., and VAN KRANENDONK, M. J., in prep., Geology of the Split Rock 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes.

BAGAS, L., and VAN KRANENDONK, M. J., 2002, Split Rock, W.A. Sheet 2854: Western Australia Geological Survey, 1:100 000 Geological Series.

BARKER, F., 1979, Trondhjemite: definition, environment and hypotheses of origin, *in* Trondhjemites, dacites, and related rocks *edited by* F. BARKER: Amsterdam, Elsevier, p. 1–12.

BARKER, F., and ARTH, J. G., 1976, Generation of trondhjemitic–tonalitic liquids and Archaean bimodal trondhjemite–basalt suites: Geology, v. 4, p. 596–600.

BARLEY, M. E., and PICKARD, A. L., 1999, An extensive, crustally-derived, 3325 to 3310 Ma silicic volcanoplutonic suite in the eastern Pilbara Craton: evidence from the Kelly Belt, McPhee Dome and Corunna Downs Batholith: Precambrian Research, v. 60, p. 185–241.

BICKLE, M. J., BETTENAY, L. F., CHAPMAN, H. J., GROVES, D. I., McNAUGHTON, N. J., CAMPBELL, I. H., and de LAETER, J. R., 1993, Origin of the 3500–3300 Ma calc-alkaline rocks of the Pilbara Archaean: isotopic and geochemical constraints from the Shaw batholith: Precambrian Research, v. 60, p. 117–149.

CHAMPION, D. C., and SHERATON, J. W., 1997, Geochemistry and Nb isotope systematics of Archaean granites of the Eastern Goldfields, Yilgarn Craton, Australia: implications for crustal growth processes: Precambrian Research, v. 83, p. 109–132.

CHAMPION, D. C., and SMITHIES, R. H., 1999, Archaean granites of the Yilgarn and Pilbara cratons, Western Australia: secular changes, *in* The origin of granites and related rocks *edited by* B. BARBARIN: Fourth Hutton Symposium, France, 1999, Abstracts, p. 137.

CHAMPION, D. C., and SMITHIES, R. H., 2000, The geochemistry of the Yule Granitoid Complex, East Pilbara Granite–Greenstone Terrane; evidence for felsic crust: Western Australia Geological Survey, Annual Review 1999–2000, p. 42–48.

COLLINS, W. J., 1993, Melting of Archaean sialic crust under high a_{H2O} conditions: genesis of 3300 Ma Na-rich granitoids in the Mount Edgar Batholith, Pilbara Block, Western Australia: Precambrian Research, v. 60, p. 151–174.

CONDIE, K. C., 1981, Archaean greenstone belts: Amsterdam, Elsevier, 434p.

DAVY, R., 1988, Geochemical patterns in granitoids of the Corunna Downs Batholith, Western Australia: Western Australia Geological Survey, Report 23, p. 51–84.

DEFANT, M. J., and DRUMMOND, M. S., 1993, Mount St. Helens: Potential example of the partial melting of the subducted lithosphere in volcanic arc: Geology, v. 21, p. 547–550.

HARKER, A., 1909, The natural history of igneous rocks: London, Macmillan.

HICKMAN, A. H., 1983, Geology of the Pilbara Block and its environs: Western Australia Geological Survey, Bulletin 127, 268p.

HICKMAN, A. H., and LIPPLE, S. L., 1978, Marble Bar, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 24p.

Le MAÎTRE, R. W., 1989, A classification of igneous rocks and glossary of terms: Recommendations of the International Union of Geological Subcommission on the systematics of igneous rocks: Oxford, Blackwell Press, 193p.

LIPPLE, S. L., 1975, Definitions of new and revised stratigraphic units of the eastern Pilbara Region: Western Australia Geological Survey, Annual Report 1974, p. 58–63.

MARTIN, H., 1994, The Archean grey gneisses and the genesis of the continental crust, *in* Archean crustal evolution *edited by* K. C. CONDIE: Amsterdam, Elsevier, p. 205–259.

MARTIN, H., 1999, Adakitic magmas: modern analogues of Archaean granitoids: Lithos, v. 46, p. 411–429.

NELSON, D. R., 2000, Compilation of geochronology data, 1999: Western Australia Geological Survey, Record 2000/2, 251p.

NELSON, D. R., 2001, Compilation of geochronology data, 2000: Western Australia Geological Survey, Record 2001/2, 205p.

NELSON, D. R., 2002, Compilation of geochronology data, 2001: Western Australia Geological Survey, Record 2002/2, 282p.

NELSON, D. R., in prep., Compilation of geochronology data, 2002: Western Australia Geological Survey, Record 2003/2.

RAPP, R. P., WATSON, E. B., and MILLER, C. F., 1991, Partial melting of amphibole/eclogite and the origin of Archean trondhjemites and tonalites: Precambrian Research, v. 51, p. 1–25.

SEN, C., and DUNN, T., 1994, Dehydration melting of a basaltic composition amphibolite at 1.5 and 2.0 GPa: implications for the origin of adakites: Contributions to Mineral Petrology, v. 117, p. 394–409.

SYLVESTER, P. J., 1994, Archaean granite plutons, *in* Archaean crustal evolution *edited by* K. C. CONDIE: Amsterdam, Elsevier, Developments in Precambrian Geology, 11, p. 261–314.

WINDLEY, B. F., 1995, The evolving continents, 3rd edition: Chester, John Wiley, 526p.

WYLLIE, P. J., WOLF, M. B., and van der LAAN, S. R., 1997, Conditions for formation of tonalites and trondhjemites: magmatic sources and products, *in* Greenstone belts *edited by* M. J. de WIT and L. D. ASHWAL: Oxford University Press, Monograph 35, p. 256–266.