Petrogenesis of High Heat Producing Granite: Implication for Mt Painter Province, South Australia

Kamonporn Kromkhun, (M.Sc)

Geology and Geophysics
School of Earth & Environmental Science
University of Adelaide

Thesis submitted for the degree of Doctor of Philosophy
in the Faculty of Science, University of Adelaide

January 2010

Chapter 8 High Heat Producing Granites of Australia

The surface heat flow of Australia is generally high. In particular, Australian Proterozoic terranes are significant higher (83±18 mWm^{-2}) than the global Proterozoic average (~50 mWm^{-2}; McLaren et al., 2005). In particular, the eastern parts of the Australian continent particularly show high temperature and heat flow (Figure 8.1a and b). The enormous heat flows in the Australian continent are suggested to be the result of U, Th and K enrichment in crustal sources (Sandiford and Hand, 1998; McLaren et al., 1999; Sandiford et al., 2002). Enriched radioactive element concentrations are largely contained within felsic igneous rocks of the upper crust (5-10 km depth; McLaren et al., 2005).

In this chapter, available data is used to investigate the origin of U, Th and K enriched granites from high heat flow region, focussing on granites from the eastern part of the Australian continent (Figure 8.1b) including the Mt Isa and Arunta Inliers, Gawler Craton, and the Broken Hill and Olary Domains. The geological setting, lithology, geochronology, geochemistry and radiogenic isotope systematics of the HHP granitic and associated rocks within these areas, are reviewed from previous studies, and compared with granites low heat production values in the same terranes and the HHP mafic

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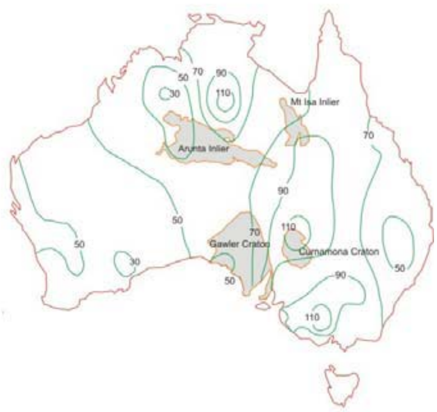

Figure 8.1: Australia Map and Heat flow a: Temperature map (after Cull, 1982); b: Surface heat flow map (modified after Sass and Lachenbruch, 1979).

and felsic rocks from the Mt Painter Province (Chapter 1-7) with the aim of identifying the petrogenesis of the HHP granites and associated rocks.

8.1. Mt Isa Inlier

The Mt Isa Inlier is located in northwest Queensland and contains a large number of Proterozoic granitic intrusions, constituting almost 14% of the area of the inlier (Wyborn and Page, 1988). It is divided into three north-south trending tectonic units; the Western Fold Belt, the Kalkadoon-Leichhardt Belt and the Eastern Belt (Blake et al., 1987; Stewart and Blake, 1992). The basement of the Inlier is formed by a series of sedimentary, volcanic and intrusive rocks. Crystalline basement in the Mt Isa Inlier was developed during the Barramundi Orogeny (1870-1840 Ma; Wyborn et al., 1988) and then sedimentation occurred during multiple rifting events in the interval *ca* 1800 to 1600 Ma. Granitic rocks were emplaced during four major events (~1860, 1820-1800, ~1740 and 1550-1500 Ma; Wyborn et al., 2001).

8.1.1 Proterozoic granites of Mt Isa Inlier

Proterozoic granites of the Mt Isa Inlier have age ranging in from ~1890 to 1490 Ma including;

- Granites of the Kalkadoon Supersuite are the oldest granitic intrusions in the Mt Isa Inlier. The supersuite comprises mainly felsic rocks that are interpreted to be restite I-type rocks and are mostly unfractionated (Belousova et al., 2001). Some net-veined complexes in the area suggest that they are bimodal (Blake et al., 1988). Zircons of the Kalkadoon diorite and the coeval Leichhardt volcanics yield U-Pb ages between 1886 and 1852 Ma (Page, 1978; 1983; Wyborn and Page, 1983). The Kalkadoon granitic rocks are typically medium- to coarse-grained, equigranular to porphyritic and metamorphosed. K-feldspar phenocrysts are more abundant in granodiorite and are up to 5 cm in size (Wyborn et al., 2001).
- The Nicholson Suite is predominantly felsic (granitic and co-magmatic volcanics) and is coeval with a basic dyke (Wyborn et al., 2001). Granitic and volcanic rocks in this suite are dated at ~1850 Ma (Scott et al., 1997). Granitic intrusions of this suite comprise biotite-muscovite

monzogranite, hornblende-biotite monzogranite and granodiorite that are generally porphyritic with exceptionally large K-feldspar phenocrysts up to 8 cm in size with zircon, apatite, fluorite and topaz as accessory minerals. The co-magmatic volcanics of the Nicholson Suite are mainly crystal-rich ignimbrites with phenocrysts of quartz and feldspar.

- The Argylla Suite is predominately extrusive with minor granitic intrusions including the Bowlers Hole and Mairindi Creek granites. Felsic rocks in this suite are evolved end members of a bimodal event (Wyborn et al, 2001). A U-Pb dating of this suite yields ages between 1810 and 1746 Ma (Page, 1978; Page, 1983). The granitic rocks in this suite are typically gneissic, porphyritic, medium- to coarse-grained and consist of quartz, plagioclase, K-feldspar, biotite, dark blue-green hornblende, with accessory allanite, opaque minerals, titanite and zircon. Volcanic rocks include rhyolitic to dacitic metavolcanics that are typically magnetic and show flow banding. Phenocrysts of quartz, plagioclase and K-feldspar with minor biotite, blue-green hornblende±opaque minerals are common (Wyborn et al, 2001).

- The Wonga Suite consists of granitic and volcanic rocks which emplaced into the Kalkadoon-Leichhardt Belt and the Eastern Fold Belt during a major extensional event between 1760 Ma and 1720 Ma (Blake 1987; Holcombe et al., 1992; Passchier 1986; Passchier and Williams 1989). This suite is interpreted to be co-magmatic with the felsic volcanics of the Argylla Suite. The Natalie Granite from the Wonga Suite has zircon U-Pb SHRIMP ages between 1778-1729 Ma (Pearson et al., 1992). Wonga intrusions are metamorphosed with some being strongly deformed to augen gneisses consisting of coarse microcline megacrysts, quartz, plagioclase, biotite and hornblende (ferrohastingsite) as major minerals and sphene, apatite, fluorite and zircon as accessory minerals (Wyborn and Page, 1988). Microgranites or microgranular enclaves contain microcline, quartz, biotite, plagioclase, sphene apatite, zircon, muscovite and allanite.

- The Burstall Suite emplaced along a linear north trend into the Eastern Fold Belt during an extensional episode (Wyborn et al., 2001; Pearson et al., 1992). The Burstall granitic rocks comprise leucogranite, porphyritic hornblende-biotite granite, tonalite and microgranite. The Burstall granites yield U-Pb ages of between 1745 and 1726 Ma (Page, 1983). The

Lunch Creek Gabbro that is interpreted to be coeval with the Burstall granites has a U-Pb age of 1740±24 Ma (Page, 1983).

- The Fiery Suite consists of mafic and felsic rocks that have ages between 1726 and 1698 Ma (Wyborn et al., 2001). It comprises granite, rhyolite, trachyte, dolerite and basalt. The intrusive rocks are typically equigranular, medium- to coarse-grained and contain quartz, K-feldspar, plagioclase, biotite, zircon, titanite, hematite and rare garnet. Volcanic rocks of the Fiery Suite include flow-banded banded rhyolite, rhyolitic agglomerate, rhyolitic ignimbrite interbedded with altered reddish vesicular basalt and trachybasalt.

- The Sybella Suite emplaced in the Western Fold Belt between 1678 and 1665 Ma (Page and Bell, 1986; Connor and Page, 1995). It comprises mainly intrusive rocks with minor extrusive rocks and has high F content (Wyborn et al., 2001). The Sybella Suites that is described by Wyborn et al (1988) as an anorogenic I-type rocks with limited fractionation ranges from granodiorite to alkali-feldspar granite including megacrystic K-feldspar granite and leucogranite, K-feldspar-bearing granite, aplite and pegmatite. These felsic rocks are typically characterized by equigranular to porphyritic textures and contain coarse K-feldspar augen up to 30 mm in length. Rapakivi textures are common in the felsic intrusions. Plagioclase, biotite and hornblende (ferrohastingsite) are major minerals and titanite, zircon, allanite apatite, sphene and fluorite are accessory minerals of the suite. Microgranite or microgranular enclaves found in the northeastern part of the suite contain abundant metasedimentary xenoliths. The microgranites are fine- to medium-grained and hornblende-free.

- The Maramungee Suite occured in the eastern part of the Eastern Fold Belt formed as a result of crustal melting (Page and Sun, 1998). It includes heterogeneous, mainly medium to fine-grained leucocratic granite, granodiorite and tonalite. The Maramungee Granite gives a SHRIMP U-Pb zircon age of 1545±11 Ma (Page and Sun, 1998).

- The Williams Suite emplaced in the Eastern Fold Belt showing major north-trending structures. It dominates the Williams and Naraku Batholiths (Carter et al. 1961; Joplin and Walker 1961) with coeval diorites and gabbros indicating a bimodal magmatic source that formed in an extensional environment (Wyborn et al., 2001). Granites and granodiorites of the Williams Suite are grouped ino two units including the older plutons (age reanging from 1754 to 1640 Ma) and the younger plutons (age ranging between 1520 and 1493 Ma; Nesbitt et al., 1983; Page and Sun, 1996). The Williams Suite typically comprises porphyritic biotite-hornblende granite, monzogranite, granodiorite, tonalite and diorite.

8.1.2 High heat producing granites of Mt Isa Inlier

Mt Isa granites and associated rocks that have heat production values of grater than 5 μWm^{-3} are mostly from the Wonga, Burstall, Sybella and Williams suites (Figure 8.2). The older Kalkadoon and Argylla suites have typically low heat production values but few samples have heat production values of greater than 5 μWm^{-3}.

8.1.3 Geochemistry

Mt Isa Inlier Proterozoic igneous rocks are typically bi-modal felsic and mafic rocks. The granites and felsic volcanic rocks predominantly contain SiO_2 contents ranging from 66 to 78 wt%. Major elements of these rocks vary due to alteration. An average K_2O content are typically between 4 to 6 wt% and the Al_2O_3 content varies from 7 to 18 wt%. The granitoids exhibit weakly to moderately peraluminous and metaluminous characteristics (Figure 8.3). Harker diagrams of TiO_2, Al_2O_5, FeO, MgO, CaO and P_2O_5 versus SiO_2 show similar negative linear trends in all suites. However, SiO_2 versus Na_2O and K_2O diagrams do not present clear relationships, possibly due to sodic-potassic alteration. Mafic rocks from Mt Isa, containing SiO_2 ranging between 46 to 58 wt%, are found in all suites but the large majority are from the Kalkadoon Supersuite. The Harker diagrams for the Mt Isa Proterozoic igneous rocks generally display continuous trends from mafic to felsic rocks (Figure 8.4).

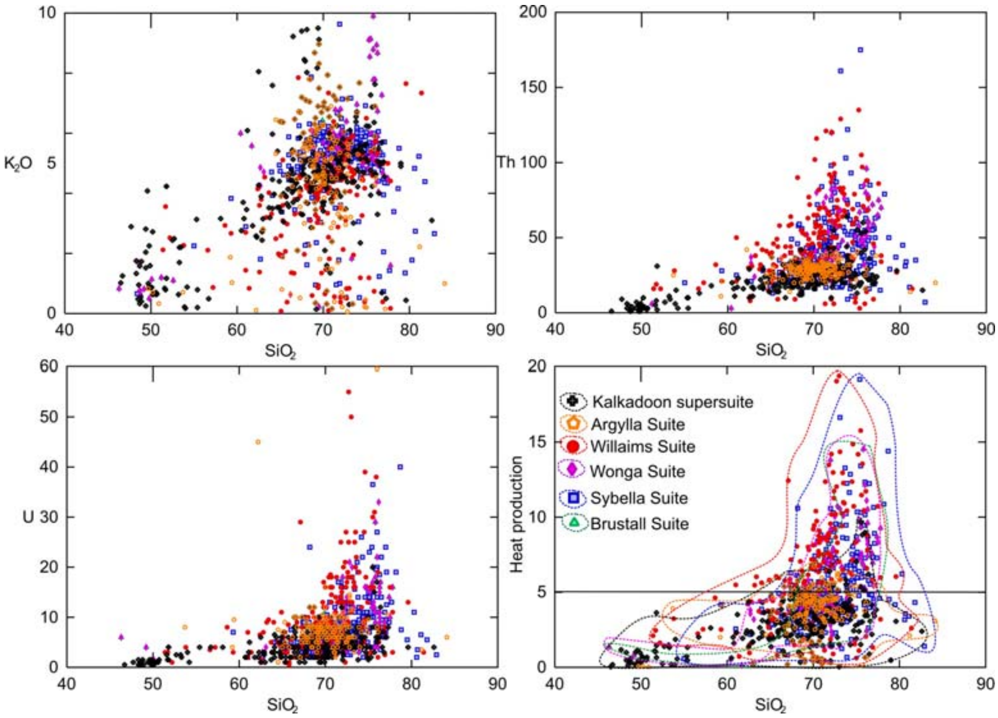

Figure 8.2 Concentration of K_2O, U and Th and heat production values of granitic and associated rocks from different suites of the Mt Isa Inlier.

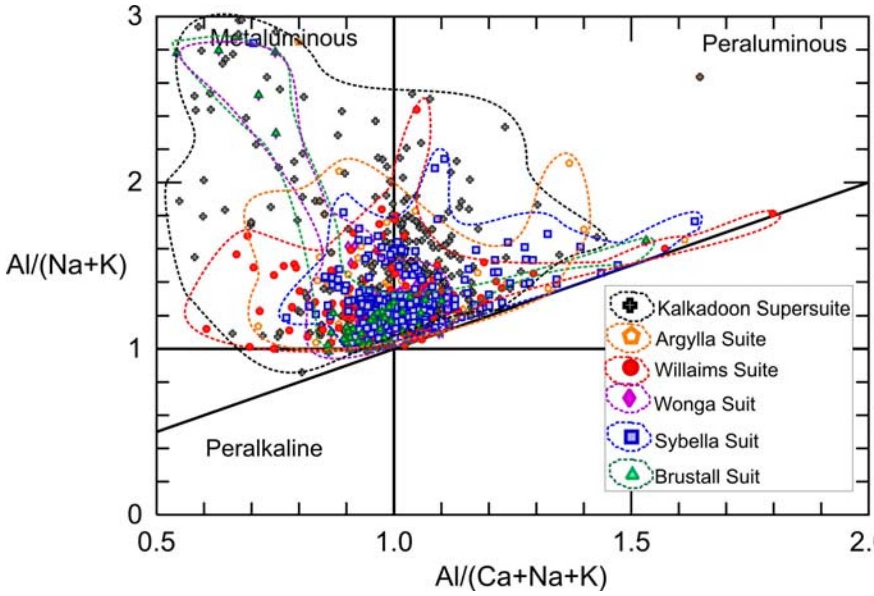

Figure 8.3 ANK vs. A/CNK plot showing the metaluminous to peraluminous nature of the Mt Isa rocks; A = Al_2O_3, N = Na_2O, K = K_2O, C = CaO (all in molar proportion).

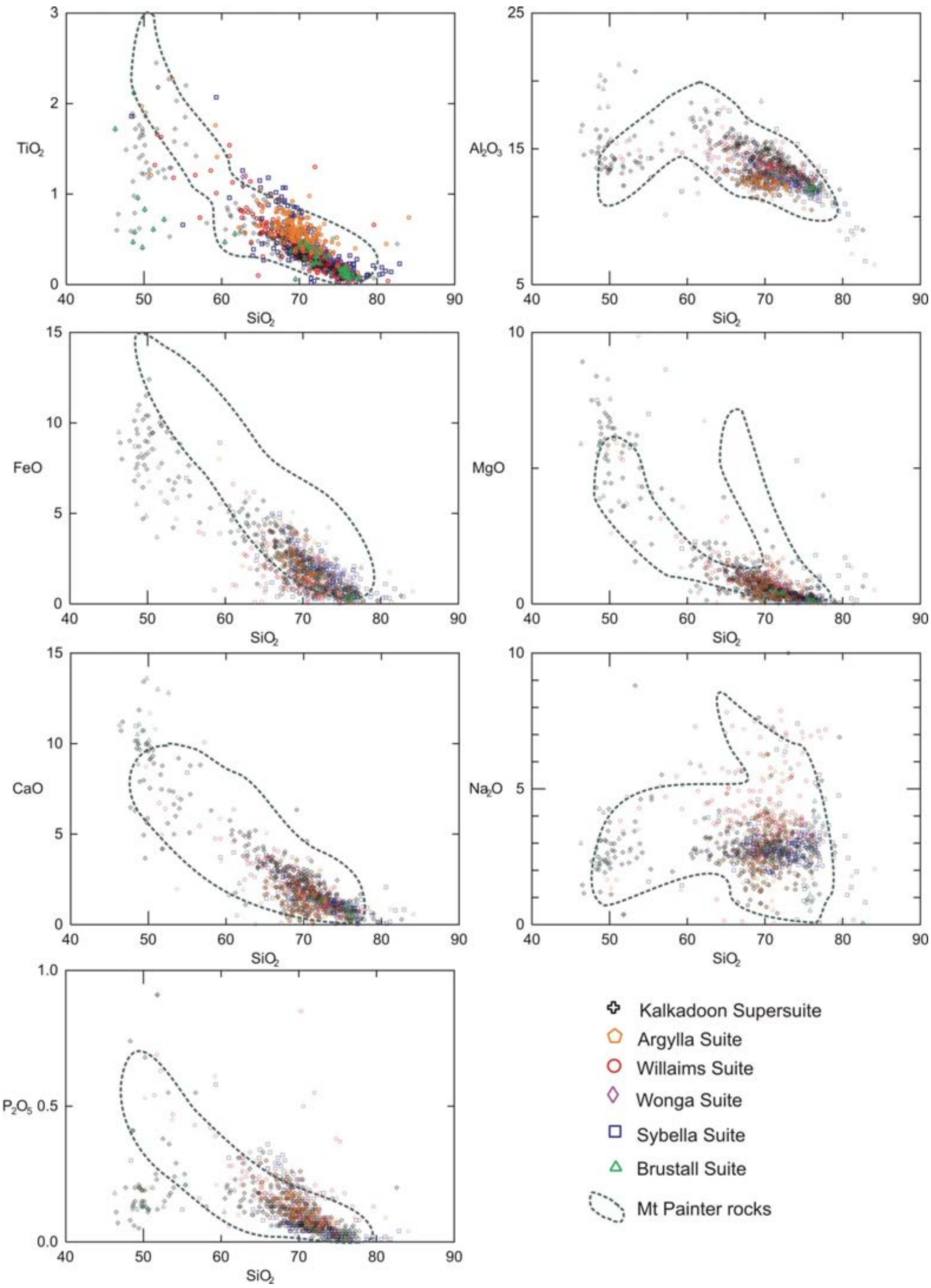

Figure 8.4 Plots of SiO_2 versus other major elements for the Mt Isa granitic and associated rocks compared to the HHP granites from the Mt Painter Province.

Granitic, felsic volcanic and mafic rocks of the Mt Isa Inlier are typically enriched in trace elements although there are variations between the different igneous suites. They are particularly enriched in U, Th, Rb, Zr, Ba, Nb, Y, Ce and REE (except Eu). The Sybella Suites have very high concentrations of Ce, F, La, Nb, Nd, Ba, Zr, Th and Y and are depleted in Sr (Figure 8.5). The Burstall, Wonga Suites and Williams Supersuite are also enriched in Ce, F, La, Ba, Nb, Nd, Zr, Th and Y although at lower concentrations than the Sybella Suite. The Argylla Suite has lower concentrations of U and Th than the Burstall, Sybella, Wonga Suites and Williams Supersuite, but has higher Zr and Y contents. In contrast, the Kalkadoon Supersuite that has the lowest heat production values among the Mt Isa granitic suites is enrichment in Sr, Ba and V but has low HFSE.

The incompatible element diagrams or spider diagrams of the Mt Isa igneous rocks are shown in Figure 8.6. Positive Rb, Th, U, La, Pb, Nd, Sm and Y anomalies and negative Ba, Nb, Ce, Sr, Zr and Eu anomalies are common in all suites.

The REE patterns of available data from the Burstall and Sybella Suites show slightly fractionated light rare earth elements (LREE) and flat heavy rare earth elements (HREE) with negative Eu anomalies (Figure 8.7).

Geochemical data from the Mt Isa granitic and associated rock is compared to the HHP granites from the Mt Painter Province (Figure 8.4, 8.5, 8.6 and 8.7). Major element concentrations and the Harker trends for the Mt Isa granitic and mafic rocks are similar to the HHP granites and associated rocks from the Mt Painter Province. However, trace element concentrations for the Mt Isa and Mt Painter granitic rocks differ. Ce, La, Nb and Zr concentrations in the Mt Painter HHP granites are higher, whereas Ba and Sr concentration are lower than the Mt Isa granitic rocks. They show similar trends in the Harker diagrams suggesting that fractional crystallization is an important process in generating the granitic rocks in both areas. REE patterns and spider diagrams of granites and associated rocks from both areas are similar with the HHP granites from the Mt Painter Province containing higher trace element concentrations (except Sr, Ba and Rb).

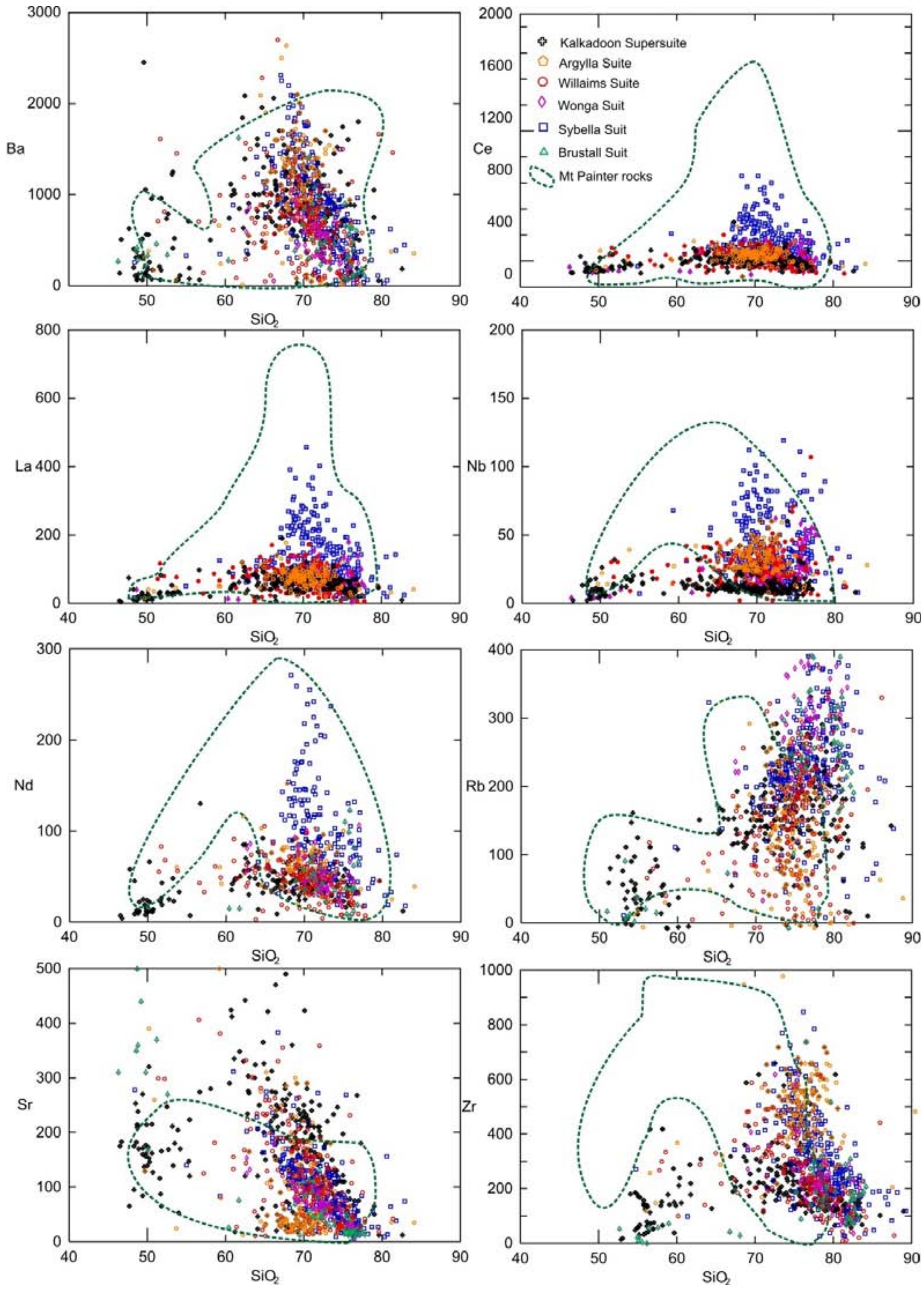

Figure 8.5 Plots of SiO_2 versus trace elements for the Mt Isa granitic and associated rocks.

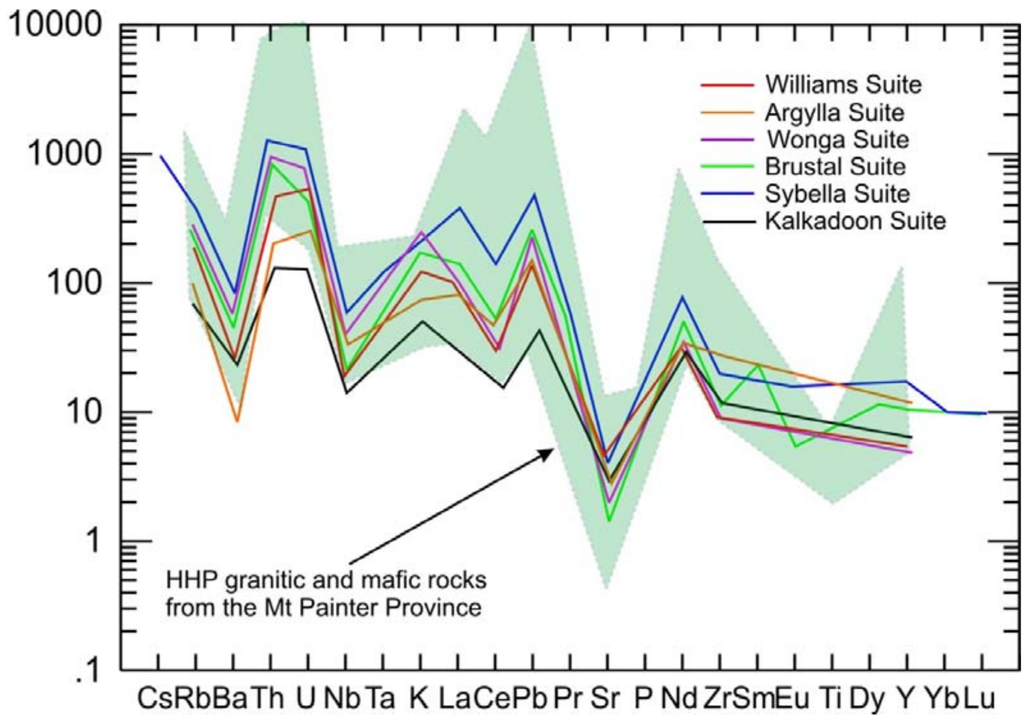

Figure 8.6 Spider diagrams of the Mt Isa igneous rock that normalise to primordial mantle value of Sun and McDonald (1987).

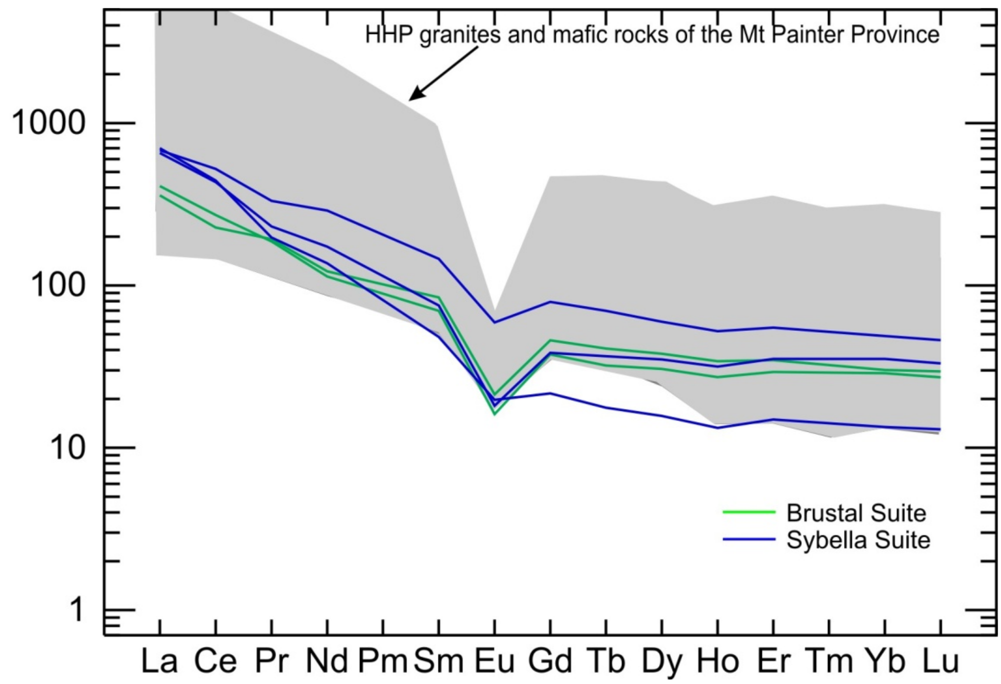

Figure 8.7 REE patterns of the Burstall and Sybella suites normalised to Chrondrite values of Sun and McDonald (1989).

8.1.4 Typology and Tectonic setting

Discrimination diagrams of Y+Nb versus Rb of Pearce et al. (1984) suggest that most granitic and volcanic rocks of Mt Isa Inlier plot within the within-plate granite (WPG) field (Figure 8.8) and can be classified as A-type granites (Figure 8.9). Most samples from the Kalkadoon Supersuite plot within post-collision granite (Post-COLG) field. Scatter plots show that the Kalkadoon granitoids are mainly in A-type and unfractionated M-, I and S-type fields (Figure 8.9).

In Y-Nb-Ce triangular discrimination diagrams of Eby (1992: which subdivide A-type granites into 2 classes; A_1 mantle-derived granites emplaced in an anorogenic setting and A_2 granites derived from the melting of continental or underplated mafic crust and emplaced in various tectonic environments), most magmatic rocks from the Mt Isa Inlier mainly plot within the subtype A_2 granite field, except some of the Wonga Suite rocks plot within the A_1 granite field.

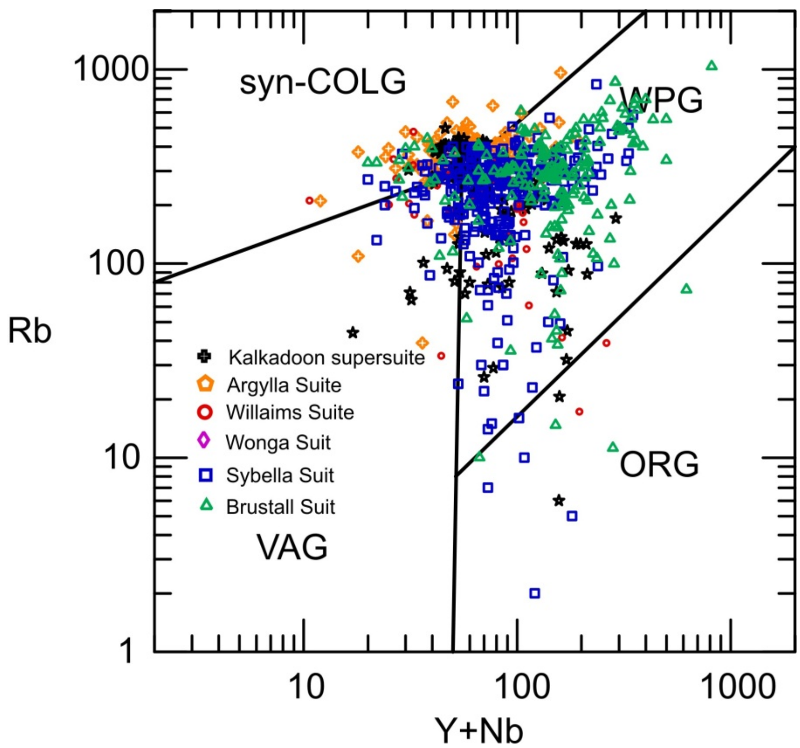

Figure 8.8 Y + Nb vs. Rb diagram of granitic rocks from Mt Isa Province after Pearce (1996); WPG-within-plate granite, Syn-COLG-Syn-collisional granite, VAG-Volcanic arc granite, ORG-ocean ridge granite.

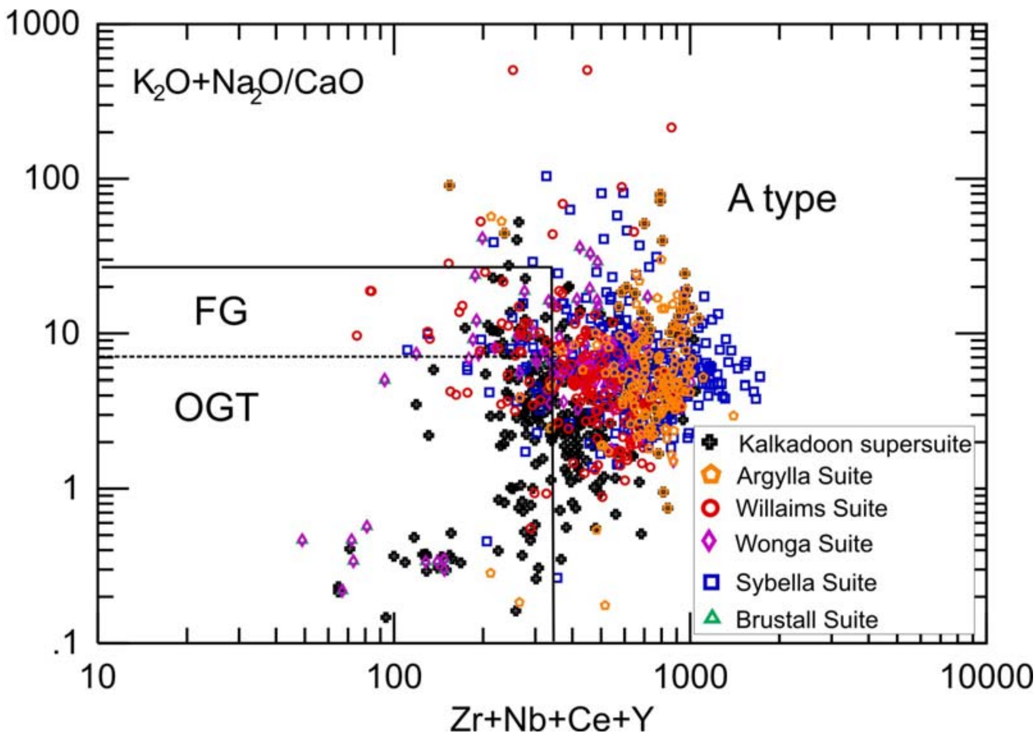

Figure 8.9 (K_2O + Na_2O)/CaO vs. Zr + Nb + Ce + Y classification diagrams after Whalen et al. (1987); FG = fractionated M-, I- and S-type felsic granites; OGT = unfractionated M-, I- and S-type granites.

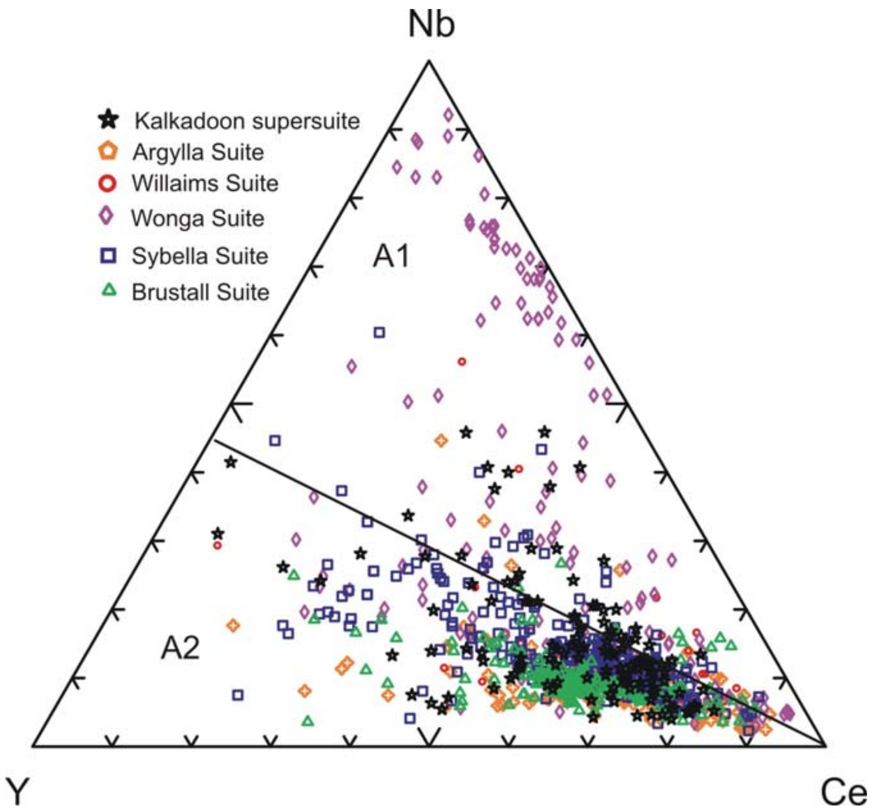

Figure 8.10 Discrimination diagrams of Y-Ce-Nb after Eby (1992) for the Mt Isa Granites.

8.1.5 Nd-Sm Isotopes

Nd-Sm isotopic compositions of granites, volcanic rocks and metasedimentary rocks from the Mt Isa Inlier were previously studied by Wyborn et al. (1988), Page and Sun (1998) and Mark (2001). Calculations of initial εNd values at the time of emplacement are based on the U-Pb zircon ages.

The oldest Kalkadoon Supersuite granitic rocks have initial εNd values ranging between -2.7 and -1.6 with T_{DM} ranging from 2.14 to 2.30 Ga (Figure 8.11; Wyborn and Page, 1988).

The Wonga batholiths yield initial εNd values ranging from -3.7 to -1.8 with T_{DM} between 2.16 and 2.28 Ga (Wyborn and Page, 1988).

One sample from the Sybella Suite yields positive initial εNd values of +1.8 with T_{DM} of 1.79 Ga (Wyborn and Page, 1988).

Granitic rocks from the younger plutons of the Williams Suite were previously analyzed Nd-Sm isotopes by Wyborn and Page (1988) yielding positive εNd values. However, the Williams and Naraku granitic samples were reanalyzed by Page and Sun (1998) and yielded negative initial εNd values ranging from -3.5 to -2.4 with T_{DM} between 2.20 and 2.26 Ga. Initial εNd values of the Jessie Granite, which is grouped as the older plutons in the Williams Suite, is -1.7 (Page and Sun, 1998).

Metasediments in this area yielding ages of 1746 - 1618 Ma have initial εNd values ranging from -2.5 to -0.8 (Page and Sun, 1998).

Initial εNd values of the younger plutons of the Williams Suite, which are same age ranges as the granites from the Mt Painter Province, overlap with εNd values of the Mt Painter rocks with slightly lower values.

8.1.6 Hf isotopes

Hf isotopes of zircons from sediments of the Eastern Succession of Mt Isa Inlier (the Soldiers Cap Group) provides information of primary magmatic episodes, contributions of juvenile material and reworked older crust at each stage of crustal evolution (Griffin et al., 2006). The LA-ICPMS U-Pb zircon age and Hf isotope from Griffin et al. (2006) suggest possible event ages and the nature of magma sources.

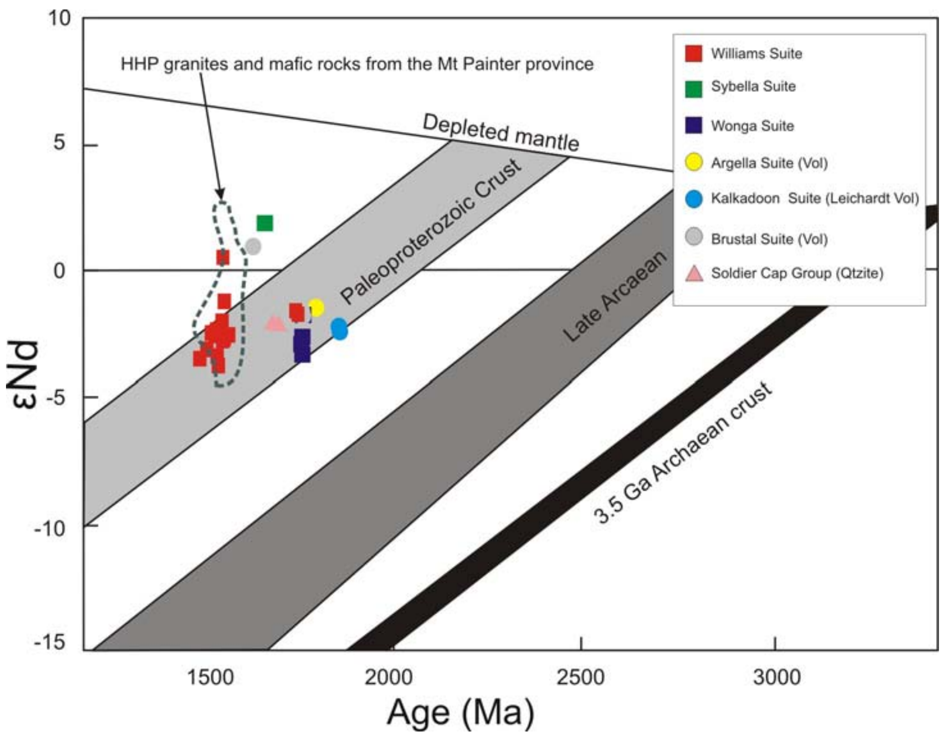

Figure 8.11 Initial ε_{Nd} values versus crystallization ages of the mafic and felsic rocks from Mt Isa (Data from Wyborn et al., 1988; Page and Sun, 1998; Mark, 2001; data of the Paleoproterozic crust, Late Archean crust and Archean data from Page and Sun, 1998 and references therein).

The oldest crust in the Mt Isa region, is indicated by inherited zircon grains with crystallization ages between ~2550 and 2300 Ma, which have εHf ranging from ~0 to +5 (Figure 8.12) indicating juvenile material and a significant period of crustal growth during this period (Griffin et al., 2006).

εHf values of the Palaeoproterozoic 1940-1880 Ma rocks vary between -5 to +5 suggesting that these rocks were mostly derived from reworking of pre-existing crust with minor mantle input (Griffin et al., 2006).

The 1810-1740 Ma event, which could be related to the Argylla, Wonga and Burstall Suites, shows εHf values clustering about zero (-5 to +5) suggesting reworking of older crust with minor input of juvenile material (Griffin et al., 2006).

The 1740-1680 Ma event, which overlaps the ages of the Burstall and Fiery Suites is dominated by high-Si granitoids. εHf values for this event indicate a slightly higher proportion of juvenile material than the 1810–1740 Ma event. The T_{DM} for this period has a major peak between 2.40 and 2.20 Ga suggesting most granitoids were derived from melting of Palaeoproterozoic crust (Griffin et al., 2006).

The 1700-1645 Ma event overlaps the ages of the Sybella Suite. It displays a larger proportion of mafic rocks and the εHf values suggest that juvenile mantle sources dominate. T_{DM} ages of 2.00-2.20 Ga indicate a mainly crustal component being the source of the granitic rocks (Griffin et al., 2006).

The 1650-1600 Ma event, which could not be related to any intrusion in the Mt Isa Inlier, shows slightly higher εHf values indicating a more juvenile source than the previous event. A large peak of T_{DM} ages from 1.80 to 2.00 Ga for this event suggests mixing between mantle-derived magmas and crustal material (Griffin et al., 2006).

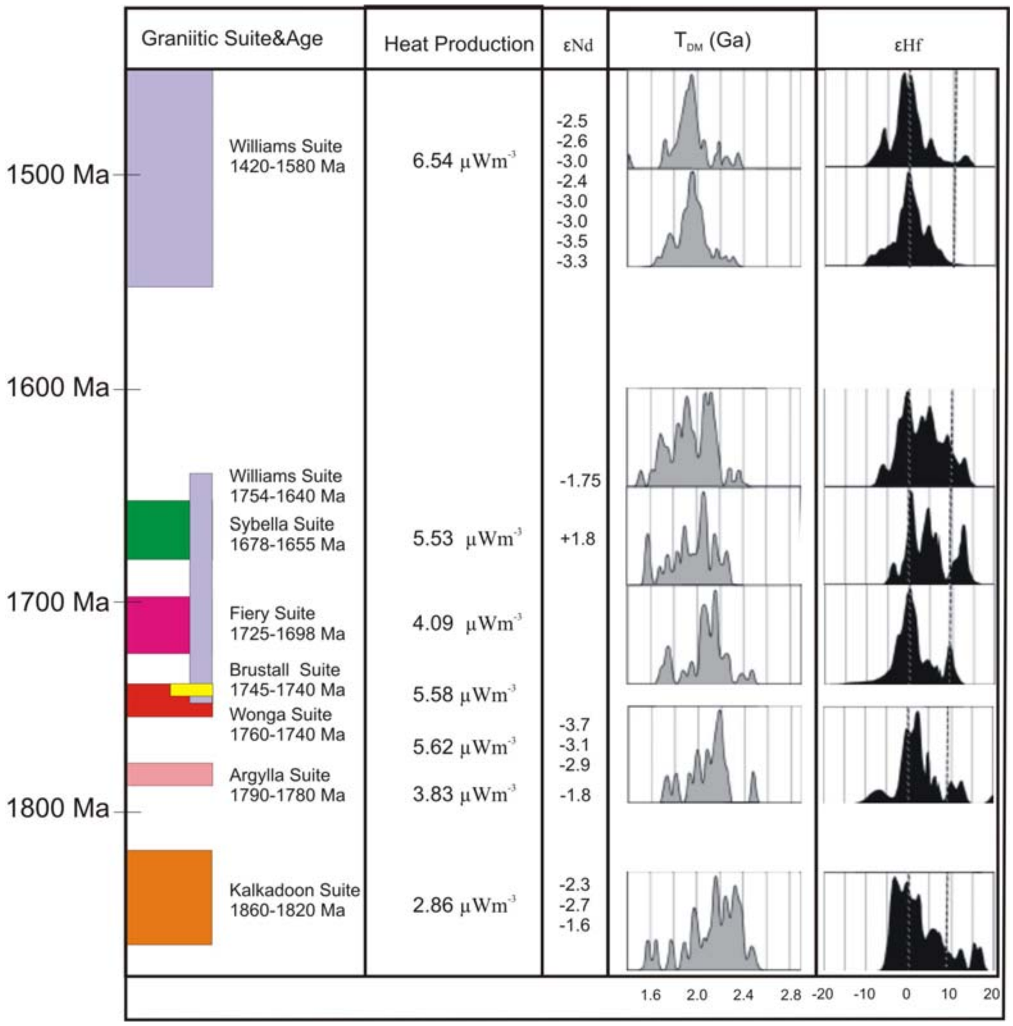

Figure 8.12 Ages, average heat production values, initial εNd values, T_{DM} and εHf values of the granitoids from the Mt Isa Inlier; εHf and T_{DM} data from Griffin et al. (2006); εNd from Wyborn et al. (1988), Page and Sun (1998) and Mark (2001).

The 1590-1540 and 1540-1480 Ma events overlap with the Williams Suites, respectively and follow a major high-grade metamorphic event in the Eastern Succession (1584±17 Ma; Page and Sun, 1998; Hand and Rubatto, 2002) and the Isan Orogeny at *ca.* 1530 Ma (Conor and Page, 1995). Zircons from this event have εHf values around zero indicating most rocks were derived by reworking of the older crust, which T_{DM} data suggests they were generated during the 1673-1622 Ma events (Griffin et al., 2006). The Williams Suites have lower mean εHf values than previous events, suggesting the involvement of less juvenile material.

The 1490 and 1420 Ma events inferred from εHf data could not be related to any intrusions in the region. Griffin et al. (2006) suggested that samples underwent lead loss after intrusion, due to hydrothermal activity. The εHf values are similar to the previous granitic magmatism (~1509 Ma) with a T_{DM} peak near 1.90 Ga.

8.1.7 Petrogenesis and Conclusion

The post-1820 Ma granites, I-type granites of the Kalkadoon Supersuite, were formed by small degree of partial melting of mafic underplates (Page and Sun, 1998). During this underplating, large volumes of incompatible element-enriched mantle-derived material accreted to the base of the lower crust and then had undergone significant fractionation.

Magmatism at 1820-1800 Ma, 1760-1740 (the Wonga Suite) and 1700-1670 Ma (the Fiery and Sybella Suites) were coeval with major extensional sedimentary sequences (Page and Sun, 1998). During 1780-1730 Ma period, mantle-plume activity induced heat flux to the crust resulted in extension and magma underplating (Oliver et al., 1991). This tectonism could cause generating of the Paleoproterozoic continental flood basalts of the Eastern Creek Volcanics of the Mt Isa Inlier. These flood basalt were derived from an initial mantle-derived magma contaminated by continental crust (Gregory et al., 2008). Partial melting of a subcontinental lithospheric mantle below the Mt Isa Inlier is a major source of crustal contamination and is responsible for the copper-rich magmas in the Eastern Creek Volcanics (Gregory et al., 2008).

The variable εNd values within the younger bimodal Williams Suite (ranging from -3.5 to -1.3) are suggested to be a result of magma generating processes involving heterogeneous sources, crustal melting, magma mixing, variable juvenile magma input and hydrothermal alteration (Page and Sun, 1998; Sun and Higgin, 1996). An amphibole-bearing crust is suggested as crustal source for generating the 1545 Ma trondhjemites from the William Suite (Mark, 2001).

Based of Hf isotopic compositions, most of the granites and associated rocks from the Mt Isa Inlier were derived from reworking of older crust (Palaeoproterozoic crust) and various degrees of mafic magma input. At the 1700-1645 Ma event (the Sybella Suite) and 1650-1600 Ma event, the Hf isotopes suggest that a juvenile mantle-derived magma is a predominate source mixing with less crustal material compared to other events (Griffin et al., 2006).

Granites from the Mt Isa Inlier are coeval with mafic and felsic volcanic rocks. They intruded the Palaeoproterozoic basement rocks at various times during the Proterozoic Era from 1860 to 1420 Ma. A porphyritic texture with coarse-grained K-feldspar phenocrysts is common in all suites. The HHP granitic suites including the Wonga, Burstall, Sybella and Willaim Suites are enriched in HFSE and REEs (except Eu) and consist of quartz, plagioclase, microcline, biotite, ferrohastingite, titanate, zircon, allanite, apatite and fluorite. Their geochemical characteristics vary but most show A-type characteristics and were emplaced in an intracontinental setting. Isotopic data of the Mt Isa magmatic rocks, mostly suggested that they were derived from melting of pre-existing crust with various amounts of juvenile magma input. A narrow range of εNd values for the Mt Isa granites reflects a homogenous soucre as a well-mixed crustal contaminated magmatic source.

8.2. Gawler Craton

The Gawler Craton is located in South Australia and is defined as a region of a crystalline basement of Archaean to Mesoproterozoic magmatic and metasedimentary rocks (Figure 8.13). It has not been substantially deformed or remobilised except for epi-orogenic movements since 1450 Ma

(Thomson, 1975; Parker, 1990a) and is unconformably overlain by Neoproterozoic to Cenozoic sediments.

The Gawler Craton is divided into three subdivisions based on lithotectonic domains;

a) Neoarchaean to Paleoproterozoic gneisses and granites occur mainly in the south and west of the craton (Daly and Fanning, 1993). The Archaean rocks (the Sleaford Complex from the southern Eyre Peninsula) consist of crustal gneisses, mafic granulites, amphibolite and granites (Fanning et al., 1980).

b) Deformed Palaeoproterozic granitic, volcanic and metasedimentary rocks occur mainly in the eastern craton as a north-south trending orogenic belt (Creaser, 1995) and are pre-Kimban magmatism (the Kimban orogeny dated at 1740-1690 Ma). Major granitic intrusions, including the Donington Suite located in the southern and central Eyre Peninsula, give an age of 1845±21, 1853±5 and 1850±5 Ma (Fanning et al., 2007). Volcanic and sedimentary rocks around the Olympic Dam area give ages of 1791±4, 1740, and 1737±7 Ma (Fanning et al., 1988).

c) The Gawler Range Volcanics and Hiltaba Suites granites dominate in the central Gawler Craton. The bimodal with dominant felsic rocks over mafic rocks have U-Pb of zircon and titanite ages between 1585 and 1595 Ma (e.g. Johnson and Cross 1995; Conor 1996; Fanning 1997).

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This figure is included on page 178 of the print copy of the thesis held in the University of Adelaide Library.

Figure 8.13 Simplified basement geology map of the Gawler Craton (after Fairclough et al., 2003).

8.2.1 Proterozoic granites and associated rocks of the Gawler Craton

Major episodes of granitic emplacements in the Gawler Craton occurred in Palaeoproterozoic and Mesoproterozoic Era. The Palaeoproterozoic magmatism is represented by the Lincoln Batholith (including the felsic Donington Suite and coeval mafic Jussieu Dykes).

Geochronologically, the granites and associated rocks of the Gawler Craton could be divided into six suites including; the Miltalie Gneiss, Donington Granitiod Suites, Minbrie Gneiss, Younger Lincoln Complex, St

Peter Suite and Hiltaba Suite. Based on availability of previous data and heat production values, only the Younger Lincoln, Hiltaba and St Peter Suites are selected for study in detail. Although, granites of the St Peter Suite have low heat production values, they have been recently studied their geochemistry, radiogenic isotopes and tectonic evolution. Comparing granites from the St Peter Suite to the HHP Younger Lincoln and Hiltaba Suites should lead to a better understanding of a genesis of HHP granites.

8.2.1.1 Younger Lincoln Supersuite

The Younger Lincoln Suite predominately occurs on the Eyre Penisula and has ages ranging between 1770 and 1600 Ma (Budd et al., 2001 and references therein). This suite could be realted to the Tunkillia Suite (1686±10 Ma; Fanning et al., 2007). Most rocks in this suite are felsic, restite-dominated fractionates and consist of granite gneiss, hornblende granite, leucogranite, hornblende monzonite, microgranite and granodiorite. The plutons are generally porphyritic to equigranular, medium-grained, massive, foliated to weakly foliated, and deformed. Major minerals are quartz, plagioclase, K-feldspar, biotite, hornblende, and accessory minerals include ilmenite, titanite, apatite, epidote, garnet and zircon. The granitic rocks Younger Lincoln Suite have heat production values ranging from 1.5 to 23.8 μWm^{-3} (Figure 8.14) with an average of 6.45 μWm^{-3}. U and Th concentrationts also vary with averages of 13 ppm for U and 35 ppm for Th.

8.2.1.2 St Peter Suite

The St Peter Suite includes granitic and mafic and felsic volcanic rocks, which emplaced around 1620-1608 Ma (Flint et al., 1990; Ferris et al., 2002; Swain et al., 2008). Granitoids from the St Peter Suite have a broad range of compositions from granodiorite to granite and typically show signs of weak fractionation. They are fine- to coarse-grained and equigranular to porphyrictic. Major minerals are quartz, microcline, plagioclase, biotite and hornblende. Enclaves of dolerite and diorite can be found within monzogranite and granodiorite. Volcanic rocks associated to this suite are typically dark grey to pink are porphyritic rhyodacite to rhyolite. The St

Peter Suite typically contains low heat production values average of 2.46 μWm^{-3} with U and Th contents average of 2 and 20 ppm, respectively (Figure 8.14).

8.2.1.3 Hiltaba Suite

The Hiltaba Suite is one of the largest granitoid suites in Australia and is relatively homogeneous over a large area. Granites of the Gawler Craton are predominately fractionated, and show various lithologies. Most granitic rocks are characterized by medium- to coarse-grained, K-felspar megacrystic and equigranular to porphyritic textures. They commonly contain quartz, K-feldspar, plagioclase, hornblende, and biotite as major minerals and pyrite, apatite, fluorite, titanite and zircon as accessory minerals. The Hiltaba Suite is co-magmatic with the Gawler Range Volcanics and is interpreted to be the result of extensive crustal melting at 1590 Ma (Giles 1988; Creaser 1989, 1995; Stewart and Foden 1990; Johnson and Cross 1991). The Hiltaba Suite shows various heat production values ranging 1.0 to 23.1 μWm^{-3} with average of 6.13 μWm^{3} (Figure 8.14). U and Th concentrations average 11 ppm and 38 ppm, respectively.

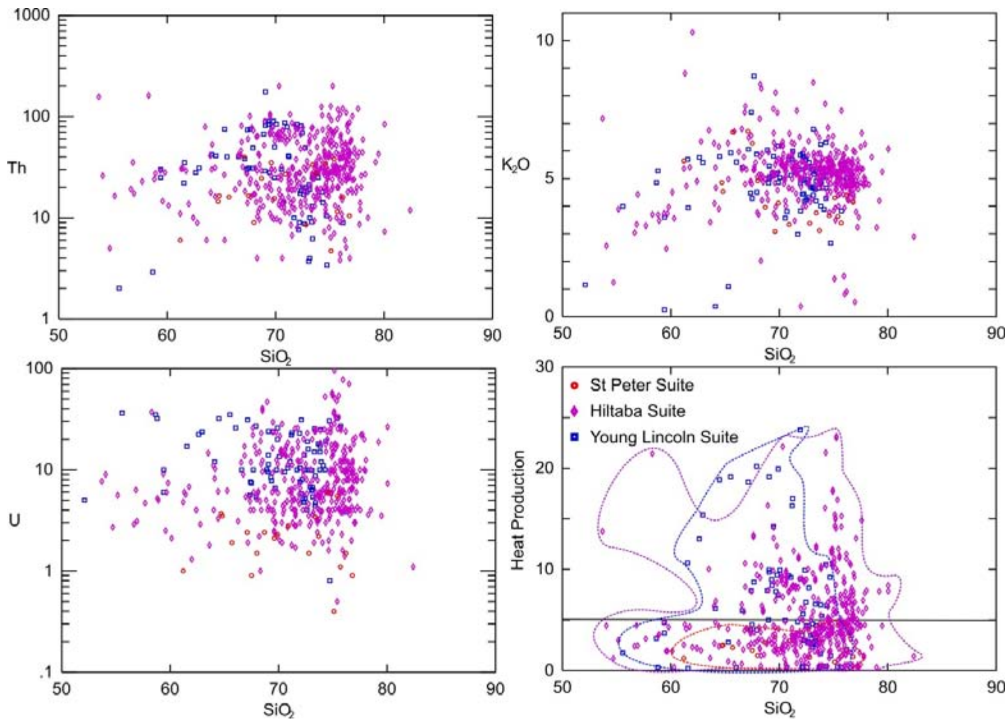

Figure 8.14 Concentration of K_2O, U and Th and heat production values of granitic and associated rocks from different suites of the Gawler Craton.

8.2.2 Geochemistry

The geochemistry of the granitic suites and associated rocks from the Gawler Craton differ between suites. The Hiltaba Suite has a mostly felsic composition, with a SiO_2 content of ~70-80 wt%, whereas the Younger Lincoln granitoids typically contain SiO_2 contents between 65-75 wt% and the St Peter Suite rocks have SiO_2 contents ranging from 61 to 77 wt% (Figure 8.15). Most rocks from the Gawler Craton are peraluminous; however some samples from the Younger Lincoln and the Hiltaba Suites are slightly metaluminous in composition (Figure 8.16). Most major element analyses of the Young Lincoln and Hiltaba granitoids form coherent arrays on Harker Diagrams with decreasing Al_2O_3, Fe_2O_3, MgO, CaO, P_2O_5 and TiO_2 SiO_2 increases (Figure 8.17). Na_2O and K_2O show no obvious trends because of hydrothermal alteration. The St Peter granitoids have higher MnO and TiO_2 and lower Fe_2O_3 than the Young Lincoln and Hiltaba granitoids. A binary plot of aluminium saturation index (ASI) versus SiO_2 for the Gawler Craton granitoid illustrates the metaluminous to peraluminous composition with increasing silica suggesting fractionation. The St Peter Suite granitic rocks mostly show S-type character based on ASI values (>1.1; Figure 8.18). However, the ASI values could not be used to classify I- or S-type granites due to a mobility of major elements in the Gawler granites.

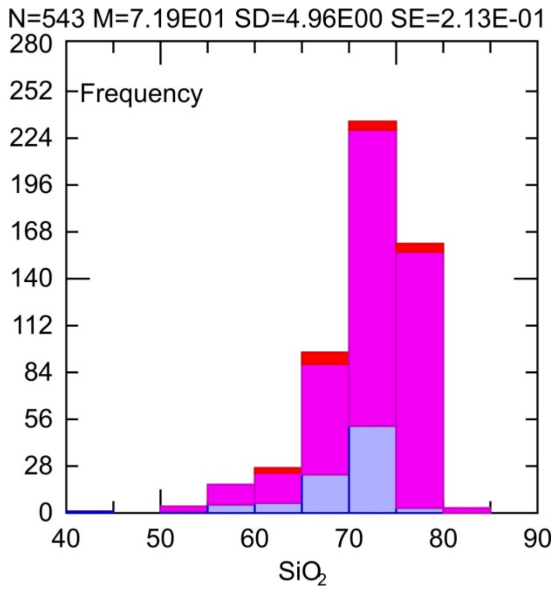

Figure 8.15 Histrogram of SiO_2 content for granitic and associated rocks from the Gawler Craton (Symbol red: St Peter Suite; pink: Hiltaba Suite; blue: Younger Lincoln).

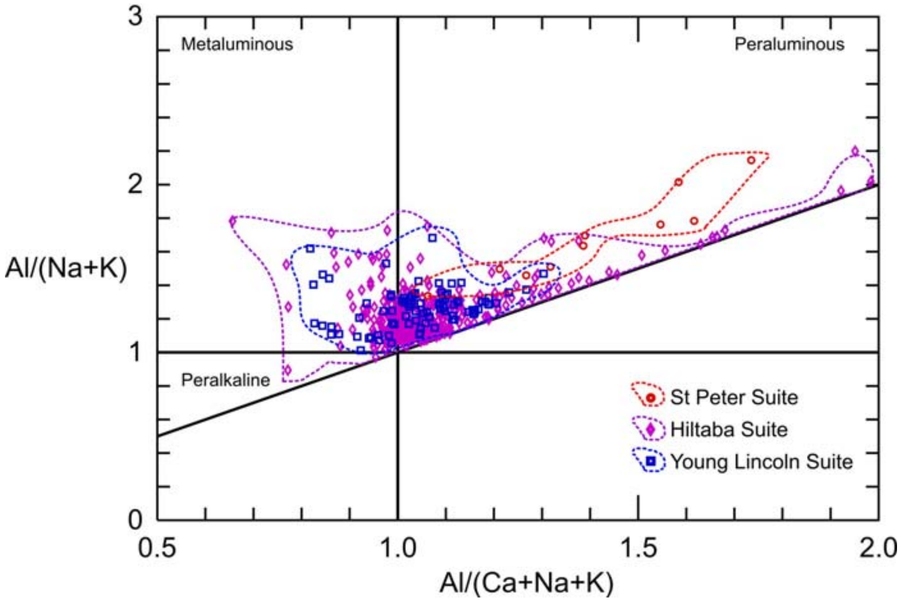

Figure 8.16 ANK versus A/CNK plot showing the peraluminous to metaluminous nature of the Gawler Craton rocks; A = Al_2O_3, N = Na_2O, K = K_2O, C = CaO (all in molar proportion).

Trace element concentrations in granitoids of the Gawler Craton vary betweeen different suites. Granitoids from the St Peter Suite typically contain lower trace element concentrations than the other two suites and have high Ba and Sr (Figure 8.19). The Younger Lincoln granitoids and Hiltaba Suite are generally enriched in U, Th, Rb, Zr, Ba, Nb, Y, Ce and REE (Except Eu). The granitoids from the Younger Lincoln Suite display two trends between the higher trace element concentrations and lower trace element concentrations in the Harker diagrams (Figure 8.19).

The incompatible element diagrams of granitic and associated rocks from the Gawler Craton are shown in Figure 8.20a, c and e. Granitic and associated rocks from the Hiltaba Suite typically contain higher levels of trace elements and show positive Th, U, K, La, Pb, Nd, Sm and Y anomalies, and negative Ba, Nb, Ce, Sr, Zr and Eu anomalies. These features are also found in the Younger Lincoln Suite although these contain lower trace elements concentrations than the Hiltaba Suite. The spidergrams of granitoid rocks from the St Peter Suite are shown in Figure 8.20c. They occur in lower concentrations that other Gawler Craton felsic suites and have a pronounced depletion in Nb, Sr and Ti and enrichment in LILEs (such as Rb, Th, and Nd).

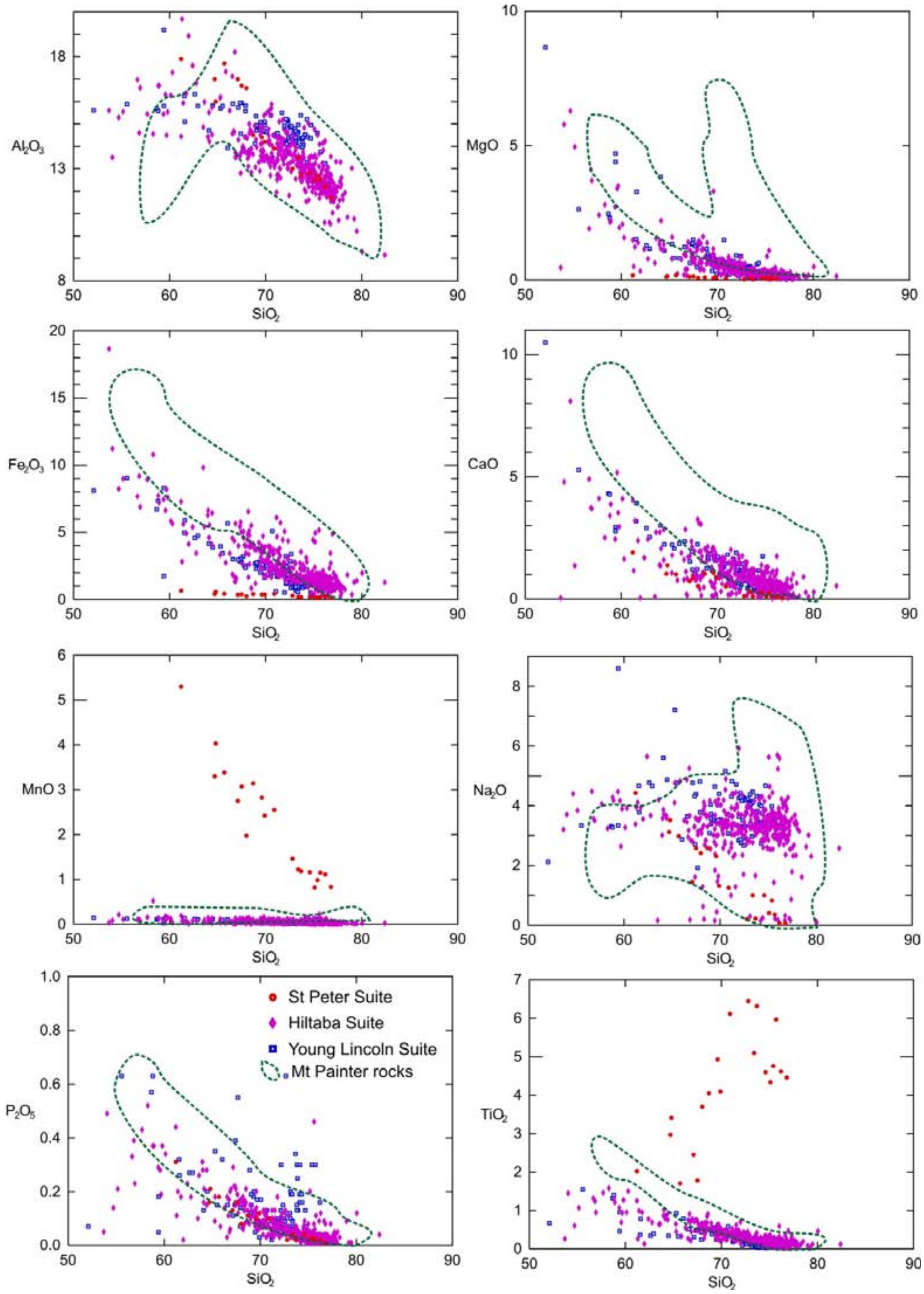

Figure 8.17 Plots of SiO_2 versus major elements for the Gawler Craton granitic and associated rocks.

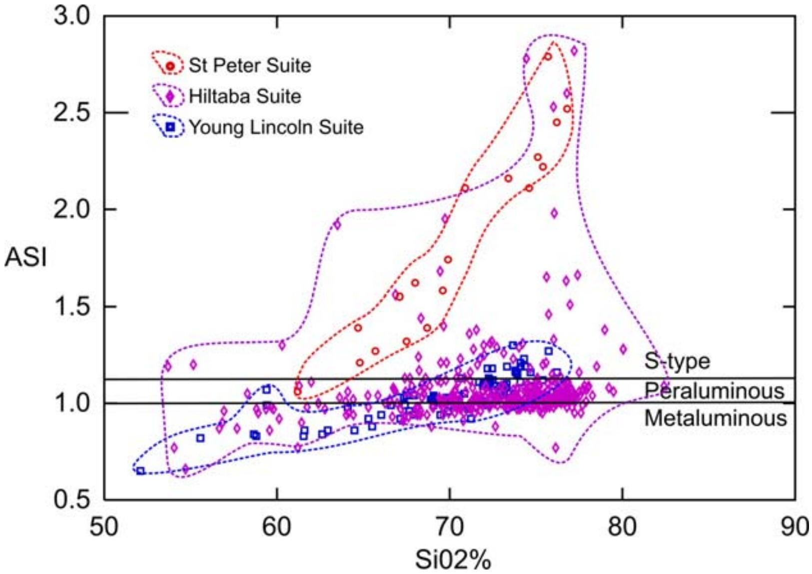

Figure 8.18 Plot of aluminium saturation index (ASI) versus SiO_2 for the Gawler Craton granitoids.

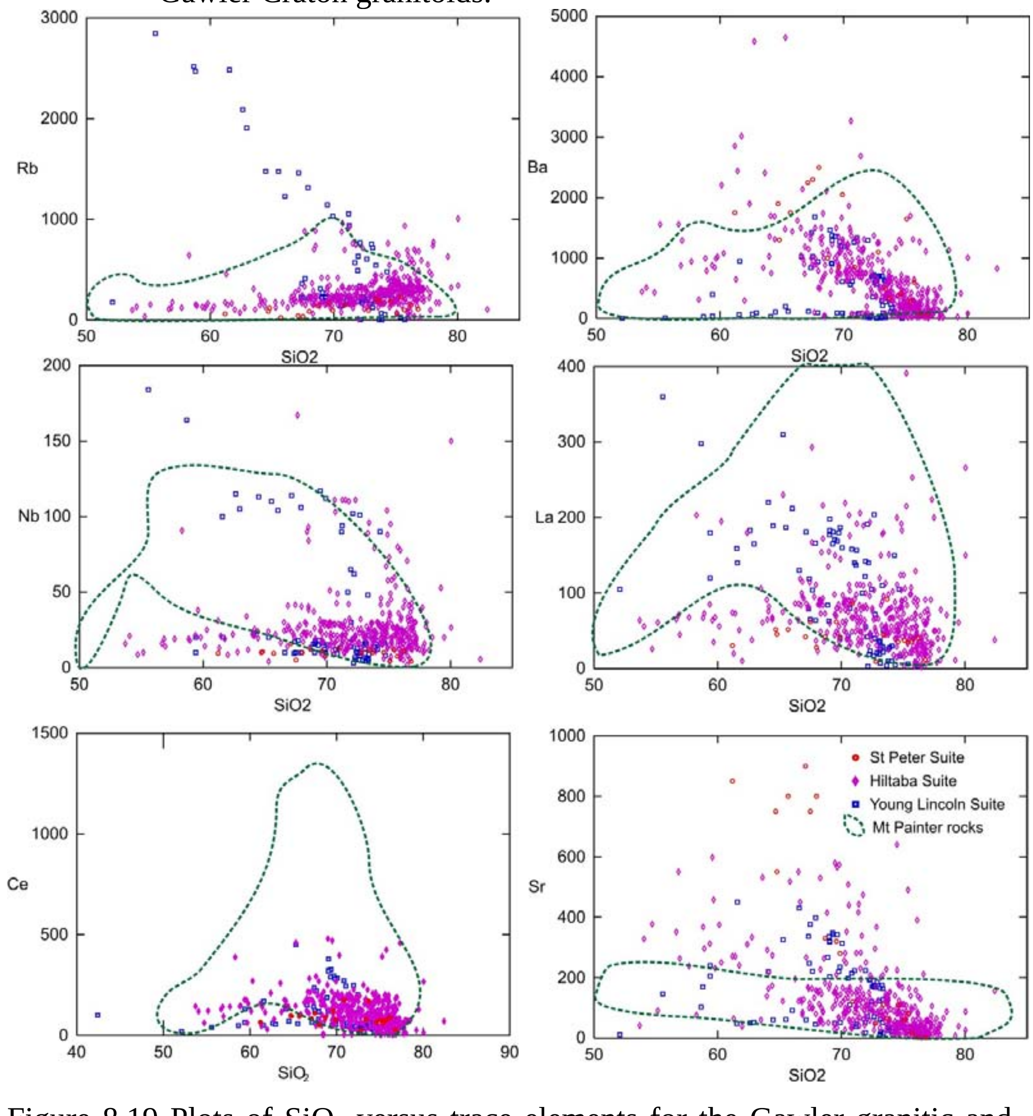

Figure 8.19 Plots of SiO_2 versus trace elements for the Gawler granitic and associated rocks.

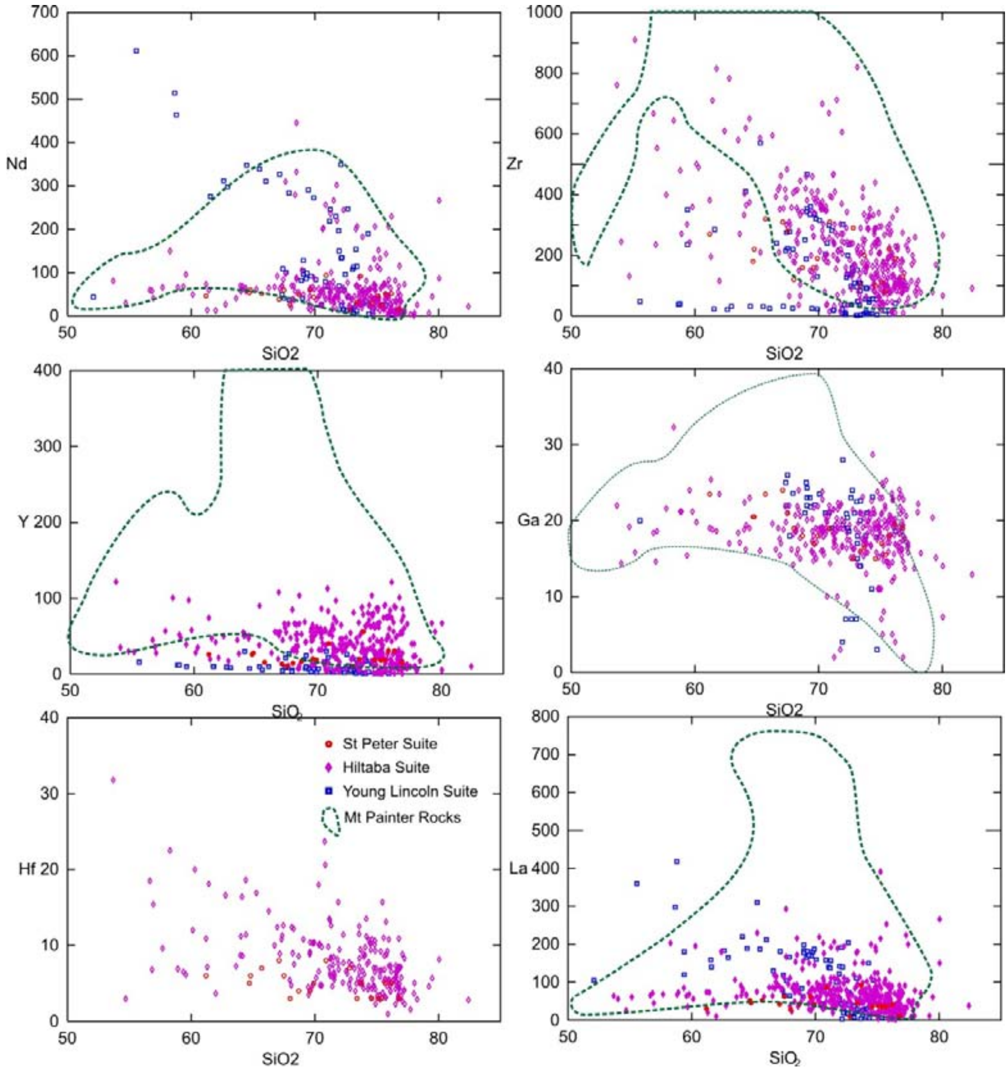

Figure 8.19 (continue) Plots of SiO_2 versus trace elements for the Gawler granitic and associated rocks (note no Hf concentration available for the Mt Painter rocks).

The REE patterns of the granitic and associated rocks from the Gawler Craton normalised to values of Sun and McDonald (1989) are shown in Figure 8.20b, d and f. All samples exhibit enrichment in LREE with moderate degree of LREE fractionation and slightly degree of HREE fractionation. Negative Eu anomalies are common in all suites.

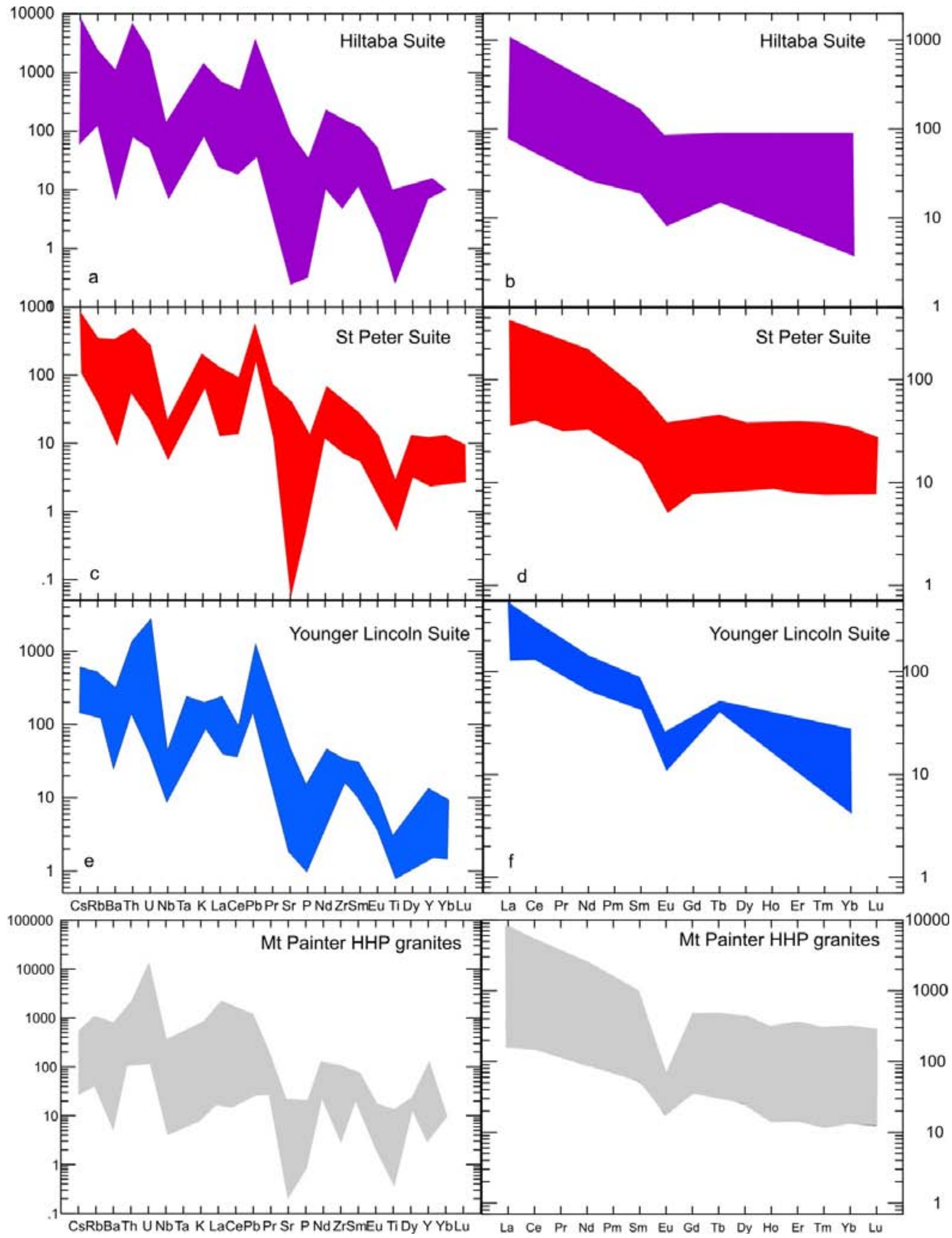

Figure 8.20 Spider diagrams (normalise to primordial mantle value of Sun and McDonald, 1987) and REE patterns (normalised to values of Sun and McDonald, 1989) of the Gawler igneous rocks a and b: Hiltaba Suite; c and d: St Peter Suite; e and f: Younger Lincoln Suite compared to the HHP granites from he Mt Painter Province (note scales of the Mt Painter granites are different due to their enriched in trace element concentrations).

Geochemical data of Gawler granitic and associated rocks is compared to the HHP granites and mafic rocks from the Mt Painter Province. The Younger Lincoln and Hiltaba Suites show similar trends of SiO_2 and major elements (Figure 8.17) with lower concentrations in the HHP granites from the Mt Painter Province. Trace element concentrations for the Gawler granitic rocks are significantly less than the HHP granites from the Mt Painter, particularly La, Ce, Zr, Y, Ga, U, Th and La. However the Gawler granitic rocks are more enriched in Sr than the Mt Painter rocks. These characteristic are also shown in the REE patterns and the spider diagrams (Figure 8.20). The granitic rocks from both areas show negative Eu anomalies but that of the HHP granites from the Mt Painter Province are relatively much larger. The Hiltaba Suite granites and Gawler Range Volcanics have very similar geochemical characteristics to the HHP granites of the Mt Painter province. The St Peter granites typically have geochemical characteristics different from the Mt Painter granites, Younger Lincoln and Hiltaba Suites.

8.2.3 Tectonic setting

Discrimination diagrams of Y+Nb versus Rb and Y versus Nb of Pearce et al. (1984) suggest that the granitic rocks of St Peter Suite plot within the volcanic arc granite (VAG) field (Figure 8.21a and b) and most samples are classified as I- or S-type granites with a few plotting within the A-type granite field. Most samples from the Younger Lincoln Suite plot within the syn-collision granite (syn-COLG) field (Figure 8.21a and b). Figure 8.22 shows that most samples from the Younger Lincoln Suite are A-type granite, however a few samples plot within the I-and S-type granite fields. The granitic and associated rocks from the Hiltaba Suite plot in the within plate, syn-collision and volcanic arc granite fields. This suggests that the Hiltaba Suite could not be classified using the Y+Nb versus Rb and Y versus Nb discrimination diagrams. However, samples from the Roxby Down granites and volcanics, which are associated with the giant breccia-hosted Olympic Dam Cu-U-Au-REE deposit plot in the within plate granite field (Creaser, 1996). This suggests that individual intrusions contain differing geochemical signatures and/or were emplaced in different tectonic settings.

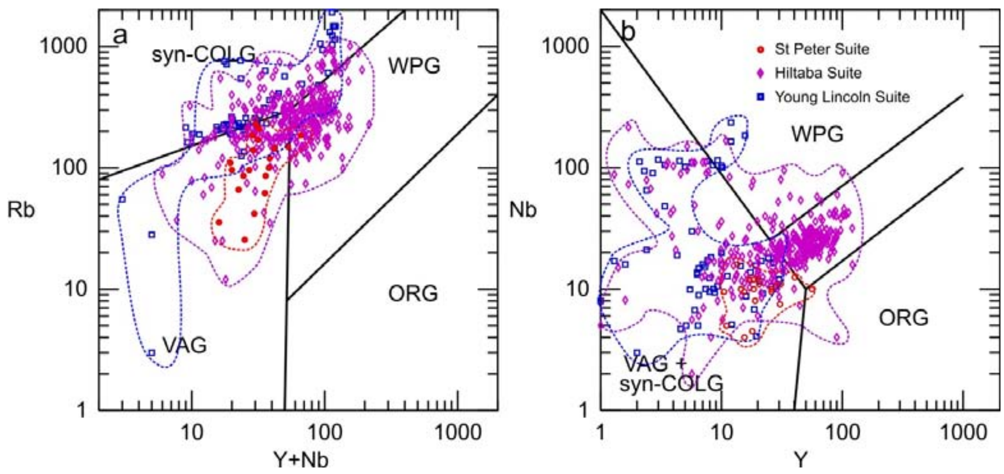

Figure 8.21 Discrimination tectonic setting diagram for the Gawler granitoids a: Y + Nb versus Rb diagram; b: Nb versus Y Pearce et al. (1984).

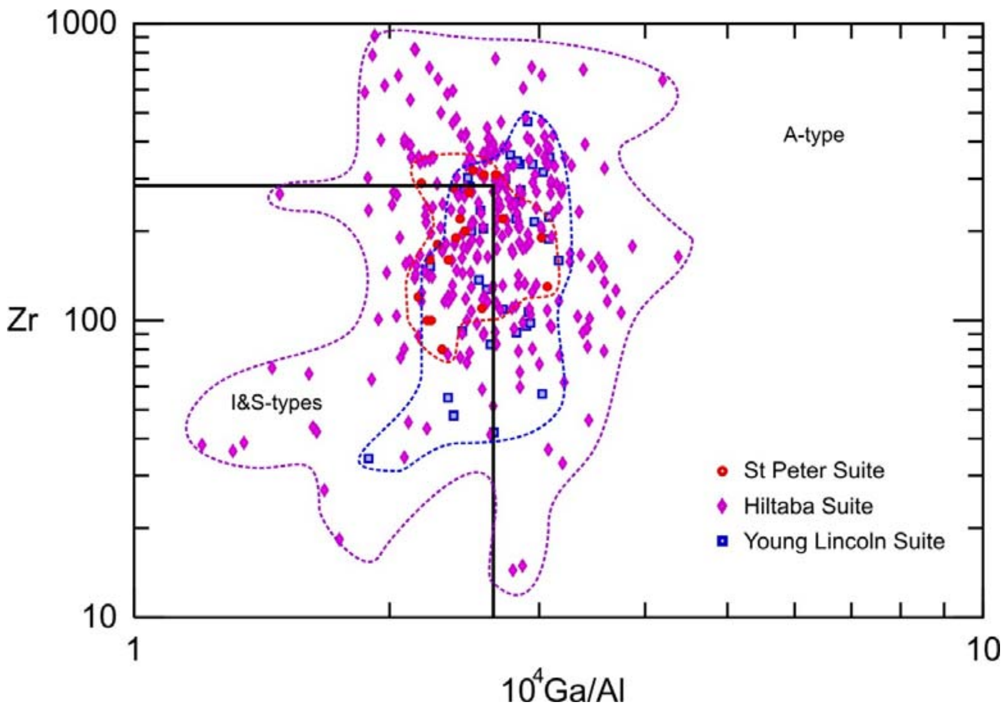

Figure 8.22 Discrimination diagrams classifying granitic types of Zr versus 10^4*(Ga/Al) after Whalen et al. (1987).

8.2.4 Nd-Sm isotopes

Nd-Sm and Rb-Sr isotopic data of the granites and associated rocks from the Gawler Craton that is discussed in this study is from preious studies of Turner et al. (1993), Simpson (1994), Schaefer (1998), Stewart and Foden (2001), Neumann (2001) and Swain et al. (2008).

The Younger Lincoln Suite including the Middlecamp, Carpa, Burkitt and Tunkillia Granites and associated rocks, dated between ~1.73 and 1.65 Ga, yield a wide range of εNd values. Most analyses give negative εNd values, ranging from -18.4 to +4.4 (Figure 8.23) with T_{DM} ranging from 3.43 to 2.03 Ga. The widely ranging εNd values not only occur in different units but also within the same plutons suggesting a heterogeneous source for generating the Younger Lincoln granitic rocks. Most εNd values of the Younger Lincoln Suite plot within the Palaeoproterozoic field which suggests melting of existing upper crust and/or igneous crust as a major source. This interpretation is supported by inherited zircons with ages of ~2.0 Ga (equivalent to Archaean Miltalie Gneiss) found in the Middlecamp and Carpa granites (Fanning, 1997). Melting of Archaean crust is also a possible source of the Younger Lincoln Suite but it is only minor component due to very low εNd values. Melting of existing crust could not produce positive εNd values, therefore mantle-derived input is needed to generate the Younger Lincoln granitoids.

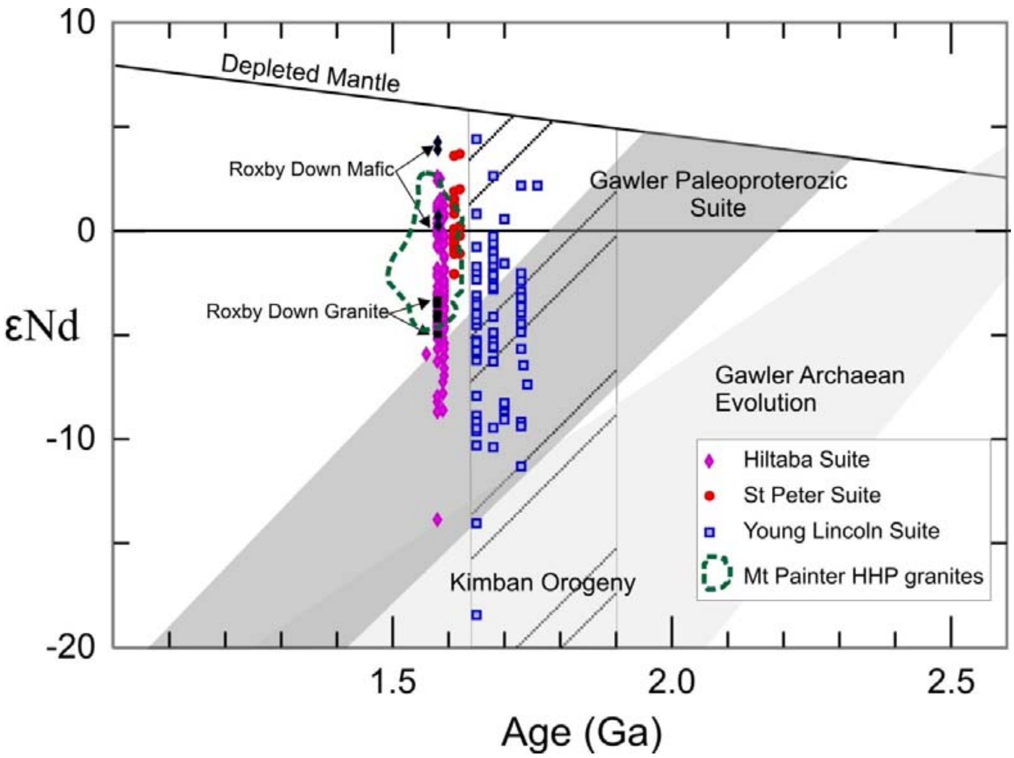

Figure 8.23 Initial ε_{Nd} values versus crystallization ages of the mafic and felsic rocks from the Gawler Craton (see references in text).

The samples from St Peter Suite yields higher εNd values than other granitic suites (-2.05 to 3.61), with T_{DM} ages from 2.44 to 1.93 Ga. These data indicate a relatively juvenile magmatic source which is suggested to be a crustal contaminated magma by subduction (Swain et al., 2008). Negative εNd values from the St Peter Suite samples are caused by large amount of mantle-derived magma mixing with reworked older crust (Swain et al., 2008).

The Hiltaba granites and Gawler Range Volcanics show overlapping (within a wide range) εNd values suggesting that they are coeval. Most samples yield εNd values from -8.6 to +3.7, however one analysis from the Charleston Granite gives a very low εNd values (-13.9). T_{DM} ages of the Hilbata Suite range from 2.97 to 1.85 Ga. There are four samples of mafic and ultramafic dykes that intrude the Roxby Downs Granite (adjacent to the Olympic Dam deposit) and have εNd values of up to +4.0 suggesting a juvenile mantle source (Johnson and McCulloch, 1995). This mafic magma has been suggested as the source of U-enriched fluids that formed the Olympic Dam Deposit (Creaser, 1995). The very low εNd values and T_{DM} ages of the Charleston granite of the Hiltaba Suite suggested that the granitic rocks were mainly derived from partial melting of existing crust (both Archaean and Paleoproterozoic crusts). Budd et al. (2006) suggested that partial melting of granodiorite composition played an important role for this granitic suite. The relatively high εNd values compared to the Charleston granite of the Hiltaba granites and Gawler Range Volcanics display εNd values which lie between mafic magma and the older crust. These indicate mixing of Archaean and/or Paleaoproterzoic melting crustal sources and mantle-derived magma as a main process to generate the Hiltaba Suite.

The εNd values of the felsic Hiltaba Suite are typically lower and show greater variation than the Mt Painter HHP granites but the Hiltaba mafic rocks (from the Roxby Down Granite) εNd values are higher. These suggest that sources of the felsic Hiltaba Suite rocks have a higher proportion of crustal-derived components (possibly through assimilation the Palaeoproterozoic basements), whereas sources of the Hiltaba mafic rocks have more depleted-mantle εNd signatures.

8.2.5 Conclusion and petrogenesis

The granite and associated rocks that have high heat production values from the Gawler Craton are mainly from the Younger Lincoln (ages of ~1770-1600 Ma; correlated to the Tunkillia Granite) and Hiltaba Suites (ages of ~1598-1585 Ma). The HHP granites are typically coeval with felsic and mafic volcanic rocks. They are characterized by porphyritic, equigranular, fine- to coarse-grained and deformed textures. K-feldspar megacrystic phenocrysts are common in the Hiltaba Suite granites and Gawer Ranges Volcanics. The Younger Lincoln and Hiltaba granitic rocks are mainly peraluminous with slightly metaluminous; generally contain high Th, U, K, La, Pb, Nd, Sm and Y contents, and have low Ba and Sr concentrations. They have ASI values <1 suggesting that they are not S-type granites. Geochemistry of the Young Lincoln and Hiltaba Suites suggests that they could be classified as A-type and I-type granites and emplaced in a within plate setting. However, some samples have geochemical characteristics similar to volcanic arc and syn-collisional granites. Most Young Lincoln granitic rocks have the geochemical characteristics of syn-collisional granites.

Nd isotopic signatures of the Younger Lincoln granites suggest that the Younger Lincoln granites were derived from a mixture of depleted mantle and less than 30% of pre-existing crustal component of the Paleoproterozoic igneous basement with minor Archaean crust (Fanning, 1997; Schaefer, 1998). Based on Nd isotopes, the Hiltaba Suite and Gawler Ranges Volcanics were derived by partial melting of pre-existing Palaeoproterozic crust in response to mantle-derived magma intrusions (e.g. Creaser, 1996; Budd, 2006). They are suggested to have been emplaced in a back-arc distal to a continental subduction zone (Budd, 2006).

8.3. Curnamona Craton

The Curnamona Craton consists of the Mt Painter Province in the northern part and the Willyama Inlier in the southern part (Figure 8.24). A detailed study of felsic rocks of the Mt Painter Province is presented in Chapters 1-7. The granitic and associated rocks of the Willyama Inlier will be reviewed in this section.

The Willyama Inlier comprises the Olary Domain in South Australia and Broken Hill Domain in New South Wales (Figure 8.25). Both are dominated by the Palaeoproterozoic Willyama Supergroup (Stevens et al., 1990). Stratigraphically and lithologically, the Willyama Inlier consists of late Palaeoproterozoic meta-sedimentary and meta-igneous rocks (with ages between ~1715–1645 Ma; Page et al, 1998; 2000; 2003), which are intruded by Mesoproterozoic granitic intrusions and felsic volcanics (dated between ~1590–1580 Ma, Page et al., 2003).

The Willyama Supergroup sequence in both the Olary Domain and the Broken Hill Domain are similar and correlatable, and has been interpreted to have been deposited in an intracratonic rift setting (Willis et al., 1983; Stevens et al., 1990; Cook and Ashley, 1992). However, the Olary Domain contains more calcsilicate-bearing rocks with less mafic rocks and exhalative chemical sediments than the Broken Hill Domain (Ashley et al., 1996). The lower sequences of the Willyama Supergroup consist of psammo-pelitic metasediments, migmatised quartzo-feldspathic rocks and calc-albitites, albite-quartz rocks (the Thackaringa and Wiperaminga Groups), and syn-sedimentary A-type (Basso Suite) and S-type (Alma Gneiss) felsic volcanic to subvolcanic rocks, which are no younger than ~1715 Ma (Page et al., 1998, 2000, 2003).

8.3.1 Olary Domain

The Olary Domain consists of isolated sub-volcanic mafic intrusives (*ca.* 1700 Ma) occurring as irregular pods and plugs within A-type felsic intrusions (Ashley et al., 1996; Conor, 2000). Intrusions and sub-volcanic basaltic magmas of the Lady Louise Suite intruded the lower Willyama Supergroup at *ca.* 1685 Ma (Page and Laing, 1992; Nutman and Ehlers, 1998; Conor and Fanning, 2001). Their intrusions coincide with an increase in accommodation space within the Willyama basin, resulting from thinning of the sub-continental lithospheric mantle (Page et al., 2003).

Mafic I-type tonalite and/or adamellite and granodiorite intruded into the metasediments of the Olary Domain between 1660 and 1640 Ma, in the Antro and Poodla areas (Fanning et al., 1998).

Syn- to post-deformational granitic magmatism mostly occurred in the Olary Domain during the Mesoproterozoic (*ca*. 1590–1580 Ma; Fanning et al., 1998; Page et al., 2003). Rock types include S-type granite, monzogranite, trondhjemite and I-type granodiorite to diorite. Syn- and post-tectonic volcanism and bimodal magmatism (including rhyolite-rhyodacite and amygdaloidal basalt- the Benagerie Volcanics) in the Plumbago region and under Neoproterozoic to Recent cover in the Benagerie Ridge have a U-Pb SHRIMP age of 1582±4 Ma from porphyritic rhyolite sample (Fanning et al., 1998). The unexposed Benagerie Volcanics that are suggested as a plutonic emplacement root and are likely parts of LIP (Williams et al., 2009).

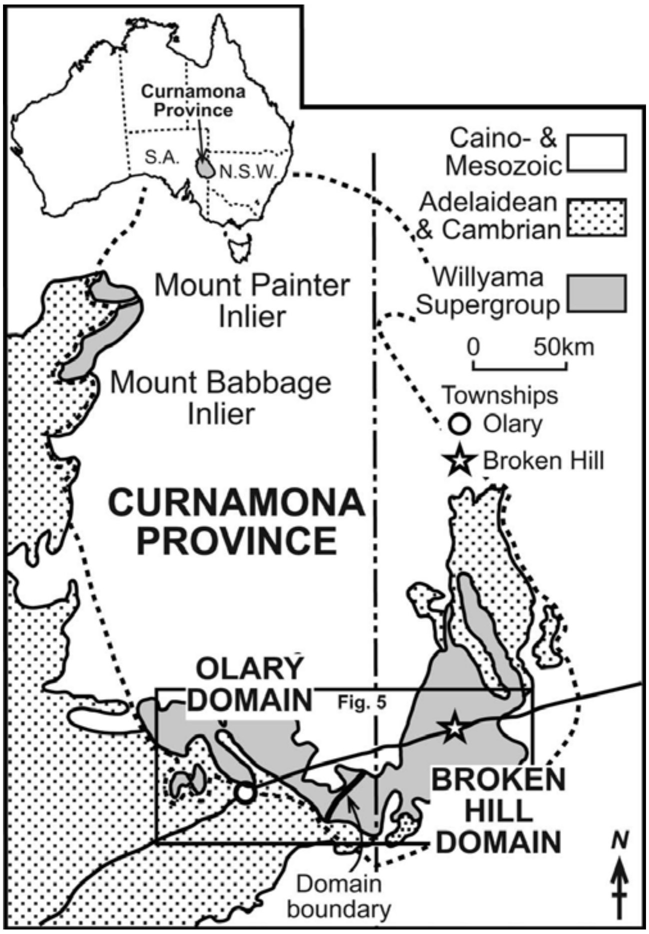

Figure 8.24 Location of the Curnamona Craton in northeastern South Australia and western New South Wales (After Rutherford et al., 2007).

Figure 8.25 Simplified geologic map of the Broken Hill and Olary Domains (after Page et al., 2005b). The inset shows the full extent of the outcropping Curnamona Province.

8.3.1.1 Proterozoic granite of the Olary Domain

Granitic and volcanic rocks of the Olary Domain can be divided into three groups according to Stewart and Foden (2002): 1) A-type granites and volcanics (~1700 – 1710 Ma), 2) I-type granitoids (1616 – 1680 Ma) and 3) S-type granites (1590 Ma).

A-type granitoids in the Olary Domain are widely distributed in the central and eastern areas and include quartzofeldspathic gneisses. These granitoids are equivalent to the Thackaringa Group in the Broken Hill Domain. The gneisses are characterised by massive to foliated, leucocratic, medium-grained and equigranular textures and contain prominent scattered quartz grains (up to 5 cm in size), sometimes showing quartz augens. Petrographically, large quartz grains representing relict igneous phenocrysts (Vernon, 1986) are set in a recrystallised groundmass of albite, quartz, and microcline. The zircon U-Pb SHRIMP age of the A-type Ameroo Gneiss from the Olary Domain is 1703±6 Ma (Cook et al., 1994).

I-type granitoids have limited outcrops and are relatively small. The granitoids commonly contain mafic to intermediate rocks and are found in the Poodla Hill, Tonga Hill, Alconie Hill, Antro Woolshed and Bimbowrie regions (Wyborn et al, 2001). The mafic granitoid at Poodla Hill has a U-Pb zircon age of 1629±12 Ma (Cook et al. 1994). The I-type mafic granitoids have granodioritic to tonalitic compositions and are typically porphyritic, massive to weakly foliated and coarse-grained. Major minerals include microcline, quartz, plagioclase, biotite and/or chlorite. K-felspar phenocrysts are generally subhedral to ovoid and 10-30 mm in size. Accessory minerals are apatite, zircon, fluorite, hornblende and opaque minerals. Brecciated texture is locally found with granitoid clasts in biotite-rich matrix.

S-type granitoids are the most extensive in the Olary Domain and are typically leucocratic trondhjemite and alaskites with a crystallization age of ~1590 Ma (Cook et al. 1994). The dominant granitoids are considered to be S-type (Plimer, 1996; Ashley et al., 1995; Ashley, 1984), however Wyborn (2001) suggests that these granitoids are possibly I-type due to their lacking cordierite or garnet, and the small range of SiO_2 (~70-75 wt%). The grantitoids are predominantly potassic and biotite-rich, leucocratic, massive to foliated and equigranular to porphyritic.

8.3.1.2 Mafic magmatism of the Olary Domain

Mafic magmatism of the Olary Domain occurred at *ca.* 1700 Ma with the Montstephen Metabasalt (the Weekeroo Amphibolites or metabasite or metabasalt; Drexel et al., 1993; Conor, 2000; Conor, 2004; Page et al., 2000; Rutherford, 2006) and at 1685±6 Ma with the Lady Louise Suite (Conor and Fanning, 2001). The Montstephen metabasalts consist of metamorphosed plagioclase–hornblende bearing mafic rocks. They are intercalated within meta-sedimentary sequences comparable to the ones intruded by the A-type granites (Raveggi et al., 2007). The mafic rocks of the Lady Louise Suite are typically medium-grained, weakly layered, hornblende, plagioclase ± garnet bearing amphibolites intruding the Olary Domain (Crooks, 2002; Conor, 2004; Rutherford et al., 2006). The Billeroo alkaline magmatic rocks were emplaced between approximately 1610 and 1550 Ma and include ijolite, syenite and lamprophyric dykes (Rutherford, 2006). Mafic magmatism is less abundant in the Olary Domain relative the Broken Hill Domain (Conor, 2004).

8.3.1.3 The High Heat Production granites of the Olary rocks

Heat production values of the granitic and mafic rocks of the Olary Domain vary within each group. The S-type granitoids contain relatively high heat production values, and are enriched in K_2O, U and Th compared with the A- and I-type granites (Figure 8.26). However, some examples from all three groups can be classified as high heat producing granites. The S-type granite has heat production values average of 2.25 μwm^{-3}, K_2O content average of 4.5 wt%, U and Th concentrations average of 8 ppm and 44 ppm. The I-type granite has heat production values average of 3.87 μwm^{-3}, K_2O content average of 2.0 wt%, U and Th concentrations average of 5 ppm and 32 ppm. The A-type granite has heat production values average of 4.41 μwm^{-3}, K_2O content average of 1.7 wt%, U and Th concentrations average of 9 ppm and 38 ppm. The mafic rocks of the Olary Domain commonly contain lower heat production values than the felsic rocks, however, the Mesoproterozic ijolite, syenite and lamprophyric dykes show higher heat production values than normal mafic rocks.

8.3.1.4 Geochemistry

Granitic and volcanic rocks from the Olary Domain have different SiO_2 concentrations within each group. The oldest A-type granitoid has the most felsic component showing SiO_2 contents, ranging from 84 to 70 wt%. Associated microgranular enclaves contain an average SiO_2 content of 66 wt%. The I-type group have a more mafic composition with SiO_2 ranging between 53 and 73 wt%. S-type granitoids have SiO_2 contents ranging between 64 and 76 wt%.

The I-type granites have higher concentrations of TiO_2, $Fe2O_3$ and CaO than the A- and S-type groups. The A-type group typically show low Al_2O_3, CaO, TiO_2, MnO and P_2O_5 contents and high Fe_2O_3 and Na_2O contents. The S-type group commonly contains low contents of TiO_2, Fe_2O_3, MgO, CaO and Na_2O. Mafic rocks, including the Palaeoproterozoic metabasite and the Mesoproterozoic ijolite, syenite and lamprophyre have SiO_2 contents ranging from 44 to 56 wt%. Palaeoproterozoic metabasites have lower Al_2O_3, MnO, Na_2O and P_2O_5 and higher Fe_2O_3, MgO and CaO contents than the Mesoproterozoic mafic rocks.

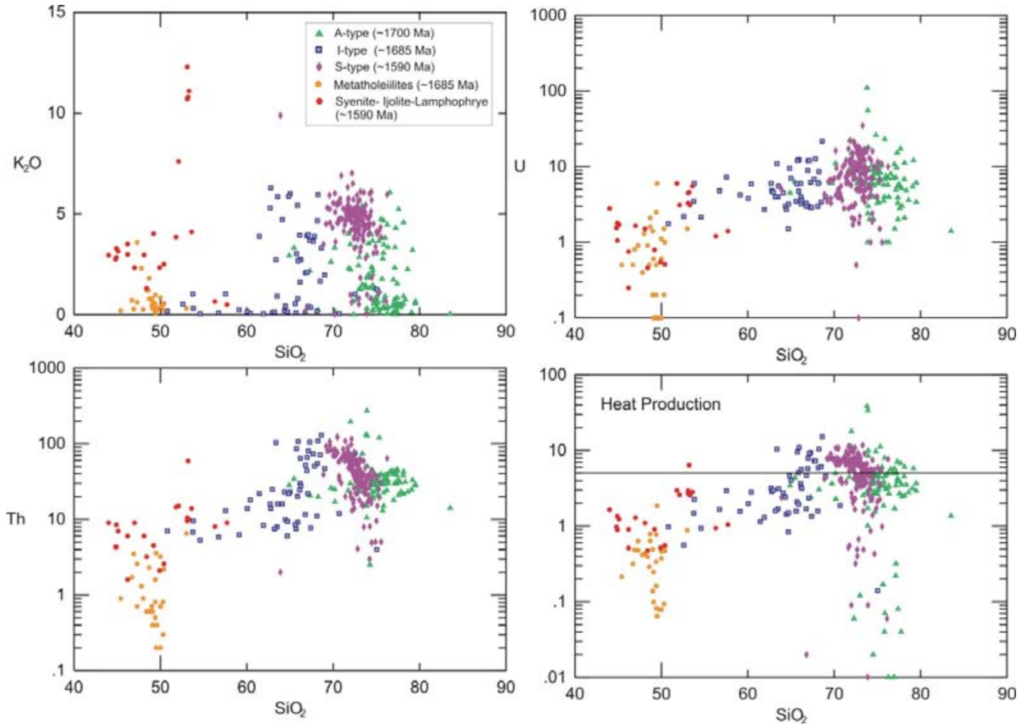

Figure 8.26 Concentration of K_2O, U and Th and heat production values of granitic and associated rocks from different suites of the Olary Domain.

Harker diagrams of major elements versus SiO_2 for the mafic and felsic rocks mostly display negative trends with different slopes among the groups (Figure 8.27). The plot of Na_2O versus SiO_2 does not display a clear relationship due to sodic alteration. Most S-type granitoids have peraluminous characteristics (Figure 8.28) whereas the A-type granitoids mainly plot in peraluminous field with a minority of samples showing slightly peraluminous compositions. The I-type granites are typically metaluminous to slightly peraluminous.

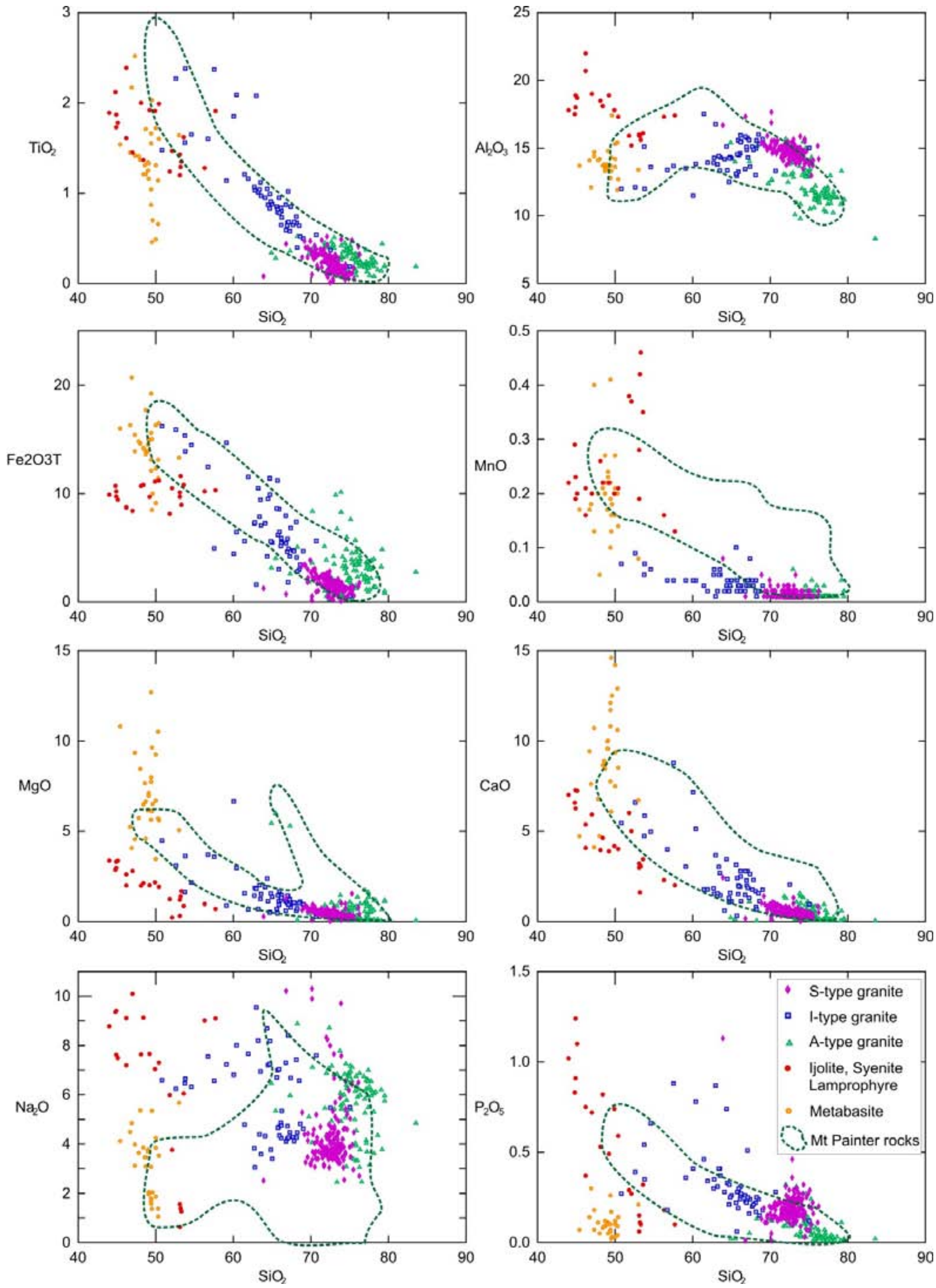

Figure 8.27 Binary plot of SiO_2 versus major elements for the mafic and felsic rocks from the Olary Domain.

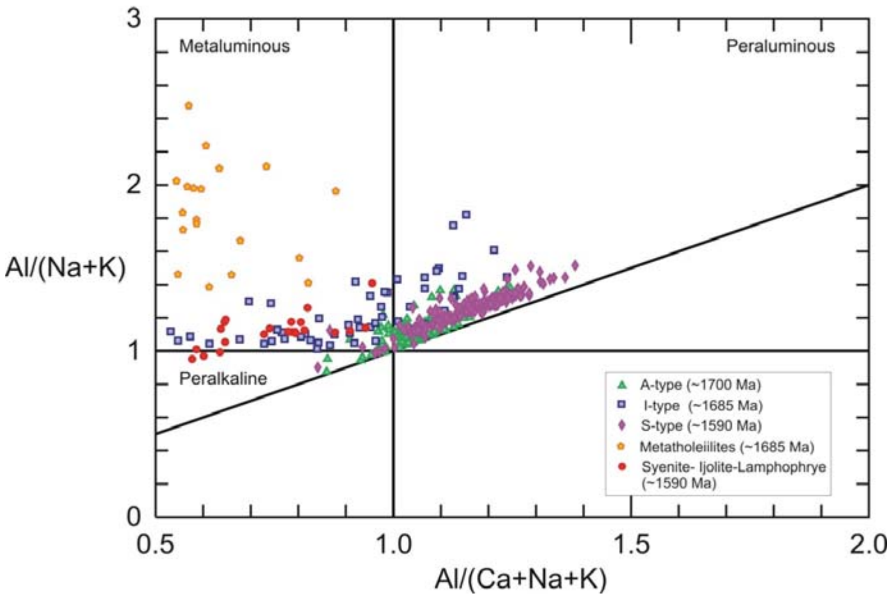

Figure 8.28 ANK versus A/CNK plot showing the peraluminous to metaluminous nature of the Olary rocks; A = Al_2O_3, N = Na_2O, K = K_2O, C = CaO (all in molar proportion).

Trace element concentrations of granitoids in the Olary Domain vary widely between the different groups (Figure 8.29). The oldest A-type group is typically enriched in Ce, Ga, La, Nb, Y and Zr, and depleted in Pb and Rb. The I-type group shows depletion and enrichment in same elements as the A-type group but with lower concentrations. In contrast, the S-type group is typically depleted in Ga, Nb, Y and Zr, and enriched in Pb and Rb. Metabasites generally contain low concentrations of trace elements and display a continuation of the trend from the same age I-type group. The ijolite-syenite-lamprophrye group have low trace element concentrations and do not show the same relationships as the coeval S-type group.

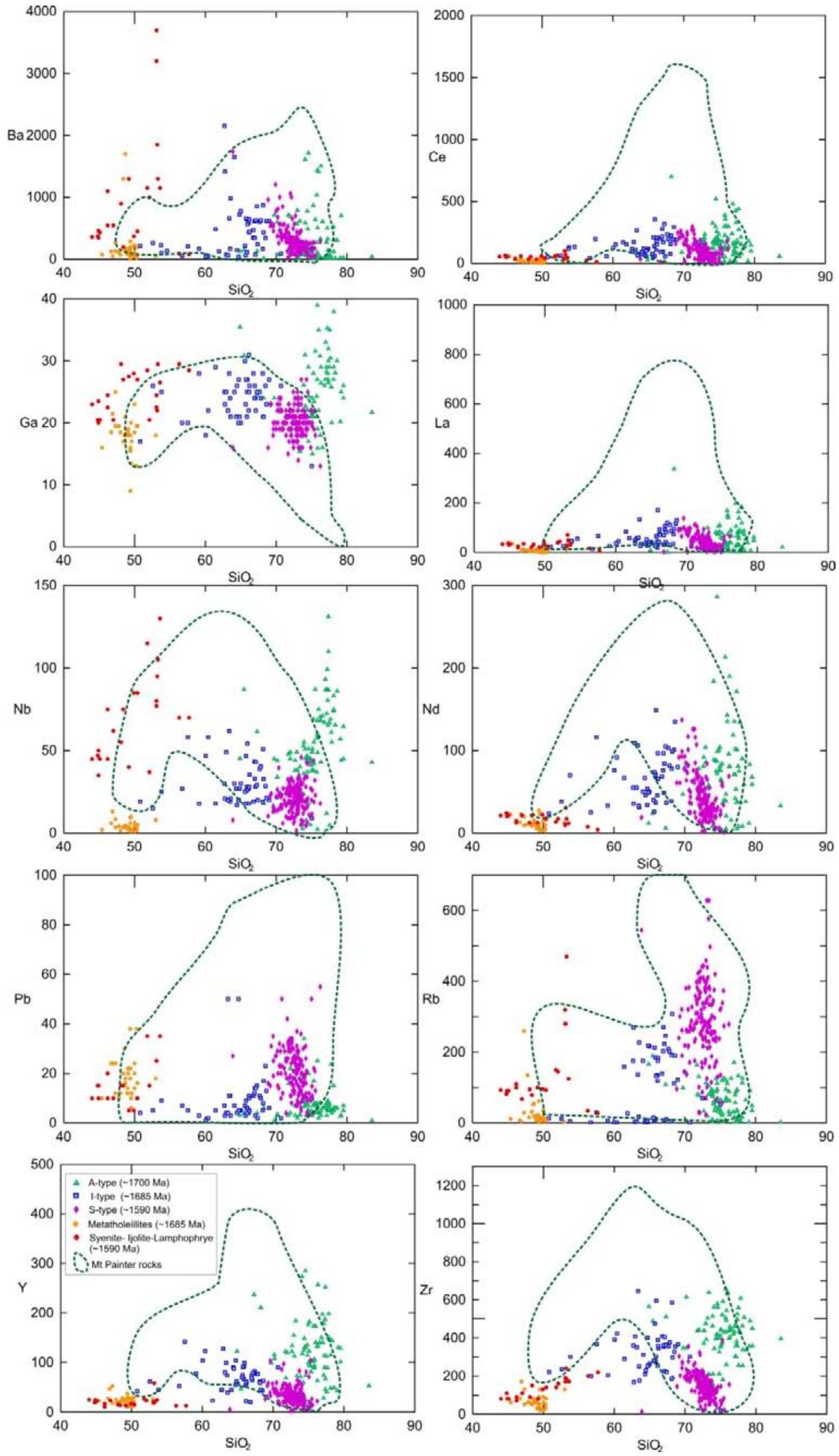

Figure 8.29 Binary plot of SiO_2 versus trace elements for the mafic and felsic rocks from the Olary Domain.

Primitive mantle normalized rare earth element diagrams of the Olary granitoids (Figure 8.30) display enriched LREE and slightly depleted HREE patterns with negative Eu anomalies. The I-type group exhibits the highest degree of LREE fractionation among the three groups. The Mesoproterozoic ijolite, syenite and lamprophyric dykes show high fractionated LREE, flatter HREE patterns and positive Eu anormalies (Figure 8.31a). The REE patterns of the metabasitic rocks are typically flat showing negative Ce anomalies and both positive and negative Eu anomalies (Figure 8.31b).

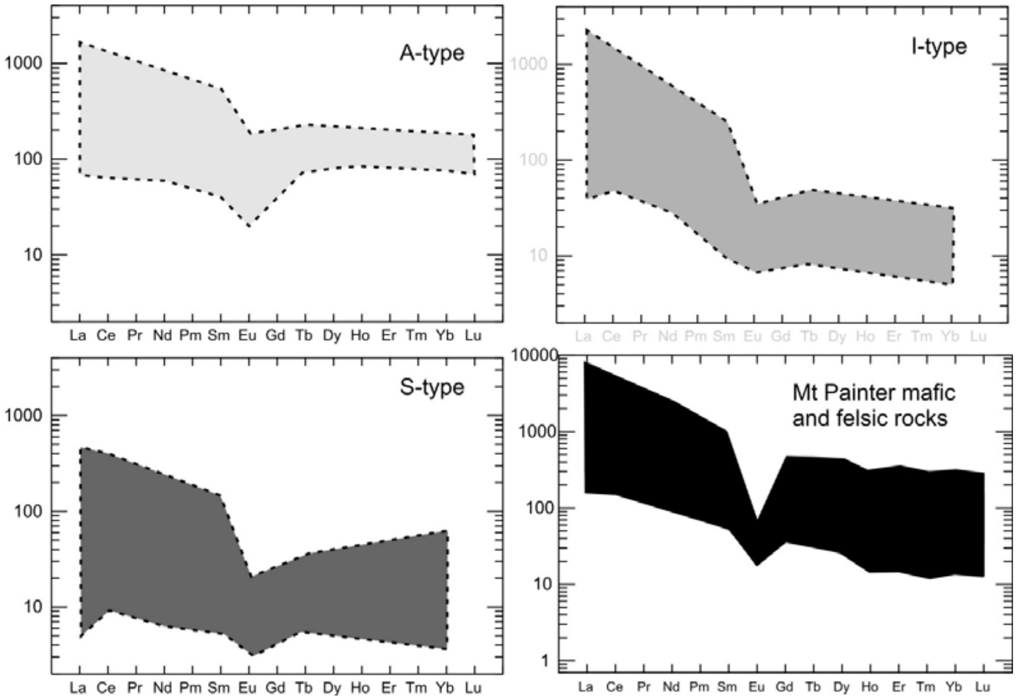

Figure 8.30 REE patterns of the Olary granitic rock normalised to chondrite value of Sun and McDonald (1989).

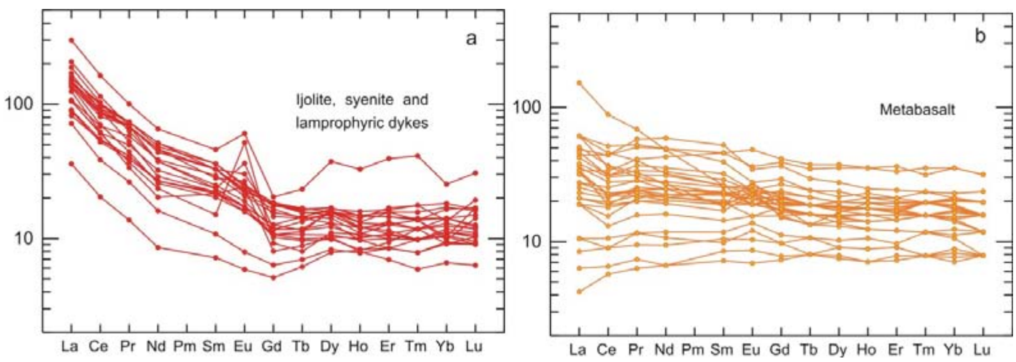

Figure 8.31 REE patterns of the Olary mafic rock normalised to chondrite values of Sun and McDonald (1989) a) ijolite, syenite and lamprophyric dykes; b) metabasalt.

Spider diagrams of the felsic and mafic rocks are shown in Figure 8.32. The A- and I- type groups have similar patterns (Figure 32a, b and c) showing positive Th, U, La, Pb, Nd, Sm and Y anomalies and negative Ba, Ti and Sr anomalies with trace elements more abundant in the A-type granitoids. The S-type spider diagrams shows less negative Sr and positive U and Th anomalies than the other groups. Spider diagrams of the metabasite and ijolite-syenite-lamprophry group are slightly different. The ijolite-syenite-lamprophry group show positive anomalies for Pb, Sr, P, K and Eu (Figure 8.32d) whereas the spider diagram of the metabasite displays positive anomalies for U, Pb, Sr, P, K and Eu (Figure 8.32e).

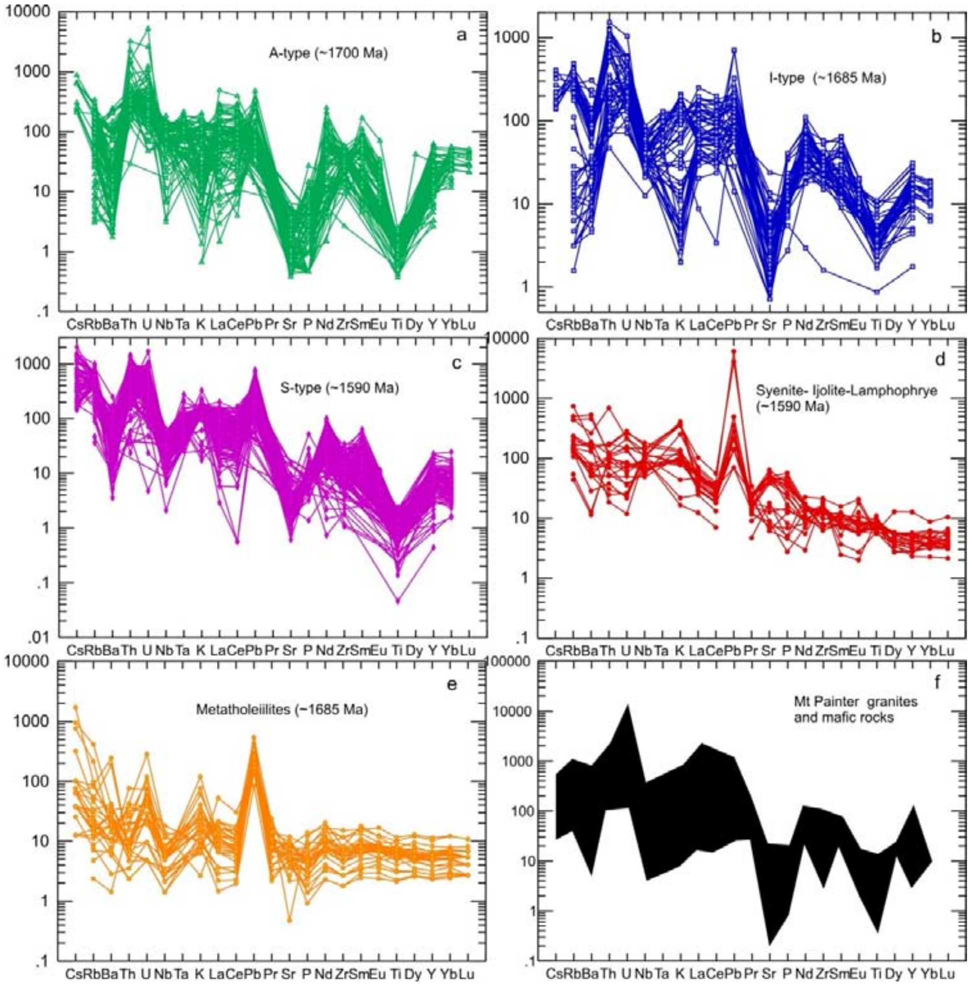

Figure 8.32. Spider diagrams of the Olary mafic and felsic rock that normalise to primordial mantle value of Sun and McDonald (1987) a: A-type granite; b: I-type granite; c: S-type granite; d: ijolite, syenite and lamprophyric dykes; e: metabasalt; f: Mt Painter mafic and granitic rocks.

The Olary magmatic rocks have slightly lower major element concentrations compared to the HHP granites from the Mt Painter Province with the exception of P_2O_5. The Olary rocks also typically have lower trace elements concentrations, in particular Ce, La, Pb, Rb, Y, U, Th and Zr. REE patterns of the Olary granitic rocks are comparable to the Mt Painter granites but contain significantly lower concentrations of the rare earth elements and a lesser degree of fractional crystallization. REE patterns for the mafic rocks of the Olary Domain that also differ from those of the Mt Painter mafic dykes do not show negative Eu anomalies. The source of the Olary mafic rocks is more primitive, with a greater proportion of mantle-derived magmas and less of a crustal signature than the Mt Painter mafic dykes

8.3.1.4 Tectonic setting and Typology

Discrimination diagrams of Y+Nb versus Rb and Y versus Nb of Pearce et al. (1984) suggest that the A- and I-type granites of the Olary Domain mostly plot in the within plate granite (WPG) field (Figure 8.33a and b) and can be classified as A-type granites in the discrimination diagram of Whalen et al. (1987; Figure 8.34). The samples from the S-type group mainly plot in the within plate granite (WPG) field with few samples in the volcanic arc granite (VAG) field, and plot in both the A-type field and the I- and S-type fields (Figure 8.34). Metabasite samples plot in the volcanic arc granite (VAG) field (Figure 8.33a and b) and plot in both A-type and I- and S-type fields (Figure 8.34).

The 1590 Ma S-type group is described as being multiply deformed metasedimentary and meta-igneous rocks emplaced in an intracontinental rift environment (Willis et al., 1983). However, the discrimination diagrams (Figure 8.34 and 8.35) and other evidence from Wyborn et al. (2001) suggest that the 1590 Ma Supersuite may be I-type rather than S-type granites. The evidence to support this suggestion includes; absence of cordierite or garnet; identical complementary fractionation trends with the coeval Kokatha subsuite of the Gawler Ranges Volcanics and Hiltaba Suite; more felsic composition with a narrow ranges of SiO_2 content (~70-75 wt%) and strong oxidization (Wyborn et al., 2001).

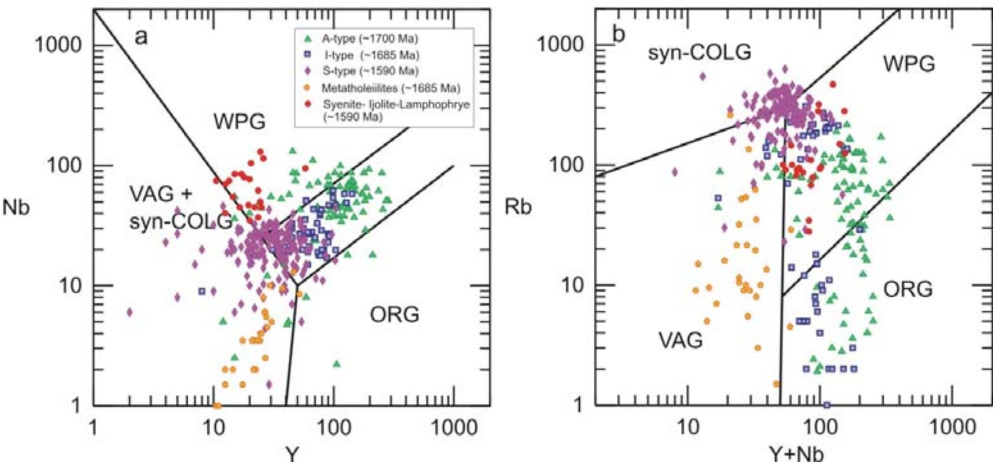

Figure 8.33 Discrimination tectonic setting diagrams for the mafic and felsic rock from the Olary Doamin a: Y + Nb versus Rb diagram; b: Nb versus Y Pearce et al. (1984).

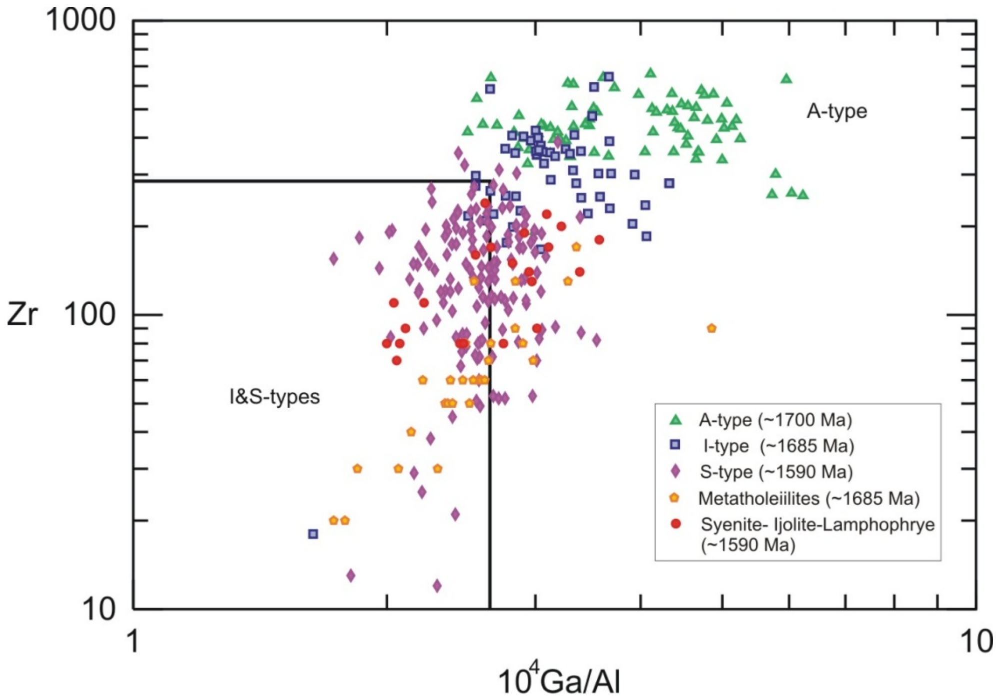

Figure 8.34 Discrimination diagrams classifying granitic types of Zr versus 10^4*(Ga/Al) after Whalen et al. (1987).

8.3.1.5 Nd-Sm Isotope

Nd-Sm isotope data of the granites and associated rocks from the Olary Domain are taken from previous studies of Ashley et al. (1996), Stewart and Foden (2002), Rutherford (2006) and Barovich and Hand (2008).

Initial εNd values of the A-type granitic rocks calculated at 1700 Ma ranges from –6.1 to +1.0 with T_{DM} ages of 2.28 Ga (Figure 3.35; Ashley et al., 1996). The I-type granites have initial εNd values between -5.2 and -0.9 and the S-type granites have initial εNd values between -8.6 and -2.4 (Stewart and Foden, 2002).

The ijolite, syenite and lamprophyre yield εNd values (1590 Ma) between -0.3 and 2.8 with T_{DM} ages from 1.80 to 2.20 Ga (Rutherford, 2006). εNd values (1700 Ma) for the Montstephen metabasalt and εNd values (1685 Ma) from the Lady Louise metabasalt range from -3.8 to +2.6 (Conor, 2000; Conor and Fanning, 2001; Rutherford et al., 2007).

εNd values for metasediment samples from the Olary and Broken Hill Domain calculated at the estimated stratigraphic age (Page et al., 2005a,b; Barovich and Hand, 2008;) vary from -6.1 to +0.0 (Barovich and Hand, 2008).

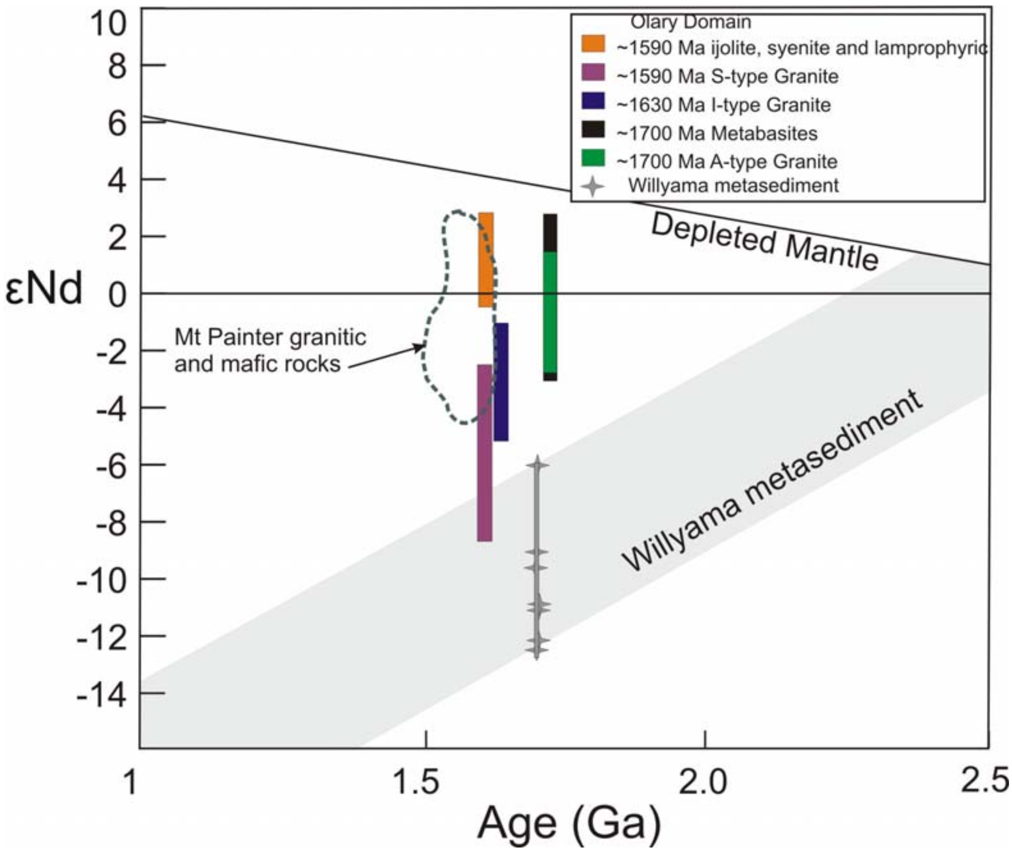

Figure 8.35 Initial εNd values versus crystallization ages of the mafic and felsic rocks from the Olay Domain (data from Ashley et al., 1996); Stewart and Foden, 2002; Rutherford, 2006 and Barovich and Hand, 2008).

8.3.1.6 Conclusion and petrogenesis

The A-type (~1700–1710 Ma), I-type (1616–1680 Ma) and "S-type" granites (~1590 Ma) of the Olary Domain are lithologically and geochemically different but examples of each are HHP granites. A-type Olary granites are typically equigranular and medium-grained whereas the I-type granites are porphyritic and coarse-grained with 1-3 cm K-feldpar phenocrysts. S- and I-type granites are coeval with mafic rocks, which contain slightly high heat production values. The A- and S-type granites are peraluminous to slightly metaluminous whereas the I-type granite is mainly metaluminous to slightly peraluminous. A- and I-type groups are enriched in Ce, Ga, La, Nb, Y and Zr, and depleted in Pb and Rb whereas the S-type group is typically depleted in Ga, Nb, Y and Zr, and enriched in Pb and Rb.

The initial εNd values of the 1700 Ma granitic gneiss (the A-type granite) and the absence of zircon inheritance suggested that the A-type magmas were formed from materials, which have had a shorter crustal residence than most Willyama Supergroup rocks. These magmas were derived from the input of material from depleted mantle (Ashley et al., 1996; Stewart and Foden, 2001). The A-type granites represent highly differentiated magmas in hot and dry conditions, which have undergone a large degree of fractional crystallization (Stewart and Foden, 2001).

Based on their geochemical and isotopic characters, the 1700 Ma metatholeiitites (1700 Ma) were derived from a heterogeneous source region of primitive composition with minimal crustal contamination, (Rutherford, 2006). The LREE-enriched and positive εNd metatholeiitites were sourced from subducted sediments (Droux and Delaloye, 1996; Whalen et al., 1999; Rutherford et al., 2006).

The I-type granites are suggested to have been the product of mafic mantle melts which were subject to variable degrees of contamination during their ascent through the continental crust (Stewart and Foden, 2001).

Lastly, the S-type granites were a product of melting processes within the crust, which is confirmed by the similarity of their εNd isotopic signatures and those of the Willyama Group metasediments (Stewart and Foden, 2001;

Benton, 1994; Barovich and Hand, 2008). Anatexis of the meta-sediments is intepreted to be the dominant source of the S-type granitoid.

8.3.2 Broken Hill Domain

The Broken Hill Domain is situated on the southeastern margin of the Proterozoic Curnamona Province (Figure 8.24) and contains the world class Broken Hill Pb-Zn-Ag deposit. Magmatic events in the Broken Hill Domain, which played an important role in the genesis of the main ore body, are coeval with the Olary rocks (Willis et al., 1983; Stevens et al., 1988; Stevens, 1995; Page et al., 2005a).

8.3.2.1 Felsic magmatism

The most voluminous felsic magmas (quartzo-feldspathic orthogneiss) present in the Broken Domain include sheet-like bodies of the Alma Gneiss, Rasp Ridge Gneiss and Hores Granite (Willis et al., 1983; Stevens et al., 1988). The quartzo-feldspathic garnet-rich orthogneisses are coeval with high Fe-Ti metatholeiites (amphibolites) and occur in the Parnell and Cues Formations (Stevens, 1988). Previously, the Alma and Rasp Ridge Gneisses were interpreted to be metavolcanic or volcaniclastic rocks (Brown et al., 1983; Stevens et al., 1988), however they have recently been interpreted to be intrusive in origin (e.g. Vassallo and Vernon, 2000; Page et al., 2005a). Microgranular enclaves are found in all three gneissic units and metasedimentary xenoliths have been reported in the Hores Gneiss (Stevens and Barron, 2002).

The Alma Gneiss is a medium-grained, porphyritic quartz-feldspar-biotite±garnet augen gneiss with abundant K-feldspar phenocrysts (Raveggi et al., 2009). They have SHRIMP U-Pb zircons ages of 1691±12 Ma (Nutman and Ehlers, 1998a) and 1704±3 Ma (Page et al., 2005a). The Rasp Ridge Gneiss is typically a medium-grained quartz-feldspar-biotite-garnet gneiss and locally contains K-feldspar megacrysts and occasional sillimanite. It has SHRIMP U-Pb zircon ages of 1682±7 Ma (Love, 1992), 1697±12, 1688±16 Ma (Nutman and Ehlers, 1998a) and 1683±3 Ma (Page et al., 2005a). The Hores Gneiss is commonly quartz-feldspar-biotite gneiss, and has SHRIMP

U-Pb ages of 1689±5 Ma (Page and Laing, 1992) and 1685±3 Ma (Page et al., 2005a). The Rasp Ridge and Hores gneisses are broadly coeval with the widespread high Fe-Ti metatholeiitic rocks which are dated at 1685 Ma (Raetz et al., 2002; Raveggi et al., 2007).

The Farmote Leucogneiss is a leucocratic orthogneiss with a crystallisation age of *ca.* 1650 Ma, and has been interpreted to be an A-type felsic intrusive rock (Nutman and Ehlers, 1998b). Younger felsic magmatic rocks in the Broken Hill Domain, dated between *ca.* 1640-1620 Ma and 1600-1590 Ma, are classified as syn-orogenic felsic rocks (Ashley et al., 1996; Fanning et al., 1998; Page et al., 2005a; Rutherford et al., 2008).

8.3.2.2 Mafic magmatism

Mafic rocks in the Broken Hill Domain occur as concordant, discontinuous tabular sheets or lenticular bodies with thicknesses between 1 and 10 m (Raveggi et al, 2007). Available U–Pb SHRIMP zircon dating suggests that the main mafic magmatic event occurred at *ca.* 1685 Ma. Rocks that were emplaced at this time include; a mafic intrusion at Round Hill which has a SHRIMP U-Pb age of 1683 ± 5 Ma (Nutman and Ehler, 1998) and amphibolite dykes with ages of 1674 ± 8, 1685 ± 13 and 1691 ± 9 Ma (Gibson and Nutman**,** 2004**).**

The mafic igneous rocks are strongly re-crystallised and are interpreted to have been basalt (Raveggi et al., 2007). Based on their mineralogy and texture, they can be divided into four lithological types; amphibolites, pyroxene bearing mafic granulites, leucocratic amphibolites and leucocratic garnet bearing amphibolites (Raveggi et al., 2007). All four types show partial to complete regression of the primary metamorphic prograde assemblages to greenschist facies mineral assemblages with static growth of tremolite, chlorite, sericite and fine-grained garnet (Raveggi et al., 2007).

8.3.2.3 The High Heat Producing granites of the Broken Hill Domain

The magmatic rocks of the Broken Hill Domain generally have heat production values less than 5 μWm^{-3} (Figure 8.36). The Broken Hill magmatic rocks having heat production values greater than 5 μWm^{-3} are commonly felsic to intermediate in composition. In this study, the Broken

Hill magmatic rocks will be divided into three groups including the mafic and felsic rocks (ages between ~1675 and1700 Ma) and syn-orogenic felsic rocks (ages between 1640 and 1590 Ma). The felsic rocks consist of both granites that of having heat production grater than 5 μwm^{-3} and less than 5 μWm^{-3}. Few samples from the mafic rocks (indermediate compositions) and syn-orogenic felsic rocks can be classified as HHP granites.

8.3.2.4 Geochemistry

The Broken Hill magmatic rocks are felsic to intermediate in compositions. Typically, the granitic rocks contain low TiO_2, MnO, CaO and MgO. They also have low Fe_2O_3/FeO indicative of a reduced state. The *ca.* 1704-1685 Ma granitic rocks are typically peraluminous with a few examples having a slightly metaluminous composition while the *ca.* 1640-1590 Ma samples plot within the peraluminous field (Figure 8.37).

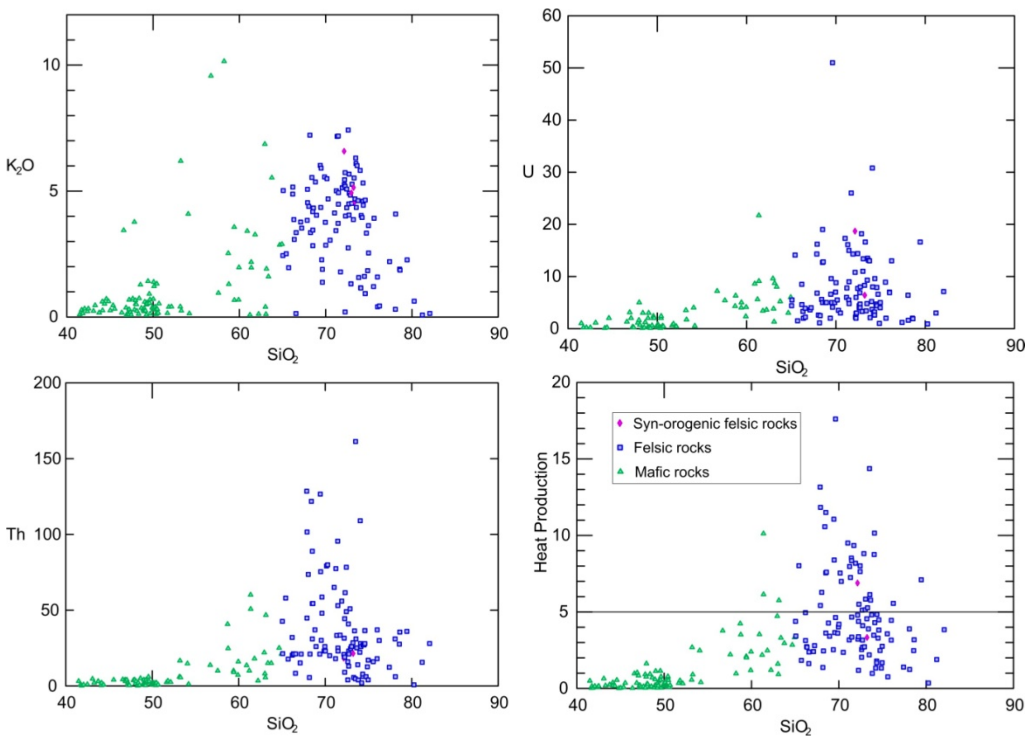

Figure 8.36 Concentration of K_2O, U and Th and heat production values versus SiO_2 of mafic and felsic rocks for the Broken Hill Domain.

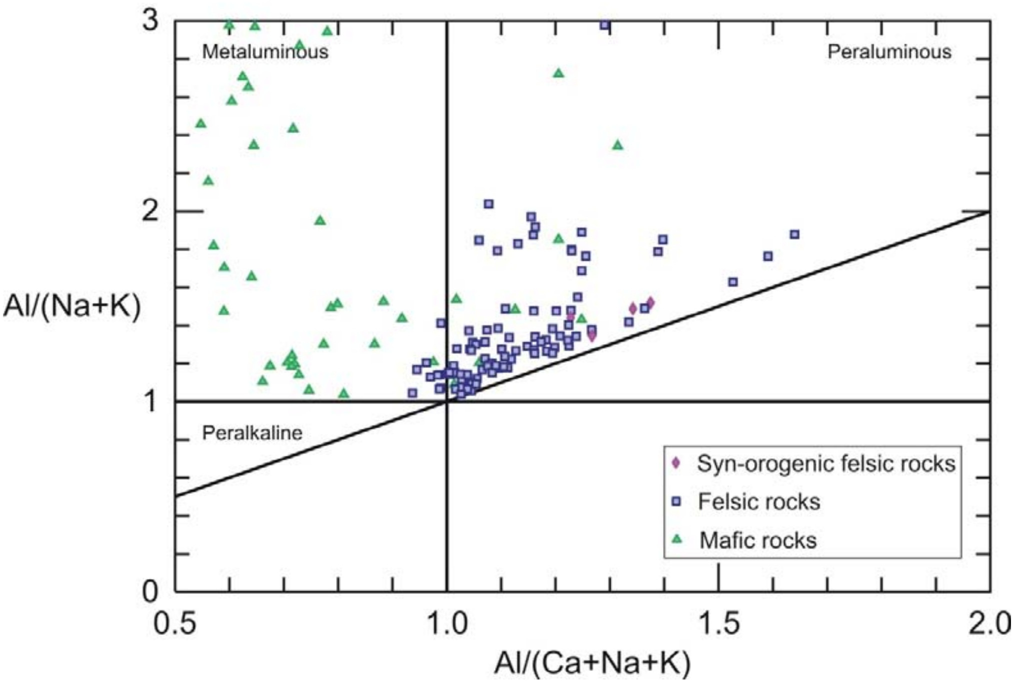

Figure 8.37 ANK versus A/CNK plot of the mafic and felsic rocks from the Broken Hill Domain; A = Al_2O_3, N = Na_2O, K = K_2O, Ca = CaO (all in molar proportions).

Harker variation diagrams for major elements typically display negative trends (Figure 8.38). The negative correlation between TiO_2, Al_2O_3, Fe_2O_3 and MgO and SiO_2 suggest fractionational crystallizations of feldspar, Fe-Ti oxides and ferromagnesian phases (such as biotite or hornblende). Harker diagrams for CaO, Na_2O_3 and K_2O do not show any correlation with SiO_2, likely due to later alteration.

Mafic rocks, which are referred to as amphibolites, are mainly classified as tholeiitic basalt and contain TiO_2 content from 0.6 to 4.1 wt%; Fe_2O_{3tot} varies from 7.7 to 27 wt% and MgO from 0.8 to 11.1 wt%.

The granitic rocks of the Broken Hill Domain contain a wide range in concentrations of trace elements but are slightly enriched in Ce, La, Rb, Nd and Zr (Figure 8.40). Harker diagrams for Ba, Ce, La, Eu and Zr versus SiO_2 show negative correlations (Figure 8.39). This relationship could indicate fractionation in the felsic rocks. Mafic rocks contain low trace element concentrations. Raveggi et al (2007) suggests that the mafic rocks have undergone crystal fractionation of olivine and pyroxene based on negative correlations of Mg# and Zr against SiO_2. Generally felsic, intermediate and mafic rocks do no show obvious continuing trends or correlations.

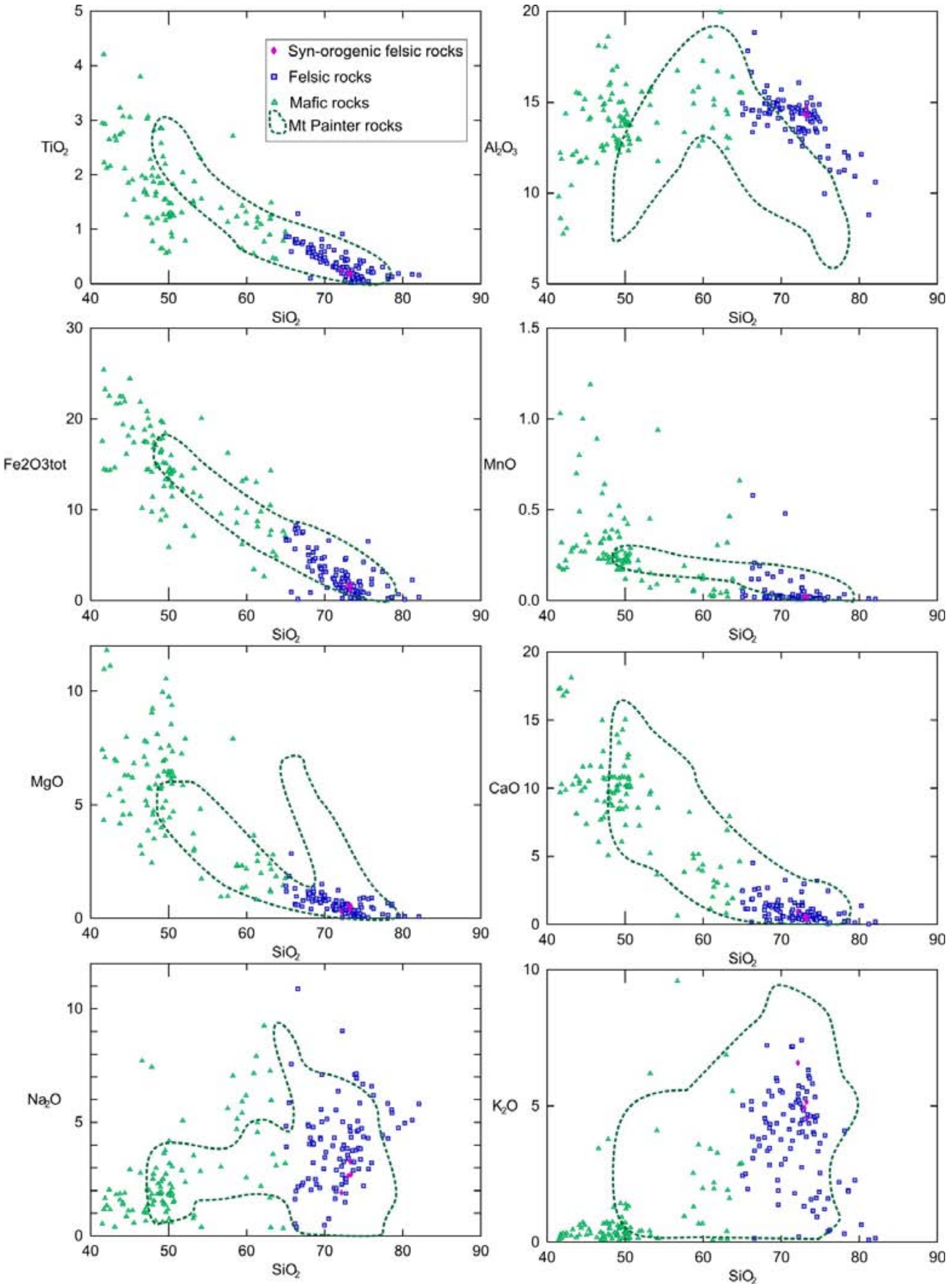

Figure 8.38 Binary plot of SiO_2 versus major elements for the mafic and felsic rocks from the Broken Hill Domain.

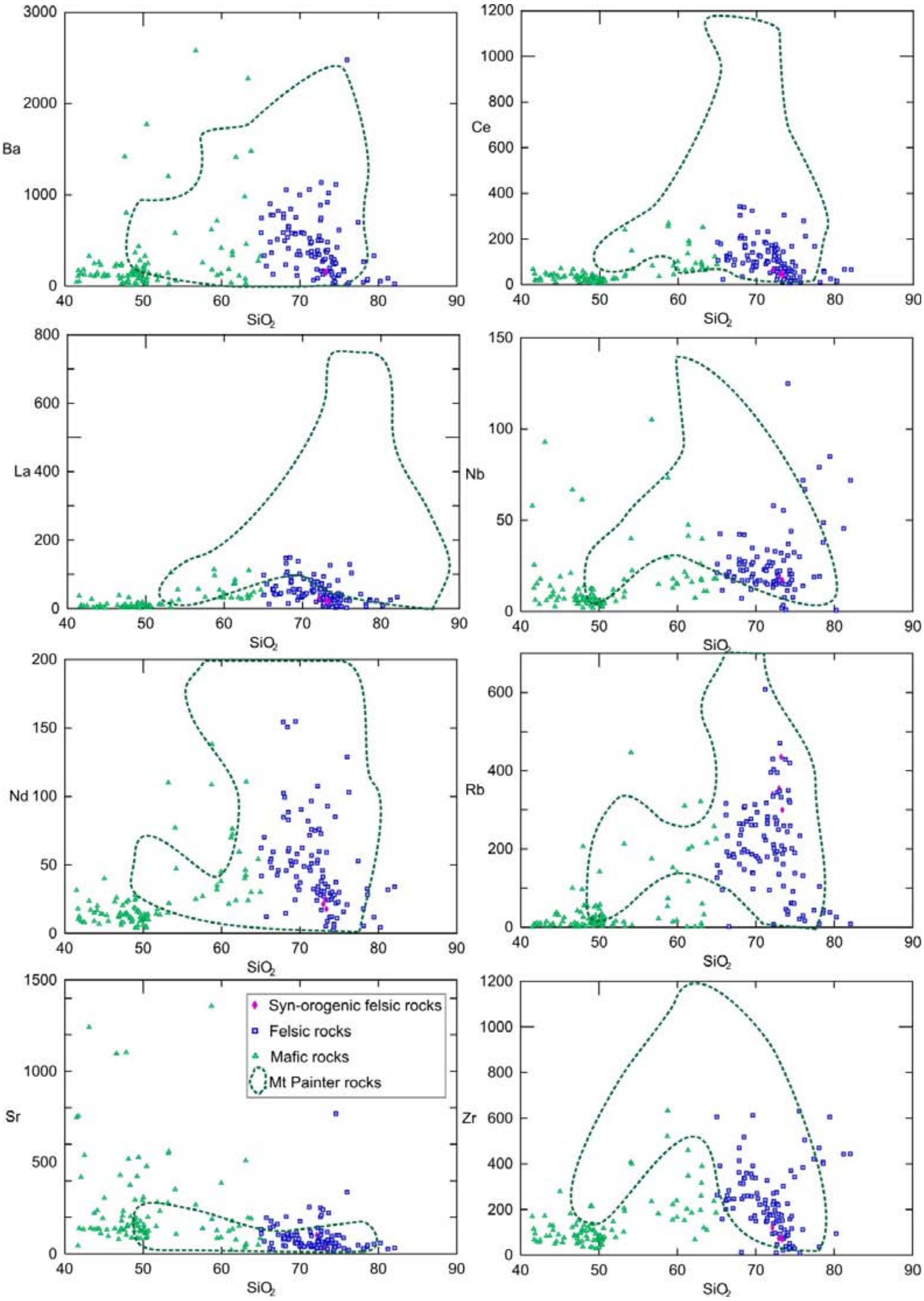

Figure 8.39 Binary plot of SiO_2 versus tracer elements for the mafic and felsic rocks from the Broken Hill Domain.

The felsic rocks of the Broken Hill Domain show similar correlations between SiO_2 and other major elements to the HHP granites from the Mt Painter Province (Figure 8.38). Most major element concentrations of the Broken Hill felsic rocks are in same range as the Mt Painter rocks, although with slightly higher Al_2O_3. Trace element concentrations of the Mt Painter granitic rocks are much higher than the Broken Hill felsic rocks.

8.3.2.5 Tectonic setting and typology

Granitic and mafic rocks from the Broken Hill Domain vary considerably in the Rb versus Y+Nb diagram (Figure 8.40a; after Pearce et al., 1984), plotting in the within plate granite (WPG), syn-collisional granite (syn-COLG), volacnic arc granite (VAG) and orogenic granite (ORG) fields. The discrimination diagram of Nb versus Y (Figure 8.39b; after Pearce et al., 1984) show that the samples from Broken Hill plot in WPG and VAG+syn-COLG fields, and within both A-type and I- and S-type fields (Figure 8.41; Whalen et al., 1987). These plots suggest that the tectonic setting of formation and typology of the granitic and mafic rocks of the Broken Hill cannot be identified using these diagrams. This interpretation has also been proposed by Stewart and Foden, 2001) In the Zr-Nb-Y discrimination diagram (after Meschede, 1986), the mafic rocks mostly plot in the N-MORB field overlapping with the within plate tholeiitic, within plate alkaline, E-MORB and volcanic arc basalts (Figure 8.42).

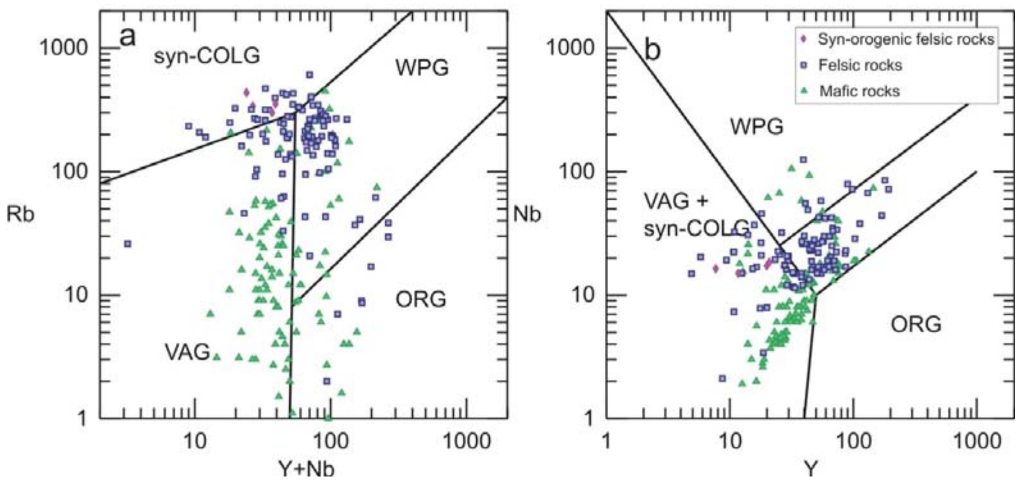

Figure 8.40 Discrimination tectonic setting diagrams for the mafic and felsic rock from the Broken Hill Doamin a: Y + Nb versus Rb diagram; b: Nb versus Y Pearce et al. (1984).

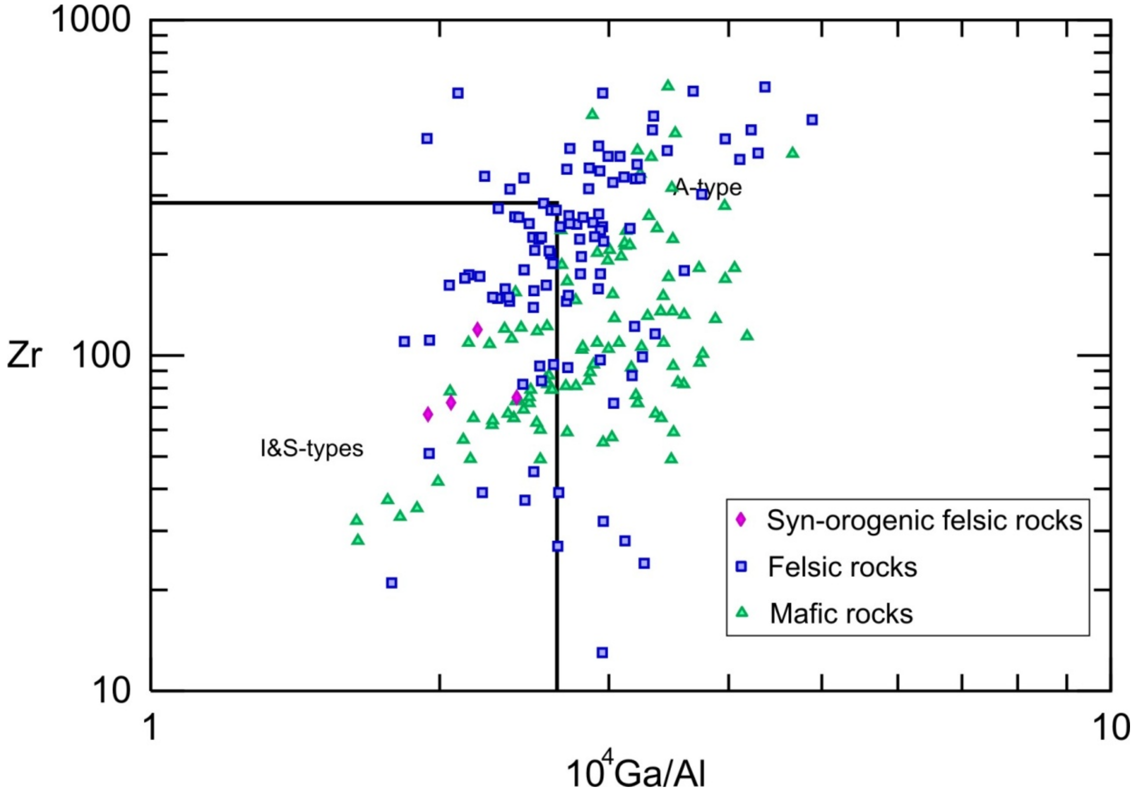

Figure 8.41 Discrimination diagrams classifying granitic types of Zr versus 10^4*(Ga/Al) after Whalen et al. (1987).

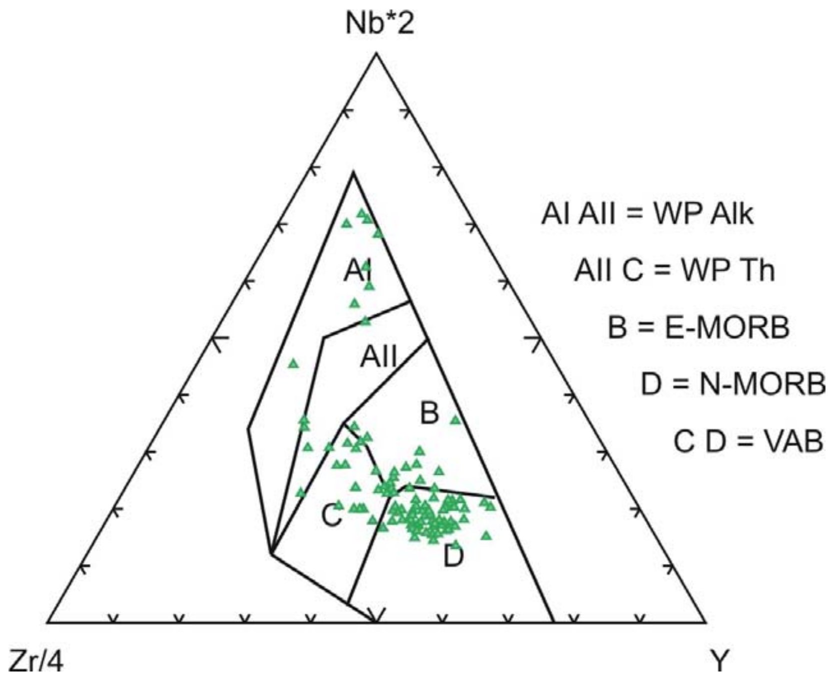

Figure 8.42 Zr-Nb-Y discrimination diagram classifying tectonic setting of mafic rocks from the Broken Hill Domain (after Meschede, 1986).

8.3.2.6 Nd Isotopes

εNd values (1685 Ma) of the ortho-gneissic samples from the Broken Hill Domain, including the Alma, Rasp Ridge and Hores gneisses range from -5.1 to -1.5 (Figure 8.43) with T_{DM} ages from 2.15 to 2.31 Ga (Raveggi et al., 2008). The syn-orogenic felsic rocks have εNd values (1600 Ma) between -4.8 and -4.3 which are comparable to the Willyama Supergroup and the Olary S-type granitoids (initial εNd between -4 and -8; Barovich and Foden, 2002). The 1600 Ma felsic rocks have T_{DM} ages from ~2.4 to 2.6 Ga. Initial εNd values (1685 Ma) of the amphibolites could be divided into two groups. The first group has positive initial εNd values from +2.1 to +3.5 and the second has negative initial εNd values from -0.7 to -0.4 (Raveggi et al., 2007).

8.3.2.7 Conclusion and petrogenesis

Some samples from the the felsic rocks (the Alma Gneiss, Rasp Ridge Gneiss and Hores Granite) and coeval metatholeiitic rocks (1674-1700 Ma) and syn-orogenic felsic rocks (1640-1620 Ma and 1600-1590 Ma) of the Broken Hill Domain are HHP granites. The felsic rocks are typically porphyritic quartz-feldspar-biotite-garnet gneiss with K-feldspar megacrystic phenocrysts. The syn-orogenic felsic rocks are mostly peraluminous and are slightly enriched in Ce, La, Rb, Nd and Zr. The syn-orogenic felsic rocks are classified as syn-collisional granites and S-type granites whereas tectonic settings of the felsic and mafic rocks can not be identified their using the geochemical data.

Nd isotopic and geochemical data of the 1685 Ma granitic rocks suggested that these rocks have formed from anatexis of the sedimentary pile (e.g. Vassallo and Vernon, 2000; Barovich and Hand, 2004; Raveggi, 2008). However, less negative initial εNd values could form by mixing or contamination of a juvenile mantle-derived component with/by evolved crust (Raveggi, 2008). Variation of the initial εNd values among the ortho-gneisses suggests various degrees of mixing between a mantle component and crustal material together with extensive fractionation for the Broken Hill 1685 Ma felsic rocks (Raveggi, 2008). The syn-orogenic felsic rocks of Broken Hill were suggested to be derived from partial melting of the Willyama Supergroup during the Olarian Orogeny (Raveggi, 2008).

The Broken Hill amphibolites that contain positive initial εNd values of approximately +3 are close to initial εNd values for depleted mantle at 1685 Ma (εNd +3.9; Michard et al., 1985), so formed from a depleted mantle source. Amphibolites with a slightly negative εNd could be affected by crustal contamination, which is supported by assimilation-fractionation crystallisation modelling (Raveggi et al., 2007).

Raveggi et al. (2007) interprets the mafic rocks to have formed by a combination of partial melting of a depleted mantle source and assimilation fractional crystallization, involving small degree of crustal assimilation within the extensional axis and depositional centre of an advanced stage intra-cratonic rift. The S-type gneissic-granitic rocks are interepreted to have formed as a product of anatexis of the Willyama Supergroup sedimentary pile with minor juvenile magma input (Raveggi et al., 2009).

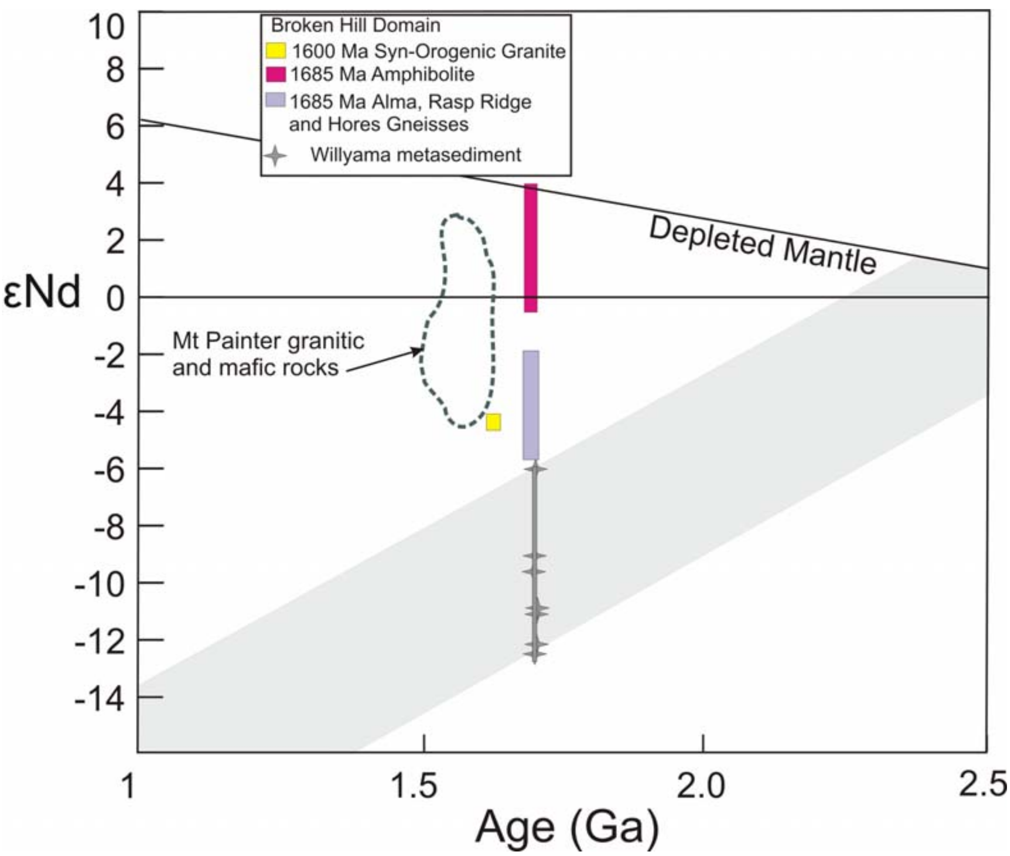

Figure 8.43 Initial εNd values versus crystallization ages of the mafic and felsic rocks from the Broken Hill Domain (Raveggi et al., 2008; Barovich and Foden, 2002; Raveggi et al., 2007).

Overlapping initial εNd values of the mafic and felsic rocks from the Broken Hill and Olary Domains suggests that they are possibly derived from the same sources (Figure 8.44). The Mt Painter mafic and granitic rocks yielded ε_{Nd} values in the same ranges of the Olary and Broken Hill magmatic rocks. The mafic rocks from the Olary and Broken Hill Domains have slightly higher εNd values whereas the felsic rocks from the Olary and Broken Hill Domains have lower εNd values than the Mt Painter magmatic rocks.

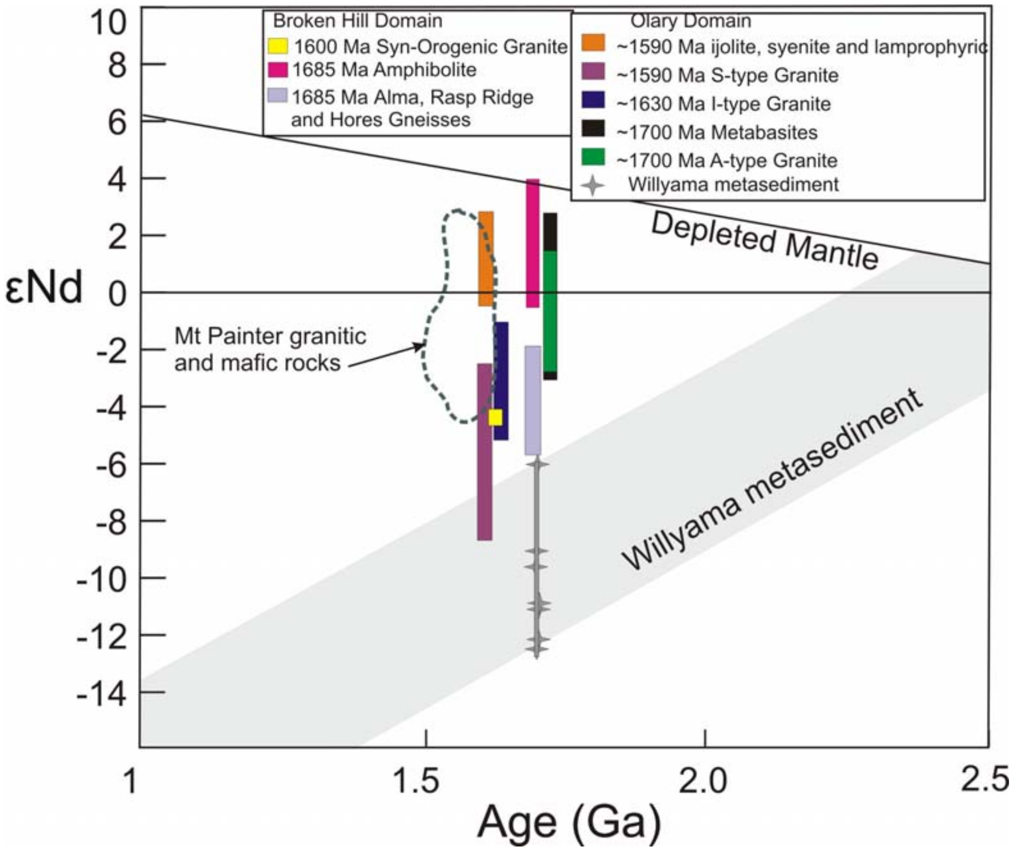

Figure 8.44 Initial ε_{Nd} values versus crystallization ages of the mafic and felsic rocks from the Olay and Broken Hill Domains (data from Ashley et al., 1996); Stewart and Foden, 2002; Rutherford, 2006 Barovich and Foden, 2002; Raveggi et al., 2007; Barovich and Hand, 2008 and Raveggi et al., 2008).

8.4. Arunta Inlier

The Arunta Inlier is the largest Proterozoic terrain in Central Australia and is located on the southern margin of Palaeoproterozoic Northern Australian Orogenic Province (Zaw and Black, 1991). It has undergone multiple deformation events, ranging in age from the Palaeoproterozoic to the

Palaeozoic (Collins and Shaw, 1995, Mawby et al., 1999, Hand and Buick, 2001, Scrimgeour and Raith, 2001, Buick et al., 2001). The tectonic evolution of the Arunta Inlier is interpreted to be the result of six cycles of crustal extension and compression spanning ~1500 Ma (Shaw et al., 1984). Based on Rb-Sr data, Black et al. (1983) concluded that five major thermal events affected the Arunta Inlier: 1800-1750 Ma (Strangways), 1700-1650 Ma (Aileron), 1450 Ma (Anmatjira), 1050-900 Ma (Omiston) and 400-300 Ma (Alice Spring).

The Arunta Inlier is divided into three distinct largely fault-bounded provinces with distinct protolith ages (Figure 8.45; Scrimgeour, 2004). Firstly, the Aileron Province, which is the largest, has depositional and intrusive ages ranging from 1870 to 1710 Ma (Collin and Shaw, 1995). Secondly, the Irindina Province in the eastern part of Arunta Inlier consists of high-grade metamorphic rocks of the Harts Range Metamorphic Complex, which is covered by Neoproterozoic to Cambrian rocks (Buick et al., 2001; Maidment et al., 2002). The third is the Warumpi Province, which is located along the southwestern margin of the Arunta Region. The Warumpi Province has igneous and sedimentary protolith ages between 1690–1600 Ma (Shaw et al., 1984) and has been interpreted to be exotic to the North Australian Craton based on a combination of distinct protolith ages, less evolved isotopic signatures, and a lack of Archaean inheritance in granites (Close et al., 2004).

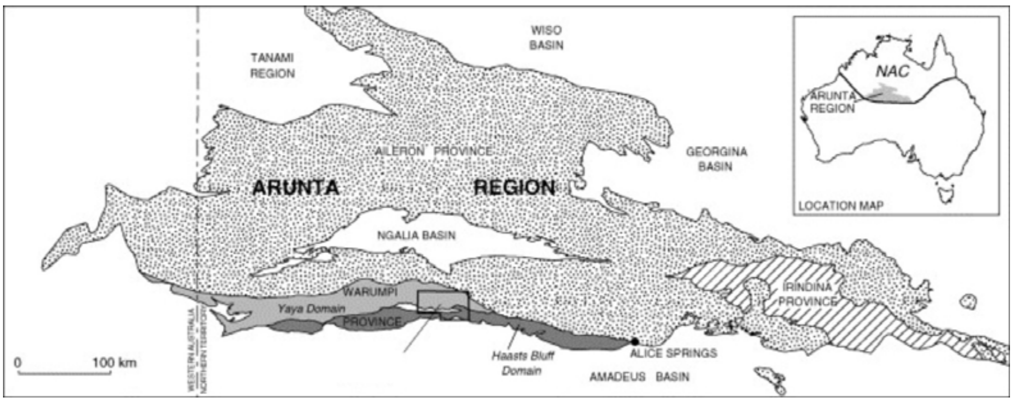

Figure 8.45 Map of the Arunta Region. Inset shows the location of the Arunta Region within the North Australian Craton (NAC); modified after Scrimgeour et al. (2005).

8.4.1 Proterozoic granites of the Arunta Inlier

Granites of the Arunta Inlier intruded supercrustal sedimentary and volcanic assemblage with ages ranging from ~ 1880 to 1140 Ma (Collin and Shaw, 1995).

The oldest granitic rocks of the Arunta Inlier, with ages between 1880-1850 Ma include; the Atnarpa Igneous Complex (1873±11 and 1879±11 Ma; Zhao and Cooper, 1995), Narwietooma feldspathic (1880±5 Ma; Sun et al., 1995), and the Harverson Suites (1820±7 Ma Sun et al., 1995). Wyborn (1988) suggested that these were generated in an intraplate environment during the Barramundi Orogeny from crustal sources enriched in incompatible elements. However, Zhao and Cooper (1995) argued that the Atnarpa Igneous Complex at the southeastern margin of Arunta Inlier represents a convergent continental margin active which undergone at least two episodes of subduction-related magmatism at 1880-1860 Ma and 1770-1730 Ma.

The younger granitic and associated rocks have ages ranging between ~1790 and 1710 Ma (e.g. the Warimbi Suite - 1785±22; Collin and Williams, 1995; the Carrington Suite - 1779±6 Ma; Young 1995, the Napperby Suite - 1780±10; 1774±6 Ma; Collins and Williams, 1995, the Barrow Creek Granites-1713 Ma; Zhao and McColloch, 1995).

Granitic rocks of the Arunta Inlier with ages between ~1680 and 1600 Ma include; the Madderns Yard Magmatic Complex (~1680-1650 Ma; Black and Zhaw, 1995; 1992), Andrew Young Igneous Complex (1635±9 Ma; Young et al., 1995), Mt Webb Suite (1643±4 Ma; Wyborn et al., 1998), Iwupataka Magmatic Complex (~1615-1603 Ma; Zhao and Bennet, 1995; Collins et al., 1995; Sun et al., 1995) and Ennugan Mtains Suite (1600±7 Ma; Sun et al., 1995).

The undeformed Southwark Suite has been dated at 1567±11 Ma (Young et al., 1995) and the youngest granite of the Arunta Inlier is the Teapot Suite dated at 1136±3 Ma (Black and Shaw, 1995).

8.4.2 High heat producing granites of the Arunta Inlier

Based on previous geochemical database of Wyborn et al. (2001) and references therein, a number of granitic rocks of the Arunta Inlier have high U, Th and K_2O concentrations and heat production values greater than 5 μWm^{-3}. These include; the Barrow Creek Suite (average heat production value of 6.04 μWm^{-3}); Haverson Suite (average heat production value of 5.24 μWm^{-3}); Jinka Suite (average heat production value of 11.43 μWm^{-3}); Mt Webb Suite (average heat production value of 5.92 μWm^{-3}); Nabberby Suite (average heat production value of 7.61 μWm^{-3}) and the Southwark Granitic Suite (average heat production values of 6.22 μWm^{-3}). These granitic suites will be the focus of discussion here.

a) The Barrow Creek Suite is characterised by fine- to medium-grained, leucocratic, porphyritic to equigranular and is weakly deformed. They typically consist of biotite, muscovite, quartz, plagioclase and alkali-feldspar as major minerals and chlorite, zircon and apatite as accessory minerals.

b) The Haverson Granite has a coarse-grained, leucocratic porphyritic and augen gneissic texture. They typically contain megacrystic k-feldspar as phenocrysts, with plagioclase, quartz, biotite, muscovite, cordierite, zircon, tourmaline, apatite, ilmenite, allanite and fluorite. The granite is commonly homogeneous in composition and is typically peraluminous. Mineralogy and geochemistry suggested that this is a S-type granite.

c) The Jinka Suite is classified as an enriched suite (enriched in K, U, Th, Rb and REE concentration; Warren, 1989) and is typically characterised by coarse-grained and porphyritic to equigranular texture. Its mineralogy comprises K-feldspar, plagioclase, biotite and hornblende as major minerals and magnetite, muscovite, zircon, tourmaline, fluorite and apatite as accessory minerals.

d) Granitic rocks of Mt Webb Suite are co-magmatic with dacites and include equigranular monzogranite, coarse-grained quartz-biotite-hornblende gneissic granite, microgranodiorite and diorite.

e) The Napperby Suite is characterised by strongly to moderately metamorphosed, medium to coarse-grained, megatcrystic, rapakivi, and porphyritic. It's mineralogy comprises K-feldspar, plagioclase, quartz, hornblende, clinopyroxene, biotite, muscovite, epidote, zircon, titanite and allanite.

f) The Southwark Granitic Suite typically has a coarse-grained to megacrystic, leucocratic, porphyritic and foliated texture. K-feldspar phenocrysts are tabular to sub-ovoid and usually 3-5 cm in size (but up to 30 cm). Major minerals are K-feldspar, plagioclase, quartz, amphibole and biotite and accessory minerals are muscovite, chlorite, epidote, apatite and zircon.

8.4.3 Geochemistry

To assist in the interpretation of their geochemistry, the Arunta granites and associated rocks are divided into two groups based on heat production values; HHP granites (heat production values >5 μWm^{-3}) and low heat producing (HP) granites (heat production values <5 μWm^{-3}).

The HHP granites of the Arunta Inlier are generally more felsic than the low HP granites, with SiO_2 concentration ranging between ~68 and 76 wt%. Harker diagrams of SiO_2 versus major elements for both granitic types show similar trends. Decreasing TiO_2, Al_2O_3, Fe_2O_{3tot}, MnO, MgO, CaO and P_2O_5 with decreasing SiO_2 are common in both HHP and low HP granites (Figure 8.46). A graph of K_2O versus SiO_2 exhibits a negative trend, which is likely due to sodic alteration. Plots of TiO_2, Al_2O_3 and P_2O_5 versus SiO_2 for the low HP granites display positive trends in mafic samples and negative trends for more felsic examples (SiO_2>60 wt%). The HHP granites are mostly peraluminous and the low HP granitic samples have peraluminous to slightly metaluminous compositions (Figure 8.47).

NOTE:
This figure is included on page 222 of the print copy of the thesis held in the University of Adelaide Library.

Figure 8.46 Binary plot of SiO_2 versus major elements for the mafic and felsic rocks from the Arunta Inlier (data from Budd et al., 2001) .

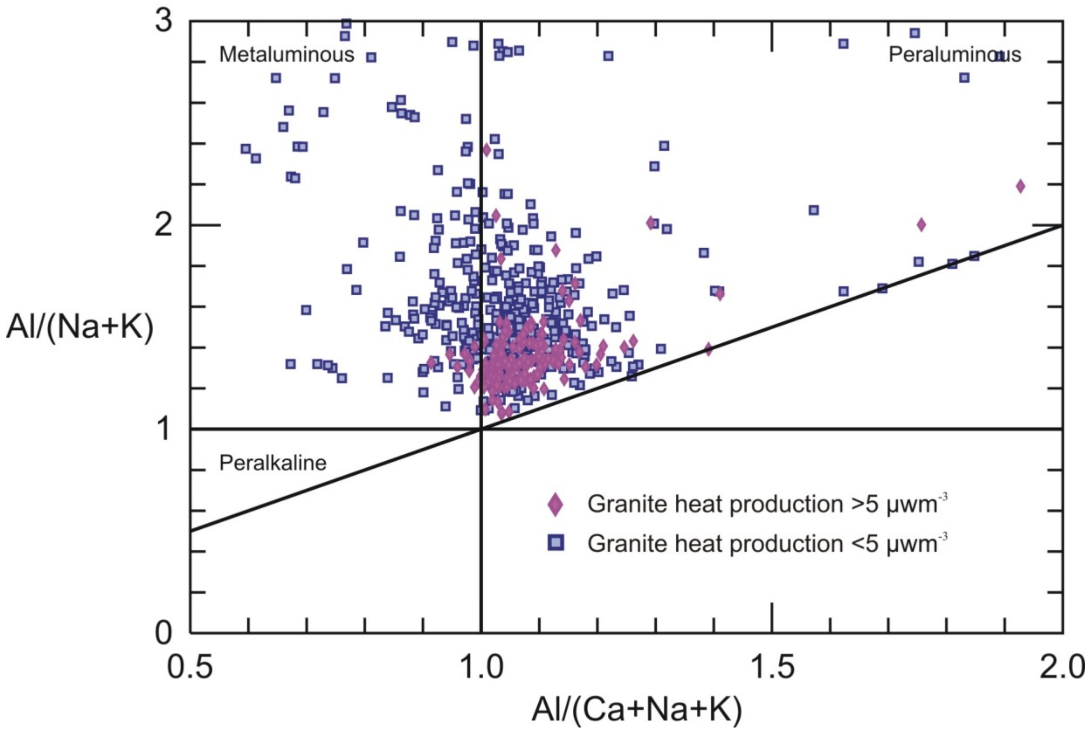

Figure 8.47 ANK versus A/CNK plot of the mafic and felsic rocks from the Arunta Inlier; A = Al_2O_3, N = Na_2O, K = K_2O, C = CaO (all in molar proportion).

Arunta Inlier HHP and low HP granites have differing trace element concentrations and trends in the Harker diagrams (Figure 8.49). The HHP granites are typically enriched in Ce, La, Nb, Nd, Pb, Rb, Th and U and depleted in Ba and Sr. In contrast, the low HP granites are enriched Ba and Sr. The HHP granites commonly show steep negative trends indicating a high degree of fractionation.

The HHP and low HP granites plot within both A-type and I- and S-type fields (Figure 8.49). Binary plots of Rb versus Y+Nb after Pearce et al. (1984) suggest that the HHP granites possibly plot in the within plate and syn-collision fields. Low HP granites plot in the syn-collision, volcanic arc and within plate granite fields (Figure 8.49).

The felsic and mafic rocks from the Arunta Inlier show similar correlations between SiO_2 and major elements to the Mt Painter granitic rocks; however TiO_2 and P_2O_5 concentrations in the mafic Arunta Inlier rocks are lower than the Mt Painter mafic rocks. The Arunta Inlier magmatic rocks typically have lower concentrations of trace elements than the Mt Painter Province rocks, with the exception of Sr.

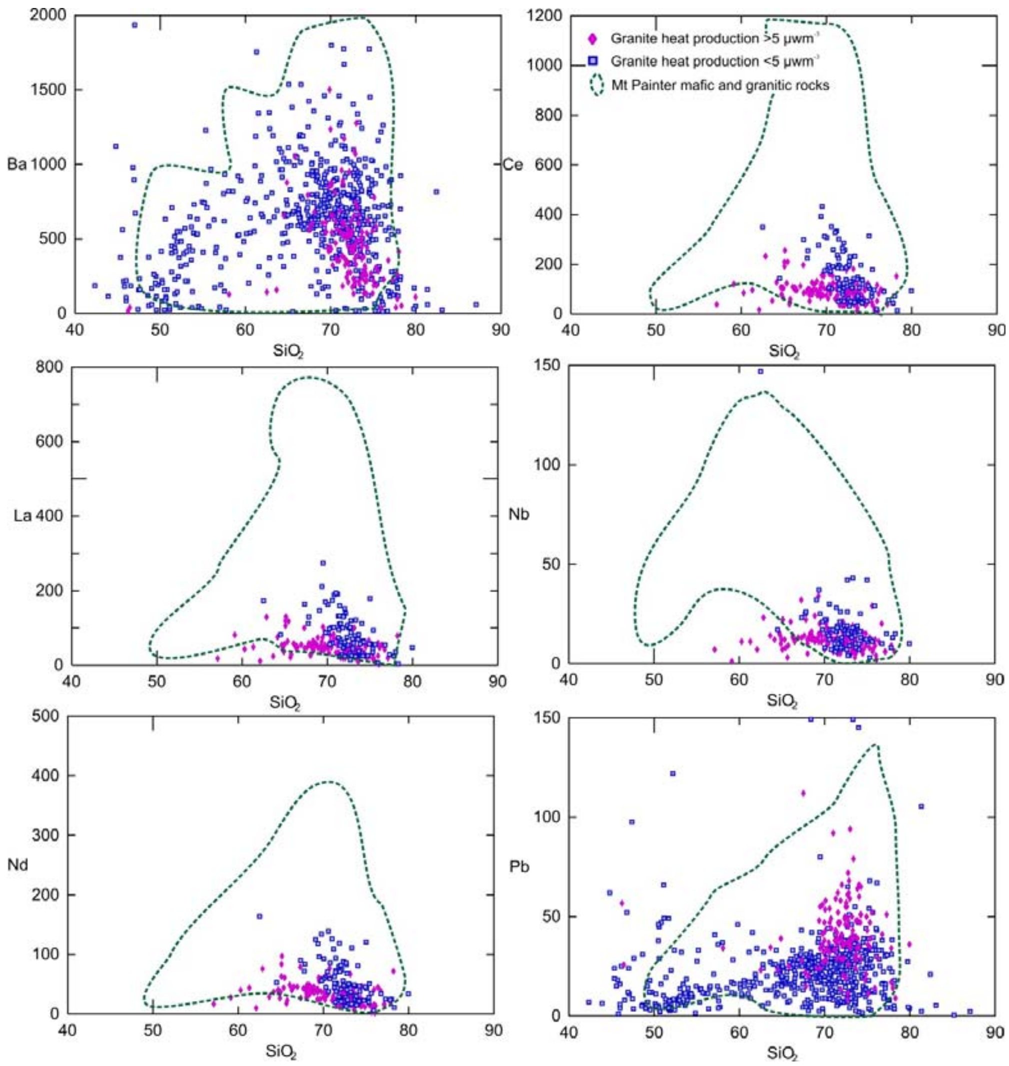

Figure 8.48 Binary plot of SiO_2 versus trace elements for the mafic and felsic rocks from the Arunta Inlier.

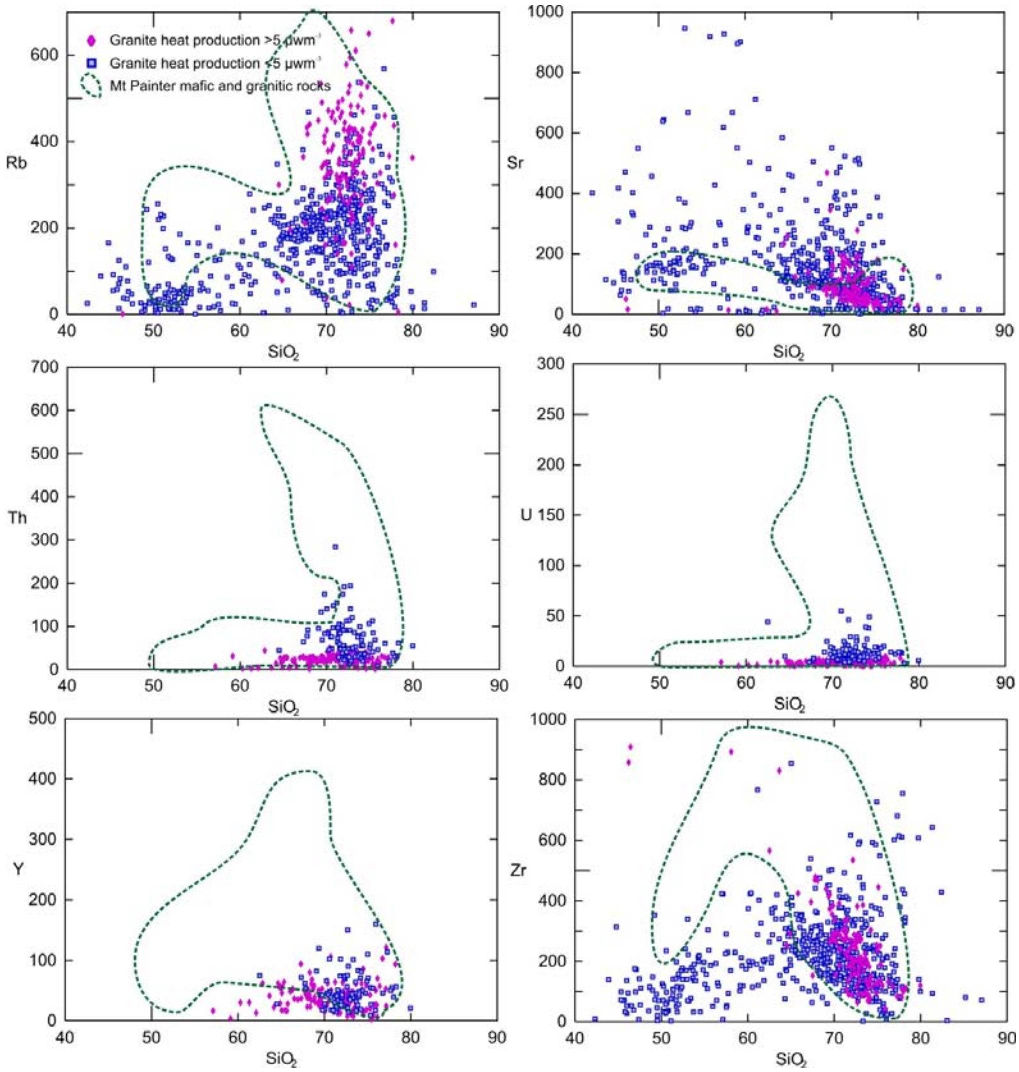

Figure 8.48 (continue) Binary plot of SiO_2 versus trace elements for the mafic and felsic rocks from the Arunta Inlier.

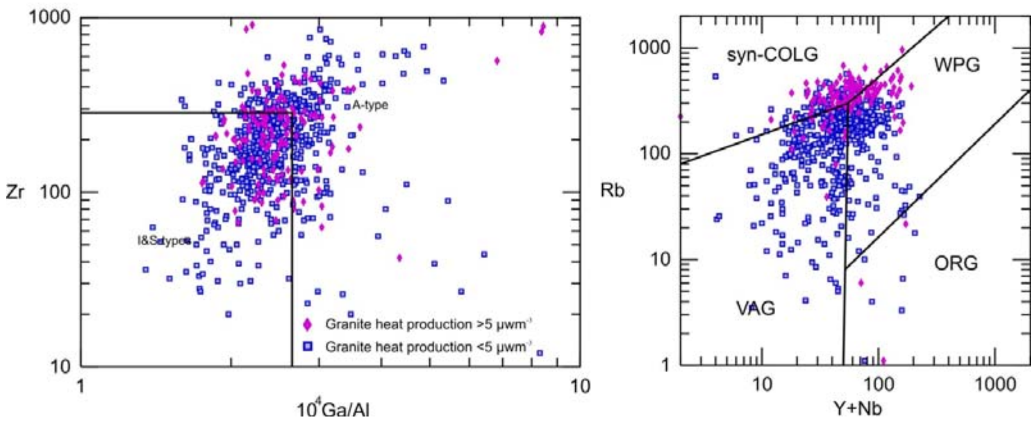

Figure 8.49 Discrimination tectonic setting diagrams for the mafic and felsic rock from the Arunta Inlier a: Zr versus 10^4*(Ga/Al) after Whalen et al. (1987); b: Y + Nb versus Rb diagram after Pearce et al. (1984).

8.4.4 Nd Isotopes

Nd isotopes of granitic rocks of the Arunta Inlier are divided into separate age ranges to assist in their interpretation. The Palaeoproterozic and Mesoproterozoic granites and associated rocks in both HHP and low HP granites show overlapping εNd values (Figure 8.50). The oldest granitic rocks have crystallization ages ranging between 1880 and 1820 Ma, and εNd values from -4.1 to -0.2 with T_{DM} between 2.33 and 2.11 Ga (Sun et al., 1995; Zhao and Malcolm 1995). Initial εNd values of the granitic and associated rocks with ages of ~1770-1710 Ma are mainly between -4.9 and +2.6 with a large majority having negative values (Sun et al., 1995; Zhao and Malcolm 1995; Wade et al., 2008). Both the HHP and low HP granites in this age range have similar εNd values and their T_{DM} varies between 2.40 and 1.77 Ga. The 1680-1600 Ma granitoids yield εNd values between -4.2 to +2.5 with T_{DM} between 2.24 and 1.72 Ga (Sun et al., 1995; Zhao and Malcolm 1995). The youngest granites of the Arunta Block, with crystallization ages of 1136 Ma have more negative εNd values of -10.1 and -8.2 with T_{DM} between 2.05 and 1.96 Ga (Sun et al., 1995).

Initial εNd values of the HHP and low HP granites of the Arunta Inlier are compared with those from the HHP granites and associated rocks from the Mt Painter Province (Figure 8.50). They have overlapping values, although overall, the Mt Painter Province rocks are slightly higher.

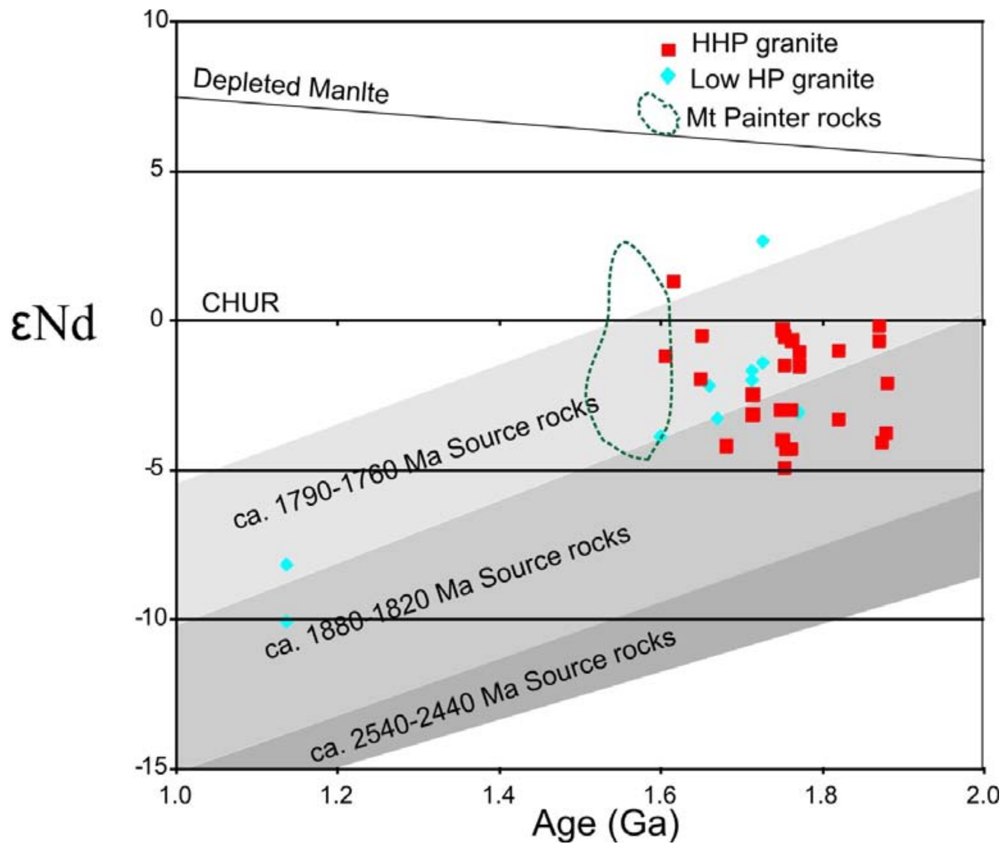

Figure 8.50 Initial ε_{Nd} values versus crystallization ages of the mafic and felsic rocks from the Arunta Inlier (data from Sun et al., 1995; Zhao and Malcolm 1995; Wade et al., 2008; source rocks in the Arunta Inlier in grey shade from Wade et al., 2008 and reference therein).

8.4.5 Conclusion and petrogenesis

The Proterozoic granites of the Arunta Inlier, which range in age from 1880 to 1140 Ma, have widely varying heat production values. Textural characteristics of the Arunta HHP granitic rocks are variable, ranging from fine- to coarse grained and equigranular to porphyritic with coarse K-feldspar phenocrysts. Rapakivi and rapakivi-like textures are found in the Napperby and Southwark Suites. Geochemically, the HHP granites are mainly peraluminous whereas the low heat producing granites are peraluminous to slightly metaluminous. Although the HHP and low heat producing granites have similar major element concentrations, the HHP granites are enriched in Ce, La, Nb, Nd, Pb, Rb, Th and U but are low in Ba and Sr. These granites are mainly classified as syn-collisional granites with some samples classified as within plate granites.

The variable and overlapping initial Nd isotope compositions for the Proterozoic Arunta granites indicate mixing of heterogeneous old crustal components. Wyborn (1988) suggested that the 1880-1850 Ma Barramundi Orogen associated rocks were derived from a chemically and isotopically uniform fractionated mafic underplate which formed during an ensialic rifting episode at 2.3-2.1 Ga. The T_{DM} model ages of the Arunta granites typically vary between 2.3 and 1.9 Ga suggesting mixing products rather than average crustal residence time (Sun et al., 1995). Zhao and McCulloch (1995) suggest a subduction-related underplating model which involves partial melting of underplated mantle sources. The sources that generated the granitic rocks could form by subduction-related processes but the granites may not necessarily be subduction related (Zhao and McCulloch, 1995). Alternatively, sources of the granites may be mixing of juvenile mantle-derived magma with an old Archean continental crustal component through lower crust assimilation or by sediment subduction. The granites were suggested to have been generated by partial melting of these mixed sources during late stage of the orogenic processes (Zhao and McCulloch, 1995). The HHP Arunta granitic rocks have been suggested to be formed by anatexis of "normal-type" granite (low heat producing granites) sources (Sun and Zhaw, 1995).

8.5. Concluding remarks

8.5.1 Age and location distribution of the HHP Granites

The HHP granites and associated rocks (felsic volcanics and mafic dykes) occurring within the selected study areas; the Mt Isa and Arunta Inliers, the Gawler Craton, and Curnamona Province (the Olary Domain, Broken Hill Domain and Mt Painter Province), have crystallization ages ranging between ~1.82 to 1.49 Ga (Figure 8.51). The oldest HHP granites are from the Haverson Suite of the Arunta Inlier and the youngest rocks are the William and Naraku suites of the Mt Isa Inlier and the Yerila granitic enclaves from the Mt Painter Province. HHP granitic and felsic volcanic rocks are more abundant in the Arunta Inlier, Mt Isa Inlier and Mt Painter Province and less abundant in the Gawler Craton, and the Olary and Broken Hill Domains of the Curnamona Craton.

The HHP granites of the Arunta Inlier were emplaced into supercrustal sedimentary and volcanic assemblages continually from 1.82 Ga (the Haverson Suite) to 1.57 Ga (the Southwark Suite). In the Mt Isa Inlier, HHP granites intruded the Palaeoproterozoic volcano-sedimentary basement in three magmatic events between 1.76 Ga (the Wonga Suite) and 1.49 Ga (the Williams Suite). HHP mafic and felsic rocks of the Mt Painter Province intruded the Palaeoproterozoic meta-sedimentary and meta-igneous rocks between 1.60 Ga (the Pepegoona Volcanics) and 1.51 Ga (the Yerila microgranular enclaves). There were two periods of HHP granitic intrusions in the Gawler Craton; between 1.76 to 1.66 Ga (the Younger Lincoln Suite) and from 1.58 to 1.59 Ga (the Hiltaba Suite and the Gawler Volcanic Ranges). They intrude the Palaeoproterozoic meta-sedimentary and meta-igneous basement of the Gawler Craton. HHP granites of the Olary Domain intruded the Palaeoproterozoic Willyama meta-sedimentary and meta-igneous basement at 1.70 Ga (the A-type granites) and 1.59 Ga (the S-type granites). Only one generation of HHP granites intruded into the Broken Hill Domain, at ~1.60 Ga (the Syn-orogenic granites).

8.5.2 Lithology and Petrography

The HHP granites display a characteristic mode of occurrence and lithological association similar to the low HP granites. They occur as elongate sills (e.g. the Wonga, Burstall and Sybella Suites of the Mt Isa Inlier; the Haverson and Napperby Suite of the Arunta Inlier), multiple small to large batholiths and stocks (e.g. the Young Lincoln Suite of the Gawler Craton, Mt Neill and Terrapinna Granites of the Mt Painter Province) and large domal outcrops (e.g. the S-type granites of the Olary Domain). The batholiths are variable in size from small intrusions (<100 km^2 including most granitic suites of the Mt Painter Province) to intrusions as large as ~19,000 km^2 (the Hiltaba Suite of the Gawler Craton).

In many instances, mafic rocks that occur in proximity to the HHP granites show textural and structural features that demonstrate their coeval relationship with the granites. Age relationships and similar isotopic compositions support this interpretation. The mafic rocks are often found as composite dykes and microgranular enclaves within the granites.

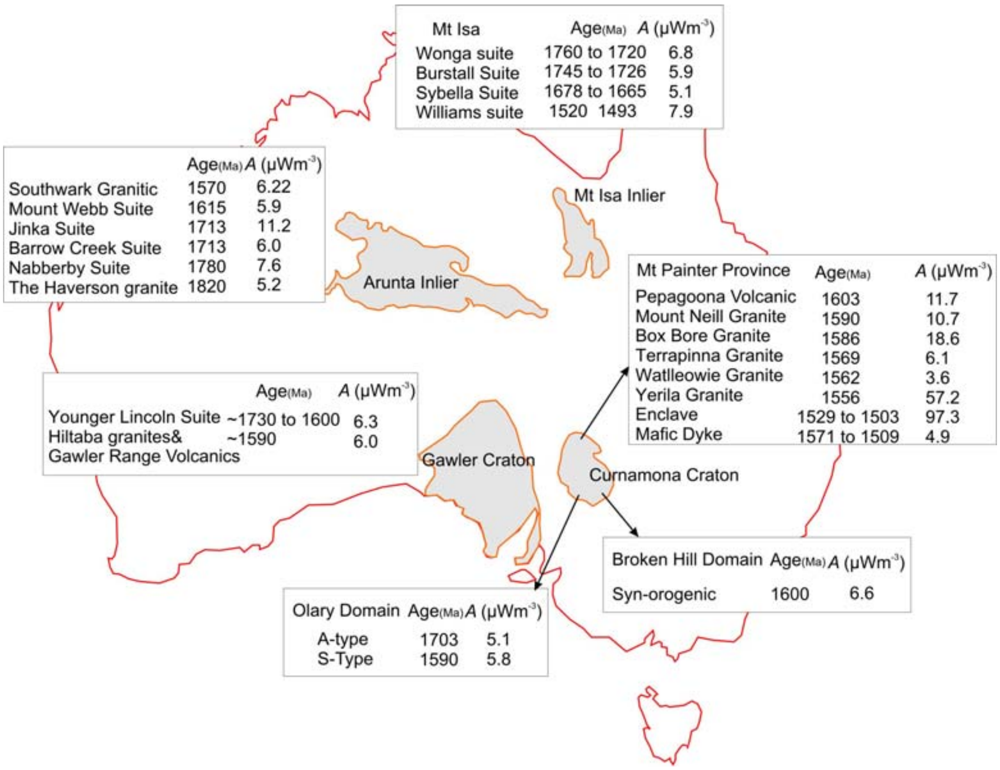

Figure 8.51 Ages allocation distribution of the HHP granites from the Mt Isa and Arunta Inlier, the Gawler and Curnamona Craton (Mt Painter Province, Broken Hill and Olary Domains).

The rock types for the HHP granites range from leucrogranite, hornblende-biotite granite, megacryst K-feldspar granite, K-feldspar bearing granite, monzogranite, pegmatitic granite, microgranite, rapakivi granite, granodiorite and augen gneiss. They are characterised by fine-, medium- to coarse-grained, porphyritic to equigranullar, slightly to strongly foliated and leucocratic textures. K-feldspar megacrystic phenocrysts with tabular and ovoid shapes are common in most suites. All HHP granitic units are variably metamorphosed and deformed, and may have a gneissic texture and quartz-feldspar augens. Mineralogical characteristics of the HHP granites are variable. They commonly consist of quartz, K-felspar, plagioclase, biotite, hornblende (enriched Cl ferrohastingite), magnetite, titanite, fluorite, allanite, zircon and apatite, epidote, tourmaline and muscovite. U and Th minerals such as uranite, uranothorite and thorite are found in the enriched U and Th granitic rocks (e.g. the Yerila Granite of the Mt Painter Province and the Roxby Downs Granite of the Hiltaba Suite).

8.5.3 Geochemistry

The HHP granites and associated rocks are mainly felsic rocks (SiO_2 >70 wt%). The HHP intermediate (SiO_2 70-60 wt%) and mafic rocks (SiO_2 <60 wt%; Figure 8.52) are not uncommon. Most HHP rocks have been affected by various degrees of metamorphism, deformation and alteration, resulting in them having variable geochemistry. They are mostly peraluminous to slightly metaluminous (Figure 8.53). Major element concentrations of the HHP rocks from all study areas are generally similar; however the HHP rocks from the Mt Isa Inlier have distinctively high TiO_2 and low K_2O contents, and the Olary Domain HHP rocks contain relatively high P_2O_5 contents compared with the other examples. HHP granites generally display negative trends in the Harker diagrams for major elements.

HHP granites are enriched in many trace elements relative to the low HP granites in the same areas. They are typically enriched in U, Th, Rb, Ce, La, Y and Zr and depleted in Ba and Sr (Figure 8.52a to l), although absolute concentrations vary between HHP suites. The HHP granites from the Mt Painter Province have extremely high Ce, Th, U, Y, La and Zr concentrations. The Gawler HHP granites have relatively high Pb and Nb contents.

HHP granites from the different areas show similar REE patterns, being enriched in LREE relative to HREE, although with differing degrees of negative Eu anomalies. Compared with HHP granites from the other areas considered here, the geochemical data of the Mt Painter HHP granitic and mafic rocks suggests that they are more evolved (with stronger fractional crystallization) than other units.

Because the HHP granites have high Rb, Nb and Y concentrations, most of the granites plot in the within plate granite field (Figure 8.54) although some samples plot within the syn-collision and volcanic arc granite fields. Although the HHP granites plot within both A-type and I- and S-type granites (e.g. the Younger Lincoln and Hiltaba Suites from the Gawler Craton, S-type or fractionated I-type units from the Olary Domain), their enriched HFSE and REE concentrations, high FeO/FeO+MgO and depleted Ba and Sr contents suggest they could be classified as A-type granites. HHP granites with A-type characteristics were mainly emplaced in back-arc and/or intracontinent settings. In most cases, the tectonic setting in which the HHP granites were emplaced was extensional. Therefore, mantle upwelling and interaction with continental lithosphere is preferred to explain HHP granite genesis.

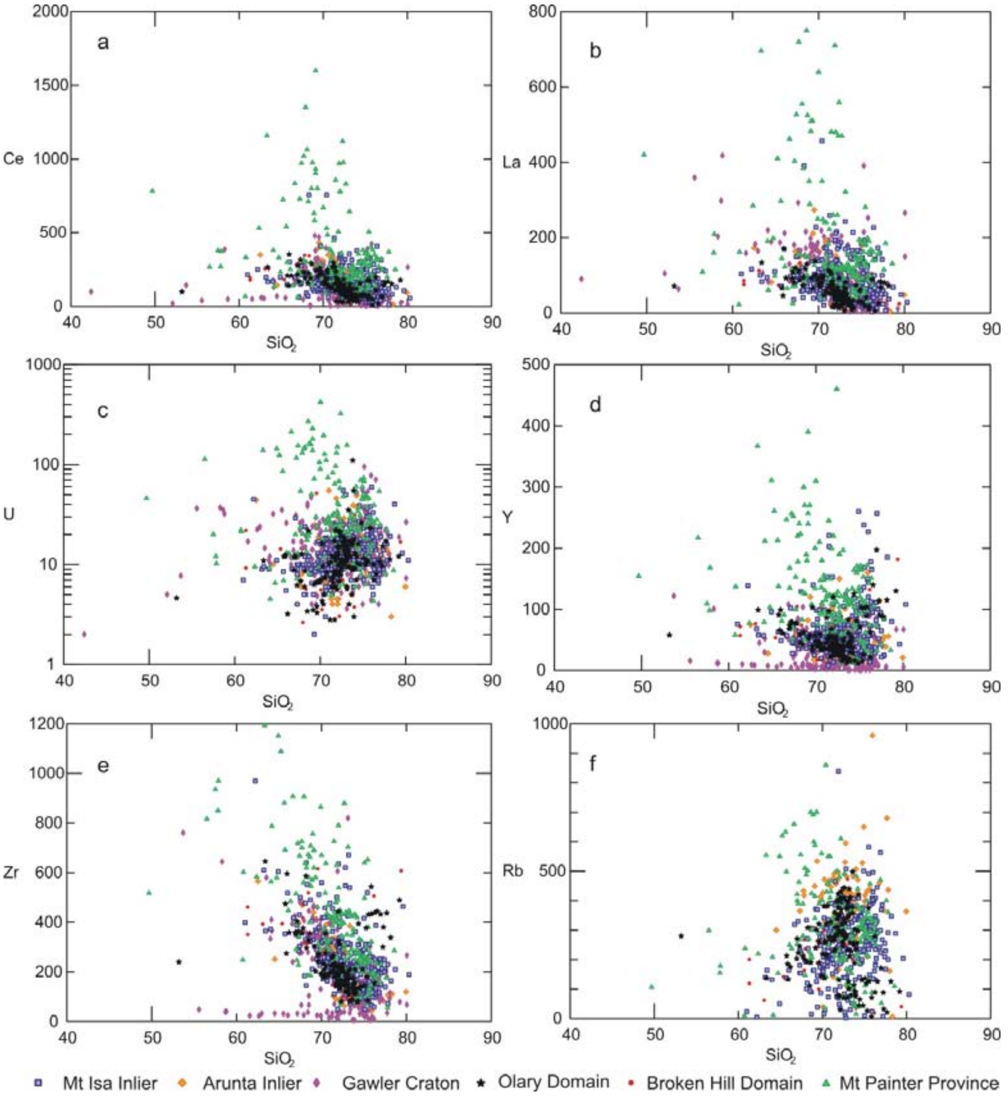

Figure 8.52 Binary plot of SiO_2 versus trace elements for the HHP granitic and associated rock from the Mt Isa and Arunta Inlier, the Gawler and Curnamona Craton (Mt Painter Province, Broken Hill and Olary Domains).

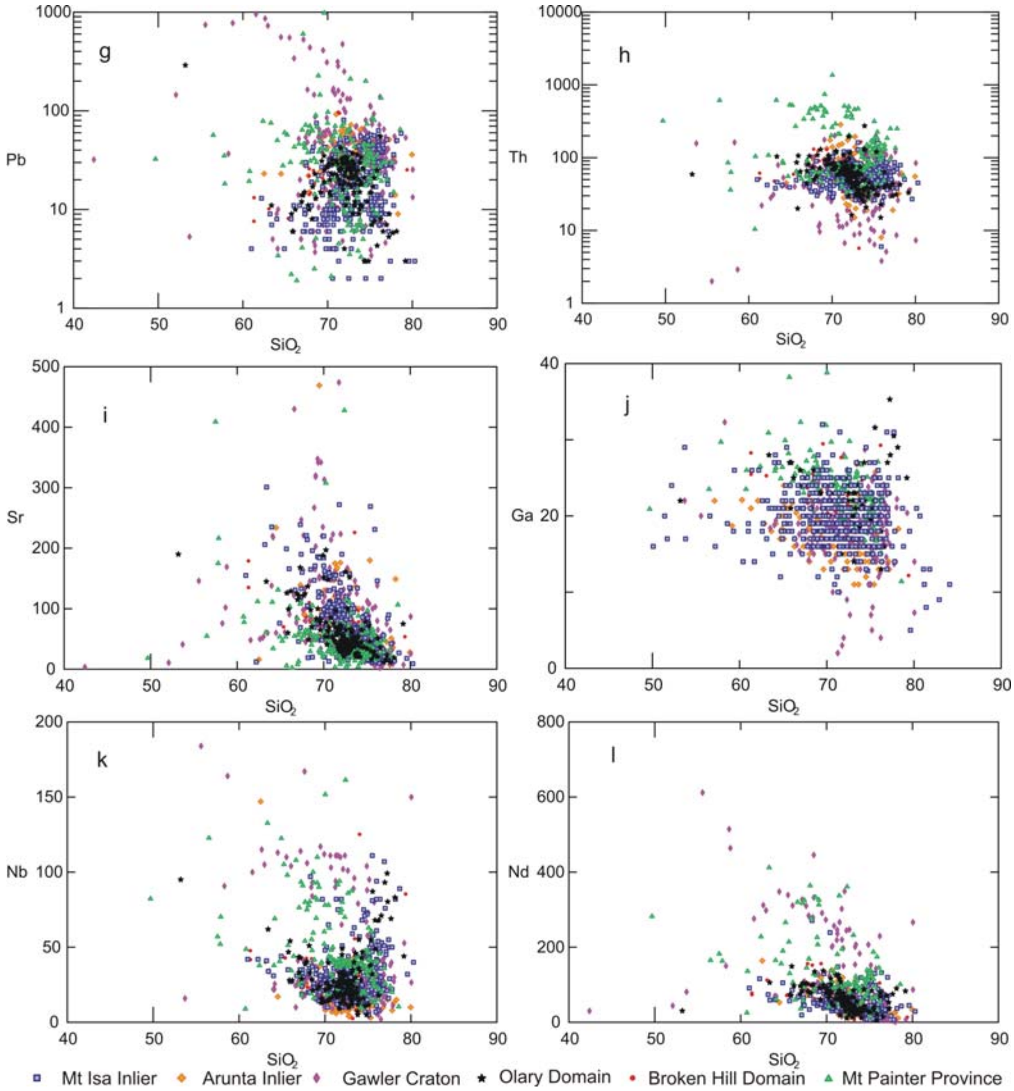

Figure 8.52 (continued) Binary plots of SiO_2 versus trace elements for the HHP granitic and associated rock from the Mt Isa and Arunta Inlier, the Gawler and Curnamona Craton (Mt Painter Province, Broken Hill and Olary Domains).

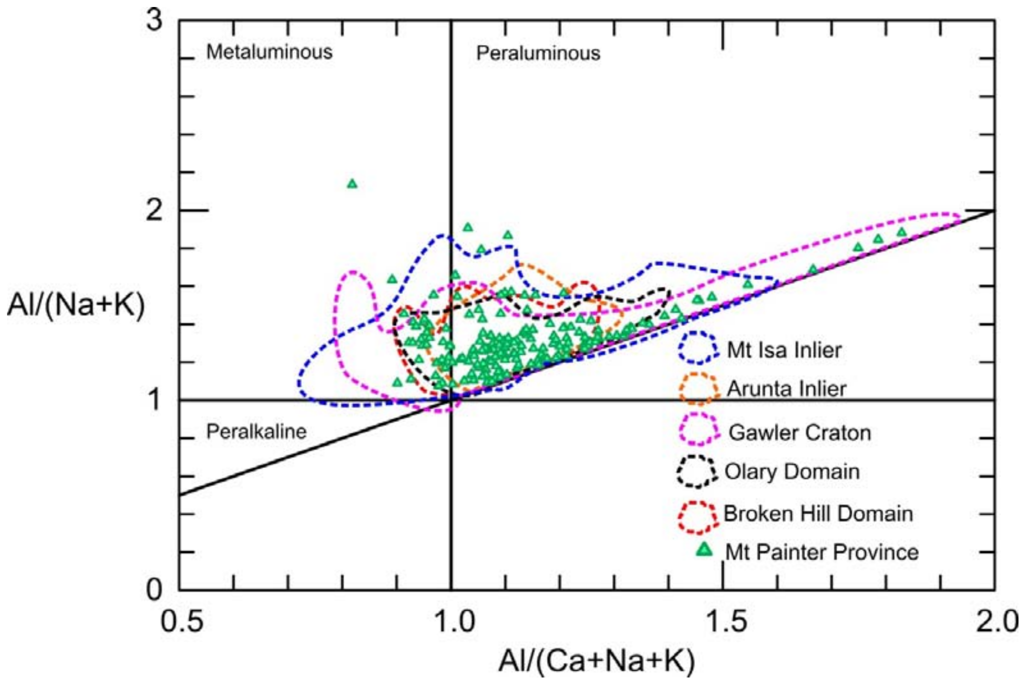

Figure 8.53 Alumina index binary plot (after Manaiar and Picolli, 1989) of the HHP granite and associated rocks from the Mt Isa and Arunta Inliers, Gawler Craton, Mt Painter Province and Olary and Broken Hill Domains.

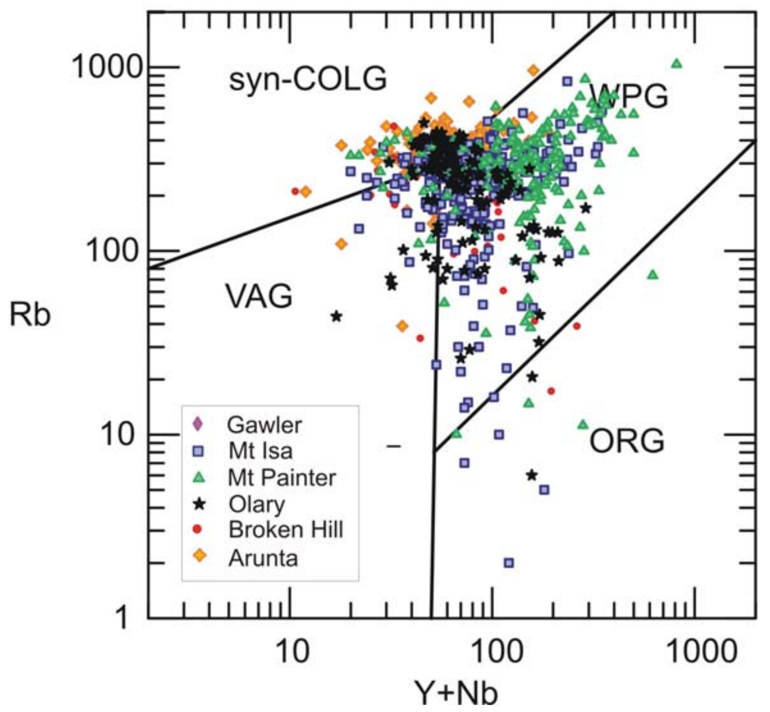

Figure 8.54 Discrimination tectonic setting diagram of Rb and Y+Nb after Pearce et al. (1984) for the HHP granitic and associated rock from the Mt Isa and Arunta Inlier, the Gawler and Curnamona Cratond (Mt Painter Province, Broken Hill and Olary Domains).

8.5.4 Nd Isotopes

Nd isotopic data of the HHP granites and associated rocks for all cratons is shown in an initial εNd value and age diagram (Figure 8.55). The initial εNd values of the Proterozoic mafic and felsic rocks vary and overlap between the different areas. Most samples yield negative εNd values with the initial εNd values varying from -18 to +4. Mafic and felsic samples from the Mt Painter Province and Mt Isa Inliers commonly have slightly higher initial εNd values than the felsic rocks from the Arunta Inlier, Olary and Broken Hill Domains and the Gawler Craton, with a large majority having initial εNd values between -4 and +1 (Figure 8.56). The Mt Isa granitic and associated rocks have initial εNd values from -4 to +2. Initial εNd values of granitic and volcanic rocks from the Mt Painter Province are relatively homogeneous (mainly ranging between -3 and +1) whereas the initial εNd values of granitic and volcanic rocks from the Gawler Craton are variable (between -18 and +4) suggesting heterogeneous sources. The Olary and Broken Hill Domain magmatic rocks yield similar initial εNd values with most samples displaying initial εNd values raging between -7 and +4. Mafic samples (which are interpreted to be coeval with the granitic rocks), from all areas, generally have positive initial εNd values overlapping with the felsic rocks.

The Nd isotopic data of the granitic and associated rocks from most areas except the granitic rocks from the Gawler Craton showing overlapping and relatively small range values, which could be interpreted to indicate that they are derived from a homogeneous source. Negative values of the εNd values for most samples suggest that they could be derived from partial melting of pre-existing crust (e.g. Sheard et al., 1992; Stewart, 1994; Creaser, 1995; Stewart and Foden, 2001). However, the positive initial εNd values indicate that juvenile mantle-derived magmas are also required to generate the final granitic and associated rocks. Therefore, it is likely that these rocks were generated by crustal contamination of mantle-derived mafic magmas. The granites containing high heat production values (<5 μwm^{-3}) and normal to low heat production values (>5 μwm^{-3}) have similar initial εNd values, which suggests that the normal and high heat producing granites are derived from the similar sources.

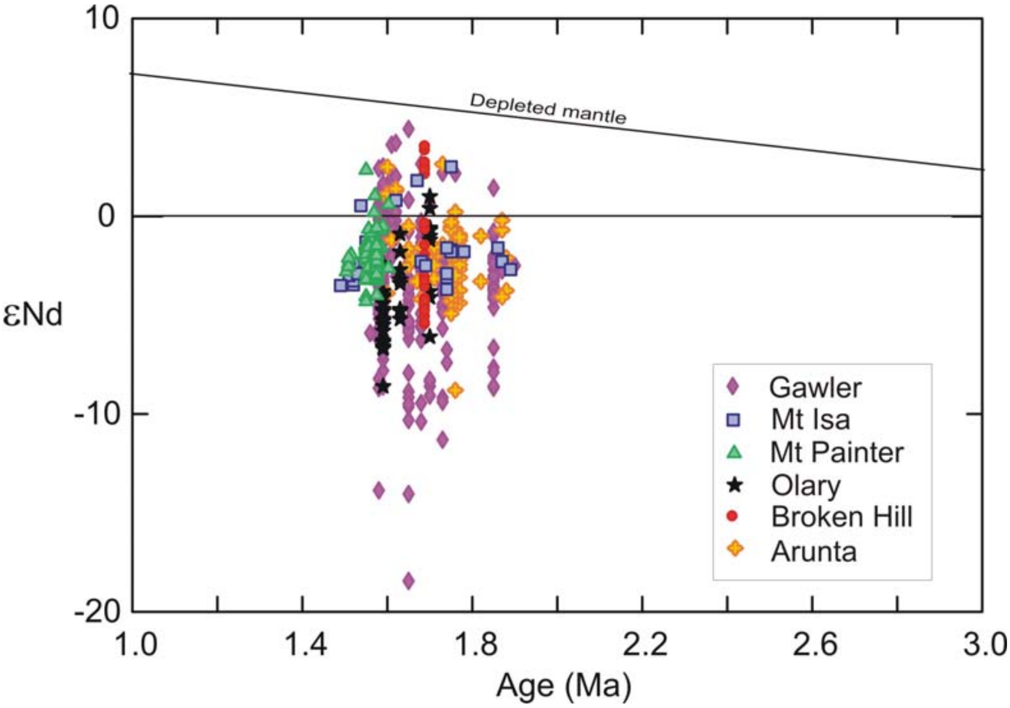

Figure 8.55 Initial ε_{Nd} values versus crystallization ages of the mafic and felsic rocks from the Mt Isa and Arunta Inlier, the Gawler and Curnamona Craton (Mt Painter Province, Broken Hill and Olary Domains).

8.5.5 Conditions of Crystallization

The Mesoproterozoic granitic rocks within the areas studied have been suggested to be mainly epizonal intrusives. For example, the Sybella Suite from the Mt Isa Inlier formed by the dehydration melting at very shallow depths (P≤4 kbar; Wyborn et al., 2002); and the Rasp Ridge Gneiss from the Broken Hill Domain intruded to a relatively shallow depth (Page et al., 2005a). Occurrences of hastingites and magmatic fluorite in many HHP granites suggest that the HHP granites were formed under low fH_2O and fO_2 environments. Based on their mineralogy and geochemistry, most HHP granitic suites are interpreted to have formed at high temperatures and low pressures. Examples include; the K-rich, A-type, metaluminous, magnetite-bearing granitoids formed during the Isan Orogeny in the Mt Isa Inlier were formed at high temperature (>850 °C) by partial melting of tonalitic crust at pressures of <0.8 – 1.0 Ga; hornblende in the Mt Angelay igneous complex crystallized at 2.7 to 3.5 kbar and >900 °C, based on hornblende – plagioclase geothermometry (Mark, 1998b); apatite and zircon saturation temperature of the Arthurton granites from the Gawler Craton indicate that the granitic melts had high temperature >960 °C for apatite saturation and >900 °C for zircon saturation (Zang et al., 2007).

8.5.6 Petrogenesis and tectonic significance

HHP granites are similar to A-type-granites in terms of their mode of occurrence, petrography and geochemistry, therefore it is appropriate to consider their origin in the broader context of A-type granite petrogenesis. Several mechanisms have been proposed to explain the generation of A-type magmas including; fractionation of mantle-derived magma, reaction of mantle-derived magma with crustal rocks, fractionation of I-type or syenitic magma, liquid immiscibility, thermogravitational diffusion and melting of deep continental crust (e.g. Barker et al., 1975; Loiselle and Wones, 1979; Collins et al., 1982; Anderson, 1983; Whalen et al., 1987; Eby, 1990).

The Nd isotopes of the HHP granites in this study (εNd values between -5 and +1) suggest that a main source of HHP granitic formation is a crustally contaminated mantle derived magma. This contaminated source was was originally enriched in trace elements, in particular HFSE. Crustal sources for forming the HHP granites were mostly suggested from partial melting of Palaeoproterozoic crust (e.g. the HHP granites from Mt Isa and Mt Painter Province). On the other hand, granites from the Gawler Craton, which have lower heat production values than the Mt Isa and Mt Painter granites, have a wide range and less values of εNd. The Gawler granites has been suggested that they were derived from melting of the Archaean, Late Archaean and Palaeoproterozoic crust. Variations of heat production values in different terranes are likely resulted from different types of continental crusts. This observation may suggest partial melting of the Palaeoproterozic crust is an important source. It seems like that the Palaeoproterozic crust of the Austalian continent is enriched in heat production elements and is a suitable source for generating HHP granites.

To generate a homogeneous and enriched in heat production melts, mixing of mantle-derived mafic magma with partial melting of the lower crust is suggested. Forming the HHP granites by deep crustal anatexis, the introduction of heat to the lower continental crust is required for melting.

Most HHP granites were mostly suggested that emplace in an intracontinental. As mentioned in Chapter 7, elevated heat fluxes in an intracontinental setting could result from thickening of previously thinned lithosphere (based on Thompson et al., 2001), mantle convection beneath the overriding plate in a subduction setting (Giles et al., 2002) and heat delivered to the base of the lithosphere by a plume of deep mantle origin (Neves and Mariano, 2004). All three mechanisms could possibly cause heat flux for partial melting the lower crust. Crustal thickening and/or extension from subduction or collision or rifting tectonism have been suggested as a cause of the HHP granites generations (e.g. the A-type granites from the Olary Domain formed by extension and rifting; Ashley et al., 1995, the HHP granites of the Arunta derived from subduction-related crutal component; (Zhao and McColloch, 1995 and the HHP granites from the Mt Painter Province; this study). The mantle plume hypothesis is one of the popular models for providing a heat source to generate the HHP granites in the study areas (e.g. Blissett et al., 1993; Betts et al., 2007, Betts et al., 2009). For example, the Hiltaba Suite and Gawler Range Volcanics from the Gawler Craton have been suggested that they were generated by interaction of the Gawler Craton continental lithosphere with a plume head (Betts et al., 2007). Moreover, the Mesoproterozoic HHP granites from the Mt Painter Province and from the Mt Isa Inlier were formed by plume tail magmatisms (Betts et al., 2007)

Mafic magmas generated by mantle upwelling arc then well mixed with partial melting of deeply buried source generating contaminated magma. Fractional crystallization of the contaminated magmas, which are already enriched in incompatible elements, is an important process for generating HHP granite. The mafic magmas undergo fractional crystallization generating felsic melts, which may then mix with sunsequent inputs of mafic magmas. High degrees of fractionational crystallization of accessory minerals such as zircon, allanite, titanite, apatite and magmatic U-Th minerals results in variable heat production values in the granitic rocks. Mixing and mingling between mafic and felsic magmas could cause intermediate components and microgranular enclaves.

Chapter 9 Petrogenesis of High Heat Producing Granites and Conclusion

9.1 Petrogenesis of HHP granite

In the previous Chapters, the Mesoproterozoic high heat producing (HHP) granites from the Mt Painter Province and other Australian terranes were documented with the aim of constraining the petrogenesis of HHP granites. HHP granites are typically enriched in incompatible trace elements, including LILE and HFSE, but low in trace elements that are compatible in mafic silicates (Co, Sc, Cr, Ni) and feldspars (Ba, Sr, Eu); these characteristics are typically used to define A-type granites. In fact, many A-type granites, located worldwide and dated to each geological era, can be classified as HHP granites due to their enriched in U and Th concentrations (see Chapter 1). The few S-type granites can be classified as HHP granites but they are only enriched in U with low Th/U and were mainly derived from crustal melt (examples include the Sn-U granites of the Scottish Caledonides and the Pitinga Mine, Brazil). Therefore, HHP granites, which, by definition, have high U, Th and K contents, are more likely to be a subgroup of A-type granites.

In most cases, HHP granites are coeval with mafic rocks that have similar geochemical characteristics and radiogenic isotopic compositions to the granites indicating that they are genetically linked. The mafic magma could either be the parental magma to the granites or provide the heat and/or fluids to drive for crustal melting that generated felsic and intermediate melt. Analyses of radiogenic isotopes from HHP granites in this study (e.g. Nd and Hf isotopes) suggest that, in addition to the mafic magma, a crustal source is also important. The narrow range of isotopic compositions (e.g. εNd and εHf) for many HHP granites (e.g. Chapter 6 and 8) and the Mesoproterozoic rapakivi granites from the Fennoscandia Shield; Rämö and Haapala, 1995, the Red Mountain and Sherman granites from the North America Craton;

likely derived from a well-mixed, crustally contaminated mantle-derived magma.

The crustal-contaminated magmas were possibly formed by a combination of partial melting of the lower crust and mantle-derived mafic magma. It has been suggested that intermediate and silicic melts could be generated in a ‘Deep Hot Zone’ (Annen et al., 2006). In this model, mafic sills emplaced at the mantle-crust boundary during plume-related basaltic melting, could cause extremely high heat flow and massive thermal transfer to the lower crust that produces partial melting to generate evolved residual melts (Annen et al., 2006; Annen et al., 2008). At the onset of intrusion, the crustal-contaminated melts formed by incomplete crystallization mafic magma and by partial melting of lower crust were likely to be trapped at the base of the continental crust because of their relatively high density relative to the overlying crust. At the onset of intrusion, the crustal-contaminated melts that were formed by incomplete crystallization of the mafic magma and by partial melting of lower crust were likely to be trapped at the base of the continental crust crust because of their relatively high density relative to the overlying crust. In the deep crust, heat from continued mantle upwelling and crystallization of the mafic magma may partially melt the most fusible portions of the lower crust (Zhong et al., 2009). Mantle upwelling providing heat soures for melting the lower crust could be resulted from various tectonisms such as thickening of thinned lithosphere, back-arc extension and mantle plumes. Minor partial melts could mixed with fractionates of the basaltic underplate resulting in isotopically homogeneous magma.

9.2 Mt Painter Province HHP granite conclusions

Major findings from this study include:

- The first geochronologic age constraints on Meosoproterozoic mafic dykes that crosscut the HHP granitic and volcanic rocks in the Mt Painter Province demonstrate that the mafic and felsic magmatic rocks were coeval. The mafic dykes yielded U-Pb zircon LA-ICPMS ages of 1571±4, 1557±4 and 1515±7

Ma overlapping with the ages of the HHP magmatic rocks, which were emplaced from ~1603 to 1504 Ma.

- The HHP granitic and associated rocks are characterized by high contents of alkalis ($Na_2O + K_2O$), Zr, Nb, Ga, Y, U, Th, REE (except Eu), and high elemental ratios, such as Ga/Al and FeO_{total}/MgO and low contents of Al_2O_3, CaO, Ba, Sr, and Eu, so can be classified as A-type granites.
- Fractional crystallization of K-feldspar, plagioclase, hornblende, apatite, zircon, Ti-bearing minerals and allanite from mafic magmas and mixing between mafic and felsic magmas are important processes in generating these HHP magmatic rocks. The Yerila Granite and its enclaves, which have extremely high heat production values, formed by strong fractional crystallization and in particular the accumulation of accessory minerals whereas other felsic units involve mixing between mafic and felsic magmas with less fractional crystallization.
- Fractional crystallization of accessory minerals that host U and Th, such as zircon, allanite, Ti and U-Th minerals controlled the abundance of trace elements in the host rocks. The enrichment of U- and Th in the Yerila Granite and its enclaves is due to the accumulation of zircon, allanite, Ti and U-Th minerals.
- Based on εNd values (ranging between -3 and +1) and εHf values (mainly ranging from 2 and +4) for the HHP mafic and granitic rocks, the parent magma for these rocks was a mixture of mantle-derived magma and pre-existing crust. Specifically the parent magma was a mixture of 80% juvenile mantle-derived magma and 20% partial melt from the lower and/or middle crust. Crustal melting is inferred to have occurred in a Hot Deep Zone, where the heat source for partial melting the crust was provided by underplating of mafic magmas and/or

thinning of the lithosphere during intraplate or back-arc extension**.**

- The hot and dry HFSE-enriched magma ascended to a shallow level in an intraplate or back arc setting by rifting or crustal extension at *ca.* 1600 Ma, forming the HHP granites and volcanic rocks.

9.3 Comparison with other Australian HHP Granites

Comparison of the Mt Painter Province HHP granites to the HHP granites of the Mt Isa and Arunta Inliers, the Gawler and Curnamona cratons suggests that these HHP granites are typically coeval with mafic and felsic volcanic rocks and are mainly classified as A-type granites. They are interpreted to have formed from crustal-contaminated mantle magmas, which fractionated and ascended to shallow levels in intraplate or back arc settings by rifting or extension crustal. The high heat production values of the granites are directly related to the enriched HFSE crustal-contaminated mantle-derived magmatic source.

9.4 Focus for Further Studies

The challenge for further research lies in the study of HHP granites on a global scale. Comparing the HHP granites from the Mt Painter Province and Australian continent to well-studied Mesoproterozoic rapakivi and A-type granites, which often have high heat production values, such as from the Fennoscandia Shield and the North American Craton may shed further light a genesis of HHP granites. It is possible that high heat production values in granites are related to a well-mixed crustal-contaminated magma emplaced in intracontinent or back-arc setting. Therefore, focussing on radiogenic isotopes of co-magmatic mafic rocks may provide direct links to sources and mechanisms responsible for generating HHP granites.