Unravelling the tectonic framework of the Musgrave Province, central Australia

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Chapter 1

Introduction

1.1 Project Overview and Aims

The 1.60-1.08 Ga Musgrave Province in central southern Australia occupies a vast area (~120,000 km^2) (Figure 1.1), however it comprises the least known Proterozoic terrain in Australia. The construction of a cohesive and data-rich geological framework for the evolution of the Musgrave Province has been hampered by two factors.

1) There is a paucity of outcrop beyond the main topographic ranges of the Province;

2) Approximately 80% of the land in the Musgrave Province falls within the traditional Anangu Pitjantjatjara, Yankunytjatjara and Ngaanyatjarra lands, creating significant difficultly in obtaining access to regions.

Due to a range of studies over the past decade, it is now generally accepted that convergent plate margin processes played an important role in the assembly of the various Archaean-Proterozoic fragments of Australia (e.g. Zhao and McCulloch, 1995; Myers et al., 1996; Scott et al., 2000; Cawood and Tyler, 2004; Giles et al., 2004; Occhipinti et al., 2004; Tyler, 2005; Betts and Giles, 2006; Wade et al., 2006). The Musgrave Province is geographically central to, and younger than, these accreted Archaean-Palaeoproterozoic fragments (Figure 1.2). This makes it a key element in the assembly of Proterozoic Australia, and therefore any models that attempt to describe the evolution of Proterozoic Australia require a sound framework for the geologic evolution of the Musgrave Province.

The aim of this thesis was to develop a framework for the protracted geological evolution of the Musgrave Province, starting from its earliest history (early Mesoproteorozic), to its latest (early Cambrian) (Figure 1.3). Also of interest was determining the timing of the final amalgamation of Proterozoic Australia. This was conducted utilising geochemical, isotopic, and geochronological means. In order to achieve this aim a five-module program was constructed that involved:

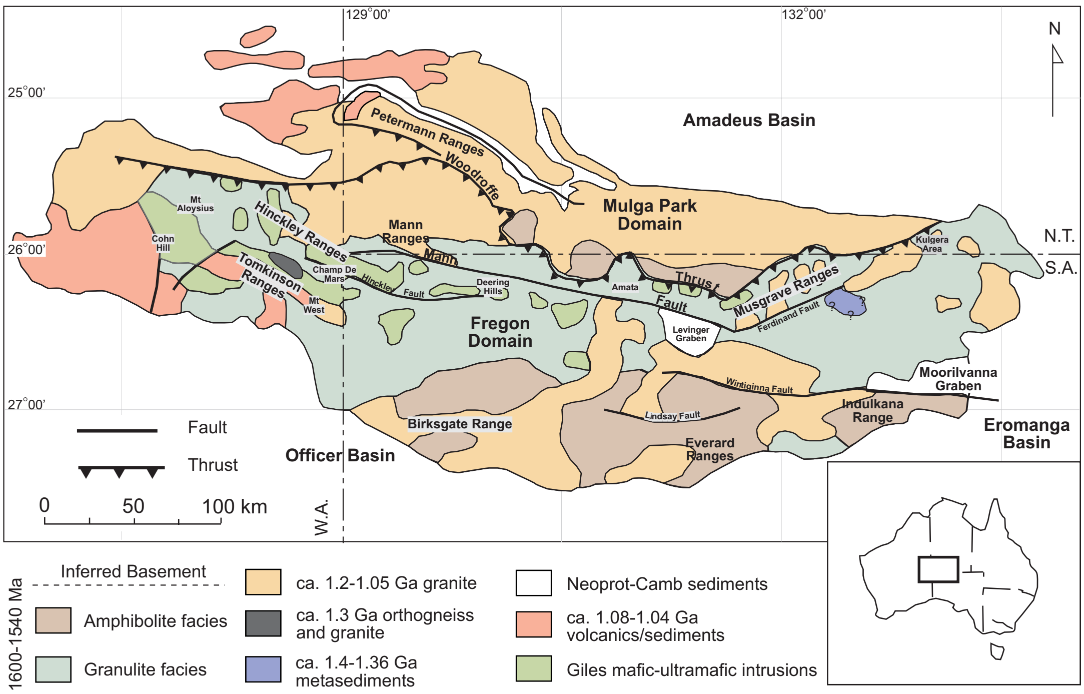

Figure 1.1 Location map of the Musgrave Province indicating main areas of fieldwork undertaken in this study and areas of interest.

· establishing the tectonic environment involved in the formation of the oldest rocks of the Musgrave Province, the ca. 1.60-1.54 Ga felsic and mafic Musgravian Gneisses (Figure 1.3 & 1.4), through application of geochemistry and Sm-Nd isotopes;

· examining detrital input to metasedimentary rocks (Figure 1.3 & 1.4) through U-Pb SHRIMP, U-Pb LA-ICMPS and Nd istopes, and what it can tell us about the Musgrave Provinces geographic position at the time of their formation;

· investigating the petrogenesis and crust-mantle relationships involved in the formation of layered mafic-ultramafic intrusions of the Giles Complex (Figure 1.3 & 1.4) utilising geochemistry and Nd-Sr isotopes;

· constraining the timing of the Petermann Orogeny through geochemical and Sm-Nd isotopic analysis of sedimentary rocks from the Officer Basin; and

· examining the nature of the basement rocks that separate the gross tectonic elements of Proterozoic Australia, namely the NAC, SAC, and WAC. This was done by geochemical, Nd-isotopic, and U-Pb age analysis of granitic lithologies in the Coompana Block (Fig. 1.2).

There were a number of motivating factors for this study:

· The Musgrave Province is of considerable economic interest to mining companies and the local SA Government Geological Survey (PIRSA). It represents a greenfields region with significant potential for Ni-Cu-Co mineralisation in the mafic-ultramafic Giles Complex, and copper-gold resource targets in the high-grade basement Musgravian Gneiss.

· The overall lack of geochemical, isotopic, and geochronological data on lithologies of the

NOTE: This figure is included on page 2 of the print copy of the thesis held in the University of Adelaide Library.

Figure 1.2 Simplified map of Australia displaying the distribution of the major Archaean-Mesoproterozoic tectonic provinces (modified after Myers et al., 1996)

Musgrave Province (Figure 1.3) has prohibited a coherent region-wide evaluation of the mechanisms involved in the formation of the Musgrave Province.

1.2 Outline and organisation of thesis

This thesis is organised in a manner that systematically provides geochemical and isotopic constraints to address a number of elements relating to the tectonic environment pertaining to the formation of various lithologies within the Musgrave Province, and also the boundaries with other tectonic domains. These elements are:

1. The origin of the ca. 1.60-1.54 Musgravian Gneiss of the Musgrave Province, and the implications for the timing of reconstruction models involving fragments of Proterozoic Australia;

2. The source of metasediments in the eastern Musgrave Province, and the subsequent implications for pre-Rodinia palaeogeographic reconstructions involving Australia;

3. The genesis and tectonic significance of the layered intrusions of the mafic-ultramafic Giles Complex;

4. The genesis of the intracratonic Petermann Orogeny as it is recorded in the sediments of the Officer Basin.

5. The genesis of the granitic gneiss of the Coompana Block, and the subsequent implications for Proterozoic reconstructions of Australia.

Chapter 2 summarises the regional geological framework of the Musgrave Province. Despite the fact that it occupies a large portion of central Australia, the Musgrave Province represents one of the least studied terranes of Proterozoic Australia. An attempted summary of the results and interpretations of published papers and Ph.D theses, as well as results recorded by State Geological surveys is presented in the paper. The chapter is divided into a description of the individual lithological units, structural framework, metamorphic

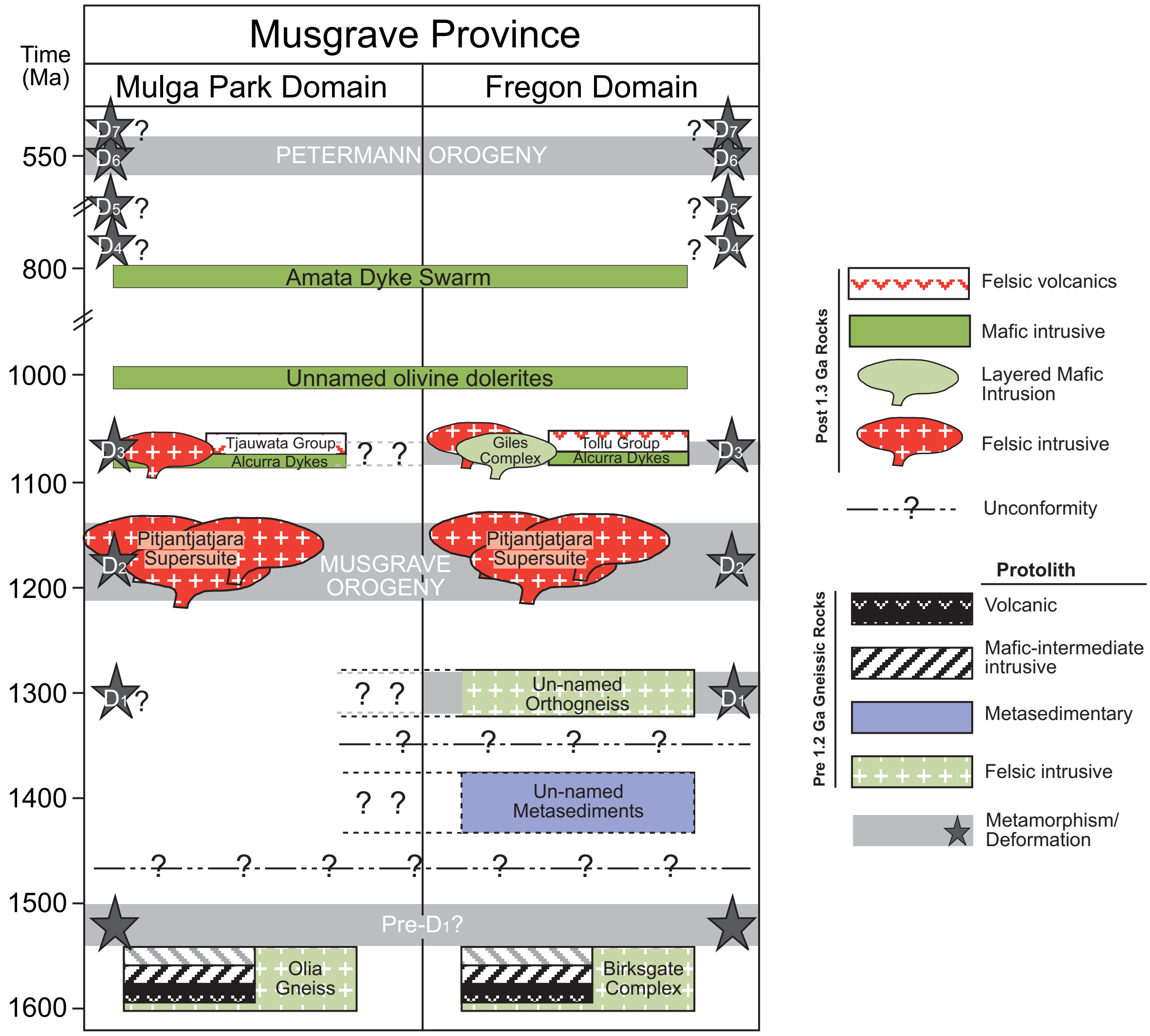

Figure 1.3 Musgrave Province lithostratigraphic sequence

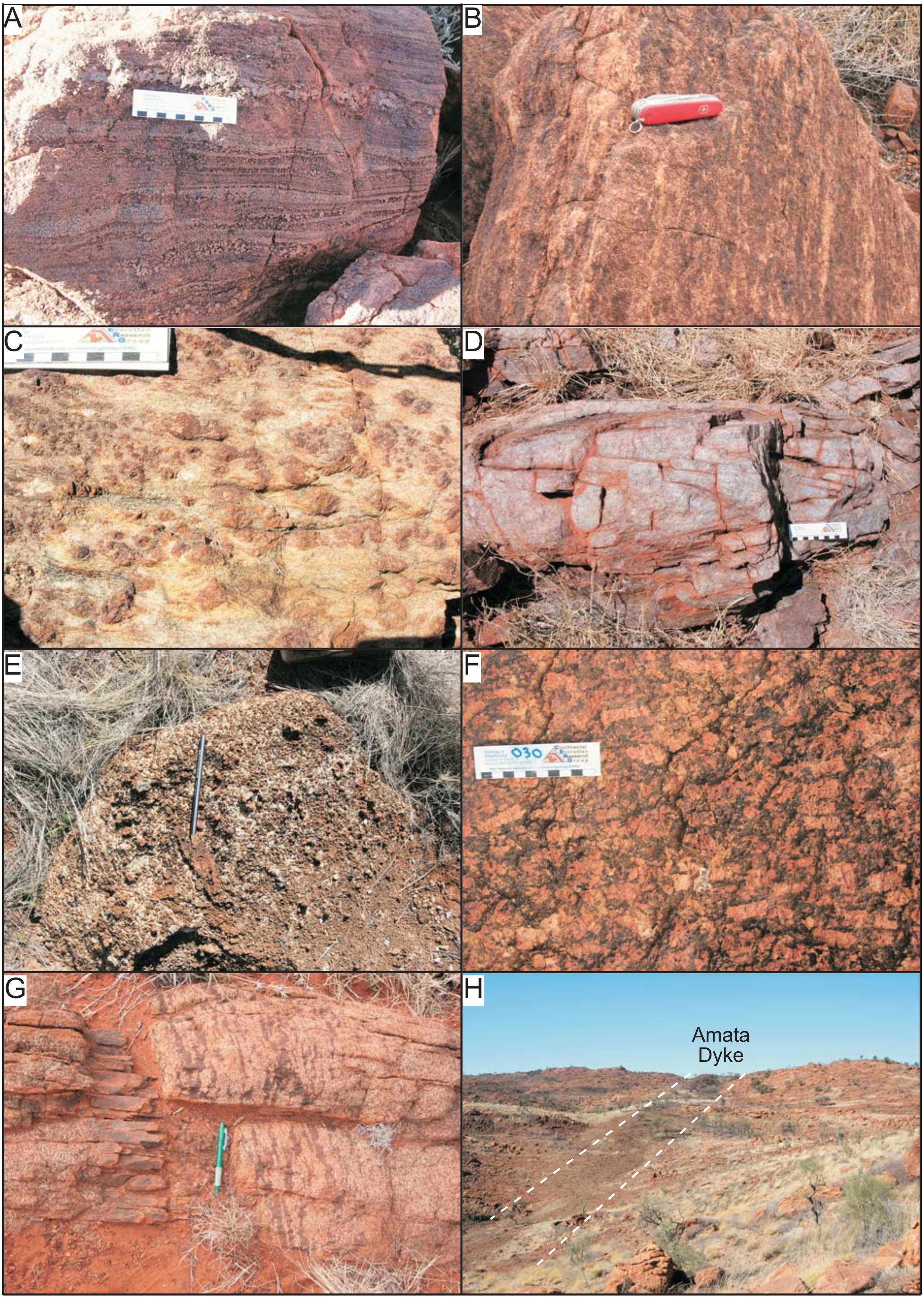

Figure 1.4 (A) Felsic gneiss of the Birksgate Complex, Deering Hills; (B) Mafic gneiss of the Birksgate Complex, Deering Hills; (C) Weathered metapelitic rock of the Birksgate Complex, Deering Hills; (D) Folded quartzite of the Deering Hills; (E) Calc-silicate of the Birksgate Complex, Deering Hills; (F) Example of Pitjantjatjara Supersuite Granite, eastern Musgraves; (G) Example of magmatic layering within the Giles Complex, Caroline intrusion; and, (H) Example of Amata Dyke cross-cutting felsic and mafic gneiss of the Birksgate Complex, Deering Hills.

record, and possible tectonic significance of the Musgrave Province.

Chapter 3 describes the geochemistry and Nd isotopic characteristics of a suite of ca. 1.60-1.54 Ga felsic orthogneisses that comprise the basement in the northern Musgrave Province. This study provides the first detailed geochemical and isotopic analysis of this magmatic event. Limited geochemical work on equivalent felsic rocks in the western Musgrave Province conclude a possible plate margin origin (e.g. Glikson et al., 1996; Wade et al., 2006). By discriminating the tectonic origin of these felsic orthogneisses through geochemical and isotopic means, it allows us to place constraints on the evolution of the Musgrave Province during the early Mesoproterozoic.

Chapter 4 reports U-Pb SHRIMP and U-Pb LA-ICPMS geochronological and Nd isotope data on metasedimentary rocks from the eastern Musgrave Province. Originally mapped as part of the ca. 1.60-1.54 Ga basement Musgravian Gneiss (Conor, 1987), detrital zircon geochronology was undertaken to ascertain possible source regions to aid in reconstructions of Proterozoic Australia.

Chapter 5 presents geochemical and radiogenic isotopic data (Nd-Sr) of sample traverses over three intrusions of the mafic-ultramafic Giles Complex within the western Musgrave Province of South Australia. Detailed mapping and sampling of the Kalka, Ewarara, and Gosse Pile intrusions has been previously undertaken during the early 1970's (e.g. Goode, 1970; Moore, 1970); however, detailed geochemical and isotopic analysis has not been applied. The aim is to understand the petrogenesis of the mafic magmatism, by characterising the magmatic processes that were in operation during their formation. Furthermore, characteristics of the possible mantle source for the Giles Complex is proposed. These characteristics form the basis for proposing models on the lithospheric evolution of the Musgrave Province and provide information for crust-mantle interactions in this part of Proterozoic Australia.

Chapter 6 investigates the geochemical and isotopic effects of the early Cambrian (ca. 550 Ma) Petermann Orogeny of the Musgrave Province on the basin fill sediments of the Officer Basin in southern central Australia. Detailed isotopic and geochemical analysis was undertaken through the stratigraphy of the Officer Basin, starting in the basal Neoproterozoic units through to upper units of late Cambrian age. By recognising the initial large influx of Musgrave derived material in the geochemical and isotopic signatures of the Officer Basin, we are able to place constraints on the duration of the intracratonic Petermann Orogeny.

Chapter 7 investigates the age and petrogenetic origin of a granitic gneiss located to the west of the Gawler Craton under cover, in what is termed the Coompana Block. This module was conducted following the interpretation of results from Chapter 4, primarily to locate potential sources of zircons within the metasedimentary rocks of the eastern Musgrave Province.

The thesis is concluded in **Chapter 8** with a summary of the implications derived from the results of this study. This section summarises the findings of the thesis and investigates the implications of these results for reconstructions of Proterozoic Australia.

Several parts of this thesis have been published or submitted in varying forms to international journals. Chapter 2 has been submitted as a review paper to a special volume of Precambrian Research concentrated on Proterozoic Australia. Chapter 3 has been published in the Journal of Geology, and Chapter 4 has been submitted to and is in review in Geology. Chapter 5 has been submitted and in review at the Journal of Petrology. Chapter 6 is published in the Journal of the Geological Society of London, and Chapter 7 has been submitted and is in review at the Australian Journal of Earth Sciences. Appendix 5 has been submitted to and is in review at Computers and Geosciences. I have also been involved in a number of related projects that are in submission in international peer reviewed journals. As the structure of this project has been focussed on producing each chapter as a stand-alone manuscript, there is some repetition in the geological background sections of each chapter.

CHAPTER 2

The Musgrave Province; Terra Anonymous?

This chapter is accepted to a Special Volume of Precambrian Research focussing on Proterozoic Australia as: Wade, B.P., Kelsey, D.E., Hand, M., Barovich, K.M. (2006) The Musgrave Province; Stitching North, West and South Australia. Precambrian Research.
See appendix for full article.

Wade, B.P., Kelsey, D.E., Hand, M., Barovich, K.M. (2006)
The Musgrave Province; Stitching North, West and South Australia.
Precambrian Research, special volume

NOTE: This publication is included on pages 6 – 23 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

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CHAPTER 3

Evidence for early Mesoproterozoic arc magmatism in the Musgrave Block, central Australia: implications for Proterozoic crustal growth and tectonic reconstructions of Australia

This chapter is published as: Wade, B.P., Barovich, K.M., Hand, M., Scrimgeour, I.R., Close, D.F. (2006) Evidence for early Mesoproterozoic arc magmatism in the Musgrave Block, central Australia: implications for Proterozoic crustal growth and tectonic reconstructions of Australia. Journal of Geology, 114, 43-63.
See appendix for full article.

Wade, B.P., Barovich, K.M., Hand, M., Scrimgeour, I.R. and Close D.F. (2006)
Evidence for early Mesoproterozoic arc magmatism in the Musgrave Block, central Australia: implications for Proterozoic crustal growth and tectonic reconstructions of Australia.
Journal of Geology, v. 114 (1), pp. 43-63, January 2006

NOTE: This publication is included on pages 24 – 36 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

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CHAPTER 4

The Musgrave province, central Australia: cinching the Belt Supergroup down under?

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Wade, B.P., Barovich, K.M., Hand, M., Maidment D. (2006) The Musgrave province, central Australia: cinching the Belt Supergroup down under?
Terra Nova

NOTE: This publication is included on pages 37 – 46 in the print copy of the thesis held in the University of Adelaide Library.

CHAPTER 5

Petrogenesis of the isotopicaly evolved layered ultramafic-mafic intrusions, Musgrave Block, Australia: modified mangle or crustal contamination?

This chapter has been submitted to the Journal of Petrology as: Wade, B.P., Barovich, K.M., Hand, M. (2006). Petrogenesis of the isotopicaly evolved layered ultramafic-mafic intrusions, Musgrave Block, central Australia: modified mantle or crustal contamination?. Journal of Petrology. See appendix for full article.

Wade, B.P., Barovich, K.M., Hand, M. (2006) Petrogenesis of the isotopicaly evolved layered ultramafic-mafic intrusions, Musgrave Block, central Australia: modified mantle or crustal contamination? *Journal of Petrology*.

NOTE: This publication is included on pages 47 – 66 in the print copy of the thesis held in the University of Adelaide Library.

CHAPTER 6

Nd isotopic and geochemical constraints on provenance of sedimentary rocks in the eastern Officer Basin, Australia: Implications for the duration of the intracratonic Petermann Orogeny

This chapter is published as: Wade, B.P., Hand, M., Barovich, K.M. (2005) Nd isotopic and geochemical constraints on provenance of sedimentary rocks in the eastern Officer Basin, Australia: implications for the duration of the intracratonic Petermann Orogeny. Journal of the Geological Society, London. 162, 1-18. See appendix for full article.

Wade, B.P., Hand, M., Barovich, K.M. (2005) Nd isotopic and geochemical constraints on provenance of sedimentary rocks in the eastern Officer Basin, Australia: implications for the duration of the intracratonic Petermann Orogeny. *Journal of the Geological Society, v.162 (3), 2005, pp. 513-530*

Chapter 7

Filling the "magmatic gap" of Proterozoic Australia

Abstract

The Coompana Block represents an essentially unknown basement province that separates the Gawler Craton of South Australian from the Yilgarn Province of Western Australia. Previously geochronologically, geochemically, and isotopically uncharacterised granitic gneiss intersected by deep drilling of the Coompana Block represents an important period of within-plate magmatism during a time of relative magmatic quiescence in the Australian Proterozoic. Samples of granitic gneiss from Mallabie 1 drill hole are metaluminous and dominantly granodioritic in composition. They have distinctive A-type chemistry characterised by high contents of Zr, Nb, Y, Ga, LREE with low Mg#, Sr, CaO and HREE. U-Pb LA-ICPMS dating of magmatic zircons provides an age of 1505±7.2 Ma, interpreted as the crystallisation age of the granite protolith. εNd values are high with respect to exposed crust of the Musgrave Province and Gawler Craton, and range from +1.2 to +3.3 at 1.5 Ga. The genetic relationship of the granitic gneiss represents a fractionated melt of a mantle derived melt parent. The tectonic environment into which the precursor granite was emplaced is also unclear; however, one possibility is emplacement within an extensional environment. Regardless, the granitic gneiss intersected in Mallabie 1 represents magmatic activity during the "Australian magmatic gap" of ca. 1.50-1.35 Ga, and is a possible source for detrital ca. 1.50 zircons found within sedimentary rocks of Tasmania and Antarctica, and metasedimentary rocks of the eastern Musgrave Province.

Keywords: Proterozoic Australia; A-type, Nd-isotopes; Coompana Block; Geochemistry

7.1 Introduction

The magmatic history of Proterozoic Australia is punctuated by intervals of relative quiescence in magmatic activity, the two main periods being ca. 2.0-1.9 Ga and ca. 1.50-1.35 Ga. These periods may represent a time of reduced activity in mantle dynamics, a preservation problem, or a sampling problem. Much like the ca. 1.60-1.54 Ga "North American magmatic gap" of Laurentia (Van Schmus et al., 1993), the only two felsic magmatic events of any note occur around ca. 1.50-1.35 Ga. These include the ca. 1.51 Ga Spilsby Suite Granite of the Gawler Craton, the outcrop of which is restricted to Spilsby Island (Fanning, 1997), and the 1.52-1.50 Ga Williams Supersuite of the eastern Mt Isa Inlier (Page and Sun, 1996; Wyborn, 1998) (Fig. 7.1). Prior to this from ca. 1.60-1.54 Ga we have voluminous magmatism throughout much of the North Australian and South Australian Cratons (NAC and SAC) associated with the Hiltaba Suite and Gawler Range Volcanics in the Gawler Craton (Fanning et al., 1988), the voluminous S-type granites in the Curnamona Province (Page et al., 2003), and the meta-igneous rocks of the Mt Isa and Yambo inliers of north Queensland (Blewett et al., 1998) (Fig. 7.1). Post 1.35 Ga is the emplacement of voluminous granitoids in both the Musgrave Province (ca.1.30 Ga orthogneiss (White et al., 1999); and ca. 1.20-1.14 Ga granites of the voluminous Pitjantjatjara Supersuite (e.g. Camacho and Fanning, 1995; Edgoose et al., 2004)), and Albany-Fraser Complex (ca. 1.33-1.14 Ga granites of the Nornalup Complex (e.g. Myers, 1995; Nelson et al., 1995).

This apparent paucity of magmatism during the interval of ca. 1.50-1.35 Ga has provided problems for many provenance studies that have identified detrital zircons falling within this time period (e.g. Goodge et al., 2002; Black et al., 2004; Chapter 4: this study). In all cases the authors have cited sources exotic to Australia, such as the voluminous A-type granitoids suites of southern Laurentia (Anderson and Bender, 1989; Van Schmus et al., 1993). Following this, the presence of ca. 1.50-1.35 Ga detrital zircons has led to palaeogeographic reconstructions involving Australia and Laurentia (e.g. Goodge et al., 2002; Chapter 4: this study). The gross tectonic elements of Proterozoic Australia, namely the North, South, and West Australian cratons (Fig. 7.1), are separated by deep and aerially extensive sedimentary basins, of which the underlying basement geology is either poorly or totally unknown. It is beneath these sedimentary basins in which the potential lies to discover magmatic belts of ages that would fill the ca. 1.50-1.35 Ga time gap in the geological record.

The Coompana Block separates the West Australian Craton (WAC) from the SAC (Figs. 7.1 and 7.2), and represents an area in which the underlying basement is shallow enough to be sampled by drillcore. Its geographical position is key in deciphering what may underlie the Officer Basin in South and Western Australia. Here we present U-Pb LA-ICPMS data, Sm-Nd isotopes, and geochemistry on granitic gneiss of the Coompana Block located in South Australia (Figs. 1 and 2, Appendix 5: Tables 1,2 and 3). The data indicate that the precursor to the granitic gneiss cored in Mallabie 1 represents a previously unrecognised ca. 1.50 Ga A-type magmatic suite, raising the possibility of undiscovered rock suites beneath the Officer Basin of an age within the “Australian magmatic gap”.

7.2 Geology of the Coompana Block

The Coompana Block represents a suite of rocks of unknown extent totally concealed beneath the Phanerozoic cover of the Eucla basin (Figs. 7.1 and 7.2). Lithologies intersected in the drillhole Mallabie 1 (Fig. 7.2) comprise a basement granitic gneiss intruded by dolerite-gabbro dykes, and overlain by flat-lying interlayered basic volcanics and arenaceous sediments (Drexel et al., 1993). The limited number and depth of drillholes within the Coompana Block prevents a detailed examination of its geology, and given its size (>200x200 km from TMI interp), there exists the potential for a further complexity in its lithologies.

The granitic gneiss intersected in Mallabie 1, which is the focus of this study, consists of an intensely foliated lithology of interlayered quartzofeldspathic (qtz + k-feld) and mafic-rich bands (bt+hbd+plag) at the cm scale, and a less segregated foliated lithology of identical mineralogy (qtz+k-feld+bt+hbdplag) (Fig. 7.3). Previous geochronology on the granitic gneiss consists of K-Ar geochronology on biotite and hornblende, and provided ages of 1159 Ma and 1185 Ma respectively (Webb et al., 1982). These ages represent the only geochronological analyses for the entire Coompana Block. These ages have been interpreted to represent a Musgrave Orogeny overprint (Drexel et al., 1993), raising the possibility of Musgrave Orogeny deformation extending from the Albany-Fraser Orogen in W.A. as far east as the western edge of the Gawler Craton in S.A. (Fig. 7.1).

Interlayered arenaceous sediments and basic volcanics are interpreted to overlie the granitic gneiss. The age of this sequence is unknown, however correlations have been proposed with the Roopena Volcanics of the GRV (Thompson, 1970), Neoproterozoic volcanics of the Adelaide Rift Complex, and the Cambrian Kulyong volcanics of the Officer Basin (Scott and Spear, 1969). Mafic gabbroic intrusives, and small satellite gabbroic bodies have also been intersected in drillhole (Fig. 7.2), again the age of which are unknown. Numerous north-northwest trending mafic dykes have been interpreted from TMI, which probably correlate with those of the Gairdner Dyke Swarm (Drexel et al., 1993).

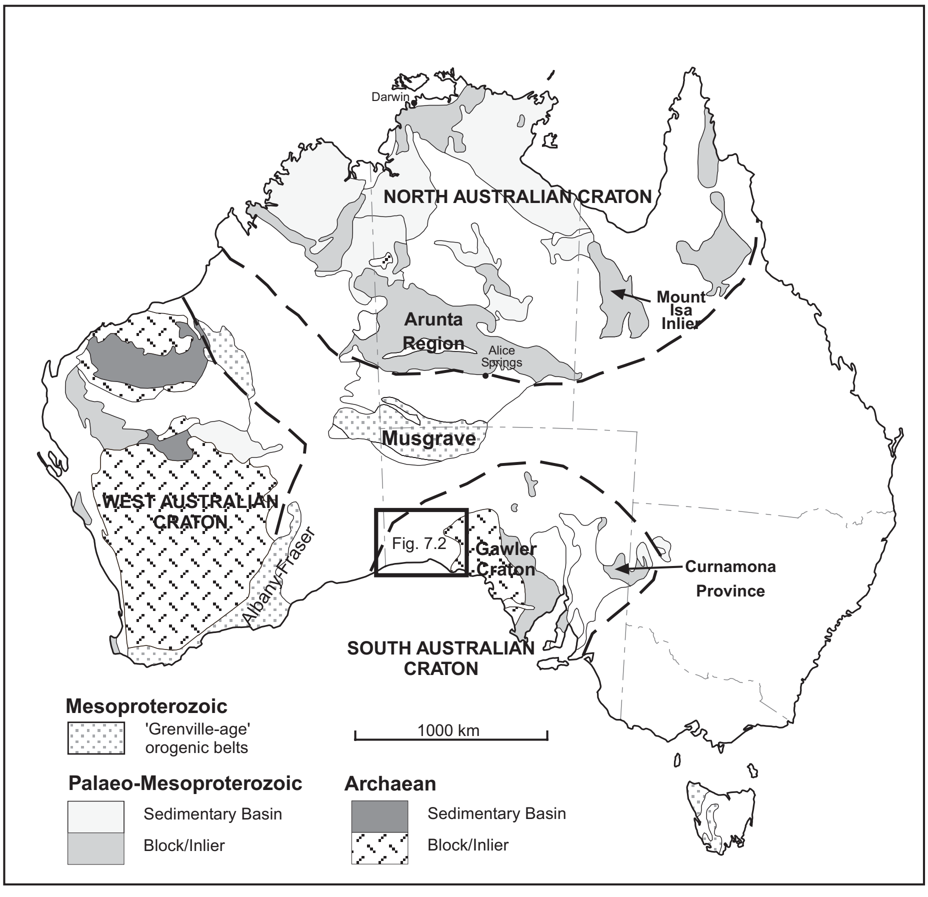


Figure 7.1 Map of tectonic elements of Proterozoic Australia including the North, West, and South Australian Cratons. Inset: represents area displayed in Fig. 7.2

NOTE: This figure is included on page 86 of the print copy of the thesis held in the University of Adelaide Library.

Figure 7.2 Simplified geological map of the Coompana Block displaying various lithologies and location of drillholes. Modified after Drexel et al. (1993).

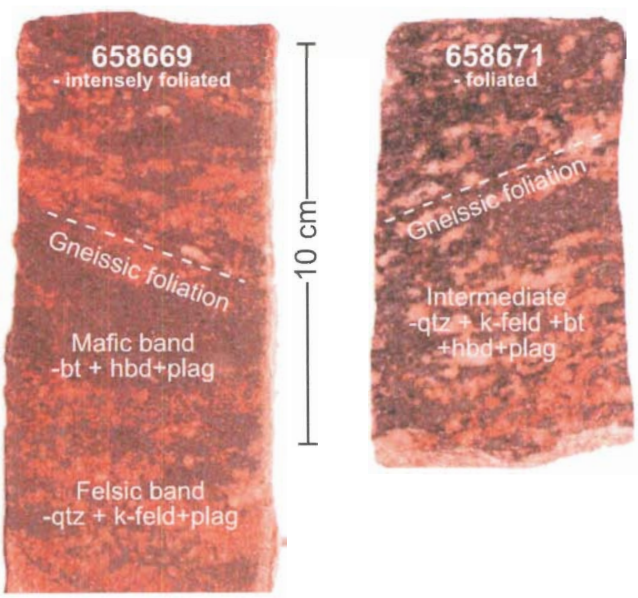


Figure 7.3 Photograph of representative foliated and strongly foliated granitic gneiss displaying mineralogical banding.

7.3 Sampling Methods and Analytical Procedures

Figure 7.2 shows the location of Mallabie 1 drillhole, which represents the only drillhole in the Coompana Block to intersect interpreted granitic gneiss basement, the remaining RC drillholes proving to be too shallow. The total cored interval of basement is approximately four metres. Five samples of cored granitic gneiss were taken for this study. Their sample depths shown in Table 1 (Appendix 5). All samples contain gneissic fabrics, and were classified as having a granitic precursor based upon bulk mineralogy of the rock, which consists of qtz-kfeld-plag-hbd-bt, with zircon, sphene and apatite common accessory minerals. Two strongly foliated samples were taken from the cored intersection at 1404.00-1406.00 m, and three moderately foliated samples from the EOH 1493.5-1495.6 m cored intersection. The two samples of intensely foliated granitic gneiss (658669 and 658670), contain mafic (dominantly bt-hbd-plag) and quartzofeldspathic bands (qtz-kfeld-plag) (Fig. 7.3).

All five samples were analysed for major and trace elements (Appendix 5: Table 1), one sample dated by U-Pb LA-ICPMS (Appendix 5: Table 2), and three analysed for Sm-Nd isotopes (Appendix 5: Table 3). Whole rock samples of granitic gneiss were crushed and powdered in a tungsten carbide mill. An aliquot was taken for isotopic analysis and whole rock geochemistry. The remaining crushate was retained for zircon separation by standard Frantz and heavy liquid separation techniques, followed by hand picking of zircons.

For analysis of major elements a 0.1 g sub-sample of the analytical pulp was fused with lithium metaborate followed by dissolution in nitric acid solution to give a "total solution" ready for ICPMS analysis. Analysis of trace and REE elements was achieved by digestion of up to 0.5 g of the analytical pulp in a HF/multi acid solution and presented to an ICPMS for the quantification of the elements of interest. All dissolution and element analysis were carried out at Amdel Laboratories in Adelaide.

U-Pb analysis of zircons from sample 658673 (foliated granitic gneiss) was conducted by LA-ICPMS at the University of Adelaide. Zircon grains were imaged using standard BSE and CL imaging techniques on a Phillips XL20 SEM with attached Gatan CL (Fig. 7.4). Equipment and operating conditions are identical to those reported by Payne et al. (2006). Ages were calculated using the GEMOC GJ-1 zircon standard to correct for U-Pb fractionation, and the GLITTER software for data reduction (Van Achterbergh et al., 2001). Fractionation of U-Pb was corrected using the GEMOC GJ-1 zircon standard (TIMS normalisation data $^{207}Pb/^{206}Pb$ = 608.3 Ma, $^{206}Pb/^{238}U$= 600.7 Ma and $^{207}Pb/^{235}U$= 602.2 Ma, Jackson et al. 2004). Accuracy was monitored by repeat analyses of the in-house internal standards comprising of a Sri Lankan zircon standard (BJWP-1, ca. 727 Ma). Over the duration of this study the reported average normalised ages for GJ-1 are 608.9±7.3, 600.6±2.0 and 602.3±1.7 Ma for the $^{207}Pb/^{206}Pb$, $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios, respectively (n = 37). Due to the LA-ICPMS inability to measure common Pb, correction was carried out using the ‘CommPbcorr’ macro (Andersen, 2002). Negligible (<0.5% 206Pb) common Pb was detected in all of the analyses when the 3D concordia method employed by ‘CommPbcorr’ was used.

Whole rock samples analysed for Sm-Nd isotopic composition were evaporated in HF/HNO_3 overnight, digested in hot HF/HNO_3 in sealed Teflon bombs for five days, then evaporated to dryness in HF/HNO_3. Samples were subsequently evaporated in 6M HCl then bombed with 6M HCl overnight. Nd and Sm concentrations were calculated by isotope dilution, with Nd isotope ratios measured by thermal ionisation mass spectrometry on a Finnigan MAT 262 mass spectrometer, and Sm isotope ratios measured on a Finnigan MAT 261 mass spectrometer. The $^{143}Nd/^{144}Nd$ ratio is normalised to $^{146}Nd/^{144}Nd$ = 0.721903. The single Nd blank carried out during the course of the analyses was 85 pg. The $^{143}Nd/^{144}Nd$ ratio of the in-house standard (Johnson Matthey) at the Adelaide University laboratory during the course of the analyses was 0.511597 ± 0.000006 (1s, no. of analyses = 2). Running average for La Jolla over the year is 0.511838 ± 0.000008 (1s, no. of analyses = 6).

7.4 Age of the Mallabie 1 Granitic Gneiss

One sample of foliated granitic gneiss (658673) was dated by LA-ICPMS. The data is presented in Table 2 (Appendix 5). Transmitted light and CL images of typical zircons are displayed in Figure 7.4, while conventional U-Pb concordia and a $^{207}Pb/^{206}Pb$ histogram of the ages are presented in Figure 7.5. All zircons were clear to pale pink in colour, ranged in morphology from acicular to stubby prisms, and were generally greater than 100um in length. Most zircons contained inclusions of apatite and hornblende (Fig. 7.4). All zircons analysed display oscillatory zoning under CL luminescence, attributed to a magmatic genesis (Fig. 7.4).

Thirty-three zircons were analysed, all of which provided excellent data with minimal to no common Pb (Appendix 5: Table 2). On a conventional U-Pb concordia diagram the data are slightly discordant, and when a Model 2 fit line is regressed through the points gives an intercept age of 1502±4.3 Ma (Fig. 7.5). The slightly high MSWD of 2.1 indicates some scatter about the mean. The weighted average of the $^{207}Pb/^{206}Pb$ ages (1505±7.2 Ma) provides an age indistinguishable from that of the concordia intercept, however its more acceptable MSWD of 0.25 suggests that it may be a more reliable age. Hence we suggest that the $^{207}Pb/^{206}Pb$ weighted average age of 1505±7.2 Ma represents the crystallisation age of the precursor to the Mallabie granitic gneiss.

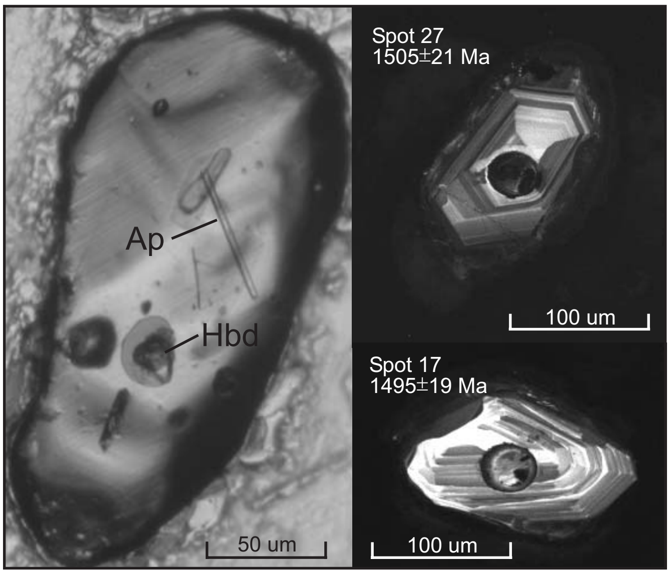


Figure 7.4 Transmitted light photograph of typical zircon from the granitic gneiss displaying inclusions of apatite and possible hornblende. CL images of typical zircons also shown displaying magmatic zoning and spot location and $^{207}Pb/^{206}Pb$ age.

7.5 Geochemistry of the Mallabie 1 Granitic Gneiss

7.5.1 Major elements

Major element analyses are summarised in Table 1 (Appendix 5), along with average values of A-, I-, and S- type granitoids of Whalen et al. (1987). SiO_2 values for the samples are intermediate, ranging from ~59-64% (Appendix 5: Table 1). The samples have been split into two groups according to the intensity of their gneissic fabric. Samples 658671, 658672, and 658673 are comparitively weakly deformed, whereas samples 658669 and 658670 are intensely deformed (Appendix 5: Table 1). Foliated samples have lower SiO_2 (58.9-61.7 wt%), higher Al_2O_3 (15.2-16.1 wt%), TiO_2 (1.04-1.32 wt%), and P_2O_5 (0.41-0.51 wt%) than those of the intensely foliated samples which conversely have higher SiO_2 (63.5-64.3 wt%), with lower Al_2O_3 (14.6-15.0 wt%), TiO_2 (0.92-0.96 wt%), and P_2O_5 (0.24-0.27 wt%) (Appendix 5: Table 1). Major element oxides generally show linear trends on Harker diagrams with an increase in K_2O, and a systematic decrease of Al_2O_3, CaO, FeOt, P_2O_5, Na_2O and TiO_2 with increasing SiO_2 content (Fig. 7.6). All samples are metaluminous with ASI<1; however, the foliated samples display slightly increased metaluminous characteristics when compared to the intensely foliated samples (Appendix 5: Table 1, Fig. 7.7).

On a CIPW normative Ab-An-Or classification diagram, the samples plot as dominantly granodioritic, with one sample of the intensely foliated granitic gneiss plotting in the tonalitic field (Fig. 7.8a). All samples fall within the calc-alkaline field defined in AFM, clustering near the tholeiitic/calc-alkaline boundary (Fig. 7.8b).

7.5.2 Trace and Rare Earth Elements

For consistency, foliated and intensely foliated samples defined in the previous section have been adopted here. All samples display a relatively restricted range in trace element compositions; however, there are subtle differences between both groups (Appendix 5: Table 1). Trace and REE spidergrams are normalised to Primitive Mantle (McDonough and Sun, 1995) and REE Chrondritic values (Taylor and McLennan, 1985)

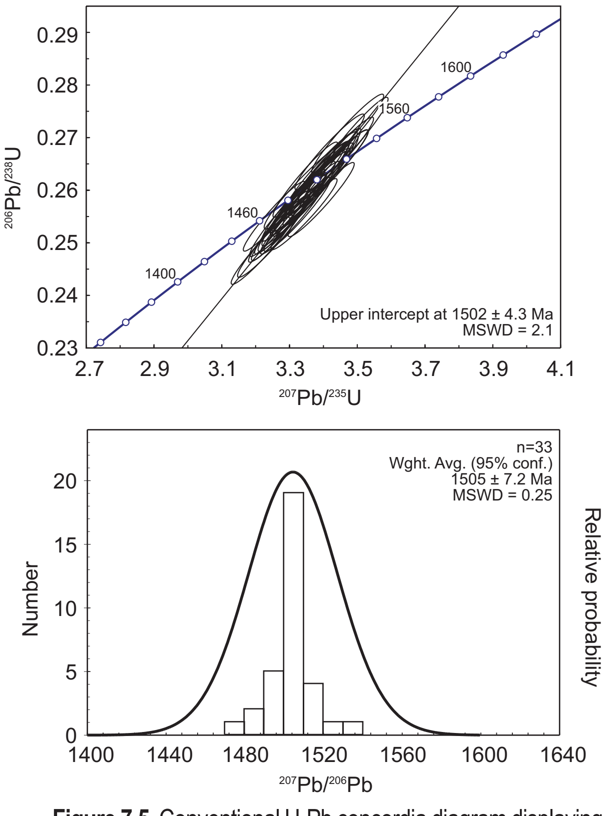


Figure 7.5 Conventional U-Pb concordia diagram displaying upper intercept age of ca. 1.50 Ga. Also shown is $^{207}Pb/^{206}Pb$ age histogram and probability density curve displaying weighted average of ca. 1.50 Ga.

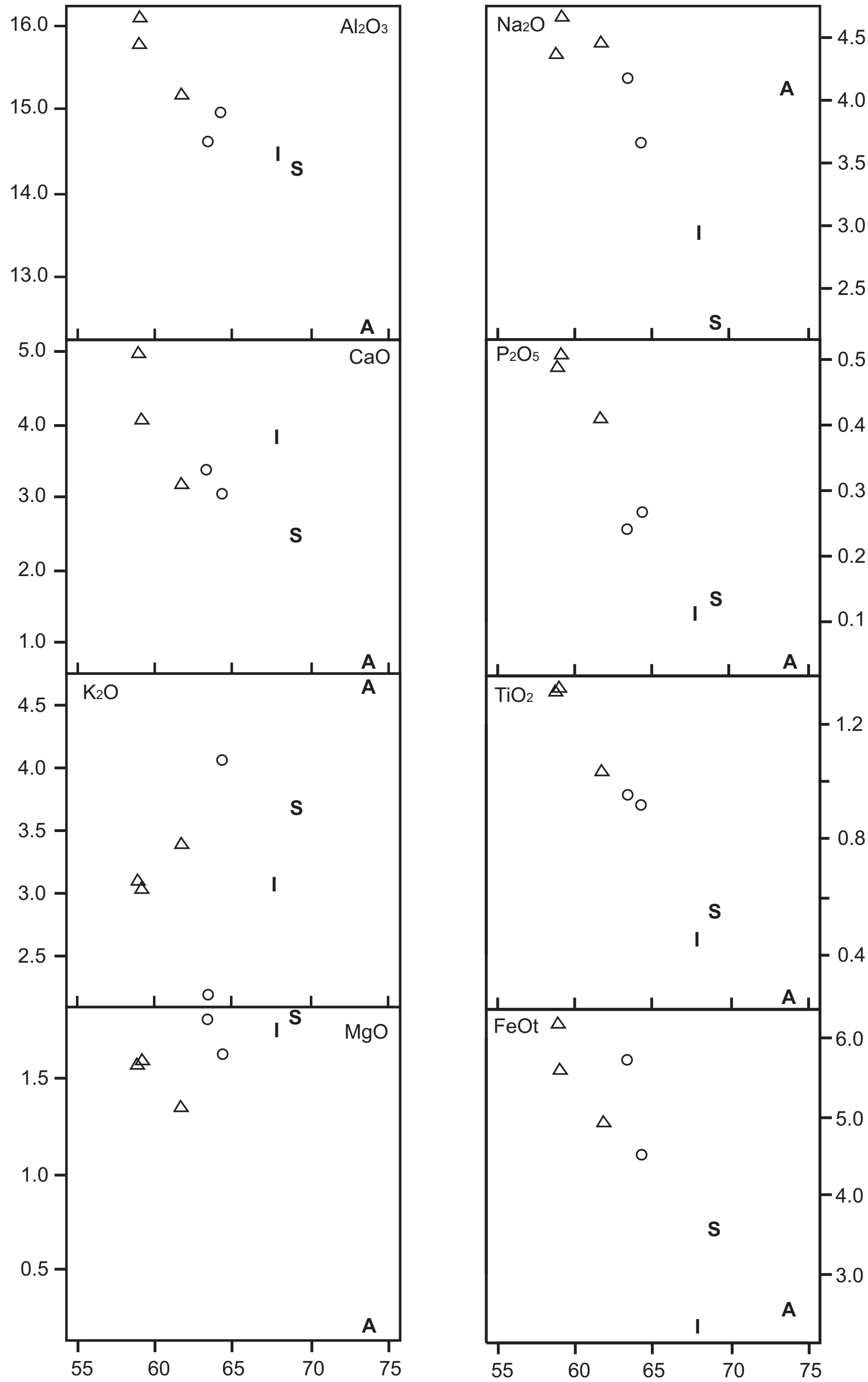


Figure 7.6 Harker variation diagrams for samples of granitic gneiss. Open triangles represent samples of foliated granitic gneiss, while open circles represent samples of intensely foliated granitic gneiss. Also plotted for comparison are average I-, S-, and A- type of Whalen et al. (1987)

(Figs. 7.9a,b).

The REE patterns for the foliated and intensely foliated samples differ (Fig. 7.9a). Samples from the foliated group have marked positive Eu anomalies ($(Eu/Eu^*)_N$ = 1.27-1.38), steep REE ($(La/Yb)_N$ = 10.05-12.21) and HREE ($(Gd/Yb)_N$ = 2.48-2.60) patterns (Appendix 5: Table 1, Fig. 7.9a). Samples from the intensely foliated group display flat to slightly positive Eu anomalies ($(Eu/Eu^*)_N$ = 0.99-1.04), and less steep REE ($(La/Yb)_N$ = 6.01-6.58) and HREE profiles ($(Gd/Yb)_N$ = 1.68-1.80) than those of the foliated group (Appendix 5: Table 1, Fig. 7.9a).

When normalised to Primitive Mantle, differences

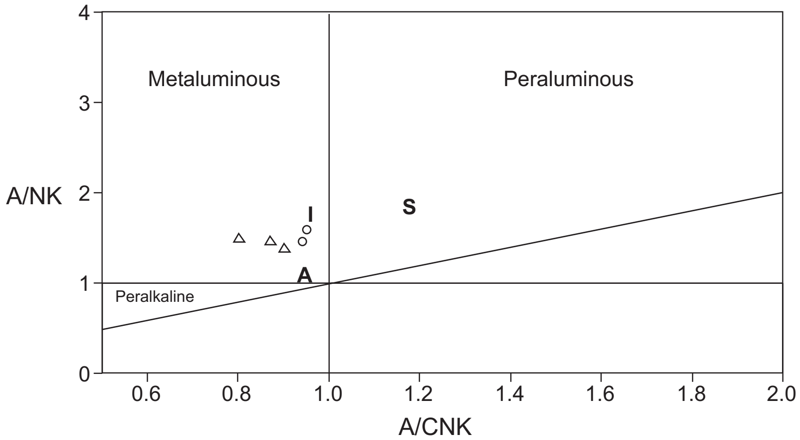


Figure 7.7 A/NK vs A/CNK plot of Shand (1943) displaying the metaluminous characteristic of the granitic gneiss. Symbols as per Figure 7.6

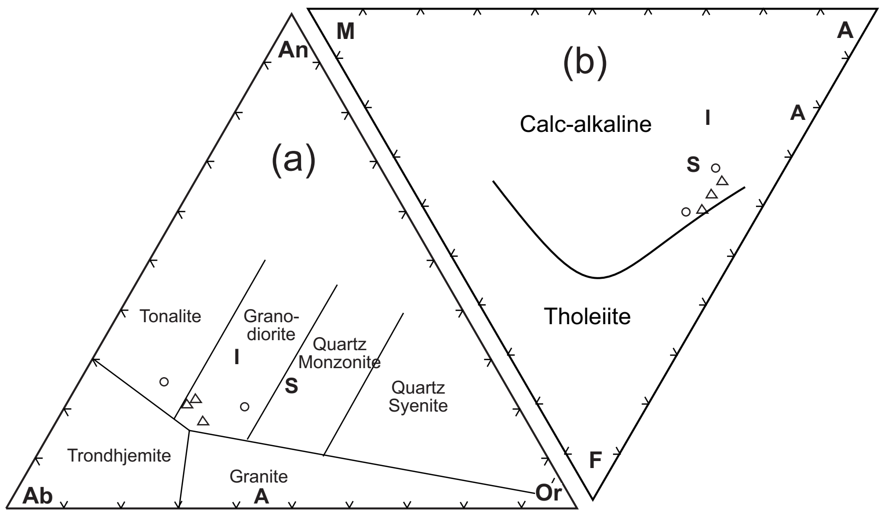


Figure 7.8 (a) CIPW normative Ab-An-Or ternary diagram displaying granodioritic composition of granitic gneiss. (b) AFM diagram of Irvine and Baragar (1971) displaying calc-alkaline characteristic of granitic gneiss samples. Symbols as per Figure 7.6

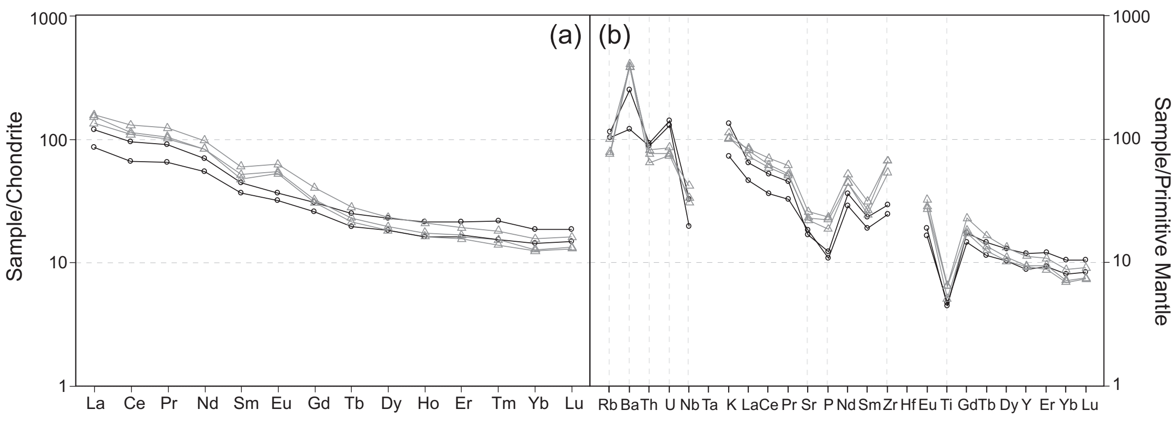


Figure 7.9 (a) Chondrite normalised REE plot of foliated and intensely foliated sampes of granitic gneiss. (b) Primitive Mantle normalised trace element plot of foliated and intensely foliated samples of granitic gneiss. Symbols as per Figure 7.6

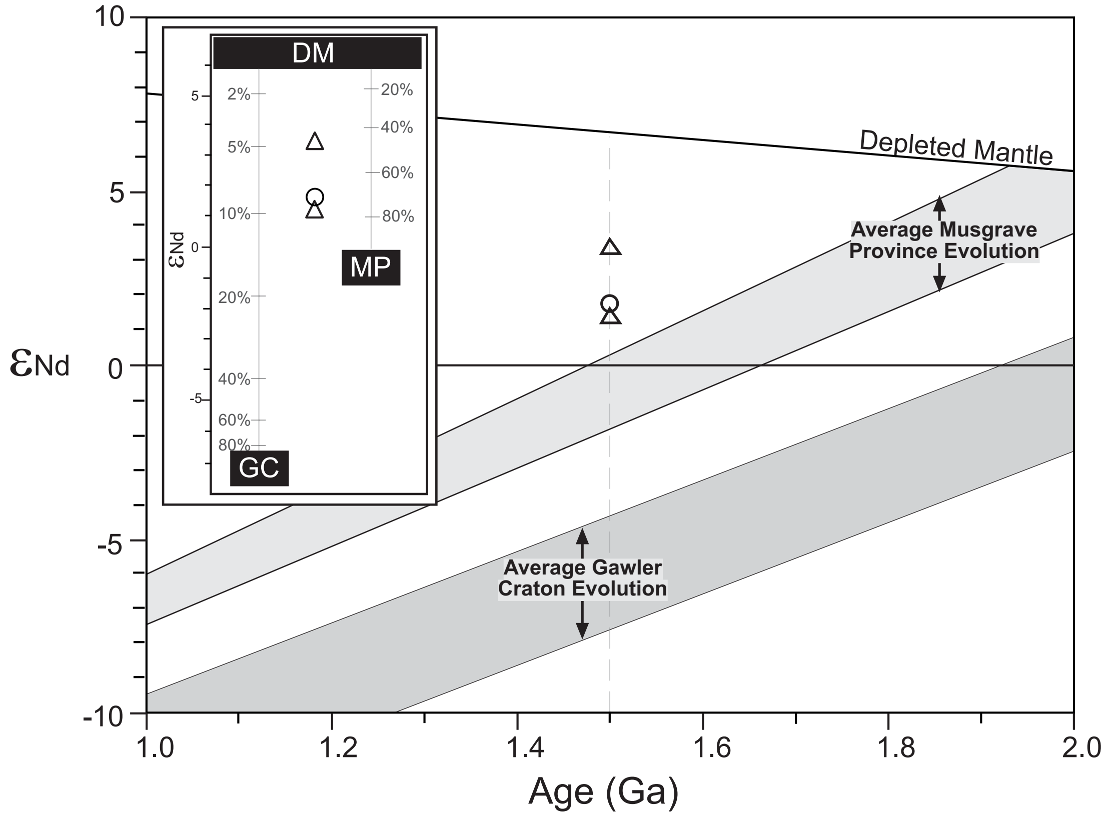


Figure 7.10 εNd evolution diagram displaying the juvenile nature of the granitic gneiss in Mallabie 1 when compared to the surrounding basement of the Musgrave Province and Gawler Craton, which comprise the nearest Proterozoic basement provinces. See text for references of isotopic evolution fields of the Musgrave Province and Gawler Craton. Inset: Mixing calculations displaying percentage of GC or MP contaminant required to be added to the Depleted Mantle to attain range of εNd values seen for Mallabie 1 granitic gneiss. Symbols as per Figure 7.6

can be observed in LILE and HFSE concentrations between both groups (Fig. 7.9b). The foliated samples display enrichment of Ba, Sr, and P, and depletion of Rb, Th, and U when compared to the intensely foliated samples (Appendix 5: Table 1, Fig. 7.9b). The HFSE Nb, Zr, and Ti are all enriched in the foliated samples compared to the intensely foliated samples.

7.5.3 Sm-Nd systematics

Table 3 displays the εNd values for three samples analysed, one intensely foliated and two foliated granitic gneisses. Values have been calculated at 1.50 Ga, which is the interpreted age of emplacement.

The single sample of intensely foliated granitic gneiss has a slightly higher isotopic Sm/Nd ratio of 0.1284 when compared to those of the foliated samples (0.1151 and 0.1153) (Appendix 5: Table 3). However, measured $^{143}Nd/^{144}Nd$ values show no grouping, ranging from 0.511894 to 0.512051 (Appendix 5: Table 3).

Nd isotopic data expressed as εNd is plotted against age in Figure 7.10. Average crustal evolution lines for proximal basement terrains, including the Musgrave Province to the north, and Gawler Craton to the east of the Coompana Block (Fig. 7.1), are also shown in Figure 7.10 (Gawler Craton: Stewart, 1992; Turner et al., 1993; Creaser, 1995; Schaefer, 1998; Musgrave Province: This study). Samples exhibit marked positive initial εNd values of +1.2 to +3.3 (Appendix 5: Table 3, Fig. 7.10). Although a limited number of samples were analysed, there appears no correlation of the two groups with εNd values (Appendix 5: Table 3, Fig. 7.10).

7.6 Petrogenetic Origin of the Mallabie 1 Granitic Gneiss

7.6.1 A-type affinity of the granitic gneiss

The classification of the Mallabie granitic gneiss as A-type is clearly distinguished on Nb vs 10000xGa/Al and Ga/Al vs Zr+Nb+Ce+Y plots of Whalen et al. (1987) (Fig. 7.11). The granodioritic composition of these samples are comparable to that from other A-type granitoids worldwide (e.g. Smith et al., 1999; Volkert et al., 2000; Mushkin et al., 2003).

Despite differences between the two groups, the overall high Ba content in all samples suggests the samples represent relatively unfractionated A-type melts (Appendix 5: Table 1, Fig. 7.9, King et al. 1997). Unfractionated A-types are distinguished from felsic I-type granites by a greater abundance of high-field-strength elements, such as Zr (Whalen et al., 1987; King et al., 1997; Mushkin et al., 2003). Strongly fractionated I-types do contain elevated HFSE, REE and Ga, but these melts usually have high silica values coupled with high Rb and low Sr and Ba values (King et al., 1997), which are not evident in the samples of this study. Thus it can be confidently concluded that these samples represent A-type melts.

Some fractionation of the primary melt is evident upon consideration of the increase in SiO_2 content from the foliated granitic gneiss to the intensely foliated granitic gneiss (Appendix 5: Table 1). The higher SiO_2 content of the intensely foliated samples may be indicating that they represent a more fractionated melt phase than that of the foliated samples. The samples show typical fractionation trends of decreasing Ba,Sr, Zr, Nb and LREE with increasing Rb (e.g. Whalen et al., 1987; King et al., 1997; Mushkin et al., 2003), moving from the less fractionated foliated samples to the increasingly fractionated intensely foliated samples. The chemical variations seen in the granitic gneiss of Mallabie 1 can be explained by partial melting of a source followed by fractional crystallisation. The coupled decrease of Al_2O_3, CaO, Sr and Ba with a shift of Eu/Eu* anomalies from strongly positive to flat, and inverse concentration relationship between Ba and Rb indicate the removal of feldspars (e.g. Bea, 1996; Roberts et al., 2000; Perini et al., 2004). Increasingly negative P and FeOt contents from the foliated to intensely foliated samples may represent fractionation and removal of apatite and Fe-Ti oxides respectively from the source (e.g. Droux and Delaloye, 1996; Whalen et al., 1999; Hussain et al., 2004; Perini et al., 2004).

7.6.2 Tectono-magmatic affinity

The general position of all samples lie within the within-plate granite field of the Rb vs Y+Nb and Nb vs Y Pearce plot (Pearce et al., 1984; Fig. 7.12)., which is not unexpected given the petrogenetic nature of A-type granitoids (e.g. Eby, 1992). When plotted on Nb-Y-3xGa and Nb-Y-Ce plots of Eby (1992) (Fig. 7.13), all samples lie within the A_2 field defined as an apparent crustal source that is not metasedimentary in origin. Despite this it is not unknown for A_2 granitoids to still have a mantle origin (Eby, 1992). A_2 granitoids can be emplaced within a variety of tectonic settings, including post-collisional and true anorogenic environments (Eby, 1992). This makes it difficult to make any definite conclusions on the tectonic origin of A_2 granitoids, however generally these magmas were generated from crust that has been through a cycle of subduction zone or continent-continent collision processes (Eby, 1992).

A-type granitoids often occur in bimodal association with intermediate to mafic rocks such as mafic dykes and gabbros (e.g. Turner et al., 1992; Mushkin et al., 2003), and in some cases their genesis is related fractionation of associated mafic magmas (e.g. Chazot and Bertrand, 1995; Volkert et al., 2000). Unfortunately, at this stage the lack of drillholes intersecting basement lithologies of the Coompana Block prevents a conclusive answer. However it remains likely that the precursor granitoids were emplaced within an extensional setting.

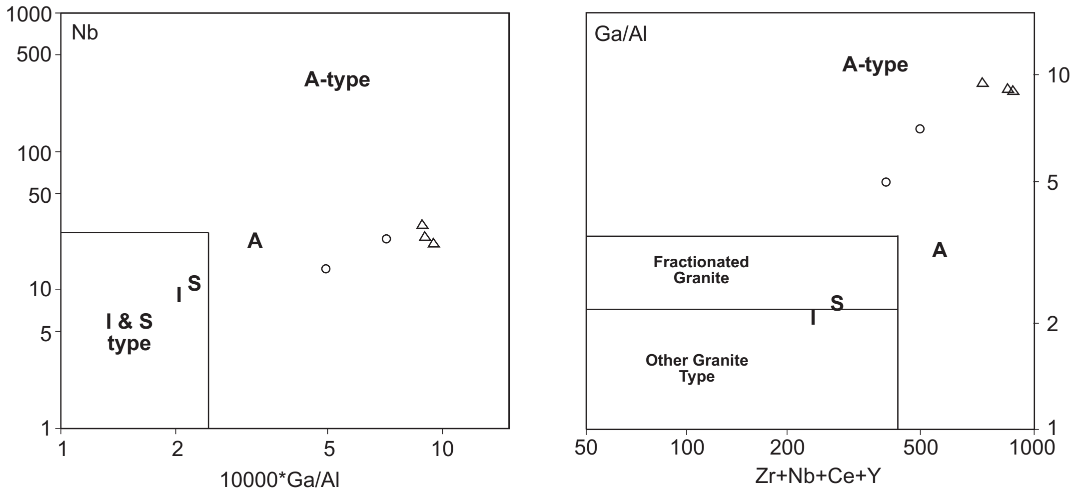


Figure 7.11 Nb vs 10000xGa/Al and Ga/Al vs Zr+Nb+Ce+Y plots of Whalen et al. (1987) displaying A-type characteristics of the granitic gneiss. Symbols as per Figure 7.6

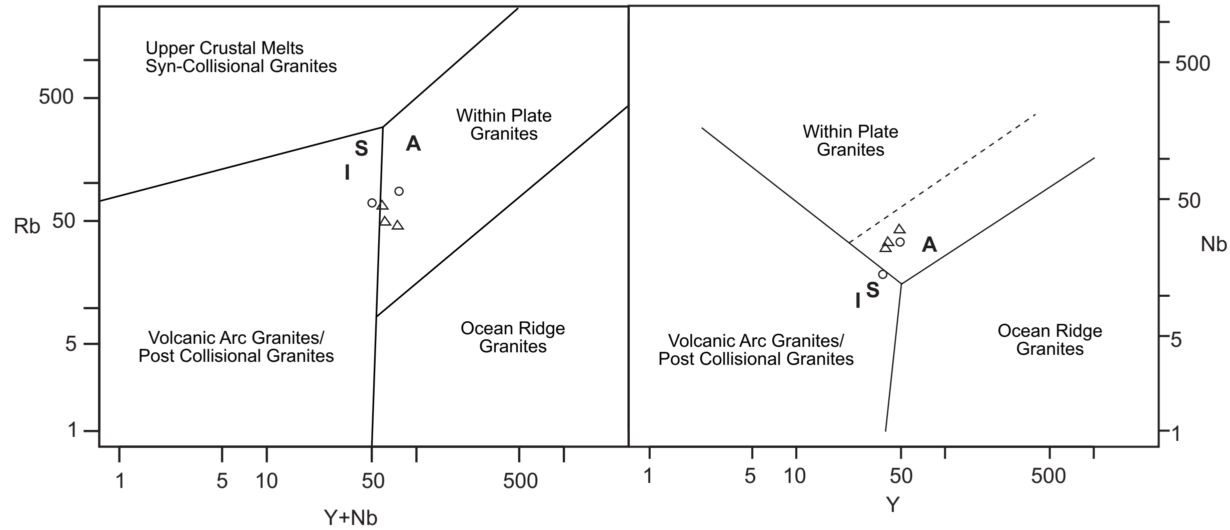


Figure 7.12 Tectonic discrimination diagrams of Pearce et al. (1984) displaying within-plate tectnonic character of the samples of granitic gneiss from Mallabie 1. Symbols as per Figure 7.6

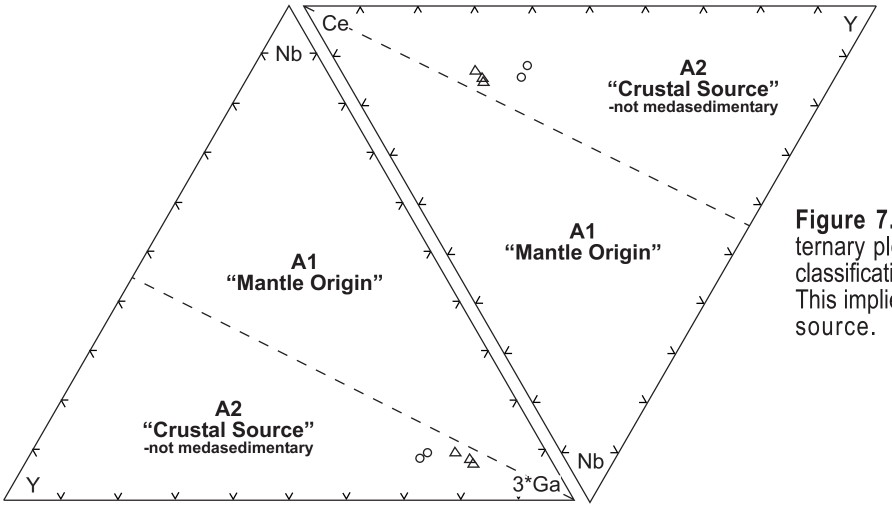


Figure 7.13 Nb-Y-3xGa and Nb-Y-Ce ternary plots of Eby, (1982) displaying A2 classification for samples of granitic gneiss. This implies a non-metsedimentary crustal source. Symbols as per Figure 7.6

7.6.3 Sm-Nd systematics

The εNd evolution of the three samples are markedly more juvenile than the evolution fields of crustal material that comprises the currently exposed adjoining lithosphere (Gawler Craton and Musgrave Province; Fig. 7.10). This suggests either limited older crustal contamination, or a more juvenile pre-existing lithosphere underneath the Coompana Block with respect to the enclosing regions. Sample 658672 has an εNd value of +3.3, suggesting some mantle component for at least part of the Mallabie 1 granitic gneiss.

Inset to Figure 7.10 shows the amount of mixing of both Gawler Craton and Musgrave Province material with depleted mantle that would be required to produce the range of εNd values calculated for the Mallabie 1 granitic rocks at 1.50 Ga. Nd concentration estimations for the Gawler Craton and Musgrave Province in the mixing calculations are 30 ppm (Gawler Craton: Stewart, 1992; Turner et al., 1993; Creaser, 1995; Schaefer, 1998; Musgrave Province: this study). The Nd concentration of potential mantle derived melts is not known. However, attempts at characterization of N-MORB sources have been carried out by various workers using a Nd concentration of 5 ppm suggested for a depleted mantle melt (e.g. Hofmann, 1988; Hart et al., 1999). Subsequently, a Nd concentration of 5 ppm is used in this study.

The mixing calculations argue for addition of only ~5-10% of Gawler Craton or 40-80% of Musgrave Province crustal material to a N-MORB like depleted mantle melt in order to attain the Nd isotopic signature of the Mallabie 1 granitic gneisses. The relatively mafic nature of the Mallabie 1 granitic gneisses would preclude the amount of mixing required using a Musgrave Province end-member, given the felsic nature of the Musgrave Province crust. Thus the Gawler Craton is seen as a preferable contaminant, if indeed the isotopic signature of the Mallabie 1 granitic gneisses are reflecting contamination of a mantle melt by crustal material.

Unfortunately no isotopic data on exists on the gabbroic rocks of the Coompana Block. This makes it impossible to consider the genetic relationship between the Mallabie 1 granitic gneisses and the mafic rocks that they may plausibly be derived from.

7.7 Implications for the source of detrital zircons whose age falls within the "Australian magmatic gap"

U-Pb detrital zircon provenance studies in Tasmania (Black et al., 2004), Antarctica (Goodge et al., 2002), and the eastern Musgrave Province (Chapter 4: this study), have identified zircons whose age that are difficult to reconcile with Australian sources. These ages range from ca. 1.50-1.35 Ga and fall in the "Australian magmatic gap", which represents a period of relative magmatic quiescence in the Australian Proterozoic, with only two recognised felsic magmatic events occuring around this age range over the whole North and South Australian Proterozoic (SAC: Spilsby Suite Granite, ca. 1.51 Ga. Fanning, 1997; NAC: Williams Supersuite, ca. 1.52-1.49 Ga; Page and Sun, 1996; Wyborn, 1998). Conversely, this period marks a time of voluminous magmatic activity in southern Laurentia such as the extensive A-type magmatic suites throughout the Yavapai and Mazatzal terranes (Anderson and Bender, 1989; Van Schmus et al., 1993). As a result, Laurentian sources for zircons of this age found within Australian sequences have generally been proposed (Goodge et al., 2002; Black et al., 2004; Chapter 4: this study), and used as a basis for broad palaeogeographic correlations. The age of the Mallabie 1 granitic gneiss (ca. 1.50 Ga) is similar to that of the Spilsby Suite Granite (ca. 1.51 Ga) in the eastern Gawler Craton, and the granites of the Williams Supersuite (ca. 1.52-1.50 Ga) in the eastern Mt. Isa Inlier. Ca. 1.50-1.49 Ga detrital zircons found in Tasmania Black et al., 2004), Antarctica (Goodge et al., 2002), and the eastern Musgrave Province (Chapter 4: this study), could therefore plausibly be sourced from these magmatic suites. However, there still remains the question of the source of detrital zircons with ages ranging from ca. 1.49-1.35 Ga found in sedimentary sequences of Antarctica, Tasmania, and the eastern Musgrave Province. At this stage sources exotic to Australia would still have to be proposed.

7.8 Summary and Conclusions

The granitic gneiss intersected in Mallabie 1 drillhole exhibit petrological and geochemical characteristics typical of A-type granites. The Mallabie 1 granitic gneiss is characterised by distinctive major and trace element compositions such as high contents of Zr, Nb, Y, Ga, LREE with low Mg#, Sr, CaO and HREE. U-Pb LA-ICPMS dating on separated magmatic zircons has provided an age of ca. 1.50 Ga, interpreted as the crystallisation age of the granite. The intersection of intensely foliated granitic gneiss further up-section of the Mallabie 1 drillhole appears to represent a slightly more fractionated melt than that of the foliated granitic gneiss intersected further down the hole. Nd isotopic analysis provide juvenile values ranging from +1.2 to +3.3 at 1.50 Ga. This could plausibly be explained by derivation from a mantle melt with minor contamination. The gabbros of the Coompana Block may be related to the genesis of the Mallabie 1 granitic gneiss, raising the possibility that they are of an equivalent age.

The identification of granitic A-type magmatism that falls within the "Australian magmatic gap" of Proterozoic Australia has implications for reconstruction models citing non-Australian sources for detrital zircons falling within the age bracket of ca. 1.52-1.35 Ga, possibly allowing for a more proximal source to be proposed. However, at this stage this is just one intersection of granitic gneiss in a single drillhole, the age of which fills just part of the magmatic gap. Despite this, the identification of granitic magmatism of this age under Neoproterozoic-Cambrian cover of the eastern Officer Basin raises the possibility that underlying the Officer Basin in S.A. and W.A. separating the Gawler Craton from the Yilgarn Block is an expansive belt of rocks of an age unusual to Proterozoic Australia, and that indeed "Australia's magmatic gap" may be hiding under cover.

Chapter 8

The Musgrave Province; terra incognito no longer?

8.1 Introduction

The aims of this thesis were to develop a tectonic framework for the evolution of the Musgrave Province, by applying a number of geochemical and geochronological techniques on various lithological units ranging in age from earliest Mesoproterozoic to Cambrian. It was envisaged that by increasing our knowledge of the tectonic processes involved in the formation of the Musgrave Province, we could better constrain reconstruction models of Proterozoic Australia. As such a five-module programme was undertaken that involved:

· establishing the tectonic environment involved in the formation of the oldest rocks of the Musgrave Province, the ca. 1.60-1.54 Ga felsic and mafic Musgravian Gneisses, through application of geochemistry and Sm-Nd isotopes;

· examining detrital input to metasedimentary rocks through U-Pb SHRIMP, U-Pb LA-ICMPS and Nd istopes, and what it can tell us about the Musgrave Provinces geographic position at the time of their formation;

· investigating the petrogenesis and crust-mantle relationships involved in the formation of layered mafic-ultramafic intrusions of the Giles Complex utilising geochemistry and Nd-Sr isotopes; and

· constraining the timing of the Petermann Orogeny through geochemical and Sm-Nd isotopic analysis of sedimentary rocks from the Officer Basin.

· examining the nature of the basement rocks that separate the gross tectonic elements of Proterozoic Australia, namely the NAC, SAC, and WAC. This was done by geochemical, Nd-isotopic, and U-Pb age analysis of granitic lithologies in the Coompana Block.

The observations and interpretations presented in the previous chapters suggests that both plate margin and within-plate processes played important roles in crustal formation and reworking within the Musgrave Province. One of the findings from this study highlights the importance of recognising rocks that have formed through plate margin processes, as their origin has important implications for all reconstruction models of Proterozoic Australia.

The findings of the four modules will be discussed in chronological order;

1) ca. 1.60-1.54 Ga Musgravian Gneiss;

2) ca. 1.40 Ga unnamed metasedimentary rocks;

3) ca. 1.08 Ga mafic-ultramafic rocks of the Giles Complex; and

4) ca. 0.56 Ga deformation associated with the Petermann Orogeny.

5) Petreogenesis of the Coompana Block

A generalised geological history of the Musgrave Province is presented in Table 8.1.

8.2 ca. 1.60-1.54 Ga Musgravian Gneiss

8.2.1 Historical views on crustal formation (or lack thereof?) during the Australian Proterozoic

Historically, crustal growth mechanisms of late Archaean to early Mesoproterozoic Australia have been dominated by the assumption that the Australian lithosphere was a single stabilised mass by the late Archaean (e.g. Rutland, 1973; Gee, 1979; Etheridge et al., 1987; Wyborn et al., 1988; Oliver et al., 1991). These models invoke processes such as vertical accretion involving underplating, and extensional tectonism driven by mantle plumes and delamination as the primary crust forming processes. This view of a contiguous late Archaean to Proterozoic Australia envisages all tectonic and magmatic activity to be intracratonic, independent of plate-boundary elements involving driving forces such as subduction zones, with little or no new crustal growth.

Recently, detailed geochemical and isotopic studies within Australian terrains such as the Arunta Region and Capricorn Orogen are recognising evidence of accreted fragments along convergent plate margins (e.g. Zhao, 1994; Zhao and McCulloch, 1995; Scrimgeour et al., 1999; Cawood and Tyler, 2004; Occhipinti et al., 2004). These datasets have been used by a number of workers to propose that the evolution of Proterozoic Australia involved important accretionary and collisional events (e.g. Myers et al., 1996; Scott et al., 2000; Betts et al., 2002; Giles et al., 2002; Giles et al., 2004; Tyler, 2005).

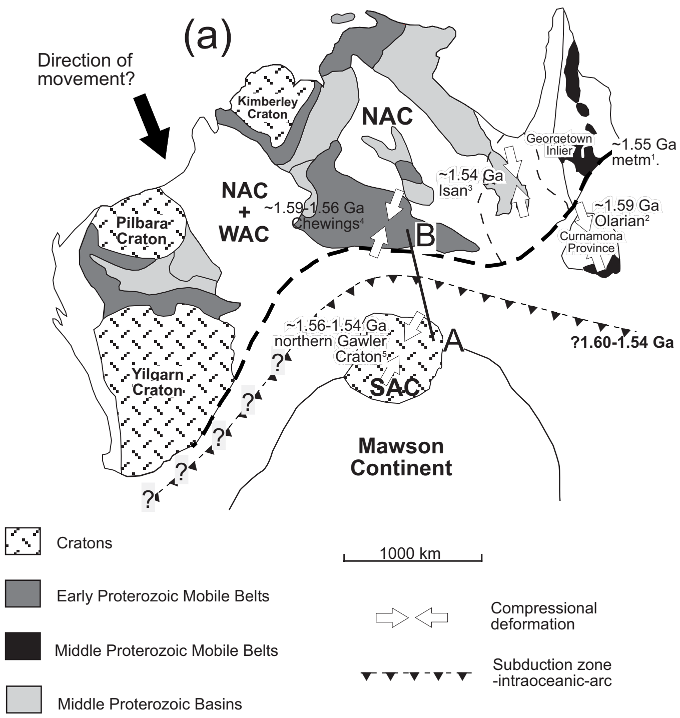
Table 8.1 - Summary of lithologies and events of the Musgrave Block

Age (Ga)	Domain	Lithology/Event	Metamorphic conditions
ca. 1.60-1.54[1,2,3,4]	Fregon and Mulga Park	Musgravian Gneiss - Olia gneiss and Birksgate Complex - dominantly felsic gneisses of granitic and volcanic origin - subduction related chemistry?[5] - minor mafic and pelitic gneisses, calcsilicates, and quartzite	
ca. 1.56[3]	Mulga Park	Pre D_1?[3] - metamorphic overgrowths in orthogneiss	Migmatisation associated with upper amhibolite facies metamorphism?[3]
Max. Dep. age ca. 1.40[6]	Fregon	Unnamed aluminous metapelites - localised in eastern Musgraves? qtz-feld-cd-sill-gt assemblages[7]	
ca. 1.324-1.296[8,9]	Fregon	Unnamed felsic orthogneiss - localised in western Musgraves?	
ca. 1.324-1.312[9]	Fregon	D_1[10] - localised in western Musgraves? -reclined isoclinal folds, layer parallel foliation - metamorphic overgrowths in orthogneiss	M_1 Granulite facies metamorphism accompanied by migmatisation[9,10]
ca. 1.23-1.15[1,2,3,4,8,9,11]	Fregon and Mulga Park	D_2[10] (Musgrave Orogeny) - isoclinal recumbent folding, mostly penetrative pure shear - ubiquitous metamorphic grains and overgrowths	M_2 Granulite facies metamorphism (P=~6 kbars T=~850°C)[10,12]
ca. 1.2-1.14[1,2,4,8,13]	Fregon and Mulga Park	Pitjantjatjara Supersuite - voluminous emplacement of granitoids - intracrustal melting of basement rocks	
ca. 1.08-1.04[4,13,14,21]	Fregon and Mulga Park	Giles Event[13,14] - emplacement of numerous mafic-ultramafic layered bodies - emplacement of minor granitic melts primarily as dykes - extrusion of the bimodal volcanics of the Tollu Group -extrusion of the Tjauwata rift succession	Near isobaric cooling from 1150° to 750°C at ~6kbars

Table 8.1 - contd.

ca. 1.08[15]	Fregon and Mulga Park	Alcurra Dolerite[15] - emplacement of tholeiitic dolerites - remnants feeders to the Giles Complex?	
ca. 1.08-1.06[10,13,14]	Fregon	D_3[10] (Giles Event) - localised to western Musgraves? - penetrative simple shear - near vertical high-strain zones	M_3 Early D_3 P=~8-11 kbars T=~650-700°C[10,13,14,20] - lithostatic loading due to emplacement of Giles Complex Late D_3 P=~4-5 kbars[13,14] - near-isothermal decompression assoc. with uplift and erosion
ca. 1.0[16]	Fregon and Mulga Park	Unnamed Olivine Dykes - poorly constrained Sm-Nd age - intrude ca. 1.07 Ga granite - geochemically similar to Alcurra Dyke Swarm	
ca. 0.82[16,17]	Fregon and Mulga Park	Amata Dolerite - plume derived	
?0.8-?0.56[10]	Fregon	D_{4-5}[10] - mylonite development localised in western Musgraves?	Greenschist-amphibolite facies[10]
ca. 0.56[1,3,10,13,18,19]	Fregon and Mulga Park	D_{6-7}[10,19] (Petermann Orogeny) - pervasive non-coaxial strain reworked the north-western Musgrave Province, evident in deep crustal mylonitic fabrics - effects in southern/eastern Musgrave Province restricted to mylonite and psuedotachylite development adjacent to the Woodroffe Thrust	M_4 Deep crustal mylonites: P=~11-13 kbars T=~700-750°C[10,19]

[1]Camacho and Fanning, 1995; [2]Maboko et al., 1991; [3]Camacho, 1997; [4]Edgoose et al., 2004; [5]Wade et al., 2006; [6]Wade et al., 2005a,b; [7]Conor, 1987; [8]Sun and Sheraton 1992; [9]White et al., 1999; [10]Clarke et al., 1995; [11]Kelly et al., 2005; [12]White et al., 2002; [13]Glikson et al., 1996; [14]Sun et al., 1996; [15]Zhao and McCulloch, 1993; [16]Shensu Sun unpublished (in Glikson et al., 1996); [17]Zhao et al., 1994; [18]Maboko et al., 1992; [19]Scrimgeour and close 1999; [20]Clarke and Powell, 1991; [21]Close et al., 2003



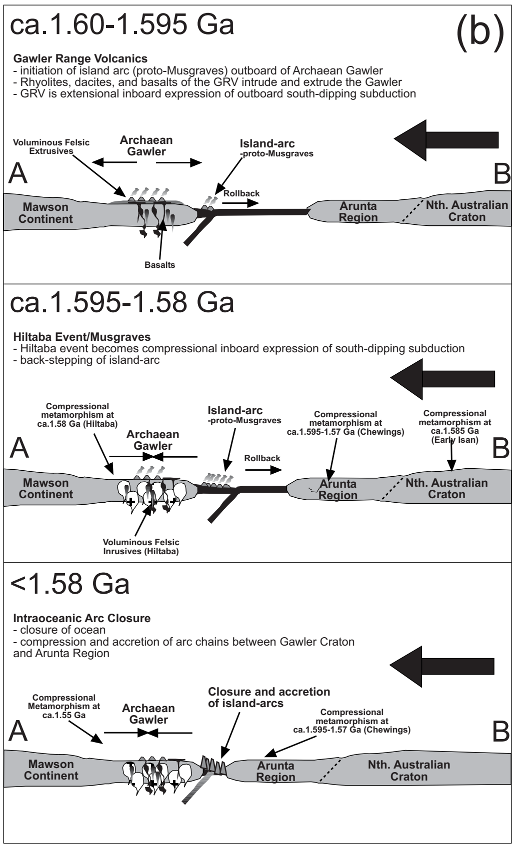


Figure 8.1 (a) Reconstrucion of Australia involving an active margin between the NAC and SAC (b) Cross-section along A-B displaying possible evolution of the margin

8.2.2 Do the oldest rocks of the Musgrave Province record the amalgamation of Proterozoic Australia?

The Musgrave Block is considered here to represent a critical link in understanding the process and timing of the suturing of the North Australian Craton (NAC) with the South Australian Craton (SAC) (Figure 8.1a) as part of the larger Mawson Continent (e.g. Fanning et al., 1996), as it lies on the interface between the two aforementioned crustal elements

Existing models of the amalgamation of Proterozoic Australia have suggested that the Albany-Fraser Orogeny, coincident with the Musgrave Orogeny, reflects the collision of the North Australian Craton (NAC) with the South Australian Craton (SAC) (Figure 8.1a) during the assembly of Rodinia at ~1.30-1.10 Ga (e.g. Pidgeon, 1990; Black et al., 1992; Myers, 1993; Myers et al., 1996; Clark et al., 1999; White et al., 1999; Clark et al., 2000). Alternatively, Sener et al. (2005) have proposed suturing of the NAC with the SAC much earlier at ca. 1.73 Ga, with similar suturing of the continents between 1.8-1.5 Ga proposed by Giles et al. (2004).

Contrary to these reconstructions, the results from this study suggest that the docking of the NAC with the SAC occurred sometime during the interval of 1.60-1.54 Ga. The isotopic and geochemical results of this study suggest that the protolith to the ca. 1.60-1.54 Ga Musgravian Gneiss was formed in an arc setting, developed in a south-dipping plate margin setting between the NAC and SAC (Figure 8.1a). Ongoing activity along the margin and resultant collision of these two crustal framgents may explain approximately coeval deformation and magmatism within the SAC, and broadly N-S compressional deformation within large parts of the NAC (Figure 8.1b).

If this conclusion is correct, models involving plate reconstrucions of Australia will now have to incorporate the formation of the Musgrave Province, where previously it has been markedly absent.

8.3 ca. 1.40 Ga unnamed metasedimentary rocks

8.3.1 Where does Australia fit within the supercontinent Rodinia?

All late Mesoproterozoic reconstructions of Rodinia involve an unidentified continent residing outboard of the western margin of Laurentia (e.g. Dalziel, 1991; Moores, 1991; Karlstrom et al., 2001; Sears and Price, 2000; Wingate et al. 2002; Li et al., 2002). Current models have involved both South China (e.g. Li et al., 2002) and Siberia (Sears and Price, 2000) as the rifted companion continent. Despite this, for approximately 15 years Australia has featured prominently in models that invoke a collision-rift setting with the western margin of Laurentia (e.g. Dalziel, 1991; Moores, 1991; Karlstrom et al., 2001; Wingate et al. 2002).

The initial reconstruction involving a Laurentia-Australia connection is referred to as the south-west U.S-East Antarctica (SWEAT) model, and was first proposed on the basis of apparent tectonic similarities between parts of Australia, southern Laurentia and Antarctica (e.g. Dalziel, 1991; Moores, 1991). Subsequent to this, an increase in palaeomagnetic evidence and the recognition of inferred continental "piercing points" led to a revision of this continental arrangement and was developed into the "AUSWUS" arrangement. This places eastern Australia adjacent to western US (e.g. Karlstrom et al., 2001). AUSWUS places importance on correlation of orogenic belts across the rifted Laurentia-Australia margin, and on late Mesoproterozoic and early Neoproterozoic palaeopoles, the reliability of which has recently been questioned (Wingate et al. 2002). Recent acquisition of precise latest Mesoproterozoic palaeopoles have led others to the conclusion that Australia was separate from Laurentia at 1.2 Ga (Pisarevsky et al., 2003), and that the two probably only came together at ca. 1.07 Ga in what has been called the AUSMEX configuration (Wingate et al. 2002). Despite this, owing to the sparseness of reliable Mesoproterozoic palaeopoles, the relative configuration and proximity of both Australia and Laurentia before 1.2 Ga is not well known.

8.3.2 Does the Musgrave Province contain a vital piercing point in Rodinian reconstructions?

Two key lines of evidence have been used in the past to support a connection between Australia and Laurentia. The first is the presence of ca. 1.60-1.54 Ga detrital zircons located in lower parts of the ca. 1.47-1.4 Ga Belt Basin in western Laurentia (Ross et al., 1992; Ross and Villeneuve, 2003). Source rocks for zircons of this age are extremely rare within Laurentia, and lie within what is termed the ca. 1.60-1.50 Ga "North American Magmatic Gap" (Van Schmus et al., 1993). Conversely, source rocks of this age within Australia are widespread, which led the authors to suggest some derivation of the lower Belt Basin rocks from sources such as the Gawler Craton (e.g. Ross and

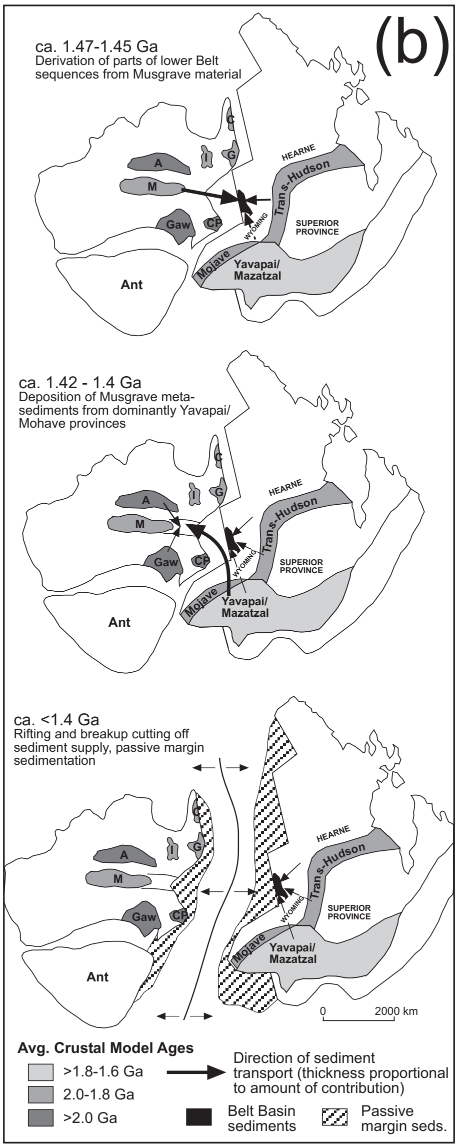
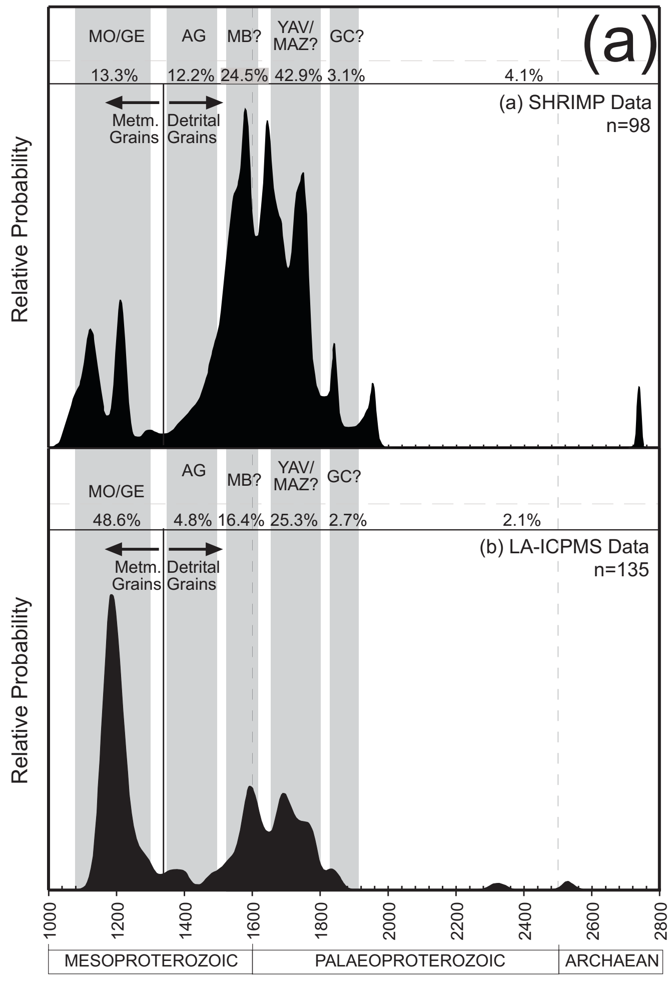


Figure 8.2 (a) Probability density plots for samples of metasedimentary rock analysed by SHRIMP and LA-ICPMS (b) Postulated Mesoproterozoic reconstructions of Australia and Laurentia



Villeneuve, 2003). The second piece of data that may allude to an Australia-Laurentia connection is the presence of ca. 1.49-1.40 Ga detrital zircons in rocks located in both Tasmania and Antarctica (Goodge et al., 2002; Black et al., 2004). Similar to the magmatic gap of North America, this time span marks a period of quiescence in magmatism within Australia, and could be termed the "Australian Magmatic Gap". This led the authors to conclude derivation of the ca. 1.49-1.40 Ga zircons from Laurentian sources such as the voluminous A-type granite suites located in southern Laurentia (e.g. Anderson, 1989; Van Schmus et al., 1993).

Results presented in this study of U-Pb detrital zircon and Sm-Nd isotopic analyses of metasedimentary rocks located in the eastern Musgrave Province suggest a piercing point between the eastern margin of central Australia and the Laurentian Belt-Purcell Group during the late Mesoproterozoic. Detrital zircon ages range from Palaeoproterozoic to late Mesoproterozoic (Figure 8.2a), constraining the maximum depositional age of the metasediments to approximately 1.42-1.36 Ga, similar to that of the Belt Supergroup. The 1.49-1.36 Ga detrital zircons in the Musgrave metasediments are interpreted to have been derived from the voluminous A-type suites of Laurentia.

Most metasedimentary rocks exhibit ε_{Nd}(1.40 Ga) values ranging from –5.1 to +0.9, inconsistent with derivationsoley from Australian sources, which are more isotopically evolved. The detrital zircon ages and Sm-Nd isotopic characteristics are consistent with derivation from a mixture of both Australian and Laurentian sources (Figure 8.2b). This interpretation supports palaeogeographic reconstructions between Australia and Laurentia during the Mesoproterozoic.

Basement to the Musgravian metasedimentary rocks includes ca. 1.60-1.54 Ga felsic granulites. Their age and isotopically juvenile characteristics make them excellent candidates for the source of the lower Belt Supergroup with its abundant ca. 1.6-1.54 Ga detrital zircons, also supporting Australia-Laurentia reconstruction models.

8.4 ca. 1.08 Ga Giles Complex

8.4.1 Layered intrusions and crust-mantle interaction

Geochemical and isotopic studies in layered mafic-ultramafic intrusions can provide important information on the nature of an ascending mafic magma and its interaction with the surrounding crustal rocks (e.g. Amelin et al., 2000; Amelin et al., 1996; Amelin and Semenov, 1996; Maier et al., 2000). Early models on interaction between mafic magmas and crustal rocks were tested using data from layered intrusions, with most initial models involved simple bulk assimilation of crustal rocks into a mafic magma (e.g. Gray et al., 1981; Zindler et al., 1981). Following this, a number of more complex models were applied involving combined assimilation and fractional crystallisation (AFC) (Depaolo, 1981) to layered intrusions such as the Kiglapait and Skaergard bodies (Depaolo, 1985; Stewart and Depaolo, 1990), and the refilling, tapping, fractionation, assimilation (RFTA) models to mafic complexes in Italy and France (O'Hara, 1977; Poitrasson et al., 1994; Voshage et al., 1990). However, magmas may also obtain their enriched isotopic and trace element signature through mantle enrichment in subduction regimes, either through subduction of slab sediment, mantle metasomatism, or some combination of both (e.g. Amelin et al., 1996; Halama et al., 2003; Lambert et al., 1994; Mazzucchelli et al., 1995). In some cases, both crustal assimilation and prior mantle enrichment may have contributed to the enriched isotopic signature (Amelin et al., 1996; Amelin and Semenov, 1996). The multiplicity of possible processes in operation during magma generation, ascent, and crystallisation makes every layered intrusion unique, which probably accounts for the numerous petrogenetic models proposed.

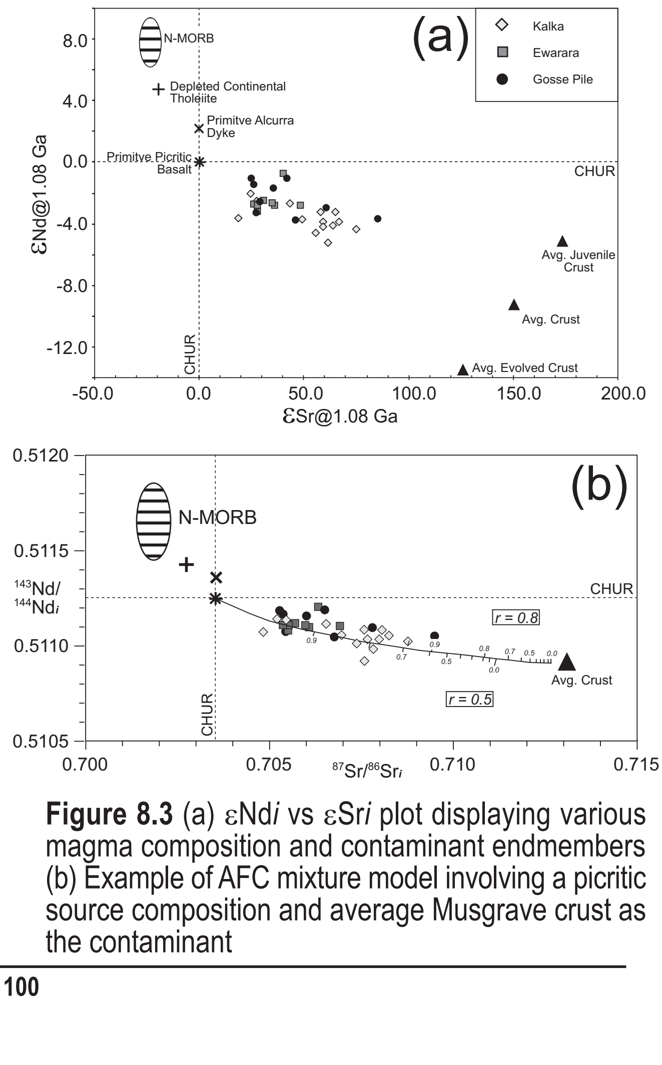


Figure 8.3 (a) εNd*i* vs εSr*i* plot displaying various magma composition and contaminant endmembers (b) Example of AFC mixture model involving a picritic source composition and average Musgrave crust as the contaminant

8.4.2 The Giles Complex; crustal contamination or modified lithospheric mantle?

The Giles Complex represents part of the erosional remnants of the Warakurna LIP, proposed to have covered much of central and western Australia between ca.1.078 and 1.07 Ga (Wingate et al., 2004). The geochemical and isotopic signature recorded in the coeval ca. 1.08 Ga high-Mg low-Ti tholeiites of the Alcurra Dyke Swarm of the Musgrave Province have been interpreted as recording modification of the sub-continental lithospheric mantle by subduction processes during the Proterozoic (Zhao and McCulloch, 1993). In addition to this, petrographic and geochemical studies on Giles Complex intrusions located in Western Australia have concluded that they were derived from an enriched source, probably involving the subcontinental lithospheric mantle (Glikson et al., 1995; Glikson et al., 1996).

In opposition to this are the findings from this study which imply that the isotopic and geochemical signature of the Giles Complex can be explained through crustal contamination of a primitive picritic mantle source. Careful isotopic (Sm-Nd and Rb-Sr) and geochemical modelling was carried out using a variety of possible source magma compositions and contaminants (Figure 8.3a). The enriched isotopic signature of the Giles Complex intrusions is best explained by addition of ~10% average Musgrave crust to a magma of picritic composition (Figure 8.3b). Shallow decompressional melting of an asthenospheric plume source beneath thinned Musgravian lithosphere is envisaged as a source for the parental picritic magma. The contamination of the magma is inferred to have occurred during ascent through the feeder conduits, during which time the magma reached suplhur saturation. This has important implications for exploration of magmatic Ni-Cu-Co sulphides within the Giles Complex, implying that exploration should be concentrated on locating these feeder dyke systems. This exploration method has been successful in both W.A. (Nebo-Babel prospect, WMC) and S.A. (Harcus prospect, PepinNini).

8.5 ca. 0.56 Ga Petermann Orogeny

8.5.1 Petermann Orogeny; look in the basin not the mountain belt?

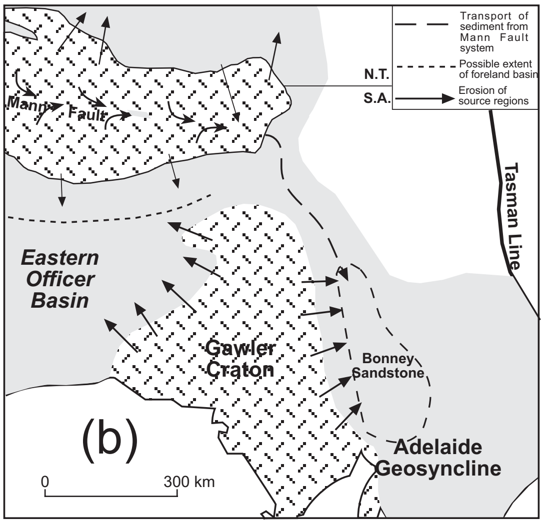
The Neoproterozoic to mid-Palaeozoic intracratonic Officer Basin in central Australia is one of a number of basins that together formerly comprised the Centralian Superbasin (Walter *et al*., 1995), which was subsequently dissected into a southern fragment (Officer Basin) through uplift of the Musgrave Province during the Petermann Orogeny (Hoskins and Lemon, 1995; Moussavi-Harami and Gravestock, 1995; Walter *et al*., 1995; Lindsay and Leven, 1996). The exhumation of the Musgrave Province marks the initiation of the Petermann Orogeny and forms the northern margin of the Officer Basin. On its southern margin, the Officer Basin is bordered by the Archaean-Palaeoproterozoic Gawler Craton.

The timing and duration of this uplift has been the subject of some debate, with two general models proposed. The first suggests that the Petermann Orogeny began at around 0.65 Ga and continued to approximately 0.53 Ga (Shaw, 1991; Calver and Lindsay, 1998). The second model suggests that the Petermann Orogeny was a relatively short-lived event, spanning ~ 0. 58-0.54 Ga (e.g. Hoskins and Lemon, 1995; Lindsay and Leven, 1996; Camacho and McDougall, 2000).

Thermochronological data on the Petermann Orogeny from within the Musgrave Province is restricted to Sm-Nd dating of garnets (Scrimgeour and Close, 1999; Camacho and McDougall, 2000), and K-Ar dating of micas (Maboko et al., 1992; Camacho and McDougall, 2000). However these dates are restricted by the closure temperature of the minerals being analysed. Geochemical and Nd isotope analyses of sedimentary rocks within the Officer Basin should determine the time at which the erosion of the Musgrave Block began to dominate the basin input, signifying initial unroofing of the Musgrave Block during the Petermann Orogeny

8.5.2 When was the initiation of the Petermann Orogeny?

Sm-Nd isotopic and geochemical data from Neoproterozoic to Cambrian sedimentary rocks in the intracratonic eastern Officer Basin in central Australia highlight the evolving provenance roles of the basement complexes that underlie and bound the basin (Figure 8.1a). Initial ε_{Nd} values of around –12.0 for the basal units indicate both were largely derived from the late Archaean to Mesoproterozoic Gawler Craton, which bounds the basin to the south (Figure 8.1a). At approximately 0.72 Ga an influx of juvenile, glacially derived sediment indicates partial uplift of the Mesoproterozoic Musgrave Block along the basin's northern margin, in a regime interpreted to be broadly extensional (Figure 8.1a). At around 0.60 Ga, synchronous with the development of a foreland architecture, was a large influx of Musgrave Block-derived sediments (Figure 8.1a). This is interpreted to mark the onset of the intracratonic Petermann Orogeny, which was a long-lived event or series of events, spanning more than 70 million years. Subsequent to ~0.60 Ga, the Nd isotopic composition of sequences within



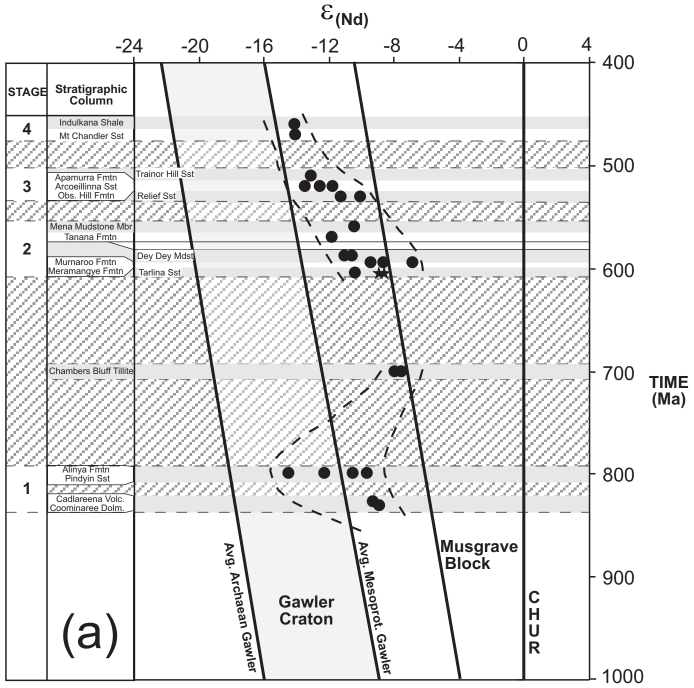


Figure 8.4 (a) εNd vs time plot of the Officer Basin units highlighting the evolving roles of the bounding basement complexes (b) Possible sediment transport directions during the Petermann Orogeny.

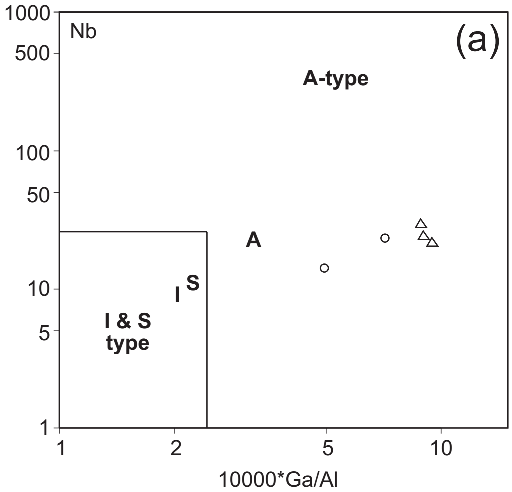
the Officer Basin indicates an increasing contribution from the Gawler Craton despite up to 45 km of denudation of part of the Musgrave Block at ca. 0.56 Ga (Figure 8.1a). This suggests that the majority of sediment derived from the Petermann Orogen bypassed the eastern Officer Basin for much of the history of the Petermann Orogeny. This may reflect the existence of a long-lived tectonic barrier such as the presence of an axial river system within the foreland basin, a filled foreland basin, and/or the development of an efficient means of transporting sediment along the axis of the orogenic belt (Figure 8.2a).

8.6 Filling the "Australian magmatic gap"; the Coompana Block

8.6.1 Why is the Coompana Block so important?

The magmatic history of Proterozoic Australia is punctuated by intervals of relative quiescence in magmatic activity, the two main periods being ca. 2.0-1.9 Ga and ca. 1.50-1.35 Ga. These periods may represent a time of reduced activity in mantle dynamics, a preservation problem, or a sampling problem. Much like the ca. 1.60-1.54 Ga "North American magmatic gap" of Laurentia (Van Schmus et al., 1993), the only two felsic magmatic events of any note occur around ca. 1.50-1.35 Ga. These include the ca. 1.51 Ga Spilsby Suite Granite of the Gawler Craton, the outcrop of which is restricted to Spilsby Island (Fanning, 1997), and the 1.52-1.50 Ga Williams Supersuite of the eastern Mt Isa Inlier (Page and Sun, 1996; Wyborn, 1998) (Fig. 7.1). Prior to this from ca. 1.60-1.54 Ga we have voluminous magmatism throughout much of the North Australian and South Australian Cratons (NAC and SAC) associated with the Hiltaba Suite and Gawler Range Volcanics in the Gawler Craton (Fanning et al., 1988), the voluminous S-type granites in the Curnamona Province (Page et al., 2003), and the meta-igneous rocks of the Mt Isa and Yambo inliers of north Queensland (Blewett et al., 1998) (Fig. 7.1). Post 1.35 Ga is the emplacement of voluminous granitoids in both the Musgrave Province (ca.1.30 Ga orthogneiss (White et al., 1999); and ca. 1.20-1.14 Ga granites of the voluminous Pitjantjatjara Supersuite (e.g. Camacho and Fanning, 1995; Edgoose et al., 2004)), and Albany-Fraser Complex (ca. 1.33-1.14 Ga granites of the Nornalup Complex (e.g. Myers, 1995; Nelson et al., 1995).

This apparent paucity of magmatism during the interval of ca. 1.50-1.35 Ga has provided problems for many provenance studies that have identified detrital zircons falling within this time period (e.g. Goodge et al., 2002; Black et al., 2004; Chapter 4: this study). In all cases the authors have cited sources exotic to Australia, such as the voluminous A-type granitoids suites of southern Laurentia (Anderson and Bender, 1989; Van Schmus et al., 1993). Following this, the presence of ca. 1.50-1.35 Ga detrital zircons has led to palaeogeographic reconstructions involving Australia and Laurentia (e.g. Goodge et al., 2002; Chapter 4: this study).
The gross tectonic elements of Proterozoic Australia, namely the North, South, and West Australian cratons, are separated by deep and aerially extensive sedimentary basins, of which the underlying basement geology is either poorly or totally unknown. It is beneath these sedimentary basins in which the potential lies to discover magmatic belts of ages that would fill the ca. 1.50-



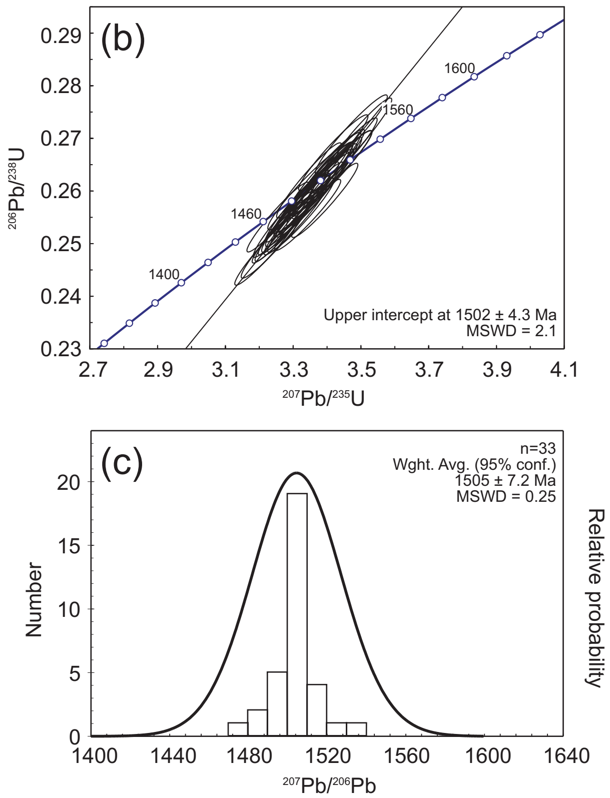


Figure 8.5 (a) Nb vs 10000xGa/Al and Ga/Al vs Zr+Nb+Ce+Y plots of Whalen et al. (1987) displaying A-type characteristics of the granitic gneiss (b) Conventional U-Pb concordia diagram displaying upper intercept age of ca. 1.50 Ga (c) $^{207}Pb/^{206}Pb$ age histogram and probability density curve displaying weighted average of ca. 1.50 Ga.

1.35 Ga time gap in the geological record. The Coompana Block separates the WAC from the SAC, and represents one such area in which the underlying basement is shallow enough to be sampled by drillcore. Its geographical position is key in deciphering what may underlie the Officer Basin in South and Western Australia.

8.6.2 What impact does the genesis of the ca. 1.50 Ga granitic gneiss have on reconstruction models?

The granitic gneiss intersected in Mallabie 1 drillhole exhibit petrological and geochemical characteristics typical of A-type granites (Fig. 8.5a). The Mallabie 1 granitic gneiss is characterised by distinctive major and trace element compositions such as high contents of Zr, Nb, Y, Ga, LREE with low Mg#, Sr, CaO and HREE. U-Pb LA-ICPMS dating on separated magmatic zircons has provided an age of 1505±7.2 Ma (Fig. 8.5b,c), interpreted as the crystallisation age of the granite. Nd isotopes provide juvenile values ranging from +1.2 to +3.3 at 1.50 Ga. This could plausibly be explained by derivation from a mantle melt with minor contamination.

The identification of granitic A-type magmatism that falls within the "Australian magmatic gap" of Proterozoic Australia has implications for reconstruction models citing non-Australian sources for detrital zircons falling within the age bracket of ca. 1.50-1.35 Ga, possibly allowing for a more proximal source to be proposed. However, at this stage this is just one intersection of granitic gneiss in a single drillhole, the age of which fills just part of the magmatic gap. Despite this, the identification of granitic magmatism of this age under Neoproterozoic-Cambrian cover raises the possibility that underlying the Officer Basin in S.A. and W.A. separating the Gawler Craton from the Yilgarn Block is an expansive belt of rocks of an age unusual to Proterozoic Australia, and that indeed "Australia's magmatic gap" may be hiding under cover.

8.7 Conclusions

This study has clearly shown that the Musgrave Province has undergone a complex tectonic evolution spanning a period of approximately 1.0 Ga. Understanding the early history of the Musgrave Province is key to reconstructions of Proterozoic Australia. The key findings of this study are:

(1) The oldest rocks of the Musgrave Province record a pre-history of plate margin activity. The protolith of these ca. 1.60-1.54 Ga mafic and felsic orthogneisses is interpreted to have been arc magmas generated in an island arc setting between the NAC and SAC. The subsequent closure of this arc and collision of the NAC with the SAC is viewed to be expressed as widespread

compressional deformation throughout much of the NAC and SAC.

(2) Metasedimentary rocks of the eastern Musgrave Province record evidence of a pre-Rodinia connection between Australia and Laurentia. Detrital zircon ages and Nd isotopes are irreconcilable with derivation from soley Australian sources. Basement ca. 1.60-1.54 Ga felsic orthogneisses of the Musgrave Province also provide a better isotopic and age match for the dominant detrital zircon peak of ca. 1.60-1.54 Ga found in the basal sequences of the Belt-Purcell Basin in North America/Southern Canada. Combined, this evidence strongly suggests a link between Australia and Laurentia pre-1.40 Ga.

(3) The mafic-ultramafic rocks of the ca. 1.08 Ga Giles Complex record a period of large scale melting of the asthenospheric mantle associated with the genesis of the Warakurna LIP. Isotopic and geochemical modelling suggests crustal contamination of a picritic magma source is the most likely process responsible for the geochemical signatures recorded in the cumulate rocks of the Giles Complex. This makes the Giles Complex extremely prospective for Ni-Cu-Co sulphide deposits.

(4) Sedimentary rocks of the Officer Basin record the ongoing evolution and denudation of the Musgrave Province during the ca. 0.60-0.55 Ga Petermann Orogeny. The isotopic record preserved in units of the Officer Basin indicates initial unroofing of the Musgrave Province and thus initiation of the Petermann Orogeny at ca. 0.60 Ga, which continued to ca. 0.55 Ga.

(5) A-type granitic magmatism recorded in the Coompana Block occured at a time of unusual quiescence in the magmatic history of Proterozoic Australia. Its discovery raises the possibility of the presence of large belts of ca. 1.50-1.35 Ga granitoids underneath the cover of the Officer Basin, in what otherwise is a magmatic gap in the history of Proterozoic Australia.

An underlying theme throughout this thesis has been the need for detailed isotopic and geochemical studies within the vastly understudied Musgrave Province. The Musgrave Province is central to the Australian continent, and central to understanding the final amalgamation of the various elements of Proterozoic Australia.