# Metamorphic and isotopic characterisation of Proterozoic belts at the margins of the North and West Australian Cratons

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# Abstract

The tectonic evolution of the cratonic elements of Proterozoic Australia has been debated for over 20 years. There is a growing view that plate margin processes were involved in the tectonic evolution and growth of the pre-Cryogenian elements of Australia, however the timing, nature and configuration of cratonic amalgamation remains contentious. This study investigates the metamorphic, geochronological and isotopic evolution of key or debated areas of Proterozoic Australia, focusing on the proposed southern margin of the Archean to Paleoproterozoic North Australian Craton (NAC) in the Arunta Region, and eastern margin of the Archean to Paleoproterozoic West Australian Craton (WAC) in the Rudall Province. The overall aim of this study is to provide new constraints on Proterozoic tectonism in the Arunta Region and Rudall Province in order to better understand the timing and nature of Proterozoic Australia assembly.

In the southern Aileron Province (Arunta Region), the Mount Hay area and Adla Domain occur close to the proposed Paleoproterozoic southern margin of the NAC. Pressure–temperature (*P–T*) constraints indicate the attainment of peak metamorphic conditions of ~8–10 kbar, ~850−900 °C for Mount Hay and the adjacent Capricorn Ridge, and ~7–10 kbar, ~850−900 °C for the Adla Domain fabrics. The granulite facies metamorphism postdates a period of extensive basin development in the Arunta Region between c. 1805−1780 Ma. This basin development was associated with magmatism and localised high temperature–low pressure (HTLP) metamorphism. Hf isotopic data on late Paleoproterozoic granitoids (c. 1650–1625 Ma) from the Aileron Province have isotopic compositions close to CHUR ($\varepsilon$Hf -6.2 to +1.5) and crustal model ages between 2200–2700 Ma. The granitoids are broadly contemporaneous with the c. 1640–1635 Ma Liebig Orogeny in the Warumpi Province, which involved coeval mafic magmatism, suggesting at least some component of extension. The Paleoproterozoic tectonic evolution of the Arunta Region (southern NAC) is considered to have involved a long-lived (>150 Ma) margin with an overall extensional character punctuated by comparatively localised and short lived periods of thickening.

In the central Aileron Province, the tectonothermal evolution of the Anmatjira Range Province has been debated considerably over the last 20 years. The timing and metamorphic evolution of the Anmatjira Range was investigated using monazite U–Pb geochronology and *P–T* pseudosections calculated for high temperature granulite facies metapelites in the south-eastern Anmatjira Range. Estimated peak conditions of ~870–920 °C and ~6.5–7.2 kbar were attained at c. 1580–1555 Ma, followed by a clockwise retrograde evolution. In the absence of concurrent magmatism, and lack of evidence of decompression from high-*P* conditions, the most probable driver for this metamorphism is heating largely driven by high-heat production from older granites (c. 1820–1760 Ma) in the region.

To the west, the Rudall Province (eastern WAC) is one of the few localities of Proterozoic, Barrovian-style metamorphism in Australia. In several previous studies, the Rudall Province has been considered to record the collision of the WAC and NAC during the Yapungku Orogeny at c. 1780 Ma. However, prior to this study, medium-*P* assemblages interpreted to have grown during the Yapunkgu Orogeny (inferred thermal gradients of minimum ~60–80 °C/kbar) had not been directly age-constrained. Monazite age data on metasedimentary rocks from both medium-*P* and high temperature–low pressure (HTLP) assemblages, and zircon U–Pb age data from a medium-*P,* garnet-diopside bearing mafic amphibolite yield age populations between c. 1380 and 1275 Ma, with one monazite age population of c. 1665 Ma. No evidence for older c. 1780 Ma metamorphism was found in this study. The large age population range of c. 1380–

1275 Ma yielded in this study may be a response of a stage-wise tectonic evolution, involving the accretion of ribbons. If the Yapunkgu Orogeny does reflect the collision between the WAC and NAC, it most likely did not occur until the Mesoproterozoic, contemporaneous with initial breakup stages of supercontinent Nuna.

The overall results of this work support a long-lived, retreating margin on the southern NAC during the late Paleoproterozoic, prior to the assembly of cratonic Australia in the Mesoproterozoic. The proposed Mesoproterozoic assembly negates the need for Australian cratons to be in close proximity in supercontinent Nuna reconstructions.

# Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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# Publications arising from this thesis

*Journal articles*

**Anderson, J. R.**, Kelsey, D. E., Hand, M. and Collins W.J. 2013. Conductively driven, high-thermal gradient metamorphism in the Anmatjira Range, central Australia. Journal of Metamorphic Geology, 31(9): 1003–1026.

**Anderson, J. R.**, Kelsey, D. E., Hand, M and Collins W.J. Submitted. Constraints on the timing and conditions of metamorphism on the Paleoproterozoic North Australian Craton margin. Precambrian Research.

*Conference abstracts*

**Anderson, J. R.**, Kelsey, D. E., Hand, M and Collins W.J. 2013. ca. 1750 Ma arc-related metamorphism in the southern Arunta Complex, central Australia? Goldschmidt, Florence, Italy.

**Anderson, J. R.**, Kelsey, D. E., Hand, M and Collins W.J 2012. P–T conditions and timing of metamorphic belts in the central and southern Arunta Region. International Geologic Congress, Brisbane, Australia.

# Statement of authorship

Where indicated at the beginning of each chapter, parts of the research presented in this thesis have been published, are under review or are in preparation to be submitted to scientific journals. The contribution of each author is described below.

**ANDERSON, J. R. (Candidate)**

Chapters 1 and 4: Project design; sample selection; petrography; SEM; LA−ICP−MS; EPMA data collection; all calculations and data processing; P−T modelling; data interpretation; manuscript design and composition.

Chapter 2: Project design; fieldwork; sample selection; petrography; part SEM; part LA−ICP−MS data collection; part EPMA data collection; calculations and data processing; P−T modelling; data interpretation; manuscript design and composition.

Chapter 3: Project design; sample selection; LA−MC−ICPMS data collection; data processing; data interpretation; manuscript design and composition.

I certify that the above statement is accurate and give permission for the relevant manuscripts to be included in this thesis.

SIGNED DATE

**KELSEY, D. E., HAND, M., COLLINS, W. J. (Supervisors)**

Chapters 1−4: Project design; fieldwork assistance; guidance with data interpretation and P−T modelling; manuscript review.

I certify that the above statement is accurate and give permission for the relevant manuscripts to be included in this thesis.

SIGNED

SIGNED DATE

SIGNED 9/4/2015

**LAWSON-WYATT, M.**

Chapter 2: fieldwork; part LA−ICP−MS; part SEM; part EPMA data collection; assistance with data interpretation.

I certify that the above statement is accurate and give permission for the relevant manuscript to be included in this thesis.

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# Introduction and thesis outline

The Paleo to Mesoproterozoic (*c.* 1850−1200 Ma) is an important timeline for understanding the evolution of Proterozoic Australia and the configuration of Australia in the development of supercontinent Nuna (Zhang et al., 2012; Pisarevsky et al., 2014). Recent reviews of global paleomagnetic data suggest that Nuna existed by *c.* 1750−1650 Ma and lasted at least until *c.* 1450 Ma (Zhang et al., 2012; Pisarevsky et al., 2014). Despite some differences in proposed cratonic paleogeography and the timing of the assembly of Nuna, these reconstructions suggested that the three major cratonic blocks of Australia, the West Australian Craton (WAC), North Australian Craton (NAC) and South Australian Craton (SAC), the latter including east Antarctica, formed a key component of Nuna (Fig. 1).

In comparison to many other Paleoproterozoic Terrains, Australia has comparatively less juvenile crust and evidence for considerable recycling and reworking (e.g. Etheridge et al., 1987; Wyborn et al., 1992; Betts et al., 2011). Consequently, it has been debated whether the tectonic evolution of Proterozoic Australia was dominated by intracratonic (Etheridge et al., 1987; Wyborn, 1988; Oliver et al., 1991) or plate margin processes (e.g. Myers et al., 1996; Giles et al., 2002; Bagas, 2004; Maidment et al., 2005; Betts and Giles, 2006; Wade et al., 2006; Bagas et al., 2008; Betts et al., 2008; Payne et al., 2009). There is a growing number of more recent plate tectonic models that favour the operation of plate margin processes during the Paleoproterozoic to Mesoproterozoic and advocate for the amalgamation and/or accretion of major cratonic elements of Australia during this time (e.g. Betts and Giles, 2006; Cawood and Korsch, 2008; Payne et al., 2009; Ahmad and Scrimgeour, 2013). However, there remains debate over the timing and nature of the assembly of the NAC, WAC and SAC (e.g. Myers et al., 1996; Betts and Giles, 2006; Cawood and Korsch, 2008; Payne et al., 2009; Ahmad and Scrimgeour, 2013; Smits et al., 2014). As a consequence, the configuration of these cratons in the Paleoproterozoic to Mesoproterozoic and in supercontinent Nuna is not fully understood.

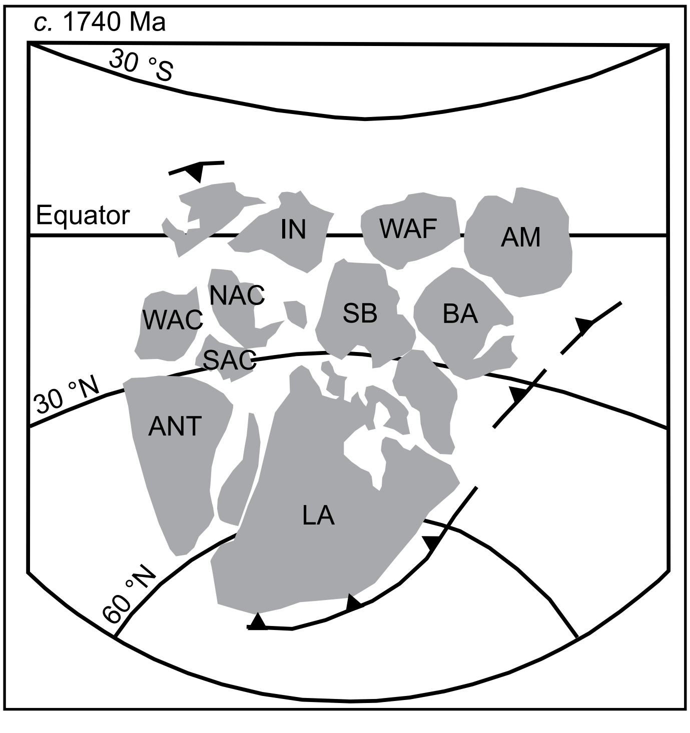

Fig. 1. Recent reconstruction of supercontinent Nuna for *c.* 1740 Ma (from Zhang et al., 2012). Reconstruction shows Proterozoic components of Australia in proposed close proximity, and following restored pre-Ediacaran fit of Australia by Li and Evans (2011). Abbreviations not discussed in text: AM−Amazonia, ANT− Antarctica, BA−Baltica, IN−India, LA−Laurentia, SB−Siberia, WAF−West Africa.

The NAC, WAC and SAC (Fig. 2) are composed largely of Archean–Paleoproterozoic components that have subsequently undergone either lateral crustal growth and/or reworking (e.g. Neumann and Fraser, 2007). Older components of the NAC and SAC share several geological similarities and have therefore been interpreted by some authors as being contiguous throughout most of their tectonic evolution (e.g. Payne et al., 2009). The WAC is commonly interpreted to have collided with the NAC at *c.* 1780 Ma, reflected by the medium- to high-pressure Yapungku Orogeny in the Rudall Province, eastern WAC (e.g. Smithies and Bagas, 1997; Bagas, 2004; see Fig. 2 for location of the Rudall Province). The *c.* 1780 Ma age for the collision of the WAC and NAC is based on crystallisation ages obtained from variably deformed orthogneisses that are inferred to have intruded the surrounding medium- to high-pressure rocks of the Rudall Province at that time (Smithies and Bagas, 1997; Bagas, 2004). In a number of Proterozoic reconstruction models, the NAC, SAC and WAC are interpreted to have been joined or in close proximity to each other since the late Paleoproterozoic (*c.* 1800-1600 Ma; e.g. Betts et al., 2006; Cawood and Korsch, 2008; Payne et al., 2009; Zhang et al., 2012). In a restored model of pre-Ediacaran Australia, Li and Evans (2011) proposed the NAC and WAC were in close proximity after *c.* 1800 Ma, with a ~40° rotation of the WAC–SAC relative to the NAC occurring at *c.* 650–550 Ma to account for discrepancies between paleopoles.

An alternative Mesoproterozoic timeline for the amalgamation of the major cratonic elements of Proterozoic Australia was proposed by Myers et al. (1996) and more recently in a U–Pb age and Hf zircon isotopic study by Smits et al. (2014). Major phases of Mesoproterozoic tectonism occur in the Albany Fraser Orogen (AFO; Fig. 2) on the eastern margin of the Yilgarn Craton (WAC) and Musgrave Province (MP; Fig. 2), central Australia (e.g. Myers et al., 1996; Giles et al., 2004; Betts and Giles, 2006; Cawood and Korsch, 2008; Wade et al., 2008; Aitken

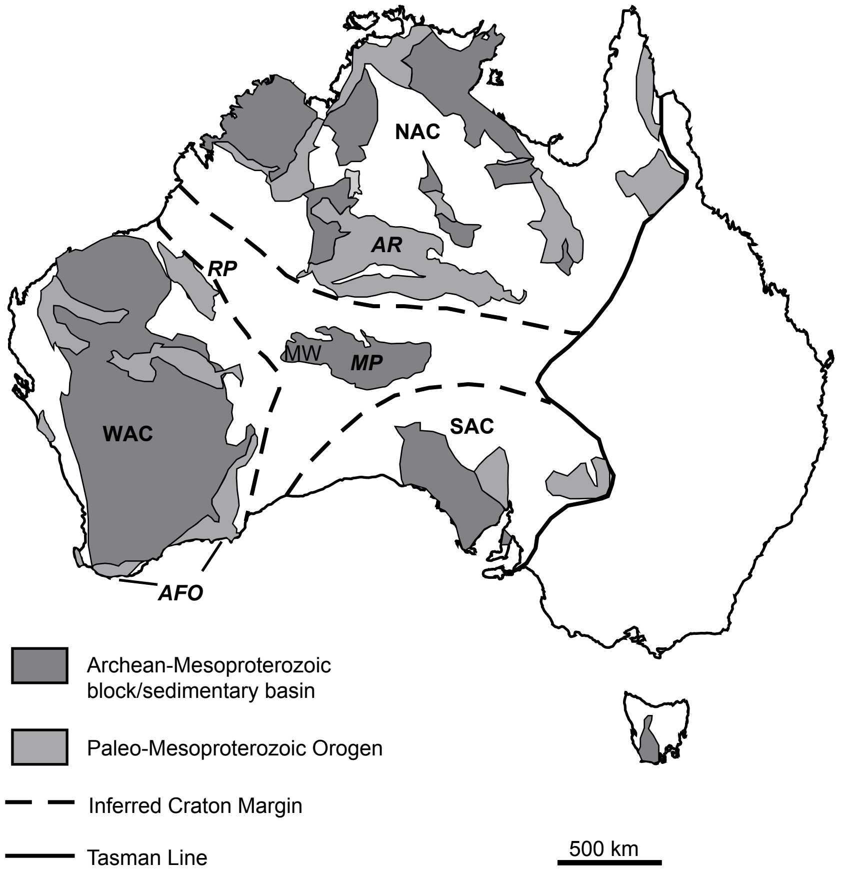

Fig. 2. Simplified map of Australia, with inferred North (NAC), South (SAC) and West (WAC) Australian Cratons indicated. AFO = Albany Fraser Orogen, AR = Arunta Region, MP = Musgrave Province, MW = Mount West Orogeny, RP = Rudall Province. Modified after Cawood and Korsch (2008) and Walsh et al. (2013).

and Betts, 2009; Spaggiari et al., 2009; Smithies et al., 2011). Stage I of the Albany Fraser Orogeny (*c.* 1340–1260 Ma) has been interpreted to be a response to the collision of the WAC with the SAC/Mawson Continent (e.g. Clark et al., 2000) and/or alternatively reflect the closure of a marginal ocean basin and accretion of the Loongana Magmatic Arc (east of the Albany Fraser Orogen) to the WAC, prior to the final convergence of the WAC and SAC/Mawson Continent (Spaggiari et al., 2014). Additional hints of the possibility of the operation of active plate margin processes in Australia during the Mesoproterozoic are reflected by the poorly preserved *c.* 1345–1292 Mount West Orogeny in the western Musgrave Province. The tectonic setting of the Mount West Orogeny remains uncertain. However, the Mount West Orogeny involved the emplacement of the metaluminous, calc to calc-alkaline granitoids of Wankanki Supersuite, which are geochemically similar to those that occur in modern day continental-arc settings (Smithies et al., 2010; Smithies et al., 2011).

Contention over the timing and configuration of cratons during Paleo−Mesoproterozoic Australia is arguably largely a consequence of the complex nature of many Precambrian Australian terrains and scarcity of available geological datasets from some key areas. This study specifically focuses on constraining the tectonic and thermal evolution of data poor, or debated areas of the southern NAC (Fig. 3) and Rudall Province (eastern WAC; Fig. 4), in order to gain further understanding into the evolution of Precambrian Australia, and its configuration in Nuna.

The aims of this project are to:

1. Quantify the tectonothermal regimes that define the southern Arunta region (Aileron Province) in a structural and temporal framework.

2. Quantify the tectonothermal events of the Rudall Province in a temporal framework

3. Characterise the crustal Hf isotopic signature of the Aileron Province during the late-Paleoproterozoic.

4. Present a revised tectonic model for the assembly of Proterozoic Australia using new and existing datasets.

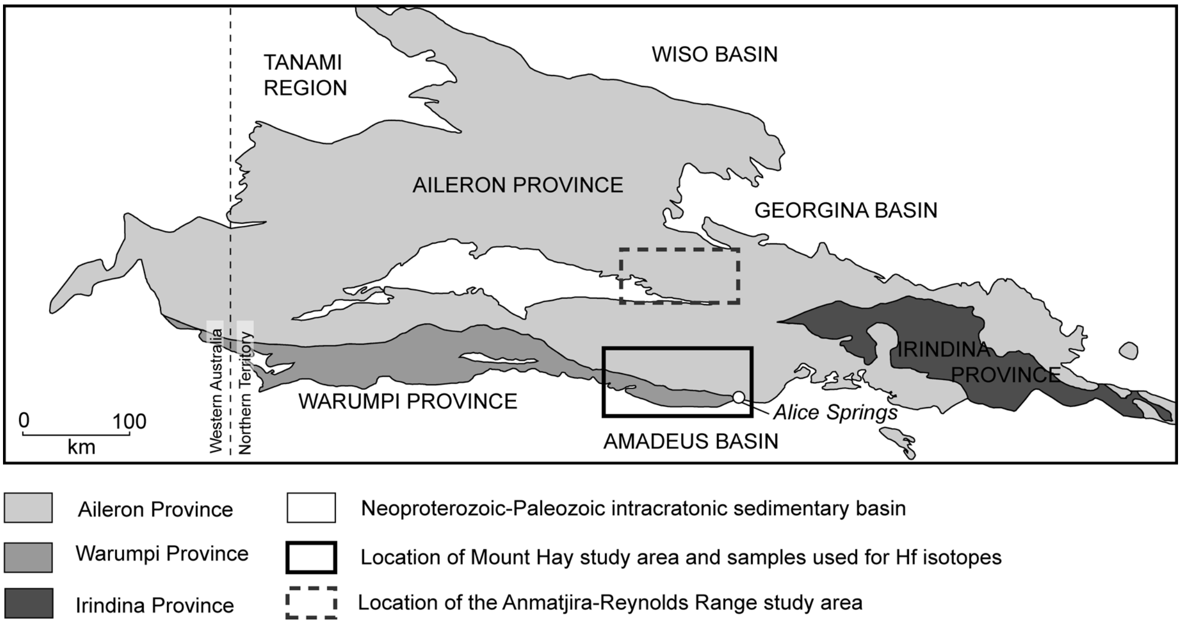

Fig 3. Simplified regional geology map of the Arunta Region, showing provinces, major structural boundaries and study areas (modified from Scrimgeour et al., 2005).

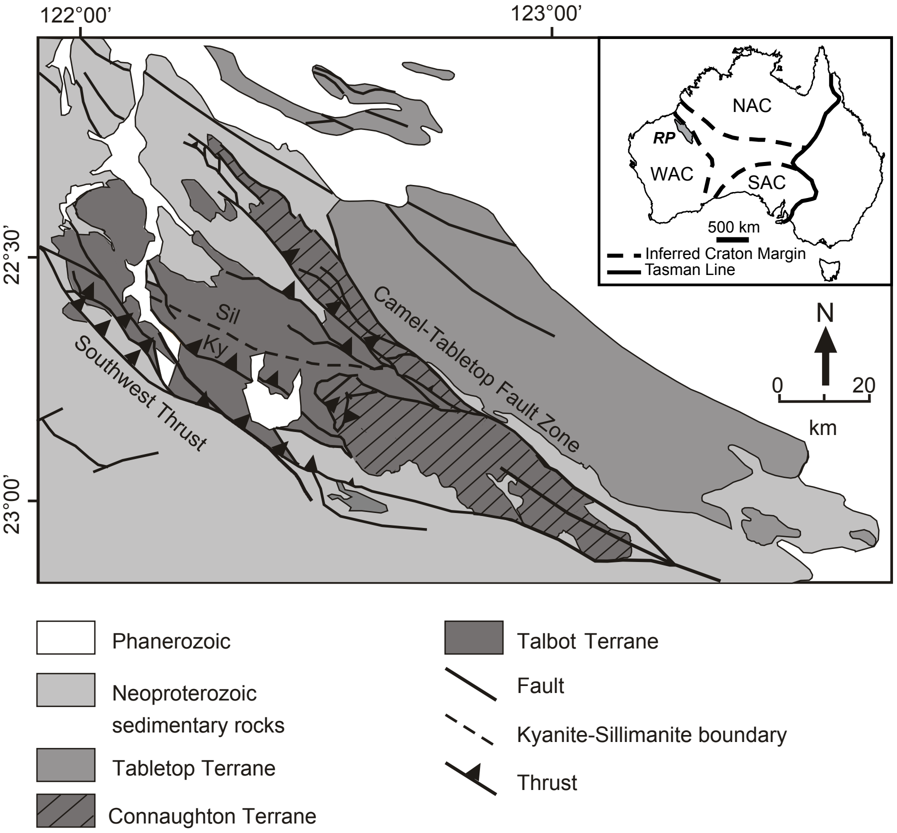

Fig 4. Map of the Rudall Province, showing lithological associations, major structures, and kyanite−sillimanite inferred isograd. Modified from Geological Survey of Western Australia (1999) and Smithies and Bagas (1997). Inset: simplified map of Australia showing the location of the Rudall Province (RP).

## Thesis Outline

**Chapter 1** provides metamorphic and geochronological constraints for the physical and temporal conditions of metamorphism in the Anmatjira Range, Arunta Region, central Australia. The high-thermal gradient metamorphosed rocks in the Anmatjira Range have been subject to substantial debate over the past 20 years involving the timing, nature, number of metamorphic events and thermal driver for metamorphism. Chapter 1 investigates the regional high-thermal gradient metamorphism in the Anmatjira Range using U−Pb monazite geochronology and $P-T$ pseudosections. Additionally, a new method for reintegrating melt into compositions for granulite facies rocks that have undergone melt loss is presented. This chapter is published as 'Anderson, J. R., Kelsey, D. E., Hand, M. and Collins W.J. 2013. Conductively driven, high-thermal gradient metamorphism in the Anmatjira Range, central Australia. *Journal of Metamorphic Geology*, 31(9): 1003–1026'.

**Chapter 2** investigates the metamorphic evolution of the Mount Hay Block and Adla Domain, southern Arunta Region, central Australia. Sparse age and metamorphic data exists for the Mount Hay Bock and Adla Domain, key areas proximal to the postulated paleo-suture of the NAC during the Paleoproterozoic. Chapter 2 combines U−Pb monazite geochronology and $P-T$ pseudosection modelling in order to constrain the timing of metamorphism, and assess the thermal footprint within a km-scale structural architecture. This Chapter has been submitted to *Precambrian Research.*

**Chapter 3** presents Hf zircon isotopic data on late Paleoproterozoic magmatic rocks from the Arunta Region (Fig. 3). These magmatic rocks are coeval with the proposed timing of the accretion of the Warumpi Province onto the Aileron Province (NAC) at *c.* 1640−1635 Ma during the Liebig Orogeny (Scrimgeour et al., 2005). The Hf isotopic signature of these rocks can therefore provide insight into crustal source interaction during late-Paleoproterozoic tectonism in the southern Arunta Region.

**Chapter 4** investigates the timing and conditions of metamorphism the Yapungku Orogeny in the Rudall Province, eastern Pilbara margin, Western Australia. The Rudall Province is one of the few Precambrian terranes in Australia that records medium-*P* metamorphism similar to those found in continental collisional orogenic settings. The timing of metamorphism has been in recent years inferred to be broadly coeval with magmatism at *c.* 1780 Ma, however medium-*P* assemblages have not been directly age-constrained. Chapter 4 addresses this 'gap' by providing zircon and monazite U−Pb metamorphic age data on rocks were metamorphosed during and after the Yapungku Orogeny ($D_2$). In addition, $P-T$ pseudosection modelling of a garnet−diopside bearing amphibolite and staurolite-bearing metapelite is used constrain the conditions of metamorphism. This chapter is currently in preparation for submission to *Precambrian Research*.

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