Reworking the Gawler Craton: Metamorphic and geochronologic constraints on Palaeoproterozoic reactivation of the southern Gawler Craton, Australia

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Chapter 2
In-situ EPMA monazite chemical dating at the University of Adelaide: Setup, procedures, comparisons and application to determining the timing of high-grade deformation and metamorphism in the southern Gawler Craton.

Abstract

Putting absolute time into structural and metamorphic analysis is a vital tool for unravelling the development of orogenic systems. Electron Probe Micro-Analysis (EPMA) chemical dating of monazite provides a useful method of obtaining good precision age data from monazite bearing mineral assemblages. Presented here is a review of EPMA monazite dating theory together with a detailed description of the EPMA monazite setup and methods developed at the University of Adelaide. This includes the initial setup and optimisation of the technique on the Cameca SX51 electron microprobe, sample preparation and data reduction and analysis techniques. EPMA measurements carried out on samples of known age, from Palaeoproterozoic to Ordovician, produce ages which are within error of the isotopically determined ages, indicating the validity of the developed setup. The technique is then applied to a sample of unknown age from the southern Gawler Craton to determine the timing of high-grade metamorphism and deformation in the Fishery Bay region. Three samples from the late Archaean to Palaeoproterozoic Sleaford Complex produced EPMA monazite ages of 1707 ± 20 Ma, 1690 ± 8 Ma and 1708 ± 12 Ma indicating that the high-grade metamorphism and deformation in this region was a result of reworking during the 1725–1690 Ma Kimban Orogeny, and not the 2450–2420 Ma Sleafordian Orogeny.

2.1 Introduction

Reconstructing pressure-temperature-time ($P-T-t$) paths is a vital tool for unravelling ancient and modern orogenic systems and attempting to deduce a tectonic model for their development (e.g. Clarke and Powell, 1991; Harley and Fitzsimons, 1991; Spear, 1993; Thoni and Miller, 1996; Mawby et al., 1999; Goscombe et al., 2003; Kelsey et al., 2003; Foster et al., 2004; Goscombe et al., 2005; Duchene et al., 2006; Halpin et al., 2007; Kohn, 2008). The process starts with developing a constrained tectonometamorphic evolution of an area using detailed structural analysis coupled with a complete metamorphic analysis, including the determination of $P-T$ constraints through thermobarometry and the use of $P-T$ pseudosections tailored to specific bulk compositions (e.g. Harley and Fitzsimons, 1991; Stuwe and Ehlers, 1997; Scrimgeour and Close, 1999; Kelsey et al., 2003; White et al., 2007). This tectonometamorphic framework then needs to be temporally constrained. The
lack of applied geochronology to proposed $P$-$T$ paths can lead to erroneous conclusions with the inferred tectonometamorphic history being an amalgam of different events, including using assemblages which have formed during reworking at a later time being used to constrain the retrograde metamorphic evolution of an orogen (e.g. Hand et al., 1992; Holdworth et al., 2001; Dutch et al., 2005).

In recognition of the importance of constraining time in geological processes, a number of different minerals and chemical systems have been developed to try to constrain the age of metamorphism and deformation. For example, dating of accessory minerals such as zircon by the ‘kober’ or dissolution methods using Thermal Ionisation Mass Spectrometry (TIMS) allows for extremely precise isotopic age determinations (e.g. Cocherie et al., 1992; Dougherty-Page and Bartlett, 1999; Crowley et al., 2007; Schaltegger et al., 2008). However, these methods require considerable time, can be expensive, and will commonly be an amalgam of any age zonation in the minerals (i.e. has poor spatial resolution) and gives no textural or chemical information. Dating of major phases involved in metamorphic reactions in this way (e.g. garnet Sm-Nd) may allow a direct constraint on the age of metamorphism but suffers from many of the same issues (e.g. Chapter 6: Mawby et al., 1999; Thoni, 2003; Jung et al., 2007). Accessory phase dating by secondary ion mass spectrometry (SIMS, e.g. Foster et al., 2000; Dutch et al., 2008) or Laser Ablation ICP-MS (e.g. Willigers et al., 2002; Horstwood et al., 2003; Payne et al., 2006; Reid et al., 2006; Payne et al., 2008) are currently the most powerful tools available for isotopic dating. Both allow for high precision isotopic ages to be determined (typically with errors between ± 3 – 10 Ma) with relatively good spatial resolution (spot sizes between ~ 5 – 60 μm). Generally they are performed on mineral separates but both can in principal be done in-situ allowing for spatial information to be retained (e.g. Carson et al., 2004; Forbes et al., 2007; Wade et al., 2008).

Electron Probe Micro-Analysis (EPMA) chemical dating of monazite provides a useful additional or alternative method of obtaining good precision age data from monazite bearing mineral assemblages (e.g. Suzuki and Adachi, 1997; Montel et al., 2000; Asami et al., 2002; Pyle and Spear, 2003; Mezeme et al., 2006; Santosh et al., 2008). Compared with the above techniques it is relatively cheap, time efficient, is readily preformed in-situ, has excellent spatial resolution (< 10μm), good age precision (c. ± 7 – 30 Ma), and can provide a full range of chemical and element zonation information (Pyle et al., 2005; Williams et al., 2006). The main disadvantage is that it is not an isotopic method, so discordant data can be difficult to discern.

This chapter provides a review of EPMA monazite dating theory together with a detailed description of the analytical method and procedures for EPMA monazite dating developed at the University of Adelaide. In order to verify the accuracy of the method for the available analytical facilities, a comparative study using previously isotopically dated monazites (methods including ID-TIMS and SHRIMP) has been carried out. The results indicate a good correspondance between the EPMA ages obtained from the developed
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2.2 Review of EPMA monazite dating theory

Since the EPMA monazite technique was first implemented by Suzuki and Adachi (1991) and Suzuki et al. (1994) using the Chemical Isochron Method (CHIME) a number of different methodologies for data acquisition and reduction have been developed. For a thorough review of EPMA monazite geochronology principles and techniques see papers by Montel et al. (1996), Williams et al. (1999), Pyle et al. (2005), Jercinovic and Williams (2005) and Williams et al. (2006).

The theoretical basis for monazite geochronology consists of measuring the Th, U
and Pb concentrations in a monazite crystal and calculating the age (τ) based on the decay rates of U and Th to Pb via the age equation (after Montel et al., 1996):

\[
Pb = \left( \frac{Th}{232} \right) \left( \frac{235}{238} \right) \left( \frac{U}{238.04} \right) + \left( \frac{U}{238.04} \right) \left( \frac{232}{235} \right) \left( \frac{U}{238.04} \right)
\]

where Pb, U and Th are in ppm and λ\textsubscript{232}, λ\textsubscript{238}, λ\textsubscript{235} are the radioactive decay constants of 232Th, 238U and 235U respectively. Individual ages are determined iteratively by entering age estimates into Eq. (1) with the known concentrations of U and Th until the calculated Pb value matches the measured Pb concentration. Because monazite can incorporate significant amounts of Th and U, EPMA measurable amounts of radiogenic Pb begins to accumulate in as little as 100 Myr.

The validity of the above method is dependant on two assumptions: (1) that non-radiogenic Pb content is negligible; and (2) there has been no subsequent modification of the U/Th/Pb ratios except by radioactive decay. Parrish (1990) indicated that monazite incorporates very little non-radiogenic Pb in its structure, and therefore common Pb contents are typically < 1 ppm and are therefore negligible for most >200 Myr old monazites.

The second assumption is that the monazite grain remains a closed system. Of the two decay systems active in monazite the U/Pb system is best documented. Previous studies (e.g. Parrish, 1990; Cherniak et al., 2004; Cocherie et al., 2005) have shown that this system typically behaves in a concordant manner. The Th/Pb system, the more important for monazite chemical dating, is poorly known despite the fact that the theoretical basis for its interpretation has been established (Steiger and Wasserburg, 1966). Experimental work by Barth et al. (1994a; 1994b) has shown that for allanite, the Th/Pb system is more resistant to diffusion than the U/Pb system, and therefore should behave in a concordant manner. Diffusion of Pb in monazite is also negligible (Cherniak, 2004). Cherniak et al (2004) has demonstrated that for a cooling rate of 10 °C Ma\textsuperscript{-1}, a 10 μm monazite grain has an effective closure temperature of c. 900 °C, meaning that for most geological processes Pb diffusion in monazite is negligible. Monazite has also been shown to be highly resistant to metamicitisation (Karioris et al., 1991; Meldrum et al., 1997). These arguments indicate that monazite should remain a closed system in most geological settings and provide concordant, geologically meaningful ages.

However, monazite often gives slightly different ages than zircon from within the same units (e.g. Foster et al., 2000; Pyle and Spear, 2003; Carson et al., 2004; Fitzsimons et al., 2005; Kelsey et al., 2008). This is primarily due to its comparatively high chemical reactivity (e.g. Bea and Montero, 1999; Spear and Pyle, 2002), particularly in melt bearing systems. The stability of monazite is primarily a function of temperature and melt composition (Rapp et al., 1987), with monazite solubility and stability being a function of the destabilising effects of P and REE solubility in felsic melts (Rapp and Watson, 1986; Rapp et al., 1987; Wolf and London, 1995; Kelsey et al., 2008). This suggests that Th-U-Pb monazite systematics, and therefore the age, is less likely to be controlled by diffusion than it is by the chemical reactivity of the monazite grains (e.g. Seydoux-
2.3 Analytical method

Generally every electron microprobe is unique, with each having different variations and combinations of electron columns, spectrometers, X-ray detectors and counters. All these factors can affect the form of wavelength-dispersive spectra (WDS). Therefore monazite dating protocols must be designed for a specific electron microprobe. The following analytical setup and procedure is for a Cameca SX51 electron microprobe (Fig. 2.2a) running SAMx software at Adelaide Microscopy, which is the major analytical facility at the University of Adelaide.

The SX51 uses a tungsten filament and is capable of producing beam accelerating voltages of 1–30 kV, beam currents of ~50 pA to 500 nA, with beam diameters adjustable between 1 and 50 μm. The central electron column has an X-ray takeoff angle of 40° and is surrounded by four WDS spectrometers and a Gresham 10mm energy-dispersive (EDS) detector.

All WDS spectrometers on the SX51 incorporate a 160 mm radius Rowland circle. Each spectrometer is equipped with a number of swappable diffraction crystals with the configuration: Spectrometer 1 PET (Pentaerythrite); spectrometer 2 PET; spectrometer 3 LiF (Lithium fluoride) and; spectrometer 4 TAP (Thallium hydrogen phthalate), being used for monazite analysis. The SX51 uses four P10 (Ar 90%-CH₄ 10%) gas-flow proportional X-ray detectors. Polypropylene entry windows are used on all detectors. Gas pressure in detectors 1, 2 and 4 are maintained at approximately 1 atm while detector 3 is maintained at approximately 3 atm.

Prior to calibration it is necessary to optimise the X-ray detectors for analysis. The X-ray detector consists of a wire anode in a cylinder of P10 gas (which acts as the cathode). The window allows the diffracted X-rays to enter the detector. The incident X-ray photons are absorbed by the counter gas which emits an inner shell electron producing a voltage pulse in the detector. This pulse is then amplified and processed by the pulse-height analyser (PHA) which, amongst other things, rejects unwanted pulses. The PHA can be operated in two modes,
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integral and differential. In integral mode all pulses, including those from second and third-order lines in the region of interest will be processed. In differential mode, a baseline and window value are set which filters out all higher order pulses and give better peak-to-background ratios. In order to calibrate the X-ray counter to maximise the voltage pulse it is also necessary to adjust the bias value.

2.3.1 SX51 operating conditions

The choice of accelerating voltage and beam current are a balance between a number of factors. Accelerating voltages in the published literature that have been used for monazite analysis (summarised in Scherrer et al., 2000) range between 15 and 25 kV. Higher voltages increase the intensity of the generated X-rays, giving greater analytical precision, but it also increases the size of the X-ray excitation volume in the sample and can lead to greater uncertainties in the ZAF corrections (Pyle et al., 2005: ZAF corrections refer to the corrections applied to account for matrix effects related to the sample composition which can effect the X-ray spectrum produced. ZAF refers to atomic number (Z), absorption (A) and fluorescence (F)).

The choice of beam current will also affect the count rate and the excitation volume. Increasing the current will increase the number of X-ray emissions reaching the detector (number of counts) while also increasing the excitation volume in the sample. The number of counts needs to be maximised for precision while not exceeding about 10000 cps where detector dead-time begins to reduce the efficiency of the detector. For typical monazites where elemental concentrations are generally < c. 25 wt% this is not a problem, but it can become an issue when calibrating on high concentration standards and is the reason for using different beam currents on different standards (Table 2.1). A high beam current placed on a spot for a prolonged period will also cause damage to the sample (Fig. 2.2b).

In order to maximise X-ray counts for precision while minimising the excitation volume to less than 10 μm diameter (providing excellent spatial resolution) and minimising sample damage for a typical analysis time of 10 minutes an accelerating voltage of 20 kV with a beam current of 100 nA is optimal for monazite analysis on the Adelaide SX51 at Adelaide Microscopy.

2.3.2 Elements and standards

Monazite is a REE-rich phosphate, (Ce, La, Pr, Nd, Th, Y)PO₄, with a complex chemistry with up to 14 end members including common solid solutions between monazite-huttonite (ThSiO₄) and monazite-brabantite (CaTh(PO₄)₂) (Franz et al., 1996; Montel et al., 2002). The number of elements required for monazite chemical age determination can range from a full monazite compositional analysis (between 15 to 20 elements: Cocherie and Albarede, 2001; Spear and Pyle, 2002; Cocherie et al., 2005) to just those elements required for the age equation and those required for interference corrections (e.g. Williams and Jercinovic, 2002; Williams et al., 2006). The advantage of analysing a smaller number of elements is it allows for longer counting times
Table 2.1. EPMA monazite parameters on the SX51.

<table>
<thead>
<tr>
<th>Element</th>
<th>Line</th>
<th>Standard</th>
<th>Xtal</th>
<th>Spectro</th>
<th>PHA</th>
<th>T-Pkc</th>
<th>T-Bgd</th>
<th>Bgd +d</th>
<th>Bgd -d</th>
<th>Slope</th>
<th>Bgd type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>Kα</td>
<td>REE 1</td>
<td>TAP</td>
<td>4(LP)</td>
<td>Int</td>
<td>30</td>
<td>30</td>
<td>400</td>
<td>1.032</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>Mβ</td>
<td>UO2</td>
<td>PET</td>
<td>1(LP)</td>
<td>Diff</td>
<td>160</td>
<td>160</td>
<td>1250</td>
<td>0.89</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Th</td>
<td>Mα</td>
<td>Huttonite</td>
<td>PET</td>
<td>1(LP)</td>
<td>Diff</td>
<td>60</td>
<td>30</td>
<td>800</td>
<td>1300</td>
<td>curved</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>Kα</td>
<td>REE 1</td>
<td>TAP</td>
<td>4(LP)</td>
<td>Int</td>
<td>10</td>
<td>10</td>
<td>700</td>
<td>1.08</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Kα</td>
<td>Apatite</td>
<td>PET</td>
<td>2(LP)</td>
<td>Int</td>
<td>10</td>
<td>10</td>
<td>1750</td>
<td>1.095</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>Kα</td>
<td>Apatite</td>
<td>PET</td>
<td>1(LP)</td>
<td>Int</td>
<td>20</td>
<td>10</td>
<td>500</td>
<td>500</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>La</td>
<td>REE 1</td>
<td>PET</td>
<td>2(LP)</td>
<td>Int</td>
<td>20</td>
<td>20</td>
<td>1600</td>
<td>0.815</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>La</td>
<td>La</td>
<td>La Glass</td>
<td>PET</td>
<td>1(LP)</td>
<td>Diff</td>
<td>20</td>
<td>20</td>
<td>540</td>
<td>1.052</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Ce</td>
<td>La</td>
<td>Ce Glass</td>
<td>PET</td>
<td>1(LP)</td>
<td>Diff</td>
<td>20</td>
<td>20</td>
<td>1750</td>
<td>1.185</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Pr</td>
<td>Lβ</td>
<td>Pr Glass</td>
<td>LiF</td>
<td>3(HP)</td>
<td>Diff</td>
<td>30</td>
<td>20</td>
<td>500</td>
<td>1</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Nd</td>
<td>Lβ</td>
<td>Nd Glass</td>
<td>LiF</td>
<td>3(HP)</td>
<td>Diff</td>
<td>20</td>
<td>20</td>
<td>1930</td>
<td>0.826</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Sm</td>
<td>Lβ</td>
<td>Sm Glass</td>
<td>LiF</td>
<td>3(HP)</td>
<td>Diff</td>
<td>30</td>
<td>30</td>
<td>300</td>
<td>0.97</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Gd</td>
<td>Lβ</td>
<td>Gd Glass</td>
<td>LiF</td>
<td>3(HP)</td>
<td>Diff</td>
<td>30</td>
<td>15</td>
<td>470</td>
<td>500</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Dy</td>
<td>Lβ</td>
<td>Dy Glass</td>
<td>LiF</td>
<td>3(HP)</td>
<td>Diff</td>
<td>40</td>
<td>40</td>
<td>305</td>
<td>0.981</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Er</td>
<td>Lβ</td>
<td>Er Glass</td>
<td>LiF</td>
<td>3(HP)</td>
<td>Diff</td>
<td>40</td>
<td>40</td>
<td>850</td>
<td>0.95</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>Mβ</td>
<td>K227</td>
<td>PET</td>
<td>2(LP)</td>
<td>Diff</td>
<td>240</td>
<td>120</td>
<td>4000</td>
<td>2695</td>
<td>curved</td>
<td></td>
</tr>
</tbody>
</table>

*Calibration current, a spectrometer number (Low-Pressure/High-Pressure), pulse height analyser parameter (Integral/differential), count time (peak/background), background sineθ positions and slope.

on each element. However, there are increased analytical uncertainties introduced because of the need to use an assumed or average total element concentration for ZAF corrections.

The analytical procedure adopted here is a near complete monazite analysis. The method analyses for U, Th and Pb, together with Ce, La, many of the REEs which substitute into monazite (Pr, Nd, Sm, Gd, Dy and Er) as well as Al, Si, Ca, Y and P (A typical monazite analysis is presented in Table 2.2). These elements account for the compositional variation between the monazite-huttonite (Lanthanide⁺⁺⁺ + P⁵⁺ = Actinide⁺⁺⁺ + Si⁺⁺) and monazite-brabantite (2Lanthanide⁺⁺⁺ = Actinide⁺⁺⁺ + Ca²⁺) exchanges (Cuney and Friedrich, 1987; Franz et al., 1996; Forster, 1998). They also give a large amount of chemical data, allowing the linking of different age and compositional domains to the growth of major phases that can be used to constrain $P-T$ conditions (e.g. Foster et al., 2000; Pyle and Spear, 2003). Analysis of Si, Ca and Al allow for quality control. Monazite typically contains < 1 wt% Si and Ca and < 0.5 wt% Al, so higher concentrations of these elements can indicate; (1) a contaminated analysis, such as the incorporation of a micro inclusion or grain edge overlap, (2) significant solid solution exchange between end members away from a true monazite composition or (3) hydrothermal or surface weathering and alteration of monazite (Franz et al., 1996; Poitrasson et al.,...
### Table 2.2 Representative analyses of the MAD age standard monazite.

<table>
<thead>
<tr>
<th></th>
<th>MAD_1</th>
<th>MAD_2</th>
<th>MAD_3</th>
<th>MAD_4</th>
<th>MAD_5</th>
<th>MAD_6</th>
<th>MAD_7</th>
<th>MAD_8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (wt%)</td>
<td>0.007</td>
<td>0.005</td>
<td>0.006</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.003</td>
</tr>
<tr>
<td>Si (wt%)</td>
<td>0.656</td>
<td>0.711</td>
<td>0.707</td>
<td>0.708</td>
<td>0.706</td>
<td>0.691</td>
<td>0.696</td>
<td>0.683</td>
</tr>
<tr>
<td>Ca (wt%)</td>
<td>0.288</td>
<td>0.288</td>
<td>0.287</td>
<td>0.280</td>
<td>0.295</td>
<td>0.284</td>
<td>0.291</td>
<td>0.294</td>
</tr>
<tr>
<td>Y (wt%)</td>
<td>0.616</td>
<td>0.697</td>
<td>0.662</td>
<td>0.608</td>
<td>0.641</td>
<td>0.642</td>
<td>0.630</td>
<td>0.663</td>
</tr>
<tr>
<td>La (wt%)</td>
<td>11.979</td>
<td>11.814</td>
<td>11.836</td>
<td>11.770</td>
<td>11.824</td>
<td>11.832</td>
<td>11.832</td>
<td>11.854</td>
</tr>
<tr>
<td>Pr (wt%)</td>
<td>2.584</td>
<td>2.606</td>
<td>2.525</td>
<td>2.539</td>
<td>2.591</td>
<td>2.615</td>
<td>2.668</td>
<td>2.629</td>
</tr>
<tr>
<td>Sm (wt%)</td>
<td>1.974</td>
<td>2.104</td>
<td>2.034</td>
<td>1.996</td>
<td>2.107</td>
<td>2.138</td>
<td>2.134</td>
<td>2.139</td>
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<tr>
<td>Gd (wt%)</td>
<td>0.724</td>
<td>0.731</td>
<td>0.777</td>
<td>0.797</td>
<td>0.786</td>
<td>0.746</td>
<td>0.833</td>
<td>0.865</td>
</tr>
<tr>
<td>Dy (wt%)</td>
<td>0.233</td>
<td>0.276</td>
<td>0.220</td>
<td>0.301</td>
<td>0.272</td>
<td>0.248</td>
<td>0.298</td>
<td>0.258</td>
</tr>
<tr>
<td>Er (wt%)</td>
<td>0.131</td>
<td>0.072</td>
<td>0.131</td>
<td>0.056</td>
<td>0.115</td>
<td>0.071</td>
<td>0.097</td>
<td>0.098</td>
</tr>
<tr>
<td>Tb* (wt%)</td>
<td>0.162</td>
<td>0.162</td>
<td>0.177</td>
<td>0.171</td>
<td>0.163</td>
<td>0.159</td>
<td>0.182</td>
<td>0.162</td>
</tr>
<tr>
<td>U* (wt%)</td>
<td>0.150</td>
<td>0.156</td>
<td>0.159</td>
<td>0.152</td>
<td>0.137</td>
<td>0.151</td>
<td>0.155</td>
<td>0.141</td>
</tr>
</tbody>
</table>

*Interference corrected, Pk-number of peak counts, Bg-number of background counts
25

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1996; Podor and Cuney, 1997; Forster, 1998; Poitrasson et al., 2000). Analysis of all these elements typically produces totals in the range 99 ± 4 wt% which is within the range to give a high precision for ZAF corrections.

The use of high quality standards is essential for accurate determination of elemental concentrations in unknowns. In order to minimise the effect of any interferences on calibration, and increase count rates to produce good statistics, high concentration single element standards are preferred (especially for the REE’s which have multiple interferences in many cases: e.g. Jercinovic and Williams, 2005; Pyle et al., 2005). The compositions of all the standards are given in Table 2.3. The Pb standard is a synthetic glass NIST K-227, UO₂ for U and a natural huttonite for Th. Ca and P are calibrated using Durango apatite (Jonckheere et al., 1993; Frei et al., 2005). Si, Al and Y are calibrated using a multi-element synthetic glass (REE1: Drake and Weill, 1972). The REE’s are calibrated using high concentration single element synthetic glasses (Edinburgh Materials and Micro-Analysis Centre, Grant Institute of Earth Sciences, University of Edinburgh).

Age standards are not required for this procedure. However, the periodic measurement of a well characterised secondary age standard of known age is routinely carried out (the MAD standard with a mean ²⁶⁰Pb/²³⁸U age of 515 Ma; Foster et al., 2000).

2.3.3 Peaks, Backgrounds and Interferences

Once the choice of elements to be analysed has been made, it is necessary to decide which energy line is best to use. It is also extremely important to decide the location of background points around the selected peak and the shape of the background curve. The best method to determine which energy lines to use, where to place background positions and if there are any potential interferences is to compile a series of WD scans over the energy regions of interest (Fig. 2.3). In order to get the best possible precision, the highest intensity line with no or minimal overlaps should be selected. Because the precision of EPMA derived monazite ages is primarily a first-order function of the precision of U and Pb analyses (monazite typically contains much more Th than either U or Pb; Spear and Pyle, 2002), it is very important to accurately determine the concentrations of these elements.

Th, U and Pb are all analysed using PET diffraction crystals (Table 2.1). For monazite, the high intensity Th Mα peak is free from interference and therefore provides a clean energy line to measure for analysis (Fig. 2.3). The choice of line for U and Pb is more difficult as both the Mα and Mβ lines are subjected to a number of interferences. The U region of the spectrum is subject to a number of interferences from Th M lines plus steps in the background caused by the Th M5, Th M4 and Ar K absorption edges (Fig. 2.3). The U Mα line suffers from a very large overlap by the Th Mβ line (Fig. 2.3) and is very near the large Ar K
Table 2.3. Standard compositions.

<table>
<thead>
<tr>
<th>Element</th>
<th>K227</th>
<th>Durango Apatite</th>
<th>Huttonite UO₂</th>
<th>REE1</th>
<th>La</th>
<th>Ce</th>
<th>Pr</th>
<th>Nd</th>
<th>Sm</th>
<th>Gd</th>
<th>Dy</th>
<th>Er</th>
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<tbody>
<tr>
<td>O (wt%)</td>
<td>17.34</td>
<td>41.67</td>
<td>19.75</td>
<td>11.84</td>
<td>40.75</td>
<td>41.98</td>
<td>40.98</td>
<td>42.07</td>
<td>41.81</td>
<td>39.75</td>
<td>39.43</td>
<td>39.19</td>
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<tr>
<td>F (wt%)</td>
<td>2.00</td>
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<tr>
<td>Al (wt%)</td>
<td></td>
<td>6.21</td>
<td>5.57</td>
<td>5.60</td>
<td>5.59</td>
<td>5.55</td>
<td>6.25</td>
<td>6.20</td>
<td>6.15</td>
<td>6.40</td>
<td></td>
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<tr>
<td>Si (wt%)</td>
<td>8.40</td>
<td>8.67</td>
<td>23.45</td>
<td>26.08</td>
<td>24.98</td>
<td>26.19</td>
<td>25.99</td>
<td>22.70</td>
<td>22.51</td>
<td>22.38</td>
<td>21.15</td>
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<tr>
<td>P (wt%)</td>
<td>17.80</td>
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<tr>
<td>Ca (wt%)</td>
<td></td>
<td>13.59</td>
<td>12.20</td>
<td>11.69</td>
<td>12.25</td>
<td>12.16</td>
<td>13.89</td>
<td>13.79</td>
<td>13.73</td>
<td>14.26</td>
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<tr>
<td>Y (wt%)</td>
<td>4.00</td>
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<tr>
<td>La (wt%)</td>
<td>14.15</td>
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<td>Ce (wt%)</td>
<td></td>
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<tr>
<td>Pr (wt%)</td>
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<td>Nd (wt%)</td>
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<td>Sm (wt%)</td>
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<tr>
<td>Gd (wt%)</td>
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<td>18.09</td>
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<td></td>
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<tr>
<td>Dy (wt%)</td>
<td>4.00</td>
<td>18.56</td>
<td></td>
<td></td>
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<tr>
<td>Er (wt%)</td>
<td>4.00</td>
<td>19.87</td>
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<td></td>
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<tr>
<td>Pb (wt%)</td>
<td>74.26</td>
<td>71.59</td>
<td>88.15</td>
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<td></td>
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<tr>
<td>Th (wt%)</td>
<td></td>
<td>100.00</td>
<td>100.08</td>
<td>100.01</td>
<td>99.99</td>
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<td>100.00</td>
<td>100.01</td>
<td>100.02</td>
<td>100.01</td>
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</tr>
<tr>
<td>U (wt%)</td>
<td></td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>99.99</td>
<td>100.00</td>
<td>99.99</td>
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<td>100.00</td>
<td>100.01</td>
<td>100.01</td>
<td>100.01</td>
</tr>
</tbody>
</table>

absorption edge making it difficult to use. The UMB line is overlapped by the ThMγ peak (Fig. 2.3), but the peak can be resolved in a typical monazite and the overlap empirically corrected for. In geological samples, the KKa line may also overlap with the UMB peak (Fig. 2.3). This overlap can be avoided by not analysing monazite grain boundaries that are in contact with K-bearing minerals and monitoring apparent U concentrations throughout the monazite grains. The choice of background positions is hampered by the numerous ThM peaks and background discontinuities. In order to avoid these, a single point linear background is used and placed 1250 Sinθ below the UMB peak, after the ThM4 edge (Table 2.1; Fig 2.3).

The choice of Pb Mα or Mβ line is similarly constrained by the interferences in the PbM region in monazite. The higher intensity Pb Mα line suffers from a number of interferences including the ThMC₂₁,₂, 2LaLa and YLγ lines (Fig. 2.4). The PbMβ line, although of slightly lower intensity, provides a better choice of energy line because of its cleaner spectrum. The PbMβ line has one first-order overlap by the UMβ line and also the second-order (2) CeLa line (Fig. 2.4). The higher order 2CeLa line can be filtered from the analysis through the differential mode PHA settings. However, there is a small 2CeLa escape peak (an artefact of the low-pressure P10 gas-flow detector) which falls within the energy window of the PbMβ peak and must be corrected for (Fig. 2.4: Pyle et al., 2005). Because the size of the 2CeLa escape peak is very small, and is proportional to the CeLa peak (and therefore the Ce concentration) it is corrected for mathematically offline by the application of a measured correction factor of 0.0003% of the Ce concentration. The UMβ interference is corrected for empirically on-
line. Because of cascading interferences, the corrections must be done in order with the Th\(M\gamma\) on U\(M\beta\) done first followed by the U\(M\zeta_2\) on Pb\(M\beta\). To get clean background positions for the Pb region a 2 point curved background is used (Fig. 2.4, Table 2.1).

The choice of REE lines is dependant on which diffraction crystal is used. Using a PET crystal gives higher count rates for the REE lines (Fig. 2.5). High concentrations of both Ce and La in typical monazites means there are no interference issues with the Ce\(L\alpha\) and La\(L\alpha\) lines and the need for accurate Ce concentrations for Pb overlap corrections means the high-intensity La lines are measured on a PET crystal (Table 2.1). For higher mass REEs the larger D spacing in the PET crystal (2d = 8.74 nm) compared to the LiF crystal (2d = 4.02 nm) means the heavier REEs occur over a smaller Sin\(\theta\) range using a PET crystal than on a LiF crystal (Fig. 2.5). This means more interference issues with the REEs using a PET crystal. This, together with machine restrictions (long count times on elements using PET crystals means the non-essential REEs can’t be efficiently analysed using a PET crystal on the SX51). As a consequence the REEs are analysed using a LiF crystal. Because of the comparatively low concentrations of most REEs in monazite and the reduced intensity of the REE lines when using a LiF crystal (Fig. 2.5) on the SX51 only the high-pressure X-ray counter will give enough counts to maintain precision. The high-pressure P10 counter also has the advantage of
suppressing higher-order interferences on the REE’s. Because of less interference issues the REE $L\beta$ lines are used (Table 2.1).

The remaining element lines have been chosen because there are no interference issues with them and because they are the highest intensity lines available. The $Y L\alpha$, Ca$K\alpha$ and $P K\alpha$ lines are measured using a PET crystal (Table 2.1). The trace elements of Si and Al are also measured using the $K\alpha$ lines using a TAP crystal (Table 2.1).

2.3.4 Counting Times

Using the SX51 at Adelaide Microscopy at an accelerating voltage of 20 kV and a beam current of 100 nA, an intrinsic detector response of between 0.2 and 0.05 counts of Pb/s·nA·wt% is measured using a PET crystal and a low pressure P10 gas flow proportional counter. Because the precision of the spot age is dependant on the precision of the Pb, U and Th analysis it is necessary to count for a number of minutes on each of these peak and background positions. To collect enough counts to produce a statistically meaningful (and precise) peak to background ratio in a typical monazite it is necessary to count on the Pb peak for approximately 240 s and on each background position for 120 s each (Table 2.1). For a typical monazite with a Pb concentration of c. 2500 ppm a 1σ error of c. 110 ppm Pb is achieved (a 1σ counting error of < 5 %). Similarly U count times are 160 s for peak and 160 s background which produces a 1σ counting error of c. 2 %.

Because of the generally high concentration of

Figure 2.4. WD scans across the Pb region using a PET crystal. A) scans on Pb, Ce, La, U and Th standards showing the 2Ce$L\alpha$ and 2Ce$L\alpha$ escape peak and the UM$\Omega_2$ interferences on the Pb$M\beta$ line. B) scan on a natural monazite showing the relative sizes of the interferences peak on Pb$M\beta$ peak and the location of the Pb background positions.
Th in monazite (5 – 20 wt%) the count times are considerably lower, with a peak count time of 60 s and 30 s on each of the backgrounds. This produces a 1σ counting error of < 0.5 %. The counting times of all other analysed elements are given in Table 2.1. A typical single spot analysis of the entire 16 element package takes c. 10 minutes. However, these counting times are not fixed, and can be adjusted to suite particular monazite compositions.

2.4 Sample Preparation

The method outlined here is generally undertaken on polished thin sections but can also be applied to mounted grain separates and polished blocks. Because of the low levels of U and Pb in monazite it is particularly important to minimise contamination from the polishing process. The effectiveness of EPMA is also dependant on the polish of the sample; therefore, a good polish is required for accurate analyses. At the University of Adelaide, thin sections are either made in-house or externally. All polishing is done in-house where the environment can be controlled. A three stage polishing process has been found to give the best results. First a 3 μm diamond grit on a tin plate, followed by 3 μm diamond on a 1μm cloth lap and finally a 1 μm diamond on a ¼ μm cloth lap. No Pb-
bear samples are polished on these laps and the plates are cleaned and replaced periodically. The samples are thoroughly washed in acetone and deionised water between each stage. When transporting the samples they are kept in sealed containers to avoid contamination.

2.5 Data Collection Strategy, Analysis and Reduction

Williams et al. (2006) suggest two alternative strategies for collecting EPMA monazite age data. The ‘top-down’ method (e.g. Suzuki and Adachi, 1991; Montel et al., 1996; Cocherie et al., 1998; Montel et al., 2000; Cocherie and Albarede, 2001) involves collecting large numbers of analyses from multiple compositional domains and then using a statistical analysis to distinguish any age populations. The ‘bottom-up’ approach of Williams et al. (2006) involves detailed measurements restricted to specific compositional domains and therefore requires detailed X-ray maps of individual grains to be acquired prior to analysis (see also Pyle and Spear, 2003). Both these methods have various pros and cons and the method developed here is a combination of the two approaches.

The approach developed here involves the collection of large numbers of point analyses from individual samples (multiple monazite grains within a thin section). Individual monazites are first located either optically or using back-scattered electron imaging either on a scanning electron microscope or on the SX51. Individual grains are then characterised texturally (e.g. located within the fabric, shielded within major phases etc.). Selected grains are targeted with as many point analyses as are practical within the spatial constraints required for clean analyses (i.e. at least 10 μm apart and at least 10 μm from a grain boundary to account for the excitation volume of the electron beam). The collection of a large data set allows for better precision ages (lower errors) as individual 1σ spot errors can be between ± 30 to 60 Ma. Individual grains are not X-ray mapped prior to analysis because: (1) to map low concentration elements in monazite requires high beam currents (~ 150 nA) focused on to small areas for long durations (dwell times of over 100 ms) which causes sample damage, element migration and carbon coating degradation; (2) the process of mapping can be time consuming and may not produce any results if there are no compositional domains; (3) not all compositional domains are also age domains.

The analytical method adopted here uses a full suite of elements to allow for greater precision in ZAF corrections and also because it can produce geologically important information. Spot ages and chemical zoning in individual grains can be investigated by plotting various elements and spot ages (e.g. Y wt% vs. Th/Ce wt% or age vs. Y wt%). Grains which show significant age/compositional variation can then be X-ray mapped without affecting the precision of the ages.

Prior to age calculation, the raw compositional data are assessed and filtered to remove suspect analyses. Generally any data with totals below 95% or above 103% are excluded from the age pool because analyses outside these ranges introduce uncertainties into the ZAF corrections (subject to monazite composition). The raw compositional data are
then further scrutinised with analyses containing > 1 wt% Si, Ca or Al being excluded from the age pool (as discussed above monazite should contain only trace Si, Ca or Al and high values may indicate a contaminated spot analysis, i.e. the excitation volume included an adjacent mineral or an inclusion).

Prior to the age calculation, the Pb concentration is corrected for the small $2\text{Ce}L\alpha$ escape peak overlap by the relationship:

$$Pb^* = Pb(\text{wt\%}) - [Ce(\text{wt\%}) \times 0.0003] \quad (2)$$

The individual spot ages are then calculated using the age equation (Eq. 1). Individual spot errors are calculated using the approach of Montel et al. (1996). Individual errors for U, Th and Pb are calculated on the basis of the counting (Poisson) statistics of the elemental analysis. U, Th and Pb counting errors are calculated using the equation:

$$M(1\sigma) = M(\text{ppm}) \times \sqrt{(p_k + b_g)/(N_c \times (p_k - b_g))} \quad (3)$$

where $M$ is either U, Th or Pb, $p_k$ and $b_g$ are the peak and background counts respectively and $c_t$ is the counting time for that element. The uncertainty is then calculated on the age by propagating the uncertainties on U, Th and Pb through Eq. (1). All statistical analysis and data presentation thereafter is done using the Microsoft Excel geochronology add-in ISOPLOT (Ludwig, 2003).

2.6 Results of Comparative Study

As a test of the validity of the EPMA monazite setup on the Cameca SX51 outlined here, four previously dated monazite samples have been analysed using the described protocols. The samples have all been previously dated using isotopic methods and the isotopic data is available in the literature. The analysed samples have been selected to reflect a variety of ages, from Palaeoproterozoic to Ordovician.

2.6.1 Sample SB17

Sample SB17 is a grain mount of monazites from a felsic mylonitic shear zone from the southern Gawler Craton. These monazites have been isotopically dated using SHRIMP II and produced a concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1720 \pm 7 \text{ Ma (2\sigma)}$ and a $^{206}\text{Pb}/^{238}\text{U}$ age of $1715 \pm 35 \text{ Ma (2\sigma; Dutch et al., 2008; Chapter 3)}$. The monazites are heterogeneous, with $3.6–18.0 \text{ wt\% Th, 0.16–1.13 wt\% U and 0.22–1.68 wt\% Pb}$, so represent a good test that the various peak overlap protocols are effective and provide accurate analyses of Pb and U concentrations.

The EPMA age is $1703 \pm 7 \text{ Ma (n=60, MSWD = 0.54; Fig 6)}$. This age is slightly younger than the $^{207}\text{Pb}/^{206}\text{Pb}$ SHRIMP age but is within error of the $^{206}\text{Pb}/^{238}\text{U}$ age.

2.6.2 Sample GL4B

Sample GL4B consists of monazites extracted from a leucosome within granulite facies metapelites from the Reynolds Range in central Australia. These monazites were dated isotopically using SHRIMP II and produced a concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1566 \pm 3 \text{ Ma (2\sigma; Rubatto et al., 2001)}$. Chemically the monazites are fairly homogeneous in composition with $3.61–5.92 \text{ wt\% Th, 0.11–0.63 wt\% U and}$
0.32–0.51 wt% Pb. The EPMA age is 1561 ± 8 Ma (2σ, n= 111, MSWD = 0.9; Fig. 2.6) which is within error of the 207Pb/206Pb isotopic age.

2.6.3 MAdel Standard

The MAdel monazite standard consists of chips of a Pan-African aged monazite from Madagascar and is used as an age standard for LA-ICP-MS monazite dating at the University of Adelaide. MAdel has been isotopically dated using TIMS at the Massachusetts Institute of Technology and has a 206Pb/238U age of 518 ± 0.25 Ma (2σ) and a 207Pb/235U age of 514 ± 0.3 Ma (2σ; Payne, 2008; Payne et al., 2008; Wade et al., 2008). MAdel was dated twice using EPMA, once at the start of the analytical session and again at the end of the session (five days apart). The EPMA monazite ages are 516 ± 5 Ma (2σ, n= 110, MSWD = 1.136; Fig. 2.6) and 521 ± 4 Ma (2σ, n= 132, MSWD = 0.95; Fig. 2.6) respectively. These ages are within error of the isotopically determined age and demonstrate the stability and consistency of the SX51 and the developed monazite protocol.

2.6.4 Sample 222

Sample 222 consists of monazites extracted from the matrix of garnet-bearing leucosomes from within a biotite – sillimanite – plagioclase – garnet – quartz metapelitic from the Harts Range Group in central Australia. These monazites were dated isotopically via SHRIMP (Hand et al., 1999) and in-house LA-ICP-MS (Payne, 2008). SHRIMP isotopic analysis produced a 206Pb/238U age of 467 ± 4 Ma (2σ; Hand et al., 1999) while LA-ICP-MS analysis produced a 206Pb/238U weighted average age of 450 ± 5 Ma (2σ) and a concordia age of 453 ± 4 Ma (2σ; Payne, 2008). The monazites are homogeneous in composition with 5.9–8.13 wt% Th, 0.17–0.42 wt% U and 0.13–0.22 wt% Pb. The EMPA monazite age is 463 ± 6 Ma (2σ, n= 121, MSWD = 0.86; Fig. 2.6). The EPMA age is within error of the SHRIMP isotopically determined age and the LA-ICP-MS concordia age.

2.7 Application to an unknown

Here I have used the described methodology and procedures for EPMA monazite dating using the SX51 to constrain the timing of deformation and metamorphism in the Fishery Bay region of the southern Gawler Craton (Fig. 2.1).

2.7.1 Geological Setting

The basement geology of the southern Gawler Craton consists of three main rock packages (Fig. 2.1). The late Archaean to Palaeoproterozoic Sleaford Complex (Thomson, 1970) consists of a series of layered ortho- and paragneisses together with the upper crustal granitoids of the Dutton Suite (Fanning et al., 1988; Daly and Fanning, 1993; Fanning et al., 2007). Unconformably overlying this are the Palaeoproterozoic Hutchison Group and Price Metasediments which consist of a deformed and metamorphosed package of shallow marine sands, silts and chemical sediments (Parker and Lemon, 1982; Parker, 1993; Vassallo and Wilson, 2001). Juxtaposed along the eastern side of the Hutchison Group metasedimentary
rocks are the deformed granitoids of the 1850 Ma Donington Suite (Mortimer et al., 1988; Hoek and Schaefer, 1998).

The southern Gawler Craton has been affected by at least two large-scale deformational/metamorphic events. The earliest of these events affecting the late Archaean component was the 2440 – 2420 Ma Sleafordian Orogeny (Fanning et al., 1988; Fanning et al., 2007). This event has been interpreted to have reached granulite-facies conditions in the Carnot Gneisses (Fig. 2.1: Daly and Fanning, 1993: Chapter 4), but little is known about the structural development of this orogen as it has been pervasively overprinted by subsequent events (Vassallo and Wilson, 2002: Chapters 3, 4).
Chapter 2

The 1730 – 1690 Ma Kimban Orogeny dominates the structural architecture of the southern Gawler Craton (Parker, 1993; Vassallo and Wilson, 2001; Vassallo and Wilson, 2002). The crustal scale Kalinjala Shear Zone, which separates the Sleaford Complex and Hutchison Group sequences from the Donington granitoid suite (Fig. 2.1), is the most obvious structural feature of the Kimban Orogeny (Parker, 1980; Vassallo and Wilson, 2002: Chapter 5). The Kimban Orogeny reached granulite-facies conditions in the south and east, decreasing in grade to the north and west (Hand et al., 1995; Tong et al., 2004: Chapters 3, 4, 5).

The Fishery Bay region of the southern Gawler Craton (Fig. 2.1) consists of highly deformed and metamorphosed interlayered migmatic garnet ± cordierite ± orthopyroxene paragneisses, augen and charnockitic orthogneiss and garnet ± clinopyroxene ± orthopyroxene mafic granulites of the Carnot Gneisses. Tong et al. (2004) determined peak metamorphic conditions from garnet-bearing mafic granulites of up to c. 10 kbar at c. 800 °C. The structure of the Fishery Bay region has been described by Vassallo and Wilson (2002). The area is located on the western flank of the Kalinjala Shear Zone (Fig. 2.1) and consists of an early layer parallel fabric (SS1?) which has been folded by a series of inclined isoclinal and sheath folds (KD1 structures). These structures are then overprinted by a series of upright tight to isoclinal folds and shear zones (KD2 structures).

Implicit in the structural and metamorphic work of Vassallo and Wilson (2001; 2002) and Tong et al. (2004) is that the deformational features are c. 1700 Ma in age and are a result of the Kimban Orogeny (Reid et al., 2007; Dutch et al., 2008; Chapters 3, 4, 5). However, these workers didn’t directly constrain the timing of deformation with geochronology. Recently Duclaux et al. (2007) attributed the structure and metamorphic features of the southern Gawler Craton to the c. 2440 Ma Sleafordian Orogeny on the basis of an EMPA age of c. 1827 Ma from a cross-cutting cordierite bearing granitic vein from the northern Eyre Peninsula. Duclaux et al. (2007) used the structural features as the type example of hot-weak Archaean orogens. Therefore constraining the timing of metamorphism and deformation of the Carnot Gneisses in the Sleaford Bay region is of vital significance to: (1) understanding the tectonic development of the southern Eyre Peninsula (Dutch et al., 2007) and; (2) to inferences about the tectonic style during the Archaean.

2.7.2 Results

Three monazite-bearing metapelitic samples have been selected to constrain the timing of metamorphism and deformation in the Carnot Gneisses at Fishery Bay.

Sample FB10 is a coarse-grained garnet bearing metapelitic gneiss from within the fabric interpreted as KS1 by Vassallo and Wilson (2002) and by Duclaux et al. (2007) to be Archaean in age. All monazite grains are located within the fabric at grain boundaries adjacent to predominantly quartz, plagioclase and K-feldspar but also biotite and garnet. Four monazite grains were analysed on the SX51 producing a unimodal age of 1707 ± 20 Ma (n= 62, MSWD = 1.04: Fig. 2.7). Chemically the monazites are homogeneous and no distinctive
chemical-age populations can be differentiated (Fig. 2.7).

Samples FB15 and FB19 are both highly strained garnet-bearing metapelitic gneisses located within vertical N-S orientated dextral shear zones which crosscut and deform the $KS_1$ fabric. The shear zones are interpreted as $KD_2$ structures by Vassallo and Wilson (2002) and contain the regional lineation attributed to Archaean deformation by Duclaux et al. (2007). All monazite grains are located within the high-strain fabric surrounded by quartz, plagioclase
and K-feldspar.

Four monazite grains were analysed from sample FB15. These grains display some clear chemical differences with mz4 having high Th and high Y (zone 1), mz3 contains a low Th, low Y zone (zone 2) and mz1 and mz2 are indistinguishable (zone 3; Fig. 2.7). Looking at the ages of these chemical zones individually; zone 1 produces an age of 1691 ± 9 Ma, zone 2 produces an age of 1693 ± 58 Ma (the low Th content introduces large uncertainties on the ages), while zone 3 produces 1694 ± 14 Ma. These ages are all within error and are therefore either equivalent or grew within the age resolution of the technique. Pooling all the analyses (excluding the low precision ages of zone 2) produces an age of 1690 ± 8 Ma ($n = 72$, MSWD = 0.79; Fig. 2.7).

Four monazite grains from sample FB19 display clear chemical differences (Fig. 2.7). Mz1 and 2 are indistinguishable with a spread of Y values and high Th (zone 1). Mz3 has a similar spread of Y values but is predominantly low in Th (zone 2) while mz4 is a high Th monazite but a very homogeneous low Y content (zone 3). Zone 1 produces a pooled age of 1697 ± 18 Ma while zone 2 produces 1650 ± 54 Ma and zone 3 produces 1718 ± 17 Ma. These ages are again within error and produce a pooled age of 1708 ± 12 Ma ($n = 50$, MSWD = 1.3; Fig. 2.7; including low Th zone 2 analyses produces an age of 1705 ± 12 Ma).

Although the precision offered by the EPMA monazite technique is not high enough to resolve chronological differences between the timing of $KD_1$ and $KD_2$ deformation recorded in the structural relationships at Fishery Bay, it does provide a clear temporal constraint, linking the structural and metamorphic development of the Carnot Gneisses in Fishery Bay to the Kimban Orogeny. This indicates that the structural interpretation of Duclaux et al. (2007) is not consistent with the age framework of the fabrics in the Carnot Gneiss, and that the structural style is not indicative of Archaean tectonics.

2.8 Conclusions

EPMA monazite dating provides an accurate and inexpensive tool for age determination. It is readily preformed in-situ and using the method developed here provides extra chemical information which may aid in the geological interpretation of the produced ages. Although EPMA monazite dating (or any low level EPMA analysis) is not a trivial procedure, with the correct protocols, machine setup and calibration it is possible to achieve monazite chemical ages which are comparable with those obtained via more traditional isotopic methods. Even though the precision of the above technique is not generally sufficient to resolve individual events within an orogenic event, it provides an efficient way to add geochronological data to any determined $P-T$ path and allows for rapid verification of the ages of deformation and metamorphism of the individual assemblages which are used to constrain them.

Acknowledgements

David Steele is gratefully thanked for all his assistance with getting me up to speed with the procedures (and pointing out the pitfalls) I needed to get this system operational on the SX51. He is also thanked for providing me
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Chapter 2

EPMA Monazite Dating


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Appendix 2.1. Sample Locations

<table>
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Datum WGS 84 Zone 53
Chapter 3
High-grade Palaeoproterozoic reworking in the southeastern Gawler Craton, South Australia.


Abstract

SHRIMP U-Pb geochronology and monazite EPMA chemical dating from the southeast Gawler Craton has constrained the timing of high grade reworking of the early Palaeoproterozoic (c. 2450 Ma) Sleaford Complex during the Palaeoproterozoic Kimban Orogeny. SHRIMP monazite geochronology from mylonitic and migmatitic high-strain zones that deform the c. 2450 Ma peraluminous granites indicates that they formed at 1721 ± 3 and 1725 ± 2 Ma. These are within error of EPMA monazite chemical ages of the same high-strain zones which range between 1691 Ma and 1736 Ma. SHRIMP dating of titanite from peak metamorphic (10 kbar at 730°C) mafic assemblages give ages of 1712 ± 8 and 1708 ± 12 Ma. The post-peak evolution is constrained by partial to complete replacement of garnet – clinopyroxene bearing mafic assemblages by hornblende – plagioclase symplectites, which record conditions of c. 6 kbar at 700°C, implying a steeply decompressional exhumation path. The timing of Palaeoproterozoic reworking corresponds to widespread deformation along the eastern margin of the Gawler Craton and the development of the Kalinjala Shear Zone.

NOTE: This publication is included on pages 45 - 74 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1080/08120090802266550
Chapter 4

Tectonothermal evolution of reworked Archaean granulite-facies metapelites in the southern Gawler Craton, Australia.

Abstract

The Shoal Point region of the southern Gawler Craton consists of a series of reworked granulite-facies metapelitic and metaigneous units belonging to the Late Archaean Sleaford Complex. Structural evidence indicates three phases of fabric development with \( D_1 \) retained within boudins, \( D_2 \) consisting of upright open to isoclinal folds producing an axial planar fabric and \( D_3 \), a highly planar vertical high-strain fabric that overprints the \( D_2 \) fabric. Chemical EMPA monazite and garnet Sm-Nd geochronology constrain the \( D_1 \) event to the c. 2450 Ma Sleaford Orogeny while the \( D_2 \) the \( D_3 \) events are constrained to the 1730–1690 Ma Kimban Orogeny. \( P-T \) pseudosections constrain the metamorphic conditions for the Sleafordian Orogeny to between 4.5–6 kbar and 750–780 °C. Subsequent Kimban-aged reworking reached peak metamorphic conditions of 8–9 kbar at between 820–850 °C during the \( D_2 \) event. This was followed by near isothermal decompression to metamorphic conditions <6 kbar and 790–850 °C associated with the development of the \( D_3 \) high-strain fabric. The \( P-T-t \) evolution of the Shoal Point rocks reflects transpressional exhumation of lower crustal rocks during the Kimban Orogeny and the development of a regional transpressional flower structure.
Dutch, R. et al. Tectonothermal evolution of reworked Archaean granulite-facies metapelites in the southern Gawler Craton, Australia. 

*Not yet published.*

NOTE: This publication is included on pages 75 - 114 in the print copy of the thesis held in the University of Adelaide Library.
Chapter 5
The tectonothermal evolution of the crustal scale Kalinjala Shear Zone, southern Gawler Craton, Australia

Abstract

The Kalinjala Shear Zone, in the southern Gawler Craton, is a crustal scale structure which forms the main structural element of the poorly exposed Kimban Orogen. Samples from the core and the flank of the shear zone record a similar structural development with an initially dextrally transpressive system resulting in a layer parallel migmatitic gneissic to mylonitic $KS_1$ fabric which was subsequently deformed and reworked by upright folds and discrete $KD_2$ east-side-down sub-solidus mylonitic shear zones during east-west compression. In-situ EPMA monazite and garnet Sm-Nd geochronology constrain the timing of deformation and metamorphism along the Kalinjala Shear Zone to the craton-wide Kimban Orogeny between 1720 and 1700 Ma. Metamorphic $P-T$ analysis and pseudosections constrain the peak $M_1$ conditions in the core of the shear zone to 10–11 kbar at c. 800 °C reflecting deep crustal conditions at depths of up to 30 km. On the flank of the shear zone the $M_1$ conditions reached 6–7 kbar at 750 °C followed by sub-solidus reworking during $KD_2$ at conditions of 3–4 kbar at 600–660 °C, suggesting a maximum burial of < 24 km. Cooling rates determined from garnet zoning profiles suggest that the core of the shear zone cooled at rates in excess of 40–80 °C Ma$^{-1}$ while the flank underwent much slower cooling at < 10 °C Ma$^{-1}$. The rapid cooling and inferred decompression in the core of the shear zone reflects rapid burial and exhumation of lower-crustal material into the mid-crust during the Kimban Orogeny along the Kalinjala Shear Zone. The absence of evidence for extension indicates that differential exhumation and the extrusion of lower-crustal material into the mid-crust was driven by transpression along the Kalinjala Shear Zone and highlights the role of transpression in creating large variations in vertical exhumation over relatively short lateral extents.
Dutch, R. et al. The tectonothermal evolution of the crustal scale Kalinjala Shear Zone, southern Gawler Craton, Australia

Not yet published.

NOTE: This publication is included on pages 115 - 155 in the print copy of the thesis held in the University of Adelaide Library.
Chapter 6
Retention of Sm-Nd isotopic ages in garnets subjected to high-grade thermal reworking: Implications for diffusion rates of major and rare earth elements and the Sm-Nd closure temperature.

Abstract

Garnet is a vital mineral for determining constrained $P$-$T$-$t$ paths as it can give both the $P$-$T$ and $t$ information directly. However, estimates of the closure temperature of the Sm-Nd system in garnet vary considerably leading to significant uncertainties in the timing of peak conditions. In this study five igneous garnets from a 2414 ± 6 Ma garnet–cordierite bearing S-type granite, subjected to high-$T$ reworking, have been dated to examine their diffusional behaviour in the Sm-Nd system. Garnets of 8, 7, 6, 6 and 2.5 mm diameter were compositionally profiled and then dated, producing two point Sm-Nd isochron ages of 2412 ± 10 Ma, 2377 ± 5 Ma, 2370 ± 5 and 2365 ± 8 Ma and 2313 ± 11 Ma respectively. A direct correlation exists between grain size and amount of resetting highlighting the effect of grain size on closure temperature. Major element EPMA and LA-ICP-MS REE traverses reveal homogeneous major element profiles and relict igneous REE profiles. The retention of REE zoning and homogenisation of major element zoning suggests that diffusion rates of REEs are considerably slower than that of the major cations in garnet. The retention of REE zoning and the lack of resetting in the largest grains suggests that Sm-Nd closure temperature in garnet is a function of grain-size, thermal history and REE zoning in garnet.

NOTE: This publication is included on pages 157 - 186 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1007/s00410-009-0418-1
Chapter 7
Summary

7.1 Introduction

The aim of this thesis was to develop a better understanding of the timing, distribution and tectonothermal evolution of the major orogenic systems expressed in the southern Gawler Craton. This process involved the development of in-situ Electron Microprobe (EPMA) monazite geochronology and a study into the diffusion properties of the major and rare earth elements in garnets subjected to reworking to appraise the use of the Sm-Nd geochronometer in reworked assemblages. Both of these techniques were utilised to constrain the timing of deformation and metamorphism in the complexly reworked rock units of the southern Gawler Craton. The structural and metamorphic evolution of the southern Gawler Craton was then constrained using a combination of these geochronological techniques, together with detailed petrographic, metamorphic and structural analysis, applied to specific regions of interest. The specific regions were chosen as they represent the different lithologies across the southern Gawler Craton, from the upper-crustal Sleaford Complex units of the Dutton Suite in Coffin Bay to the lower-crustal units of the Sleaford Complex at Shoal Point to the overlying metasediments of the Hutchison Group at Port Neill and Mine Creek. The results of this study form a significant component of a larger collaborative effort to develop a coherent and constrained geological framework for the evolution of the Gawler Craton.

The methods developed and utilised in this study are also directly relevant to any region with limited exposure. Targeted in-situ microanalysis and geochronology combined with metamorphic phase-equilibria modelling as applied here can help refine the P-T-t evolution of poorly exposed and constrained terraines world-wide.

7.2 Thesis Summary

7.2.1 In-situ EPMA monazite Geochronology as a tool for constraining event timing in reworked assemblages

Chapter 2 presented a comprehensive analytical procedure and protocol for in-situ EPMA monazite geochronology developed on a Cameca SX51 Electron Microprobe housed at Adelaide Microscopy in the University of Adelaide. In-situ EPMA monazite geochronology is particularly suited to constraining ages within complexly reworked units. The small spatial resolution allows for the dating of small mineral grains and the in-situ nature of the analysis allows for individually dated grains to be microstructurally constrained.

In order to verify the reliability and validity of the technique, a comparative study using four previously isotopically dated samples was conducted. The results showed a good correlation between the isotopically derived ages and the ages obtained via EPMA monazite
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gEOCHRONOLOGY, with a discrepancy of less than 1%, indicating the robustness of the technique. The technique developed here has the added advantage of collecting a large amount of additional chemical data from individual grains. These data allow for the ability to link the growth of accessory phases with major phases in the assemblage, thereby providing an additional control in constraining the timing of metamorphic mineral growth. Even though the age precision of the EPMA monazite technique is generally not sufficient to resolve individual ‘events’ within a single orogeny, it provides an efficient way to add geochronological data to any determined P-T path, and allows for rapid verification of the ages of deformation and metamorphism for the individual assemblages which are used to constrain them. It is particularly useful in regions such as the Gawler Craton, which has undergone a number of widely spaced (in geological time) reworking events, for differentiating between the effects of each orogenic event and therefore reducing the risk of producing an invalid, amalgamated P-T path.

7.2.2 Reworking the southeastern Gawler Craton

Chapter 3 presented EPMA and SHRIMP U-Pb monazite geochronology from shear zones and SHRIMP U-Pb titanite geochronology from mafic assemblages which constrain the timing of high-grade reworking in the upper-crustal Dutton Suite of the late-Archaean Sleaford Complex. This was coupled with structural mapping and thermobarometric analysis to determine the geological evolution of the Coffin Bay Peninsula and the P-T conditions of the metamorphism recorded in the deformed metabasic dykes.

EPMA monazite and SHRIMP monazite and titanite geochronology indicates that a series of predominantly N-NE trending migmatitic and mylonitic shear zones developed on the Coffin Bay Peninsula between 1725 and 1700 Ma during the Kimban Orogeny. Granulite facies metamorphism at this time is recorded in deformed and metamorphosed mafic dykes, which intrude the peraluminous Sir Isaac Granite. Peak metamorphism was followed by near-isothermal decompression during the exhumation and juxtaposition of these lower-crustal rocks against the upper-crustal Price Metasediments along a regional scale interpreted shear system. These results imply that the metamorphic architecture of the Kimban Orogen in the south-eastern Gawler Craton is defined by panels of dramatically contrasting metamorphic grade, reflecting large local gradients in the degree of exhumation.

7.2.3 Reworking the Sleaford Complex

Chapter 4 presents an integrated geological study into the evolution of the Carnot Gneiss from the Shoal Point region of the southern Gawler Craton. A combination of structural mapping and quantitative metamorphic modelling of metapelitic assemblages was used to constrain the evolution of this region. This was then temporally constrained by a combination of in-situ EMPA monazite and garnet Sm-Nd geochronology.

The results show that the late Archaean Sleaford Complex orthogneisses and
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Summary

metapelitic units at Shoal Point contain a complex polymetamorphic history representing two granulite-facies events. The earliest event is recorded by granulite-facies assemblages contained within boudins, protected from subsequent deformation. Geochronology places this metamorphic event at c. 2455 Ma which is interpreted to be the early stages of the Sleafordian Orogeny. The metamorphic conditions of between 4.5–6 kbar and 750–780 °C represent the first quantitative constraints on the Sleafordian Orogeny from the southern Gawler Craton.

Subsequent deformation has been temporally constrained to the 1730–1690 Ma Kimban Orogeny. Early Kimban deformation resulted in upright, open to tight, shallowly south plunging folds producing a weak $KS_1$ axial planar fabric. This was associated with peak metamorphic conditions of 8–9 kbar at between 820–850 °C. This was followed by late Kimban-aged sub-horizontal east-west flattening producing isoclinal folds and vertical, planar high-strain zones which overprint and crosscut the $KS_1$ fabric. This was associated with near isothermal decompression to metamorphic conditions <6 kbar and 790–850 °C.

7.2.4 Evolution of the Kalinjala Shear Zone

Chapter 5 presents an integrated structural, metamorphic and geochronological study from two well exposed areas of the crustal scale Kalinjala Shear Zone. Pressure-temperature constraints from thermobarometry and $P-T$ pseudosections together with cooling rates derived from garnet zoning profiles, from the core of the Kalinjala Shear Zone at Port Neill are compared with those from the flank of the shear zone at Mine Creek, highlighting the variation in metamorphic pressures across the shear zone.

The results of targeted in-situ EPMA monazite geochronology has constrained the timing of deformation and metamorphism along the crustal-scale Kalinjala Shear Zone to the craton-wide Kimban Orogeny between 1720 and 1700 Ma. In this region the Kimban Orogeny developed as a dextrally transpressive system resulting in a layer parallel migmatitic gneissic to mylonitic $KS_1$ fabric which was subsequently deformed and reworked by upright folds and discrete $KD_2$ east-side-down sub-solidus mylonitic shear zones during east-west compression. Metamorphic $P-T$ analysis and pseudosections constrain the peak $M_1$ conditions in the core of the Kalinjala Shear Zone to 10–11 kbar at c. 800 °C reflecting lower crustal conditions. Forty kilometres to the south at Mine Creek the $M_1$ conditions only reached 6–7 kbar at 750 °C followed by sub-solidus reworking during $KD_2$ at conditions of 3–4 kbar at 600–660 °C. Rapid cooling and inferred decompression of the Port Neill section units reflects rapid burial and emplacement of lower-crustal material into the mid-crust during the Kimban Orogeny along the Kalinjala Shear Zone while slow cooling and high geothermal gradients in the flank of the shear zone at Mine Creek suggest slower exhumation and longer residence times at mid-crustal depths. The absence of evidence for extension indicates that the differential exhumation and the extrusion of lower-crustal material into the mid-crust was primarily driven by transpression along the Kalinjala Shear Zone.
7.2.5 Garnet Sm-Nd isotope systematics

Chapter 6 presents a natural diffusion experiment exploring aspects of the closure temperature of the Sm-Nd system in garnet and the comparative rates of diffusion of major and RE elements in garnet. The Point Sir Isaac granite contains a magmatic garnet – cordierite bearing assemblage that formed during granite crystallisation. The age of granite crystallisation has been constrained to 2414 ± 6 Ma by LA-ICP-MS monazite U-Pb geochronology. The Sir Isaac Granite underwent thermal reworking at conditions of c. 750 °C and 10 kbar during the Kimban Orogeny at c. 1720 Ma. Five individual garnets of different sizes were analysed by major element and REE profiling and isotopically dated using the Sm-Nd system.

The results show that the Sm-Nd garnet ages from magmatic garnets display a systematic relationship with grain-size. The largest garnet (8 mm diameter) effectively records the magmatic age of 2412 ± 10 Ma, while the smaller garnets preserve slightly younger ages (2377 ± 5 Ma for a 7 mm grain, 2370 ± 5 and 2365 ± 8 for two 6 mm grains and 2313 ± 11 for a 2.5 mm grain). This suggests the Sm-Nd system remained approximately closed during high-grade reworking.

Major elements in garnet show homogeneous, flat zoning profiles. Isopleths for composition in garnet on a modelled P-T pseudosection indicate that the major elements represent Sleafordian (magmatic) compositions. REE profiles show that the garnets preserve primary, growth zoned REE patterns, suggesting that REE diffusion is considerably slower than the major elements in garnet, in disagreement with results published from experimental studies. The ability of garnet to record growth ages is a function of grain-size, thermal history and, importantly, on the way the REEs are zoned within garnet. Garnets with medium to heavy REE enriched cores are more likely to retain their peak ages compared with garnets that show medium to heavy REE enriched rims. This suggests that the utility of Sm-Nd dating of garnet is strongly controlled by the growth behaviour of medium to heavy REE partitioning accessory minerals.

7.3 Constraints on the Southern Sleafordian Orogeny

Previous workers have been divided on the age of granulite-facies metamorphism recorded in the late Archaean Sleaford Complex basement. Some workers believed the assemblages were entirely Sleafordian in age and that the Kimban overprint was lower grade (e.g. Fanning et al., 1981; Fanning et al., 1988; Daly and Fanning, 1993) while others have suggested the assemblages are purely a result of the Kimban Orogeny and there is no metamorphic evidence for a high-grade Sleafordian event (e.g. Vassallo and Wilson, 2002; Tong et al., 2004).

A study by Duclaux et al. (2007) used numerical models to investigate the evolution of warm continental lithosphere during convergence and subsequent unloading, using the southern Gawler Craton as their primary field example. They posited that the north-south trending fabrics in the southern Gawler Craton were the result of lateral, orogen-parallel, collapse during the waning stages of
Chapter 7

Summary

Sleafordian-aged deformation. Their argument is constrained by an EPMA age of 2479 ± 20 Ma for monazite included within porphyroblastic garnet and an age of 1827 ± 10 Ma for a late, cordierite-bearing, granitic dyke from an outcrop of the Sleaford Complex in the central Eyre Peninsula. From this they suggest that 2479 ± 20 Ma is the timing of fabric development and that deformation had ceased prior to 1827 ± 10 Ma. Dutch et al. (2007) suggested that the 2479 ± 20 Ma age for garnet included monazite indicates high-grade metamorphism during the Sleafordian Orogeny but contested that the bulk of the structural and geochronological data from the southern Gawler Craton indicate that these north-south orientated fabrics were the result of the Palaeoproterozoic Kimban Orogeny.

The results of the current study support the assertions of Dutch et al. (2007) and the interpretations of Vassallo and Wilson (2002) and Tong et al. (2004) which suggest that the north-south orientated fabrics in the southern Gawler Craton are a result of the Kimban Orogeny and that the Sleafordian Orogeny has been thoroughly overprinted.

Granulite-facies metapelitic assemblages contained within boudins in the Kimban-aged fabrics have retained their primary 2455 ± 7 Ma Sleafordian-aged metamorphic assemblages. A $P-T$ pseudosection for this assemblage indicates peak metamorphic conditions of between 4.5–6 kbar and 750–780 °C. These $P-T$ conditions equate to a minimum geothermal gradient of c. 47 °Ckm$^{-1}$ (based on 1 kbar = 3.5 km of burial), indicating metamorphism occurred at significantly elevated geothermal gradients. This correlates well with high-grade metamorphism in the Christie Gneiss (northern Gawler Craton) which occurred at c. 2450–2443 Ma, constrained by SHRIMP zircon (Fanning, 2002) and monazite (McFarlane, 2006). Metamorphic constraints from the un-reworked Challenger Gneiss indicate peak metamorphic conditions of 800–850 °C at 7.5 ± 1.5 kbar (Tomkins and Mavrogenes, 2002), which are consistent with conditions of 750–800 °C at 4.5–5.5 kbar obtained by Teasdale (1997) from the western Mulgathing Complex. These $P-T$ conditions equate to geothermal gradients in excess of 30 and 43 °Ckm$^{-1}$ respectively. These results suggest the Sleafordian Orogeny was a regional event, characterised by elevated geothermal gradients, which affected the entire Archaean core of the Gawler Craton.

7.4 The Evolution of the Southern Kimban Orogeny

The results of this study allow us to place constraints on the tectonothermal evolution of the Kimban Orogeny. Recent geochronological data (Fig. 7.1) from across the Gawler Craton (Teasdale, 1997; Hopper, 2001; Betts et al., 2003; Swain et al., 2005; Payne et al., 2008) and into Antarctica (Goodge et al., 2001; Zeh et al., 2004; Duclaux et al., 2008) indicate that the Kimban Orogeny was a significant craton wide thermal event. So a clear understanding of the tectonothermal evolution of this orogenic event is vital for our understanding of the evolution of the Gawler Craton, and Proterozoic Australia as a whole.

The geochronology presented in this thesis constrains the timing of the Kimban Orogeny to between 1725–1690 Ma in the southern Gawler Craton. The structural data presented
Figure 7.1. 1st VD magnetic intensity image of the Gawler Craton with the distribution of Kimban Orogeny metamorphic ages. 1, Dutch et al. 2008 (Chapter 3); 2, Chapter 4; 3, Dutch et al. 2007 (Chapter 2); 4, Jagodzinski et al. 2006; 5, Reid et al. 2007; 6, Chapter 5; 7, Fanning et al. 2007; 8, Hopper 2001; 9, Payne et al. 2008; 10, Howard et al. 2008; 11, Teasdale 1997; 12, Finlay 1993
here from across the southern Gawler Craton complement and extend the work of Vassallo and Wilson (2001; 2002). These data suggest the Kimban Orogeny involved two phases of deformation. $KD_1$ is characterised across the region by the development of north-south trending upright tight to isoclinal folds and meso- and macroscopic sheath folds produced during a dextral top-to-the-north shearing event synchronous with north-south stretching. Fold plunges parallel a primary north-south trending linear fabric defined by prolate-shaped mineral aggregates and aligned platy minerals. This linear fabric is predominantly shallowly plunging but in places plunges steeply, to the north or south. In places a strongly developed, high-grade, mylonitic fabric is developed which grades to a weakly developed axial planar fabric, both of which are primarily sub-vertical in orientation. This phase of deformation is interpreted to have formed in an overall dextral transpressional system with a component of sub-horizontal constriction.

The second phase of Kimban-aged deformation ($KD_2$) is characterised by curvilinear high-strain to mylonite zones and tight to isoclinal upright to overturned folds, grading to open to tight upright and overturned folds in the granitic lithologies of the Dutton Suite, which overprint the $KD_1$ fabrics. Conjugate shear sets and symmetrically folded mafic dykes suggest that the $KD_2$ deformation involved a component of east-west orientated flattening across the strike of the Kimban Orogeny. Mineral stretching lineations in $KD_2$ high-strain fabrics vary from steeply to shallowly plunging to predominantly the south. The variation in lineation plunge across the orogen suggests the entire orogen may have behaved in a triclinic manner, with a shear component parallel to, and a non-coaxial shortening component normal to, the strike of the orogen.

The metamorphic evolution of the southern Kimban Orogeny is characterised by large variations in the amount of exhumation over short lateral extents (Fig. 7.2). The metamorphic evolution of the Coffin Bay, Shoal Pt, Fishery Bay (Tong et al., 2004) and Port Neill regions all display peak medium-pressure high-temperature (MPHT) metamorphic conditions of 730–850 °C at between 8–11 kbar followed by near isothermal decompression to low-pressure high-temperature (LPHT) conditions below 6 kbar (Fig. 7.2). This is in stark contrast to the Mine Creek region which never experienced conditions above 6 kbar, and the Price Metasediments and Hall Bay Volcanics which contain andalusite and chloratoid bearing assemblages indicating pressures < 4 kbar (Fig. 7.2). The metamorphic grade decreases to low- $P$ amphibolite-facies conditions in the northern Eyre Peninsula (Parker, 1993). These varying metamorphic pressures indicate variations in exhumation on the order of 17–21 km (based on 3.5 km per 1 kbar) across horizontal scales of 20–30 km, suggesting a nearly 1:1 relationship between vertical exhumation and horizontal extent.

Due to the limited outcrop in the southern Gawler Craton it is difficult to accurately constrain a model for the development of the Kimban Orogeny. The lack of evidence for post orogenic extension suggests that the exhumation was primarily driven by transpressional deformation during the development of the Kimban Orogeny itself.
Figure 7.2. Collection of $P$-$T$ and geochronology data for the southern Gawler Craton displaying the variation in degree of exhumation along strike of the Kimban-aged structural fabrics. The $P$-$T$ paths suggest the Kimban Orogeny developed along a clockwise $P$-$T$ path in the southern Gawler Craton. $^1$ Geochronology of Reid et al. 2007; $^2$ $P$-$T$ data of Tong et al. 2004.
Initial $KD_1$ deformation resulted in the reactivation of pre-existing structures into predominantly dextral, sub-vertical high-strain and mylonite zones, including the crustal scale Kalinjala Shear Zone, and regional scale open to isoclinal upright folding during regionally dextral transpression (see Fig. 4.16b; Vassallo and Wilson, 2001; Vassallo and Wilson, 2002). This resulted in basement-involved basin inversion burying of much of the basement to the lower crust and producing the MPHT peak metamorphic conditions.

The $KD_2$ phase of deformation, dominated by sub-horizontal east-west flattening, led to the development of structures characterised by isoclinal folding and the development of planar curvi-linear shear- and mylonite zones (see Fig. 4.16c; Vassallo and Wilson, 2001; Vassallo and Wilson, 2002). Triclinic movement along these zones has resulted in the exhumation of lower-crustal units into the mid crust during $KD_2$. The Kimban Orogeny in the southern Gawler Craton is therefore expressed by an obliquely exposed transpressional ‘flower structure’ geometry (e.g. Vassallo and Wilson, 2001; Vassallo and Wilson, 2002; Chetty and Rao, 2006). This model provides a mechanism to produce the apparent rapid lateral variation in metamorphic grade observed across the southern Gawler Craton, which characterises the metamorphic architecture of the southern Kimban Orogeny.

7.5 Future Work

The work presented here provides an important contribution to developing a consistent constrained geological framework for the Gawler Craton. However, the southern Gawler Craton is one small part of the larger Gawler Craton which, in terms of the metamorphic and temporal evolution, has been largely unexplored and would be logical goals for future work.

1. The recent discovery of Kimban metamorphic ages from the northern and western Gawler Craton (Fig. 7.1) have opened up the possibility to constrain the metamorphic evolution of the Kimban Orogeny across the Gawler Craton. At present there has been no investigation into the metamorphic evolution of these units. The methods developed and utilised in this thesis are highly applicable to regions such as the northern Gawler Craton, where there is little or no outcrop and all geological investigations must be done through available drill core samples.

2. At present there has been little exploration of the extent of the Kimban overprint in the central Gawler Craton. Rigorous dating of fabrics in this area via targeted geochronology may help to reveal the extent of the Kimban Orogeny in the Central Gawler Craton.

3. These points above, together with further geochronological, structural and metamorphic work in Antarctica may help to produce further correlations between the southern Australia and Antarctica and further unravel the Kimban Orogeny, providing a clearer large scale model for its evolution and what it means for Proterozoic reconstructions.

4. A number of workers have recently
proposed the possibility that the Gawler Craton forms an orocline (e.g. Fraser and Reid, 2008; Stewart and Betts, 2008). Targeted geochronology in areas such as the western Gawler Craton, together with structural and metamorphic analysis, such as used in this thesis, may help provide links or preclude this hypothesis.

(5) The recent discovery of 3150 Ma granitic rocks in the southern Gawler Craton (Fraser, 2008) leads to the possibility of other undiscovered timelines existing in the Gawler Craton. A systematic geochronological exploration will help to resolve the ambiguities in the existing age framework of the Gawler Craton.

References


Chapter 7

Summary


