EPMA monazite constraints on the timing of deformation and metamorphism in the southern Kalinjala Shear Zone, Gawler Craton

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Introduction

Determining the timing of deformation and metamorphism with geochronology is vital for developing a constrained tectonic evolution for a rock package or region (e.g. Mawby, Hand and Foden 1999; Rutherford et al. 2006; Collins et al. 2007; Kelsey et al. 2007). Failure to directly constrain the timing of deformation can lead to erroneous interpretations of the geological evolution, for example, with temporally distinct metamorphic events being linked to generate a false P–T evolution or attributing structural features and the determined structural evolution to the wrong orogenic event (cf. Dirks, Hand and Powell 1991; Hand et al. 1992; Dutch, Hand and Clark 2005).

The late Archaean Sleaford Complex (Thomson 1970; Thomson 1980) in the southern Gawler Craton of southern Australia (Fig. 1) consists of a complexly deformed and metamorphosed rock package including the granulite-facies Carnot Gneisses in the Sleaford Bay region (Fig. 1). This region contains evidence for a number of high-grade metamorphic and deformation events which include: (i) the 2450–2420 Ma Sleafordian Orogeny (Fanning, Oliver and Cooper 1981; Fanning et al. 1988; Daly and Fanning 1993; Fanning, Reid and Teale 2007); (ii) the c. 2000 Ma Miltalie Event (Daly, Fanning and Fairclough 1998; Fanning, Reid and Teale 2007); (iii) the c. 1850 Ma Cornian Orogeny (Reid et al. 2008); and (iv) the c. 1730–1690 Ma Kimban Orogeny (Parker 1993; Hoek and Schaefer 1998; Vassallo and Wilson 2002; Reid et al. 2007; Dutch, Hand and Kinny 2008).

Traditionally the Sleaford Complex was interpreted to have undergone a dominantly high temperature – low pressure granulite-facies metamorphic event during the Sleafordian Orogeny at c. 2450–2420 Ma (Fanning, Oliver and Cooper 1981; Fanning et al. 1988; Daly and Fanning 1993). However, Parker et al. (1988) suggested that the Sleaford Complex only records the Palaeoproterozoic (c. 1730–1690 Ma) Kimban Orogeny, and that any evidence of the earlier Sleafordian Orogeny has been thoroughly transposed and overprinted by the latter event. Recently, Vassallo and Wilson (2001, 2002) and Tong, Wilson and Vassallo (2004) presented thorough structural and metamorphic studies of the Sleaford Complex and the Carnot Gneisses. Implicit in their determined structural and metamorphic framework is that the deformational features are c. 1700 Ma in age and are a result of the Kimban Orogeny (Reid et al. 2007; Dutch, Hand and Kinny 2008), however, they didn't directly constrain the timing of this with geochronology. More recently

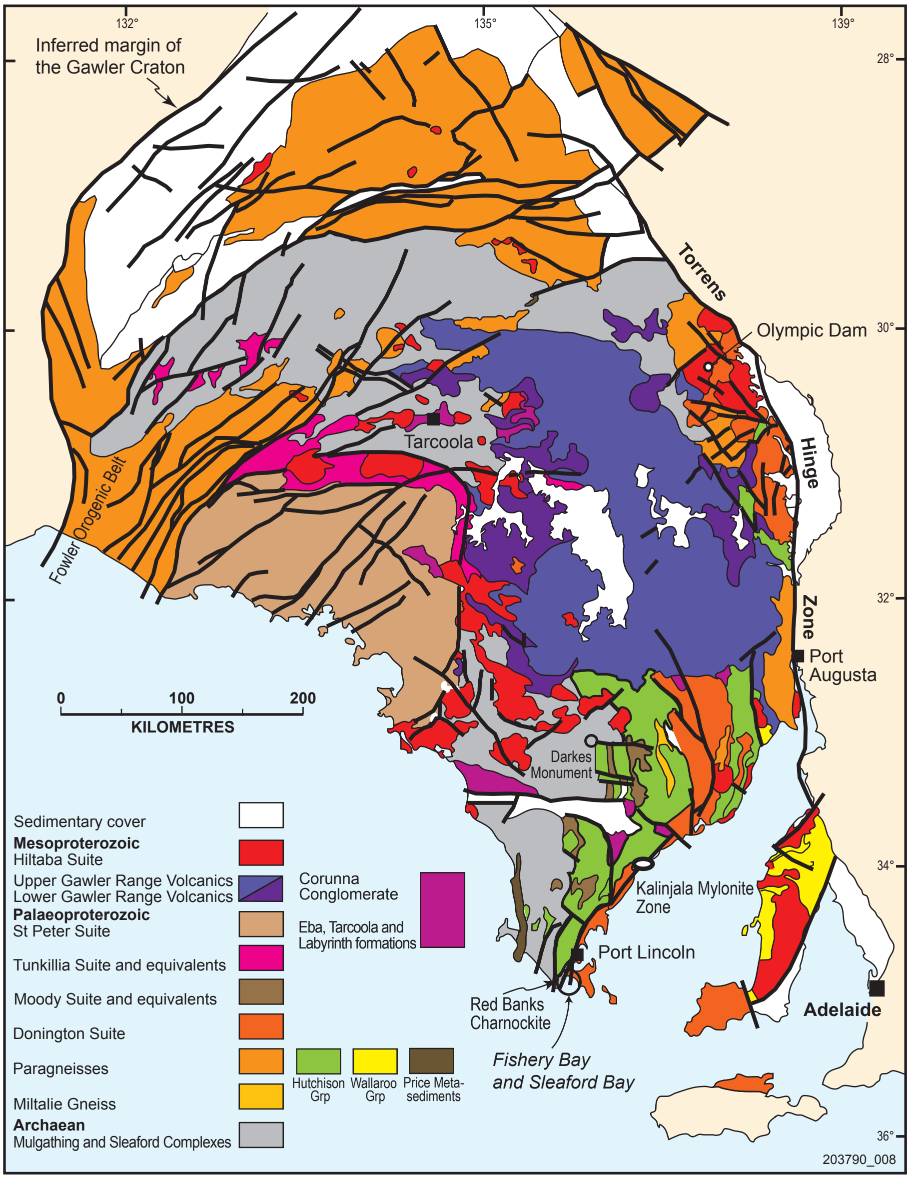

***Figure 1** Simplified interpreted subsurface geology of the Gawler Craton, South Australia, showing the location of Fishery and Sleaford bays and Darkes Monument (modified from Daly, Fanning and Fairclough 1998, Ferris, Schwarz and Heithersay 2002 and Swain et al. 2005).*

Duclaux et al. (2007) attributed these structures to the c. 2440 Ma Sleafordian Orogeny on the basis of an electron probe microanalysis (EPMA) age of c. 1827 Ma from a crosscutting cordierite-bearing granitic vein from the northern Eyre Peninsula near Darkes Monument (Fig. 1). This ambiguity in attributing the structures in the Sleaford Complex to either the Sleafordian Orogeny or the Kimban Orogeny can only be resolved by directly constraining the timing of these fabrics with geochronology. The timing of metamorphism and deformation of the Carnot Gneisses in the Sleaford Bay region (Fig. 1) is of vital significance to understanding the tectonic development of the southern Gawler Craton (Dutch, Hand and Reid 2007).

In this article we present new EPMA monazite geochronological data from the deformed and metamorphosed Sleaford Complex units at Fishery Bay (Fig. 1). The results show that these fabrics formed during the development of the Kalinjala Shear Zone during the 1725–1690 Ma Kimban Orogeny, consistent with the structural interpretation of Vassallo and Wilson (2001; 2002) and Tong, Wilson and Vassallo (2004) and contrasting with the findings of Duclaux et al. (2007).

Geological setting

The Gawler Craton consists of a late Archaean to Palaeoproterozoic core (Fig. 1; Fanning et al. 1988; Daly and Fanning 1993; Daly, Fanning and Fairclough 1998; Ferris, Schwarz and Heithersay 2002; Swain et al. 2005; Fanning, Reid and Teale 2007), surrounded and intruded by Palaeoproterozoic to Mesoproterozoic metasediments and igneous suites (Fanning et al. 1988; Parker 1993; Daly, Fanning and Fairclough 1998; Ferris, Schwarz and Heithersay 2002; Fanning, Reid and Teale 2007). The craton preserves a complex, protracted tectonic history of deformation, metamorphism, sedimentation and magmatism spanning ~1700 My from c. 3150 to 1450 Ma (Daly, Fanning and Fairclough 1998; Ferris, Schwarz and Heithersay 2002; Fanning, Reid and Teale 2007; Fraser et al. 2008). For a recent review of the tectonic framework and evolution of the Gawler Craton see Hand, Reid and Jagodzinski (2007) and references therein.

The southern Eyre Peninsula (Fig. 1) comprises three distinct, strongly deformed and metamorphosed rock packages. The oldest units form the late Archaean Sleaford Complex which comprises the high-grade para- and orthogneisses of the Carnot Gneisses, the amphibolite-facies Wangary Gneiss, the greenschist-facies Hall Bay Volcanics and the upper crustal intrusives of the Dutton Suite (Fig. 1; Fanning, Oliver and Cooper 1981; Daly and Fanning 1993; Fanning, Reid and Teale 2007). Overlying the Sleaford Complex basement is a series of shallow to deep marine chemical and clastic sediments of the Hutchison Group deposited between 2000 Ma and c. 1860 Ma (Fig. 1; Parker and Lemon 1982; Parker et al. 1988; Parker 1993; Vassallo and Wilson 2001; Fanning, Reid and Teale 2007). This package consists of basal quartzite, dolomite, banded iron formation and pelitic to psammitic schist. In the western Eyre Peninsula, a narrow N–S-trending deformed package contains the low-grade phyllitic schist of the Price Metasediments (Fig. 1; Oliver and Fanning 1997). This sedimentary unit has a maximum depositional age of c. 1760 Ma and may be a correlative of the Wallaroo Group volcaniclastics and sediments which crop out in the easternmost part of the Gawler Craton (Parker 1993; Cowley, Conor and Zang 2003). The third unit is the c. 1850 Ma Donington Suite granitoids, which comprise much of the southeastern Gawler Craton (Fig. 1). These are juxtaposed against the Sleaford Complex and Hutchison Group metasediments by the Kalinjala Shear Zone (also known as the Kalinjala Mylonite Zone; Mortimer, Cooper and Oliver 1988; Hoek and Schaefer 1998; Thiel, Heinson and White 2005).

Tectonothermal events of the southern Gawler Craton

Up to four high-grade metamorphic events have affected the southern and southeastern Gawler Craton. The c. 2450–2420 Ma Sleafordian Orogeny (Fanning, Oliver and Cooper 1981; Fanning, Reid and Teale 2007) has been interpreted to have metamorphosed the Sleaford Complex at up to granulite-facies conditions. Metamorphic events that affect the Sleaford Complex basement and the younger units of the southern Gawler Craton include: (i) the c. 2000 Ma Miltalie Event (Daly, Fanning and Fairclough 1998; Fanning, Reid and Teale 2007); (ii) the c.1850 Ma Cornian Orogeny (Reid et al. 2008); and (iii) the 1730–1690 Ma Kimban Orogeny (Parker and Lemon 1982; Vassallo and Wilson 2001; Vassallo and Wilson 2002; Dutch, Hand and Kinny 2008).

The Miltalie Event is only recognised by the presence of 2000 Ma metamorphic zircons in the Miltalie Gneiss and the Red Banks charnockite (Fig. 1; Fanning, Reid and Teale 2007), and no structures have been convincingly demonstrated to be related to the Miltalie Event. The Cornian Orogeny is best represented on the eastern side of, and within, the Donington Suite (Fig. 1), which was emplaced immediately prior to and during the deformation and granulite-facies metamorphism of the Cornian Orogeny (Reid et al. 2008). No evidence for this event has been found west of the Kalinjala Shear Zone.

The 1730–1690 Ma Kimban Orogeny is interpreted to be the most pervasive orogenic event in the Gawler Craton (Hand, Reid and Jagodzinski 2007; Payne et al. 2008). Geochronological evidence indicates it was a craton-wide event affecting the northern (Payne, Barovich and Hand 2006; Payne et al. 2008), western (Howard et al. 2008) and eastern (Hopper 2001) Gawler Craton. The best exposed section of the Kimban Orogen occurs in the southern Gawler Craton, centred around the crustal-scale Kalinjala Shear Zone (Parker 1980; Parker 1993).

A recent structural analysis of the evolution of the Kimban Orogeny was presented by Vassallo and Wilson (2001, 2002). They recognised two phases of deformation (*Kimban* D_1 and *Kimban* D_2) which they attribute to the Kimban Orogeny. The first event (KD_1) is interpreted to have produced numerous gently to steeply plunging mesoscopic sheath folds during a dextral top-to-the-north shearing event synchronous with N–S stretching. Fold plunges are parallel to a primary linear fabric (KL_1) defined by prolate-shaped mineral aggregates which are also parallel to the strike of the subvertical Kalinjala Shear Zone. A strongly developed, high-grade, mylonitic fabric lies subparallel to the lithological layering and is primarily subvertical in orientation. The second generation of structures (KD_2) are characterised by curvilinear high-strain zones and tight to isoclinal upright and overturned chevron folds formed during subhorizontal E–W flattening. The strikes of the KD_2 shears are subparallel with the KD_1 surface traces.

Lithology and structure of the Fishery Bay region

The Fishery Bay region of the southern Gawler Craton (Fig. 1) consists of highly deformed and metamorphosed interlayered migmatitic garnet ± cordierite ± orthopyroxene paragneisses (Figs 2a, b, c), augen and charnockitic orthogneiss and garnet ± clinopyroxene ± orthopyroxene mafic granulites of the Carnot Gneisses. Tong, Wilson and Vassallo (2004) determined peak metamorphic conditions from garnet-bearing mafic granulites of up to 10 kbar at ~800 ºC and interpreted a clockwise P–T path for the metamorphic evolution of these units. 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. 1) and consists of an early layer parallel fabric (*Sleafordian* S_1?; Figs 2a, d) that has been folded by a series of inclined isoclinal and interpreted sheath folds (KD_1 structures), which developed during predominantly dextral transpression (Fig. 2d). These structures are then overprinted by a series of upright tight to isoclinal folds and shear zones (KD_2 structures) developed during E–W flattening (Figs 2b, c, d).

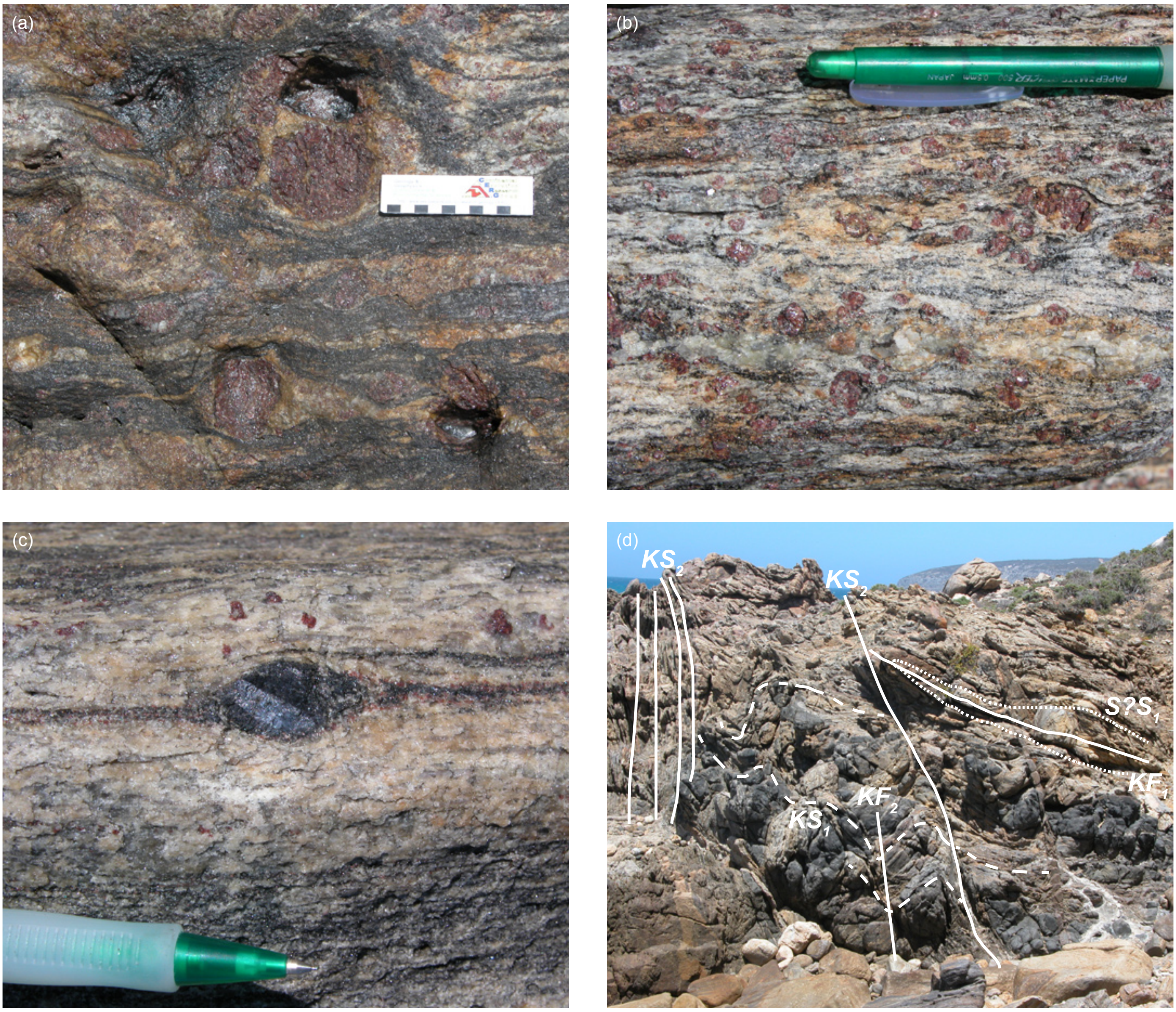

Figure 2 (a) *Large garnet porphyroclasts wrapped by the migmatitic KS_1 fabric.* ***(b)*** *Garnet–cordierite–biotite metapelitic gneiss containing the KS_2 fabric.* ***(c)*** *Garnet – orthopyroxene metapelite with the high strain KS_2 fabric. Orthopyroxene σ clast indicates a dextral sense of movement.* ***(d)*** *Representative outcrop of metapelitic and concordant mafic units at Fishery Bay highlighting the early formed SS_1? fabric which is folded by isoclinal KF_1 folds and transposed by the KS_1 fabric. This is then overprinted by a series of upright KF_2 folds and high-strain zones developing a planar KS_2 fabric. (Photos 407711–407714)*

EPMA monazite geochronology methods

Three monazite-bearing metapelitic samples were selected to constrain the timing of metamorphism and deformation in the Carnot Gneisses at Fishery Bay. Analyses of monazite were conducted using a Cameca SX51 electron microprobe at Adelaide Microscopy at the University of Adelaide. A thorough outline of the procedures used can be found in Dutch (2009). The analyses were run at an accelerating voltage of 20 kV and a 100 nA beam current. Thorium, U, Pb and Ce were analysed concurrently with PET crystals using the *Mα* line for Th, *Mβ* lines for Pb and U, and *Lα* line for Ce. The standards used were huttonite (Th), UO_2, synthetic Pb glass (K227) and single element REE glasses. The full range of elements which are typically partitioned into monazite were analysed. Offline corrections were made to account for the overlap of the second order Ce*Lα* escape peak with the required Pb*Mβ* peak (Pyle et al. 2005), while online corrections were made for the overlap of the Th*Mγ* peak on U*Mβ* and UMζ_2 on Pb*Mβ*. The ages for each spot were then determined using the U–Th–Pb concentrations and the statistical methods outlined in Montel et al. (1996). Probe element calibration was tested against the standards, with analysed concentrations for U, Th, Pb and Ce being ± 0.5% of the standard composition. All other elements were within ± 1% of the standard composition.

Probe performance was monitored by comparison with a 518 Ma monazite standard with known U–Th–Pb concentrations. Reproducibility of the standard during the course of the analytical sessions (n = 91) was 526 ± 8 Ma (2σ; mean squared weighted deviates (MSWD) = 1.4). Statistical analysis of the geochronological data was performed using the Excel add-in ISOPLOT v. 3 (Ludwig 2003).

EPMA monazite results

Sample FB10 is a coarse-grained garnet bearing metapelitic gneiss from within the fabric interpreted as KS_1 by Vassallo and Wilson (2002). 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 grains were analysed producing a unimodal age of 1707 ± 20 Ma (n = 62; MSWD = 1.04; Fig. 3). Chemically the monazites are fairly homogeneous and no distinctive chemical populations can be differentiated (Fig. 3).

Samples FB15 and FB19 are both highly strained garnet-bearing pelitic 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 linked to the development of the Kalinjala Shear Zone. All monazite grains are located within the high-strain fabric surrounded by quartz, plagioclase and K-feldspar.

Four monazite grains (mz 1–4) were analysed from sample FB15. These grains display some clear chemical differences: mz 4 has high Th and high Y (zone 1), mz 3 contains a low-Th, low-Y zone (zone 2), and mz 1 and 2 are indistinguishable (zone 3; Fig. 3). Looking at the ages of these chemical zones individually, zone 1 produces an age of 1691 ± 9 Ma, zone 2 an age of 1693 ± 58 Ma (the low-Th content introduces large uncertainties on the ages), while zone 3 produces an age of 1694 ± 14 Ma. These ages are all within error and are therefore most likely equivalent. 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. 3).

Four grains from sample FB19 were also analysed and again display clear chemical differences (Fig. 3). Monazites 1 and 2 are indistinguishable with a spread of Y values and high-Th (zone 1). Monazite 3 has a similar spread of Y values but is predominantly low in Th (zone 2), while mz 4 is high in Th but has a very homogeneous low-Y content (zone 3). Zone 1 produces a pooled age of 1697 ± 18 Ma, zone 2 an age of 1650 ± 54 Ma and zone 3 an age of 1718 ± 17 Ma. These ages are again within error and produce a pooled age of 1708 ± 12 Ma (n = 50; MSWD = 1.3; Fig. 3). (Including low-Th zone 2 analyses produces an age of 1705 ± 12 Ma.)

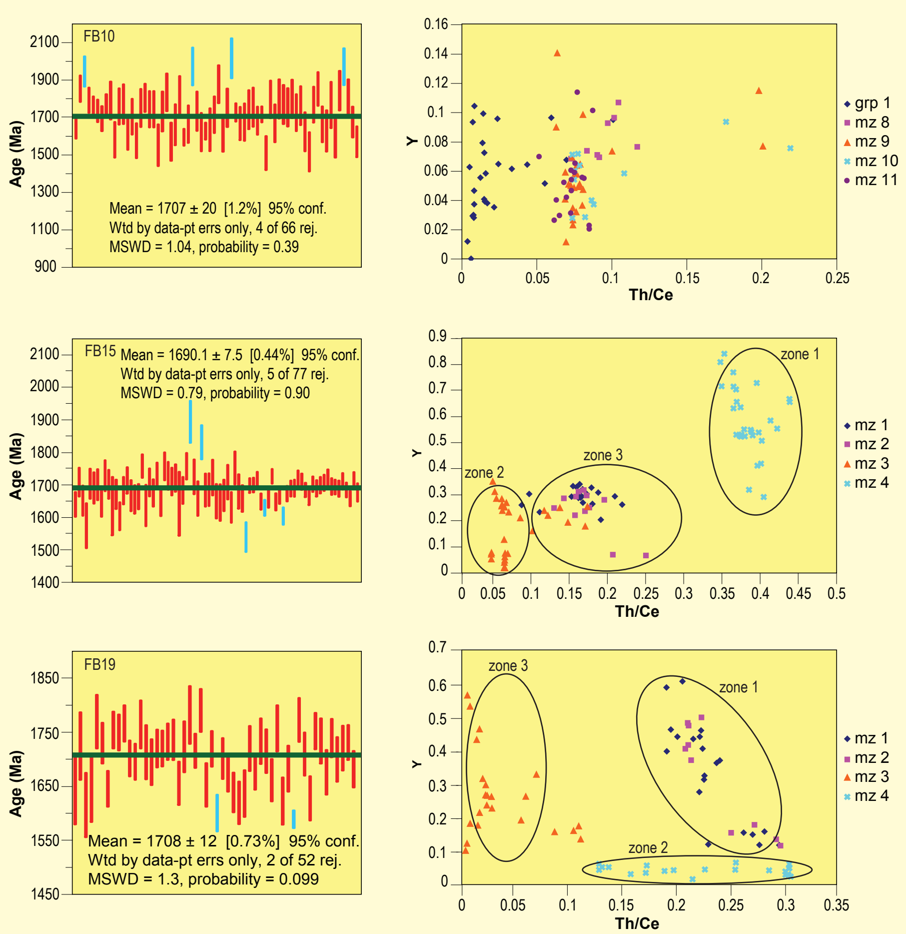

Figure 3 *EPMA monazite geochronological (left) and chemical (right) data plots. Each spot age is represented by a 1σ error bar. Blue analyses fell outside 95% confidence and were excluded from the average age calculations. The chemical plots show Th/Ce composition against Y wt% for each analysed spot. Similar chemical domains have been grouped into zones which are shown by the ellipses. Analyses which fell outside 95% confidence were excluded from the chemical plots.*

Implications for the timing of deformation in the southern Kalinjala Shear Zone

The EPMA monazite geochronological results presented here provide a direct geochronological constraint on the timing of fabric development in the Carnot Gneisses. The data indicates that the structural fabrics and the associated metamorphic assemblages developed in the Carnot Gneisses in the Sleaford Bay region developed between 1708–1690 Ma during the Kimban Orogeny, and not during the 2450–2420 Ma Sleafordian Orogeny.

The recent study by Duclaux et al. (2007) suggested that the majority of the structures seen in the southern Gawler Craton are a result of the Sleafordian Orogeny. However, this interpretation contradicts the geochronological data of Dutch, Hand and Kinny (2008), Reid et al. (2007) and that presented here, together with the structural interpretations of Parker et al. (1988), Vassallo and Wilson (2001, 2002) and Tong, Wilson and Vassallo (2004), which all suggest that little is known about the structural development or kinematic setting of the Sleafordian Orogeny as it has been thoroughly overprinted by the Kimban Orogeny. The geochronological interpretation presented here does not rule out the possibility that the Kimban Orogeny is not represented in the area around Darkes Monument (Fig. 1), however it does rule out the broad interpretations of Duclaux et al. (2007).

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 the Sleaford Bay region 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 Gneisses.

Acknowledgements

The authors would like to thank Wayne Cowley and Alan Collins for thorough and constructive reviews which improved this manuscript. Angus Netting from Adelaide Microscopy is thanked for assistance with EPMA monazite work. Michael Szpunar is thanked for assistance with fieldwork. PIRSA is thanked for logistical support. Funding for this study has been provided by Australian Research Council Grant LP0454301.

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