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Tectono-metamorphic evolution of the Eastern Fold Belt, Mount Isa, NW Queensland, Australia

Volume 1

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In September 2010

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VOLUME I

INTRODUCTION AND THESIS OUTLINE

The Mount Isa Inlier, which occupies the northwest corner of Queensland, Australia, contains three N-S trending tectonostratigraphic belts that are juxtaposed along major tectonic contacts (Blake, 1987; Blake and Stewart, 1992). These belts are the Western Fold Belt (WFB), the central Kalkadoon-Leichhardt Belt (KLB) and the Eastern Fold Belt (EFB). The Snake Creek anticline region is situated about 30 km southeast of Cloncurry on Roxmere Cattle Station. It lies between latitudes $140^{\circ}37'23''$ and $140^{\circ}43'47''$ E and longitudes $20^{\circ}00'01''$ and $21^{\circ}00'35''$ S and covers an area of about 300 km^2. It represents an essential part of the Soldiers Cap Group, which occupies the northeastern part of the Eastern Fold Belt of the Mount Isa province.

This thesis investigates the tectono-metamorphic evolution of the Snake Creek anticline region. This region exposes Mesoproterozoic volcano-sedimentary rocks that are metamorphosed at greenschist to upper amphibolites metamorphic facies conditions (Foster and Rubenach, 2006 ; Rubenach *et al*., 2008). The rocks of the study area have been affected by multiple deformation and metamorphism that accompanied the 1650– 1500 Ma Isan Orogeny (Loosveld, 1989; Bell *et al*., 1992; Lally, 1997; Lewthwaite, 2000; Giles *et al*., 2006). This region represents a key portion of the Mount Isa inlier as it hosts W–E and N–S-trending macroscopic folds whose origin and timing relationships have been debated for many years and are still controversial in the literature (Bell, 1991; Bell and Hickey, 1998; Lister *et al*., 1999; Giles *et al*., 2006). The metamorphic history of the area under investigation is complex and contains multiple overprinting metamorphic events (Rubenach and Barker, 1998; Foster and Rubenach 2006). Low-P/high-T metamorphism characterizes the Mount Isa inlier in general, and the Soldiers Cap Group rocks in particular (Reinhardt, 1992; Foster and Rubenach 2006; Rubenach *et al*., 2008).

It has been realized recently that the visible matrix foliations in complexly deformed and multiply metamorphosed orogenic belts preserve little of their complete deformation history; they rarely preserve more than 2 or 3 foliations in addition to a schistosity parallel to the compositional layering, S_0 (Bell, 2010). Little of the complete tectono-metamorphic history is preserved in the simple history suggested by the visible matrix foliations. In particular, the tendency for shearing parallel to the compositional layering during matrix reactivation to rotate and destroy pre-existing and developing foliations (Bell *et al.*, 2003; Ham and Bell, 2004) dramatically hinders preservation of more than a small fraction of the deformation history. Quantitative studies on porphyroblasts over the last two decades have provided access to this lengthy history (Bell, 1981; Bell and Rubenach, 1983; Bell and Johnson, 1989; Hayward, 1992; Vernon *et al.*, 1993; Aerden, 2004; Aerden and Sayab, 2008; Bell, 2010; Bell and Hobbs, 2010).

Under suitable P-T metamorphic conditions and bulk chemical composition (Spear, 1993), in the presence of coaxial deformation (Bell *et al.*, 2004), porphyroblasts begin to grow in metapelitic rocks and cease growth once a differentiated crenulation cleavage develop against their margins (Bell and Bruce, 2007). Porphyroblasts entrap the matrix foliation in the form of inclusion trails, preserving the asymmetry of developing crenulation cleavages at the time the porphyroblasts grew, and locally that or the earlier matrix foliation. Inclusion trails are protected from the destructive effects of reactivation and decrenulation of the matrix foliation that accompanies later deformation events. Indeed, inclusion trails preserved within porphyroblasts commonly contain evidence of earlier deformation events that no longer exist in the surrounding matrix. They can be used as kinematic indicators of the sense of shear of the matrix foliation at the time these porphyroblast grew. The intersection between two overprinting foliations defines a Foliation Intersection/Inflection Axis within the porphyroblasts that is called a FIA. Measuring FIA trends (Bell *et al.*, 1995) allows correlation of porphyroblasts of the same generation across a region or orogen. They form at right angles to the direction of bulk horizontal shortening (Cihan, 2004) and provide quantitative information on the direction of movement during orogenesis.

This thesis consists of four sections (A-D) each of which has been written in a paper format and submitted to international journals. The thesis is in two volumes; volume 1includes the text and references whereas volume 2 contains the figures, figure captions, tables and the appendices.

Section A of the thesis deals mainly with the changes in the direction of bulk horizontal shortening during the lengthy Isan orogeny. On the macroscopic and mesoscopic scales, planar and linear structural elements have been measured and dealt with geometrically to deduce the different phases of deformation. On the microscopic scale, the FIAs were measured, in all possible porphyroblasts, and their relative timing was established based on microstructural and textural relationships. The resulting macro, meso and microscopic structural data, were integrated, discussed and interpreted in terms of their significance for the tectono-metamorphic history of the Snake Creek anticline.

A new deformation scheme has been introduced (Table 1) and a new tectonic model (e.g. Fig. 19) has been introduced at the end of that section showing the tectonic history of the Snake Creek anticline area during the 1670–1590 Ma long-lived Isan Orogeny.

Section B uses mesoscopic (e.g. planar and linear fabric elements) and microscopic (e.g. FIA trends preserved in different porphyroblasts) structures to resolve the relative timing of the orthogonal N–S (Snake Creek anticline and Weatherly Creek syncline) versus W–E (Toole Creek and Davis synclines, and Mountain Home anticline) trending folds in the Soldiers Cap Group, in particular, and the Mt Isa inlier, in general, and their significance to deformation partitioning. The origin and relative timing between these orthogonal folds have been problematical for many years and a range of solutions have been suggested (Bell, 1991; Bell and Hickey, 1998; Lister *et al*., 1999; Lewthwaite, 2000; Giles *et al*., 2006).

Microstructural data including FIAs and the relationship between the inclusion trails within porphyroblasts (internal fabric) and the surrounding matrix foliation (external fabric) supported with the meso and macroscopic structures, were the keys to resolve the quandary regarding the relative timing between the orthogonal W–E and N–S folds in the Snake Creek anticline during the Isan Orogeny.

Section C uses (EPMA) dating of monazite grains entrapped within garnet, staurolite and andalusite porphyroblasts to constrain the absolute timing of the FIA succession relative to N–S- versus W–E-trending folds. Microstructural relationships, i.e. porphyroblast to matrix relationships, together with absolute age dating, were used to figure out the relative directions of motion that accompanied orogenesis and interpret it in the framework of plate tectonics.

A possible correlation between the Mount Isa, Broken Hill and Gawler provinces and between the Isa terrane and the SW Laurentia was suggested. The latter sheds light on the reconstruction of Rodinia during the 1670–1590 Ma Isan Orogeny.

Section D of the thesis represents a multi-disciplinary approach that comprised integrated microstructural and textural relationships, geochronology, phase diagram modeling (using THERMOCALC computer software) and garnet core maps to infer the P-T conditions and the metamorphic history of the Snake Creek anticline during the tectono-metamorphic events that took place during the Isan Orogeny. Light was thrown, in general, on the metamorphic history that accompanied the different periods of deformation throughout the orogeny and, in particular, on those P-T conditions that prevailed during the W–E and N–S shortening events (e.g. Fig. 17). The interrelationship between sedimentation, tectonism and metamorphism is discussed briefly.

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SECTION A

RADICAL CHANGES IN BULK SHORTENING DIRECTIONS DURING OROGENESIS: SIGNIFICANCE FOR PROGRESSIVE DEVELOPMENT OF REGIONAL FOLDS AND THRUSTS

CONTENTS OF SECTION A

Radical changes in bulk shortening directions during orogenesis: Significance for progressive development of regional folds and thrusts

Abstract

Polyphase folding and metamorphism of rocks in the eastern Mount Isa Inlier resulted from four distinct orogenic cycles. These consist of NE–SW shortening (O_{00}) from 1672 to ~1648 Ma, involving a succession of five phases of deformation, which was responsible for the development of first generation NW–SE- striking macroscopic folds, plus cleavages that are mainly only preserved in porphyroblasts. N–S shortening (O_1) followed to 1600 Ma, involving at least three phases of deformation. This period of N–S- directed orogenesis rotated large portions of the NW–SE-trending regional folds into W–E trends and the dominance of locally well-preserved W–E-trending sub-vertical matrix foliations as well as the intensification of foliation parallel to bedding. Subsequent W–E shortening (O_2) from 1600 to ~1515 Ma was accompanied by the development of N–S-trending folds. These dominate the Mount Isa Inlier and where best developed involved the formation of at least three near orthogonal foliations. Where these large-scale folds regionally are weakly developed or not visible, only one sub-vertical foliation has developed. Finally NW–SE shortening (O_3) produced locally developed SW–NE-trending folds and weak crenulations until ~1500 Ma.

The asymmetry of steep to gentle pitch changes in inclusion trails preserved in garnet porphyroblasts that developed during O_{00} indicates thrusting to the SW. Similar inclusion trail asymmetries in garnet, staurolite and andalusite porphyroblasts that developed in O_1, indicate thrusting to the N confirming a change in thrust direction across the Wonga Duchess belt to the W. Formation of the Meerenurker roof thrust near Mount Isa by thrusting to the SW during O_{00} with subsequent development of the Kokkalukkernurker duplex below by thrusting to the S during O_1 reduces the displacement required for the roof thrust from 234 to ~ 45 kms. Foliations preserved in O_{00} garnets are truncated by foliations associated with the development of O_1 in the matrix. O_1 garnet, staurolite and andalusite porphyroblasts preserve inclusion trails that are commonly truncated against a differentiated crenulation cleavage in the matrix that formed during O_2. The inclusion trails entrapped within O_{00} and O_1 generated porphyroblasts reveal that the foliations that progressively developed in the matrix during these orogenies were composite fabrics resulting from the effects of multiple discrete orthogonal increments in each case. Numerous phases of sub-vertical foliation development due to horizontal bulk shortening were followed by phases of gently dipping foliation formation due to gravitational collapse that accompanied thrusting during O_{00} and O_1.

Key words: deformation partitioning, inclusion trails, porphyroblasts, thrusting, shear sense, Mount Isa Inlier.

1. Introduction

The foliations observed in the matrix of most rocks within multiply deformed and metamorphosed orogenic belts are the end result of prolonged and lengthy overprinting periods of deformation. Generally, only 3 or 4 overprinting matrix foliations can be recognized and yet the rocks in the metamorphic cores of most orogens have been through many periods of deformation and metamorphism (Bell and Newman, 2006). Deformation partitioning and reactivation of the compositional layering during the same and/or successive tectonic events (Ham and Bell, 2004) hinder elucidation of complete deformation sequences in complexly deformed and metamorphosed terrains. Advances in understanding of progressive deformation resulting from quantitative studies of foliations preserved in porphyroblasts have revealed that most orogenic belts have undergone much more extensive deformation histories than what can be inferred from matrix foliations alone (Hayward, 1992; Hickey and Bell, 2001; Bell and Welch, 2002; Aerden, 2004; Cihan and Parson, 2005; Bell, 2010). The progressive but episodic growth of porphyroblasts throughout deformation in the cores of orogens entraps inclusion trails, preserving them from the rotation or destruction during subsequent tectonic events. They provide a direct record of the microstructural and geometric effects that occurred during deformation events for which little or no evidence is preserved in the matrix. This study uses this new approach to resolve the meso and macroscopic structural development of the multiply deformed metasedimentary and metavolcanic rocks in the Eastern Mount Isa Inlier (Fig. 1).

2. Geologic setting

The Mount Isa Inlier, in northwest Queensland, Australia contains Early to Late Proterozoic sub-greenschist to upper amphibolite facies metasedimentary and metavolcanic rocks that underwent multiple deformation and metamorphism during the Isan Orogeny (~1670 to ~1490 Ma; Blake and Stewart, 1992; Page and Bell, 1986; Page and Sun, 1998; Rubenach, 2008; Rubenach *et al*., 2008). Three N–S-trending tectono-stratigraphic belts (Fig. 1), the Eastern, Kalkadoon-Leichhardt and Western Fold Belts, are juxtaposed along major tectonic contacts (Blake and Stewart, 1992). An extensional event separates two major compressive orogenic cycles. A contractional event, the Barramundi Orogeny formed at 1900–1850 Ma (Blake, 1987; Etheridge *et al*., 1987; McDonald *et al*., 1997; Bierlein and Betts, 2004). Three major rifting phases are believed to have followed. The first resulted in the deposition of cover sequence 1 (Blake, 1980) and the intrusion of Kalkadoon granite at 1870–1850 Ma (Wyborn and Page, 1983). The second resulted in the deposition of cover sequence 2 from 1800 to 1740 Ma (Williams, 1989; Potma and Betts, 2006) and intrusion of the Wonga granite at 1740 Ma (Holcombe *et al*., 1991; Pearson *et al*., 1992). The third resulted in the deposition of cover sequence 3 from 1740 to 1670 Ma (Derrick, 1982; Blake and Stewart, 1992; Page and Sun, 1998; Page and Sweet, 1998; Jackson *et al*., 2000; Page *et al*., 2000) and the intrusion of the Sybella granite at ~1680 Ma (Page and Bell, 1986). No evidence of internal unconformities was recorded between the three units, which represent a continuous depositional sequence.

N–S-striking kilometer-scale upright folds with a generally penetrative axial planar foliation dominate the structural grain of the inlier (e.g., that in the south half of Fig. 1). The timing of locally preserved W–E-trending folds within these rocks (those in the north half of Fig. 1) has always been problematic as to whether they pre- or post-date development of the N–S-trending structural grain (e.g., Bell, 1983; Loosveld, 1989; Bell *et al*., 1992; O'Dea *et al*., 1997; Giles *et al*., 2000, 2006).

The Soldiers Cap Group (1685–1655 Ma; Page and Sun, 1998; Giles and Nutman, 2002, 2003; Neumann *et al*., 2006) occupies the eastern part of the Eastern Fold Belt and is made up of low pressure/high temperature Mid-Proterozoic metasedimentary and metavolcanic rocks that are intruded by post-tectonic intrusions (Figs. 1 and 2). It is divided into three distinct rock units, which from base to top are the Llewellyn Creek Formation, Mount Norna Quartzite and Toole Creek Volcanics. Page and Sun (1998) gave the Soldiers Cap Group a maximum depositional age of approximately 1670 Ma, placing it within the Cover Sequence 3 of Blake (1987). A 700-m-thick gabbroic to tonalitic sill intruding the Llewellyn Creek Formation yielded an age of 1686±8 Ma (Rubenach *et al*., 2008), which indicates that this formation might have been deposited prior to that age.

3. Regional geology

The area shown in Fig. 2 represents a very critical part of the Eastern Fold Belt, as it hosts both macroscopic NW–SE and W–E folds and contains a boundary that separates W–E-and NW–SE-trending structures in the north from N–S-dominated structures to the south (Fig. 1). Two main rock units within the region are the Mount Norna Quartzite and the Toole Creek Volcanics (Figs. 1 and 2). The former forms a distinct marker that allows the recognition and tracing of folds of different trends and styles across the region (Fig. 1). It is a porphyroblast-poor psammitic unit made up of metamorphosed massive and finely cross-bedded quartz sandstone, mudstone, siltstone and metadolerite. The Toole Creek Volcanics are mainly a psammitic to psammopelitic unit (Fig. 3) made up of carbonaceous pelitic metasediments together with metadolerite and metabasalt. Pelitic portions contain garnet (Figs. 3a and 5) staurolite and andalusite porphyroblasts. Deformation is greatly partitioned in the region and can be divided into two main structural belts; a northern belt hosting macroscopic NW–SE- striking folds, and a southern belt dominated by W–E- striking folds (Fig. 1). Porphyroblastic rocks with different generations of porphyroblasts grown concurrently with different orogenic cycles allow which of these occurred first to be established.

4. Structural review

The Isan Orogeny (~ 1670–1490 Ma) was a major period of contractional deformation within the Mount Isa Inlier and is interpreted to have produced three main macroscopic phases of deformation (Bell, 1983; Swager, 1985; Page and Bell, 1986; Winsor, 1986; Loosveld, 1989; Bell, 1991; Nijman *et al*., 1992; Stewart, 1992). D_1 was due to N–S shortening and produced N–S- directed thrusting and W–E- trending regional folds. D_2 formed the penetrative N–S fabric that dominates the whole region and resulted from W–E bulk horizontal shortening. Recent studies suggest that the metamorphic peak occurred during the D_2 event at 1580–1600 Ma (Rubenach *et al*., 2008). D_3 was relatively mild and is attributed to a phase of W–E shortening. It was responsible for the development of small-scale, locally developed N–S-trending folds with near-vertical axial planes at 1510 Ma (Page and Bell, 1986).

The Soldiers Cap Group is a critical unit within the Mount Isa Inlier. It hosts rocks where periods of orogenesis have strongly partitioned their deformation effects into three different structural domains. The southern fold belt is dominated by N–S- striking macroscopic folds including the Snake Creek Anticline (e.g., Fig. 1) and

Weatherly Creek Syncline; the central belt hosts E–W-to ENE–WSW-trending folds including the Mount Home anticline and Davis and Toole Creek synclines (Fig. 1); the northern belt is dominated by NW–SE-trending folds close to the abandoned Gilded Rose Mine (Fig. 1). This paper focuses on the central and northern belts of the Soldiers Cap Group for the boxed area shown in Fig. 1. The macro, meso and microstructural interrelationships among the northern, central and southern belts are presented in Abu Sharib (unpublished data).

Different deformation schemes have been introduced in the literature for the Soldiers Cap Group. It is noteworthy that, until now, no agreement has been achieved regarding the sequence of deformation events as, on one the hand, the relative time relationship among some of these events is still a matter of controversy and, on the other, not all deformation events are recognized by all authors. This, together with the usage of different, conflicting, deformation schemes adds further complications to an already complicated region. Table 1 summarizes some of these deformation schemes in comparison to that of the present study.

5. New structural findings

The structural framework of multiply deformed rocks in the region reflects the effects of four orogenic cycles. Three of the four orogenic cycles resulted in the development of multiple phases of deformation. Consequently, O_n is used as a shorthand terminology rather than D_n and all subscripts correspond with the orogeny in which the structure developed. O_{00} is used for the first period of orogeny to allow the reader to easily mesh the new structural findings described herein with the wealth of previous literature on the effects of O_1 and O_2. O_{00} is used rather than O_0 so that structures such as S_{00} can be distinguished from bedding. Since more than one foliation is commonly preserved for each orogeny, they are distinguished by subscripts A, B, C for the matrix and a, b, c within porphyroblasts.

5.1. O_{00}

Structures related to this cycle can be distinguished in the northern part of the region to the west and east of the abandoned Gilded Rose Mine (Fig. 2). They are represented by tight macroscopic (Fig. 2) and mesoscopic NW–SE-striking, gently southeast plunging (Figs. 4a and b) folds and their associated penetrative, NW–SE-trending composite axial planar cleavage, S_{00} (Fig. 4a). Due to the overprinting effects of later deformation phases, the plunge direction locally switches to the northwest giving the folds a double plunging morphology (Fig. 1). Mesoscopic fold axes and intersection lineations form southeast and northwest plunging linear fabric elements (Figs. 4a and b).

5.2. O_1

This orogenic cycle can be penetrative on scales from micro-to-macroscopic. It is more prominent and better preserved in the Soldiers Cap Group than any other units in the Mount Isa Inlier. It generated the macroscopic Mountain Home anticline and the Toole Creek and Davis synclines as well as smaller scale folds (Figs. 2 and 5). W–E-trending folds appear to have a steeply dipping cleavage (S_1) parallel to their axial planes (Figs. 3 and 5). This foliation has commonly been rotated into orientations other than its original W–E trend due to the effect of younger deformation events. It overprints an earlier bedding parallel foliation, S_{00} (Fig. 5). Second generation linear fabric elements are represented by gently to moderately east and west plunging axes of mesoscopic folds and lineations (Fig. 5).

5.3. O_2

The effects of this period of orogeny dominate the Mount Isa province. This orogeny was responsible for the upright, tight to isoclinal, N–S-striking regional folds with steep axial planes that affect most of the Inlier. It formed the Snake Creek anticline shown in Fig. 1. However, it decreases dramatically in intensity northward and is only weakly developed in the region shown in Fig. 2 where S_{2A} is generally a steeply dipping, weakly differentiated, N–S-trending crenulation cleavage that lies axial planar to O_2 folds. It crenulates any S_{00} and S_1 cleavages present in the rock (Figs. 6a and b). Crenulation axes (Figs. 6a and b) and a few mesoscopic folds are the main expression of linear structures associated with this period of orogeny.

5.4. O_3

This appears to be the last orogenic cycle in the Isan Orogeny that affects the region shown in Fig. 2. It resulted in locally developed mesoscopic and macroscopic upright NE–SW-trending, northeast plunging folds (Figs. 2 and 7a) associated with a mild, nearly vertical axial planar foliation (Fig. 7a). Folds, including kinks, and lineations generated by this period of orogeny plunge towards the northeast and southwest (Figs. 7a and b), varying by more than 90°.

6. Structural domains

The region has been divided into three structural domains, I, II and III (Fig. 8), each of which is dominated by fold trends associated with one period of orogenesis. None of these domains are dominated by N–S-trending folds. All of them contain schistosity parallel to bedding called $S_{0,00}$ in the shorthand terminology used below.

6.1. Domain I:

This domain hosts the first formed NW–SE-trending folds. In this domain S_{00} occurs as a steeply SW-dipping, NW–SE-striking foliation that is axial planar to tight, upright gently plunging northwest folds (Fig. 8a). L^0_{00} lies very close to the F^0_{00} folds and along the two traverses shown in Fig. 2 plunges NW at gentle to moderate angles (Fig. 8a) even though overall the macroscopic folds are SE plunging. S_1 is a steep south dipping, W–E-striking cleavage that is axial planar to very shallow west–northwest-plunging tight, upright second generation F^0_1 folds (Fig. 8b). L^0_1 plunges both W and E with the plunge angle varying from gentle to steep (Fig. 8b). S_2 is a NNW–SSE-trending foliation that dips steeply towards the west (Fig. 8c). L^0_2 plunges gently to moderately approximately to the north and south (Fig. 8c).

6.2. Domain II:

This domain is dominated by the second-generation regional W–E-striking Toole Creek and Davis synclines and the Mount Home anticline. In this domain S_1 varies from a W–E-to ENE–WSW-trending foliation (Figs. 8e and f) that is axial planar to gently westwards plunging tight, upright $F^{0,00}_1$ folds. L^0_{00} plunges moderately to steeply NW and SE. $L^{0,00}_1$ variably plunges W or E at gentle to moderate angles. L^0_2 plunges moderately to steeply N and S. L^0_3 is generally gently NE plunging.

6.3. Domain III:

This domain hosts NE–SW-striking fourth generation folds. Their axial planes S_3 dip moderately NW (Fig. 8d). L^0_3 is moderately NE plunging.

7. Foliations

A detailed and quantitative examination was made of 65 oriented porphyroblastic samples that contain structures representative of those mapped across the region. Different generations of garnet, staurolite, and andalusite porphyroblasts are preserved within these samples. Textural relationships suggest that garnet porphyroblasts grew first followed by staurolite and andalusite. The rocks commonly contain garnet, staurolite, andalusite, biotite and muscovite. Six vertical thin sections were cut every 30º degrees around the compass for each sample. This allowed structures present within both the matrix and porphyroblasts to be measured from section to section and generated in 3-D. The sequence of orogenic periods 0, 1, 2 defined above using regional folds has produced successions of foliations both within porphyroblasts and the matrix. These are labeled a, b, c within porphyroblasts and A, B, C in the matrix. Thus S_{1a} denotes the first foliation that formed during orogenic period 1 that is trapped as inclusion trails in porphyroblasts. S_{1A} refers to the first matrix foliation that developed during the same period of orogenesis.

7.1. Foliation in porphyroblasts

Inclusion trails were recorded in porphyroblasts that grew during each of the three orogenic cycles.

S_{00}

Some of the garnet porphyroblasts preserving foliation that formed during this period of orogenesis are characterized by spectacular spiral-shaped inclusion trails (e.g., Figs. 9a, b and 10) preserving a succession of at least 5 nearly orthogonal foliations S_{00a}, S_{00b}, S_{00c}, S_{00d} and S_{00e}. In such samples, the first foliation to develop was a sub-vertical (S_{00a}). It was crenulated and a nearly sub-horizontal differentiated crenulation cleavage S_{00b} developed. This cleavage was crenulated and a sub-vertical differentiated crenulation cleavage S_{00c} formed. S_{00c} was also crenulated and a sub-horizontal differentiated crenulation cleavage S_{00d} was developed and so on for S_{00e}.

S_1

Foliations preserved in porphyroblasts that grew during the second orogenic cycle O_1 result from two cycles that produced at least 3 nearly orthogonal foliations S_{1a}, S_{1b}, and S_{1c} (Figs. 11 and 12). S_{1a} is a steeply dipping foliation that is preserved in the cores of garnet porphyroblasts. S_{1b} is a gently dipping differentiated crenulation cleavage that overprints S_{1a} (from which a pseudo FIA can be measured, see below) and is preserved in the rims of some garnet porphyroblasts (e.g., Fig. 12). It was crenulated when a steeply dipping differentiated crenulation cleavage S_{1c} was formed.

S_2

This is a steeply dipping differentiated crenulation cleavage across the region shown in Fig. 2. It increases in intensity to a schistosity within the Snake Creek anticline to the south (Fig. 1). Inclusion trails associated with three or more foliation producing events that formed during this third orogenic cycle are present in the Snake Creek anticline to the south (Abu Sharib, unpublished data). However, only the first of these foliations S_{2A}, which is sub-vertical, is preserved within porphyroblasts within the region shown in Fig. 2, although 2 more, S_{2B} and S_{2C}, can be seen locally in the matrix (e.g., Fig. 11).

S_3

This forms the steeply dipping axial planes of crenulations (Fig. 7a). Locally the latter structures intensify into a crenulation cleavage.

7.2. Matrix foliations

S_{00}

This fabric is only locally preserved as matrix foliation oblique to bedding in NW–SE-trending portions of the folds shown in Fig. 2. However, it is well preserved as inclusion trails within O_{00} formed porphyroblasts.

S_{1A}, S_{1B}, S_{1C}

These foliations are well developed in much of the northern part of the region in Fig. 1, particularly where the folds trend W–E. S_{1B} is commonly present as a schistosity sub-parallel to bedding in the field but can be distinguished locally (Fig. 3b and c). S_{1C} can only be distinguished from S_{1A} in the matrix where S_{1A} was rotated by the effects of S_{1B} (e.g., Fig. 3). Where it is unaffected it was simply intensified by the development of S_{1C}. S_{1A} and S_{1C} in such situations trend W–E to ENE–WSW (Figs. 11 and 12) except where rotated by the effects of later folding events.

S_{2A}, S_{2B}, S_{2C}

These foliations are best developed in the southern part of the region in Fig. 1 but can be distinguished in thin section in the north (e.g., Fig. 11). S_{2A} is a locally strongly developed differentiated crenulation cleavage that crenulates and truncates previous fabrics and trends ~N–S (Figs. 9a, b and 10).

S_3

S_3 occurs as the axial planes of folds and crenulations.

8. FIAs

Foliation Intersection/Inflexion Axes in porphyroblasts or FIAs were measured by locating the flip in asymmetry of curved inclusion trails within porphyroblasts in the above-mentioned thin sections when viewed in one direction (Fig. 13a). To locate the FIA within a 10° range 2 extra vertical thin sections need to be cut between those at 30° between which the asymmetry flipped. This was done for many but not all samples taken from across the region shown in Fig. 1 (Table 2). Four clusterings of FIAs can be seen in Fig. 13b trending NW–SE, W–E, N–S and SW–NE.

8.1. NW–SE FIAs

Six samples contain garnet and cordierite porphyroblasts with inclusion trails that preserve 120°–150° trending FIAs (Fig. 13b; Table 2). Garnet porphyroblasts hosting this FIA contain spiral (Figs. 9a, b and 10) and sigmoidal shapes. The inclusion trails begin with steeply or gently pitching foliations in the core that curve clockwise or anticlockwise into the subsequently developed gently or steeply pitching one. Porphyroblasts containing these FIAs are always truncated by a matrix foliation that strikes W–E (e.g., Figs. 9a, b and 10).

8.2. W–E FIAs

Thirty-four samples contain FIAs with this trend and they dominate the rose diagram in Fig. 11b (Table 2). Garnet, staurolite and andalusite porphyroblasts preserve 85°–110° FIA with excellent sigmoidal shape inclusion trails (Figs. 11 and 12). Inclusion trails in some porphyroblasts exhibit stage 3-4 of differentiated cleavage development (Bell and Rubenach, 1983). Samples containing this FIA trend only locally have inclusion trails that are continuous with the foliation in the matrix (e.g., Fig. 12). Some samples with W–E FIAs in porphyroblast cores contain N–S FIAs in their rims (see Table 2).

8.3. N–S FIAs

Twenty-three samples contain garnet, staurolite and andalusite porphyroblasts with FIAs ranging from 165° to 195°defined by well-developed sigmoidal-shaped inclusion trails (Fig. 13b; Table 2). Sample G3 contains garnet porphyroblasts preserving W–E FIAs that are truncated by the matrix foliation (Fig. 14). They are surrounded by younger staurolite and andalusite porphyroblasts that contain a N–S FIA defined by inclusion trails that are continuous with the matrix foliation. Sample G390 contains garnet porphyroblasts with a W–E-trending FIA defined by inclusion trails in the core that are truncated by N–S-trending foliations in the rim defining a N–S-trending FIA. Staurolite and andalusite porphyroblasts also host inclusion trails preserving N–S-trending FIA (Fig. 15).

8.4. SW–NE FIAs

Eleven samples contain garnet, staurolite and andalusite porphyroblasts with FIAs with trends in the SW–NE quadrant (Table 2). These FIA trends show greater variability than those above (Fig. 13b) because several were identified from sections 30° apart rather than 10° and consequently lie at 45° and 75° since the sections from which they were measured were cut at 30°, 60° and 90°. The inclusion trails defining these FIAs were always continuous with matrix foliations.

9. Overprinting foliation orientations and asymmetries preserved within porphyroblasts

The asymmetry of inclusion trails entrapped within the porphyroblasts preserves the differentiation asymmetry associated with crenulation cleavage development in the surrounding matrix at the time that the porphyroblasts grew (e.g., Bell and Bruce, 2007; Bell and Hobbs, 2010). The asymmetries with which crenulated cleavages curve towards differentiated crenulation cleavages were determined for all the porphyroblasts preserved in vertical thin sections from all samples in which the NW–SE-and W–E-trending FIA sets were measured. These asymmetries were projected onto histograms (Fig. 16) drawn as a vertical section orthogonal to each FIA trend. For NW–SE-trending FIAs the asymmetry was determined looking northwest; for W–E-trending FIAs the asymmetry was determined looking west. This histogram shows the frequency of clockwise and anticlockwise asymmetries of the inclusion trails within the porphyroblasts defining each FIA trend and whether they change from sub-horizontal (g) to sub-vertical (s) or vice versa as shown in Fig. 16.

10. Interpretation

10.1. FIA succession

The peaks in the distribution of FIAs shown in Fig. 13b are interpreted to result from a succession of FIA sets trending NW–SE, W–E, N–S and SW–NE. This succession, labeled FIA Sets 00, 1, 2 and 3 respectively, is apparent from the following relationships (e.g., Bell and Hickey, 1997). Samples containing NW–SE-trending FIAs (Set 00) in garnet or cordierite porphyroblasts are always truncated by W–E-striking matrix foliations in samples from the north of Fig. 1, and N–S-striking ones in the south. Sample P12 contains a NW–SE-trending FIA (Set 00) in garnet cores and a N–S-trending FIA (Set 2) in its rim (Table 2). Sample N17 contains a W–E-trending FIA in garnet cores (Set 1) and a N–S-trending FIA (Set 2) in its rim (Table 2). Sample E200 contains a differentiated crenulation cleavage overgrown by a andalusite porphyroblast defining an approximately N–S-trending pseudo FIA (Set 2) that was inflected during porphyroblast growth to define a FIA trending at 30° (Set 3;

Table 2). Furthermore, inclusion trails defining W–E FIA (Set 1) are commonly truncated by a N–S-trending matrix foliation and those defining N–S FIA (Set 2) are generally not truncated. SW–NE-trending FIA (Set 3) are defined by inclusion trails that are always continuous with the matrix foliation. This succession indicates that these rocks have been affected by deformation during four cycles of orogeny during which the directions of bulk horizontal shortening were directed SW–NE, N–S, W–E and finally NW–SE.

10.2. Key structural relationship from rocks from near the Gilded Rose Mine

Folds in the north of Fig. 1 vary in trend from NW–SE to W–E. This variation could be due to the overprinting effects of the development of younger N–S-trending folds on earlier formed W–E-trending folds and this has been one interpretation for the regional structural relationships. However, the discovery that the first FIA set formed in this region is NW–SE-trending revealed a previously unrecognized possibility. This is that the regional folds in the northern portion of Fig. 1 were originally NW–SE-trending and were rotated to a W–E trend due to the spatially partitioned effects of subsequent N–S bulk shortening. This was readily tested using samples from key locations relative to these regional folds. This is shown using sample G5 collected from the northern limb of the major anticline shown in (Figs. 2 and 17a). It contains northwest-striking bedding defined by alternating pelitic porphyroblast-rich and psammitic porphyroblast-poor lamellae. If the large-scale folds formed with a W–E trend then what formed as a W–E-trending axial plane cleavage should have a vergence asymmetry in plan view that is clockwise relative to bedding as the plunge of this fold is to the SE. However, this is not the case. Bedding is crosscut by a west–east-striking foliation, S_{1A}, which is crenulated by a north–

south-striking S_{2A} crenulation cleavage as shown in Figs. 17b, c. Relics of S_{00} sub-parallel to bedding can be seen in the more psammitic layers that are little affected by S_2 crenulations. This orientation relationship relative to bedding reveals that NW–SE-trending folds have been overprinted by a period of N–S shortening resulting in the development of the W–E $S_{1A,1C}$ foliation shown in Fig. 15.

10.3. Periods of orogenesis

NE–SW bulk shortening (O_{00})

The first period of orogenesis produced at least 2.5 cycles of sub-vertical and sub-horizontal foliation development forming five foliations S_{00a}, S_{00b}, S_{00c} and S_{00d} and S_{00e} that are now only preserved as inclusion trails within porphyroblasts defining FIA set 00. S_{00} matrix foliations related to this tectonic event lying oblique to S_0 are not commonly preserved because reactivation of the compositional layering during younger deformations has decrenulated and/or rotated them into parallelism with it (Ham and Bell, 2004). A bedding parallel foliation ($S_0//S_{00}$, Fig. 18) is present in porphyroblastic rocks throughout the eastern Mount Isa Block (Jaques *et al.*, 1982; Adshead-Bell, 1998; Rubenach and Lewthwaite, 2002; Giles *et al.*, 2006 a, b; Rubenach *et al.*, 2008).

N–S bulk shortening (O_1)

N–S bulk horizontal shortening is well preserved in the Gilded Rose Mine area as penetrative W–E-striking planar fabric elements. It produced a succession of at least 3 foliations within the matrix (S_{2A}, S_{2B}, S_{2C}; Fig. 3b and c) that are alternately oriented sub-vertical and sub-horizontal where preserved as inclusion trails within porphyroblasts (S_{1a}, S_{1b}, S_{1c}).

W–E bulk shortening (O_2)

W–E bulk horizontal shortening (Beardsmore *et al.*, 1988; Adshead-Bell, 1998; Betts *et al.*, 2000; Hatton and Davidson, 2004) dominates the structural grain of the Mount Isa Inlier producing a very intensely developed N–S-striking fabric. In the northern portion of Fig. 1 the effects of this period of orogeny are much more weakly developed and it locally formed a differentiated crenulation cleavage rather than the very intensely developed schistosity that is present in the southern part of Fig. 1. The succession of cleavages associated with this period of orogeny are only easily observed in thin section in the north off Fig. 1 (e.g., Fig. 11).

NW–SE shortening (O_3)

NW–SE bulk shortening is not common across the inlier but is present locally across Fig. 1.

10.4. Inclusion trail asymmetries

Inclusion trails defining FIA Set 00 that change from sub-vertical to sub-horizontal orientations always preserve an anticlockwise asymmetry looking NW (Fig. 16). This indicates a top to the SW sense of shear (e.g., Bell and Hobbs, 2010) and the consistency of the asymmetry suggests that it involved NE to SW-directed thrusting (e.g., Yeh, 2001; Rich, 2006; Bruce, 2007). Porphyroblasts entrapping inclusion trails defining the W–E-trending FIA Set 1 show steeply dipping foliations that are strongly overprinted by gently dipping ones are dominated by a clockwise asymmetry looking W (Fig. 16). This strongly indicates that S to N-directed thrusting took place during this period of orogenesis. It accords with the interpretation of the Wonga-Duchess Belt of Bell *et al*. (1992) as a mega transform like shear zone across which the direction of thrusting changed from N to S in the West to S to N in the east.

10.5. The progressive development and rotation of regional NW–SE and W–E folds

The recognition of NW–SE-trending FIAs preserved in the first formed porphyroblasts of the Gilded Rose region requires consideration of a different tectonic history for the development of this region than has previously been proposed. An early period of orogenesis O_{00} during NE–SW-directed bulk horizontal shortening is required to form this FIA set. This produced NW–SE-trending regional folds across the region as shown in Fig. 19a. Metamorphism during this period of orogenesis led to the growth of garnet porphyroblasts preserving inclusion trails whose top to the south differentiation asymmetry from steeply to gently dipping foliations (Fig. 16a) indicates top to the SW thrusting. S_{00} has generally been destroyed in the matrix due to the reactivation of the compositional layering that accompanied the many deformation events that postdated the development of FIA set 00. Significantly, rather than new regional folds form during N–S bulk shortening, these NW–SE-trending regional folds were simply rotated towards W–E trends during development of the second period of orogenesis O_1 (Fig. 19b). This is proven by the overprinting relationships of the composite sub-vertical matrix foliation $S_{1A,1C}$ that overprints both limbs of these folds with the same asymmetry (Fig. 17). Metamorphism accompanying this period of orogenesis O_1 was responsible for the growth of porphyroblasts contain the W–E-trending FIA 1 that preserve successions of inclusion trails in garnet, andalusite and staurolite porphyroblasts. W–E-directed bulk horizontal shortening during the third period of orogenesis O_2 resulted in the development of the regional N–S structures that dominate the entire Mount Isa province (Fig. 19c). The various matrix S_2 foliations that accompanied this period of orogenesis and crenulated earlier foliations lying parallel to S_0 and associated with O_1

(Fig. 17c). The final period of orogenesis O_3 is relatively weakly developed across the region in Fig. 1, but was locally accompanied by porphyroblast growth. It could have resulted in rotation of the southern end of the Snake Creek anticline towards a NW–SE trend or this could in part be a relic of the effects of O_{00} as is tentatively suggested in Fig. 19; this is the subject of further investigation.

10.6. The Wonga-Duchess Belt tear Fault

The top-to-the-north shear sense shown by the curvature of inclusion trails from sub-vertical to sub-horizontal orientations in porphyroblasts hosting the W–E-trending FIA Set 1 indicate S to N thrusting. In the western Mount Isa province thrusting occurs from N to S. This confirms a proposal that the Wonga-Duchess belt acted as a N–S-striking vertical tear fault that accommodated different directions of thrusting across the Mount Isa block (Bell *et al*., 1992). They proposed that N to S directed thrusting in the west was directed S to N in the east to explain the sinistral shear sense preserved by elongate mafic xenoliths relative to the vertical N–S-striking matrix foliation during the development of sub-horizontal stretching lineations in the Wonga-Duchess belt.

10.7. Timing shifts in direction of bulk shortening from O_{00} through O_3

Using age data from across the Mount Isa Province, the timing of changes in the direction of bulk shortening can be proposed. The Mt Gordon Arch lies 110 kms to the west of Fig. 1 and passes NNW through Mount Isa township to at least 80 kms further north. Arching of Haslingden Group and Myally Subgroup rocks older than 1672 Ma accompanied development of a foliation that formed at depths around 4.5 kb at 1672 Ma and trends W–E near the northern boundary of the Sybella Granite (Rubenach, 2008). The latter pluton was emplaced at 1671 Ma (Neumann *et al*., 2009). These arched sediments were eroded prior to deposition of the Mount Isa Group. Deposition of the latter group took place from 1670 to 1652 Ma (Page, 1981; Neumann *et al*., 2009) producing a spectacular regional unconformity to either side of the arch (Bell, 1991). The Warrina Park Quartzite overlies progressively deeper rocks towards the arch center where up to 5 kms of rock were eroded in the Bonaparte Basin region ~ 60 kms N of Mount Isa prior to their deposition (Bell, 1991). Significantly, where relatively protected by the Sybella granite from the effects of W–E bulk shortening associated with development of the N–S-trending FIA Set 2, the Mt Gordon Arch has a NW–SE trend (Bell, 1991). Where unprotected or well north of the strain shadow created by the Sybella Granite it is more N–S-trending. It appears likely that the Mt Gordon Arch and the W–E-striking 1672 Ma foliation that formed at 4.5 kbar (mentioned above) formed at the commencement of the O_{00} period of orogeny during SW–NE-directed bulk shortening. The W–E trend possibly resulted from localized rotation of the foliation from a NW–SE trend against the competent coarse feldspar granite during subsequent N–S-directed bulk shortening that formed FIA set 1. The remains of the Mt Gordon Arch exposed with the Kokkalukkernurker Duplex lay well to the NE plus at a higher crustal level during N–S shortening and would not have been compressed against the Sybella granite (see below; Bell, 1983, 1991). SW–NE-directed orogenesis associated with development of the NW–SE-trending FIA set 00 continued to at least 1650 Ma as monazite grains amongst inclusion trails defining this FIA set in the Snake Creek anticline have been dated at this age (Rubenach, 2008).

N–S-directed bulk-shortening orogenesis began by 1640 Ma (Rubenach, 2008; Abu Sharib, unpublished data). The transition from N–S bulk shortening directed orogenesis (FIA set 1) to W–E-directed orogenesis (FIA set 2) is now well known and took place around 1600 Ma (compare Page and Bell, 1986; Rubenach, 2008 and Rubenach *et al*., 2008). W–E bulk shortening orogenesis continued until at least 1515 Ma (Page and Bell, 1986) and NW–SE bulk shortening orogenesis occurred to ~1500 Ma (Rubenach, 2008).

10.8. The Meerenurker roof thrust versus the Kokkalukkernurker duplex

The NW–SE trend of the Mt Gordon Arch was a vital structure for resolving the geometric relationship between the Meerenurker roof thrust and the western lateral ramp to the underlying Kokkalukkernurker duplex of repeated Mount Isa group rocks (Bell, 1983, 1991). Significantly, the Meerenurker roof thrust lies at a higher stratigraphic level than the imbricates within the duplex, which requires that this fault form first (fig. 6a in Bell, 1983). For N to S-directed thrusting this resulted in more than 234 kms of southwards displacement of the roof rocks prior to displacement due to the creation of the imbricates in the duplex below. Recognition that top to the SW-directed thrusting occurs SE of Cloncurry prior to S–N-directed thrusting provides an alternative possibility that dramatically reduces the amount of displacement. The Meerenurker roof thrust could have formed during SW directed thrusting that accompanied O_{00} with a minimum of just 45 kms of displacement. The imbricates within the Kokkalukkernurker duplex could then have formed below it during the subsequent N–S-directed thrusting that accompanied O_1 in the western Mount Isa Province as shown in fig. 6b in Bell (1983)!

10.9. The continuity of orogenesis

O_{00}, O_1 and O_2 were prolonged orogenic cycles as each regionally produced a succession of four or more foliations (Bell *et al*., 1992; Bell and Hickey, 1998; Sayab, 2005, 2006, 2008; Bell and Bruce, 2006) involving horizontal shortening followed by gravitational collapse of the thickened crust. Orogenesis across the Mount Isa Province now appears to have been episodically continuous from 1672 Ma to around 1500 Ma. With the quantitative access to correlating and dating multiple sets of foliation development that FIAs provide such continuity will probably become a commonly recognized feature of orogenesis (e.g., Bell and Newman, 2006). It certainly gets much better with the continuity of relative plate motion than the 3 or 4 phases of foliation development that previously were accepted as all that had occurred within the matrix of multiply deformed rocks (Bell, 2010).

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PLAN VIEW ORTHOGONAL REFOLDING: RESOLVING PROBLEMS ASSOCIATED WITH TIMING FOLDS THAT FORM NEAR PERPENDICULAR TO ONE ANOTHER USING FOLIATION INTERSECTION AXES PRESERVED WITHIN PORPHYROBLASTS (FIAS)

CONTENTS OF SECTION B

Plan view orthogonal refolding: Resolving problems associated with timing folds that form near perpendicular to one another using foliation intersection axes preserved within porphyroblasts (FIAs)

Abstract

The relative timing of the sequence of events is problematic where deformation partitioning strongly separates zones dominated by folds that formed in different periods of orogeny. This is particularly the case where they form orthogonal to one another in plan view. A succession of foliation inflection/intersection axes preserved within porphyroblasts (FIAs) readily resolves the sequence. The succession of FIAs, as well as foliations in the matrix in the Soldiers Cap Group of the eastern Mount Isa Inlier, reveals W–E-directed bulk horizontal shortening followed N–S bulk horizontal shortening in spite of the apparent regional lack of curvature of the W–E-trending folds around those trending N–S. Furthermore, N–S-and W–E-directed bulk shortening both resulted in at least 2 cycles of sub-vertical and sub-horizontal foliation development that define the W–E-and N–S-trending FIAs.

Key words: deformation partitioning, foliation inflection/intersection axes, bulk horizontal shortening, Soldiers Cap Group, Mount Isa Inlier.

1. Introduction

Relatively timing near orthogonal deformations in plan view is difficult from map relationships. Commonly, the axial planes for either deformation are not obviously refolded. Furthermore, if the deformations are spatially strongly partitioned, one event will dominate in one area and the other in another. This is the case for W–E-versus N–S-trending folds in the Cloncurry region of the Precambrian Mount Isa Terrane shown in Fig. 1. These folds interfere on a large scale in the region north of the Snake Creek Anticline (Fig. 1). The W–E-trending folds (Toole Creek and Davis synclines and Mountain Home anticline) dominate the northern part, whereas the N–S-trending folds (Snake Creek anticline and Weatherly Creek syncline) dominate the southern part of the area (Fig. 1). The relative timing between these folds has been problematical for many years and a range of solutions have been suggested.

Discussions about the relative timing or even the existence of N–S versus W–E shortening in the Mount Isa Province have occurred in the literature for many years (Bell, 1983, 1991; Reinhardt, 1992; Adshead-Bell, 1998; Bell and Hickey, 1998; Lister *et al.*, 1999; Sayab, 2005, 2006; Giles *et al.*, 2006). Bell (1983, 1991) proposed that the first orogeny to affect most of the rocks of the Mount Isa province was caused by north–south shortening and this resulted in the widespread east–west trending folds. Giles *et al.* (2006) argued against this notion and recognized no folding events prior to the N–S-trending ones in the Snake Creek anticline region because they argued that the W–E-trending ones formed as a crumpled frontal zone in the same event.

This paper seeks to resolve the quandary raised by these previous authors, and determine whether or not a continuum of folding, nappe development and folding or simply two overprinting near orthogonal periods of tectonism were involved in the structural history of this region. The approach used involved detailed structural mapping, multiple oriented sample thin sectioning and quantitative analysis of the microstructural history that was trapped in the porphyroblasts. This work reveals that W–E followed N–S bulk shortening, but SW–NE-directed bulk shortening, which is not obvious from the maps, also played a significant role. This resolves all aspects of this historically problematical deformation succession in the Cloncurry region.

2. Geological setting

The Mount Isa Inlier, which occupies the northwest corner of Queensland, comprises three N–S-trending tectonostratigraphic units, namely, the Western Fold Belt, the Kalkadoon-Leichhardt Belt and the Eastern Fold Belt. These are bordered by major fault zones and expose Lower to Middle-Proterozoic metasediments, metavolcanics and intrusives. Two main cycles of crustal extension, separated by the Barramundi Orogeny, were suggested for the deposition of the supracrustal rocks of the Mount Isa Inlier (1870 Ma; Etheridge *et al.*, 1987; Blake and Stewart, 1992). During each of these cycles, intraplate sedimentary basins were formed with deposition of volcanics and rift sag sequences (Blake, 1987).

The first episode of extension (1900 Ma; Blake and Stewart, 1992) was characterized by the development basement sediments, volcanics and intrusives that were collectively metamorphosed and deformed during the Barramundi Orogeny (1870 Ma). Three distinct stratigraphic packages or cover sequences (Blake, 1987) occurred during the second episode of extension. Cover Sequence 1 (~ 1860 Ma) is restricted to the central part of the Mount Isa Inlier (Blake and Stewart, 1992) and consists of felsic volcanics and coeval granites. Cover Sequence 2 (~ 1800–1740 Ma, Williams, 1989; O'Dea *et al.*, 1997; Potma and Betts, 2006) is dominated by bimodal volcanics, clastics and carbonate sediments. Cover Sequence 3 (~ 1740–1670 Ma, Derrick, 1982, 1992; Page and Sun, 1988; Blake and Stewart, 1992; Lister *et al.*, 1999; O'Dea *et al.*, 1997; Page and Sweet, 1998; Jackson *et al.*, 2000; Page *et al.*, 2000) consists predominantly of rhyolites, dolerites, sandstones and mudstones. The latter two cover sequences occur right across the inlier. Crustal shortening and metamorphism occurred with commencement of the Isan Orogeny around 1610 Ma

(Page and Bell, 1986) and led to basin development termination and cessation of deposition of Cover Sequence 3. Emplacement of the post-tectonic Williams Naraku Batholiths at 1520–1480 Ma (Wyborn *et al.*, 1988; Page and Sun, 1998; Wyborn, 1998) signified termination of the Isan Orogeny.

The Soldiers Cap Group (1685–1655 Ma: Page and Sun, 1998; Giles and Nutman, 2003; Neumann *et al.*, 2006) occupies the eastern part of the Eastern Fold Belt and is made up of Mid-Proterozoic metasedimentary and metavolcanic rocks that are intruded by post-tectonic intrusions (Fig. 1). The three main units within this group, from base to top are the Llewellyn Creek Formation, Mount Norna Quartzite and Toole Creek Volcanics. The Llewellyn Creek Formation is a porphyroblastic unit made up of well-bedded metaturbidites (Fig. 2a and b). The Mount Norna Quartzite is a porphyroblast-poor unit made up of metamorphosed massive finely cross-bedded quartz sandstone, mudstone, siltstone and metadolerite. The Toole Creek Volcanics consist of metadolerite and metabasalt together with carbonaceous pelitic metasediments. Page and Sun (1998) gave the Soldiers Cap Group a maximum depositional age of approximately 1670 Ma, placing it within the Cover Sequence 3 of Blake (1987). A 700-m-thick gabbroic to tonalitic sill intruding the Llewellyn Creek Formation yielded an age of 1686±8 Ma (Rubenach *et al.*, 2008), which indicates that this formation was deposited prior to that time.

3. Structure

The Isan Orogeny (~ 1650–1490) was the main contractional deformation in the Mount Isa province. It comprised three main macroscopic phases of deformation that portrayed the tectonic configuration of the Inlier (Bell, 1983, 1991; Swager, 1985; Page and Bell, 1986; Winsor, 1986; Loosveld, 1989; Nijman *et al.*, 1992;

Stewart, 1992). D_1 was attributed mainly to a period of north–south shortening and produced east–west striking regional folds. D_1 E–W-striking folds have been described in both the Western (Bell, 1983, 1991; Loosveld and Schreurs, 1987; Stewart, 1992; Lister *et al.*, 1999) and Eastern Fold Belts (Loosveld, 1989; Bell *et al.*, 1992; Lally, 1997). D_2 resulted from W–E bulk shortening and dominates the structural grain over most of the inlier. It formed regional folds with N–S-striking sub-vertical axial planes at 1544 Ma (Page and Bell, 1986). D_3 was mainly due to W–E shortening, and produced small-scale, locally-developed N–S-trending folds with near-vertical axial planes at 1510 Ma (Page and Bell, 1986).

3.1 W–E-and N–S-trending folds in the Soldiers Cap Group

The Soldiers Cap Group hosts both macroscopic W–E-and N–S-trending folds and determining the structural relationships across transitions between these differently oriented structures should resolve the problems in timing that plague this region. Different deformation schemes have been introduced in the literature for the Soldiers Cap Group. The events described commonly conflict, with some never recorded by several of the authors, adding a complex and conflicting fold and deformation terminology to a complicated region. Table (1) summarizes some of these deformation schemes in comparison to that of the present study.

Highly deformed and regionally metamorphosed rocks in orogenic belts are commonly affected by strong partitioning of deformation at all scales (Bell *et al.*, 2004). Consequently different rock types as well as different portions of the same rock units behave differently during progressive deformation. This partitioning is mainly attributable to the extreme heterogeneity of strain in deformed rocks (Bell, 1981) and can dramatically influence the structural relationships observed by different workers from region to region. The northern Snake Creek anticline area is typical of this problem with some meso and macroscopic folds well preserved only in certain domains relative to the others (Fig. 1). Tracing and correlating foliations throughout the entire area is quite difficult. In particular, determining the relative timing relationships between the different generations of folds is not simple, because of their large scale and a very lengthy history of multiple foliation development.

3.2 Previously suggested structural relationships

Large-scale approximately E–W-and N–S-trending folds affect the Proterozoic rocks of the Soldiers Cap Group and interfere in the region north of the Snake Creek Anticline (Fig. 1). The E–W-trending folds (Toole Creek and Davis synclines and Mountain Home anticline) dominate the northern part, whereas the N–S-trending folds (Snake Creek anticline and Weatherly Creek syncline) dominate the southern part of the area (Fig. 1). The resulting large-scale orthogonal interference pattern has attracted the attention of numerous workers, but no real accord has been reached in the literature on fold timing and development. Ryburn *et al*. (1988) proposed that the W–E-trending Toole Creek and the N–S-trending Weatherly Creek synclines represented a continuum with W–E-trending folds refolded around N–S-trending second generation folds such as the Snake Creek anticline. Loosveld (1989) and Loosveld and Etheridge (1990) attributed the orthogonal pattern of folding to refolding of a E–W-trending overturned nappe about N–S-trending second generation folds, including the Weatherly Creek syncline (Fig. 3a). Giles *et al.* (2006), in accordance with Loosveld and Etheridge (1990), argued that the refolding structure originated as a shallowly inclined fold nappe. They argued that the north–northwest-trending thrusts and an overturned nappe structure, the Snake Creek Anticline, developed a crumpled frontal zone with W–E upright folds due to a phase of horizontal shortening (Fig. 3b). These structures were refolded about N–S-trending folds such as the Weatherly Creek syncline. Therefore, they effectively argue that the Snake Creek anticline and the Toole Creek syncline developed during the same phase of deformation. Loosveld and Etheridge (1990) believed that the Snake Creek anticline and the Toole Creek syncline represent first generation structures.

4. Structural data

Investigation of the meso and macroscopic structures of the Soldiers Cap Group in the Snake Creek anticline region has revealed that the area was multiply deformed during at least 4 periods of orogenesis (Abu Sharib and Bell, unpublished data). Only the 2 most obvious of these periods of orogeny, which formed the W–E and N–S structures are dealt with in this paper because they are so striking, spatially separated and seemingly non-interfering on regional maps (Fig. 1). O_n for orogeny is used rather than D for deformation event throughout this manuscript because both the W–E-and N–S-trending periods of orogeny involved several periods of foliation development and porphyroblast growth. To avoid any timing connotation being initially implied in the description of these structures, N–S and W–E are used initially as labels to differentiate between the 2 periods of orogeny involved.

4.1 W–E-trending folds

W–E-trending folds in the area around the Gilded Rose Mine (Fig. 1) are gently to moderately plunging (Fig. 4a) upright folds. A steeply dipping W–E-striking crenulation cleavage $S_{W–E}$ trends sub-parallel to the axial plane of these folds and crenulates earlier formed foliations (see Abu Sharib and Bell unpublished data for the information on the earlier formed foliations). A bedding parallel foliation S_{00}//S_0 is widespread throughout the Eastern Fold Belt (Jaques *et al.*, 1982; Adshead-Bell, 1998; Rubenach and Lewthwaite, 2002; Giles *et al.*, 2006b; Rubenach *et al.*, 2008). Linear fabric elements related to the $O_{W–E}$ orogeny, represented by the axes of mesoscopic folds $F_{W–E}$ (Fig. 4b) and an intersection lineation. $L^{0,00}{}_{W–E}$, vary regularly in plunge from W to E (Fig. 5 domains I and II).

4.2 N–S-trending folds

The N–S-trending Snake Creek anticline is a tight, upright non-cylindrical fold that extends for about 10 km southwards with a moderately to steeply east-dipping axial plane (Fig. 1). The core of the fold is occupied by the metasediments of the Llewellyn Creek Formation with the Mount Norna Quartzite and Toole Creek Volcanics in a normal stratigraphic order on its rim as revealed by good younging criteria via the Bouma sequence in many outcrops (Fig. 5a). The western limb of the fold is overturned and dips east. The Snake Creek anticline has a very-well developed axial planar foliation that strikes nearly N–S and dips east at moderate to steep angles ($S_{N–S}$). Towards the western limb and close to the Cloncurry Fault zone, $S_{N–S}$ shows a slight variation in strike from nearly N–S in the northern part to NNW–SSE in the southern part. (Fig. 1). Sigmoidal shaped quartz veins (Fig. 5b) and strain shadows around some andalusite porphyroblasts (Fig. 5c) are locally present. The asymmetry of these structures changes across the fold.

$L_{N–S}$ fabrics are represented by axes of mesoscopic folds, $F_{N–S}{}^{0,00}$, (Fig. 5d) crenulation axes, $L_{N–S}{}^{0,00}$ (Fig. 6a, b) as well as a few mineral lineations $L_{N–S}{}^{N–S}$. They plunge towards the north and south with variable amount of plunge (Figs. 7 (domain Ib) and 8) reflecting the non-cylindrical nature of the $O_{N–S}$ folds.

4.3 Late formed kinks

Late formed kinks in the Snake Creek anticline are variably oriented with different amounts of plunge and overprint all previous ductile structures. North, southwest, and northeast directions of plunges were detected (Fig. 9a). Most of the kinks have nearly vertical axial planes (Fig. 9a) that developed during phases of horizontal shortening but some with almost horizontal axial planes were also recorded (Fig. 9b).

5. Porphyroblast data

Foliations preserved as inclusion trails within porphyroblasts are most commonly straight with curvature only being apparent on their rims at high magnification. The curvature can be more obvious with the trails having a sigmoidal shape (Figs. 10 and 11), but this is less common. Locally, the trails have staircase (Fig. 12) or spiral shapes. The axis of curvature or foliation inflection/intersection axes in porphyroblasts (FIAs) can be measured by cutting six vertical thin sections for each sample every 30° of strike and observing where the switch in curvature of the asymmetry of the inclusion trails from clockwise to anticlockwise takes place when viewed from the one direction (Fig. 13a; Hayward, 1990; Bell *et al.*, 1995, 1998, and 2004). The FIA can be measured to within 10° by cutting 2 intervening sections 10° apart between those where the change in asymmetry occurred. The inclusion trails entrapped within the different porphyroblasts of the different generations, exhibit different stages of differentiation of Bell and Rubenach (1983).

5.1 Porphyroblastic phases

The metamorphic minerals encountered include Grt, St, And, Bt, Ms, Crd, Sil, a few Ctd and rare Ky (mineral abbreviation symbols follow Kretz, 1983). Some samples contain more than one phase of garnet growth revealed by the change in the composition and size of the inclusions from the core to rim of these porphyroblasts.

5.2 FIA measurements

5.2.1 Gilded Rose

A prominent FIA trend of 80°–110° (Fig. 13b) occurs in the Gilded Rose area (Fig. 1; 34 samples, Table 2). This FIA was mainly measured using inclusion trails in garnet and staurolite. It was also found in some samples with andalusite porphyroblasts. The same FIA was measured from the core and rim of these porphyroblasts (Table 2). This orientation was also preserved in pre-porphyroblast growth crenulation axes called pFIA. Excellent sigmoidal-shaped inclusion trails characterize this FIA trend (Fig. 11). The porphyroblasts have cores dominated by sub-vertical trails that curve towards sub-horizontal at the outer rim with a clockwise or anticlockwise asymmetry (Fig. 14). Garnet porphyroblasts with perfect sigmoidal inclusion trails preserving this FIA trend show four internal nearly orthogonal foliations. These begin with sub-vertical trails in the cores that are truncated by a nearly horizontal differentiated crenulation cleavage. This cycle repeats towards rim (Fig. 11). Around the Gilded Rose Mine area the inclusion trails appear continuous with the matrix (Fig. 12). The rims of some porphyroblasts contain a N–S-trending FIA (sample N17; Table 2). Some andalusite porphyroblasts (Fig. 15) preserve stage 3-4 of differentiated cleavage within them (Bell and Rubenach, 1983).

5.2.2 Snake Creek Anticline

Garnet, staurolite, andalusite and chloritoid porphyroblasts contain FIAs trending 345°-015° (Fig. 13b). This is the dominant FIA in the Snake Creek anticline area (23 samples, Table 2). Andalusite is the most common porphyroblast preserving this FIA trend. Close to the Snake Creek anticline the trails are truncated by the matrix foliation. Three samples preserve both W–E and N–S FIA trends (samples G3, G390 and N17, Table 2; Figs. 11 and 12b, c). Some samples contain porphyroblasts preserving a N–S-trending FIA with inclusion trails that are continuous with the matrix foliation.

5.3 Inclusion trail asymmetry

The asymmetry of curvature of a crenulated cleavage into a differentiated crenulation cleavage in the matrix is identical to that within porphyroblasts that formed during the same deformation event, unless a millipede geometry has developed (Bell and Bruce, 2007; Bell and Hobbs, 2010). The asymmetries were ascertained using vertical thin sections oriented near orthogonal to the FIA trends. The asymmetries of overprinting foliations defining the W–E-and N–S-trending FIA sets were determined looking west and north respectively. The histogram in Fig. 14 shows the frequency of clockwise and anticlockwise asymmetries of the inclusion trails within the porphyroblasts of the different samples for each FIA set and whether they change from gentle to steeper pitches on their rims or vice versa.

5.4 Deformation history

The study area has been multiply metamorphosed and deformed during several periods of orogenesis, each of which was accompanied by the development of a number of foliations and the concurrent growth of porphyroblasts. This multiplicity of foliations is commonly preserved in porphyroblasts but rarely in the matrix. This occurs because the foliations in the porphyroblasts are preserved as they were developed at the time of porphyroblast growth whereas those in the matrix get destroyed and/or rotated into parallelism with the compositional layering due to reactivation of the later (Bell el al., 2003; Bell and Hobbs, 2010). Consequently it is rare that more than 2 or 3 foliations oblique to bedding are preserved in the matrix and $S_0//S_{00}$ routinely truncates inclusion trails preserved in porphyroblasts in 3D (Bell, 2010). Correlating 3 to 4 foliations from inside to outside of porphyroblasts is impossible once the inclusion trails are truncated by the matrix foliation due to reactivation of the compositional layering (Ham and Bell, 2004). Therefore, the succession of internal foliations within porphyroblasts are numbered in sequence S_{na}, S_{nb}, S_{nc} …etc, whereas matrix foliations are numbered S_{nA}, S_{nB}, S_{nC}. Where n is the number of the orogeny as defined by the FIA succession (see below).

5.5 Foliations in porphyroblasts

5.5.1 Foliations associated with the W–E-trending FIA

Garnet porphyroblasts with perfect sigmoidal inclusion trails preserving this W–E FIA contain four nearly orthogonal foliations of which the first is sub-vertical $O_{W–E}S_a$, $O_{W–E}S_b$, …etc (Fig. 10). In some samples, $O_{W–E}S_d$ is truncated by a sub-vertical differentiated crenulation cleavage, $O_{N–S}S_a$.

5.5.2 Foliations associated with the N–S-trending FIA

Two foliations preserved as inclusion trails, $O_{N–S}S_a$, and $O_{N–S}S_b$ are common in porphyroblasts preserving this FIA trend (Figs. 14–16). $O_{N–S}S_a$, is a sub-vertical cleavage that is crenulated by a well-developed differentiated crenulation cleavage, $O_{N–S}S_b$ (Fig. 14). In some samples, $O_{N–S}S_a$, occurs as a differentiated crenulation cleavage crenulating sub-horizontal $O_{W–E}S_b$ or $O_{W–E}S_d$. In some samples, staurolite and andalusite porphyroblasts preserving the N–S FIA set were found wrapping around garnet porphyroblasts preserving the W–E FIA set (see below).

5.6 Foliations in the matrix

Matrix foliations throughout the region shown in Fig. 1 are complex and heterogeneously developed. A foliation S_{00} always lies parallel to bedding. Overall W–E-striking foliations, range from gently to steeply dipping. Locally $O_{W–E}S_C$ and $O_{W–E}S_D$ can be correlated with $O_{W–E}S_c$ and $O_{W–E}S_d$ foliations within porphyroblasts preserving the W–E-trending FIA set and no foliation prior to $O_{W–E}S_C$ was detected in the matrix. Matrix foliations also developed that are N–S-striking and range from gently to steeply dipping. $O_{N–S}S_A$ is the dominant penetrative planar fabric element in the south of the area (Figs. 10 and 11). A subsequent gently dipping foliation $O_{N–S}S_B$ is also commonly developed as a crenulation cleavage or as the rotated relics of $O_{N–S}S_A$. $O_{N–S}S_A$ is a crenulation cleavage that crenulates earlier foliations. Near the Gilded Rose Mine area, $O_{N–S}S_A$ matrix foliation can be seen to crenulate $O_{W–E}S_C$, S_D matrix foliations. On the northern part of the hinge of the Snake Creek anticline, sub-vertical $O_{N–S}S_A$ forms axial plane to crenulations in $O_{W–E}S_B$, S_D.

6. Interpretation

6.1 The succession of FIA sets

The core of a porphyroblast must form before its rim. The consistent relationship of porphyroblasts preserving N–S-trending FIAs in their rim and W–E-trending FIAs in their cores indicates that the W–E predates N–S-trending FIAs. Therefore the foliations that formed during the development of the earlier formed W–E-trending FIA are denoted by O_1 and those that formed during the development of the subsequent N–S-trending FIA are denoted by O_2.

6.2 N–S bulk shortening O_1

N–S bulk horizontal shortening is better preserved in the Soldiers Cap group in the Gilded Rose region than any other portion of the Mount Isa Inlier. It developed a succession of four nearly orthogonal foliations S_A, S_B, S_C and S_D about the W–E-trending FIA (Fig. 13b) that are well preserved in porphyroblasts but most commonly form a bedding parallel plus a sub-vertical composite O_1 fabric in the matrix. Two cycles of a sub-vertical and sub-horizontal foliations produced successively O_1S_A, O_1S_B, O_1S_C and O_1S_D (Fig. 18). N–S predates W–E bulk shortening as the effects of W–E bulk shortening that formed the O_2 foliations overprint O_1 foliations both in the matrix and in porphyroblasts. The dominant asymmetry of overprinting of sub-vertical foliations by sub-horizontal ones preserved in porphyroblasts in the Gilded Rose area (Fig. 14) indicates that the motion of rock during gravitational collapse periods was top to the north. This is the opposite to that to the west of the Wonga-Duchess belt and confirms the prediction of Bell *et al*. (1992) that the latter belt is a large scale transfer zone that resulted from a dramatic change in the direction of thrusting from N to S in the west to S to N in the east.

6.2 W–E bulk shortening O_2

W–E bulk shortening during O_2 produced the N–S-striking fabric that dominates the entire grain of the Mount Isa Inlier. In the Snake Creek anticline area

O_2 formed three distinct foliations O_2S_A, O_2S_B and O_2S_C. The development of sub-vertical O_2S_A (Beardsmore *et al.*, 1988; Adshead-Bell, 1998; Betts *et al.,* 2000; Hatton and Davidson, 2004) produced regional N–S-trending tight to isoclinal upright folds with steep axial planes (Figs. 1, 7 (domain I b), 8 and 19a, b). The subsequent development of a gently dipping crenulations cleavage, O_2S_B, resulted in formation of recumbent to isoclinals folds (Fig. 19c). Similar structures were recorded in the Selwyn Zone north of the study area for a group of N–S folds with shallow dipping axial planes (Rubenach *et al.,* 2008, fig. 3). O_2S_A clearly crenulates the earlier composite O_1 cleavage in the northern area (Figs. 5b and c, 10, 11, 15–17). It is the most prominent and well-developed fabric in the Snake Creek anticline. O_2S_B is equivalent to the $S_{2.5}$ of Bell and Hickey (1998). Similar mesoscopic and macroscopic structures related to this event were first recognized by Bell and Hickey (1998) in the area northwest of Mount Isa (Bell and Hickey, 1998, fig. 3a), within Mount Isa and Hilton mines (Bell and Hickey, 1998, fig. 5c) and in the area to the north of Spear Creek (Bell and Hickey, 1998, fig. 6). Large folds related to that tectonic event were mapped in the Snake Creek anticline (New, 1993) the Tommy Creek block (Lally, 1996, 1997) and smaller folds at Dugald River (Xu, 1996, 1997), Fairmile (Mares, 1996, 1998) and the area east of Starra (Adshead-Bell, 1998). O_2S_C equals to the S_3 of Bell and Hickey (1998).

7. Discussion

7.1 FIAs

FIAs result from porphyroblasts preserving a history of overprinting of successively developed sub-horizontal and sub-vertical foliations (Bell and Newman, 2006). Decrenulation during the same and/or later tectonic events (Ham and Bell, 2004) destroys developing oblique to bedding foliations commonly leaving only portions of the most recently formed ones preserved in the matrix. Porphyroblasts thus provide windows into the early history of orogenesis. They allow the unravelling of the effects of matrix foliation recycling.

7.1.1 Earlier N–S compression during the Isan Orogeny

Quantitative study of 60 oriented porphyroblastic samples from across the region in Fig. 1 revealed that porphyroblasts developed concurrent with N–S bulk shortening preserve a succession of four foliations that formed about a W–E FIA trend. Two cycles of sub-vertical and sub-horizontal foliations were developed with vertical shortening and the development of sub-horizontal foliations accompanying phases of gravitational collapse that followed phases of sub-vertical foliation development (e.g., Bell, 2010). W–E bulk shortening driven orogeny produced another extended period of porphyroblast growth that preserves N–S-trending FIAs. Giles *et al.* (2006) argued against the existence of N–S compressional phase predating the W–E shortening Snake Creek anticline event and attributed the W–E-trending folds in the area north of the Snake Creek anticline to crumpling in the frontal zone of a northwest propagating nappe. This study reveals that the W–E-and N–S-trending folds developed independently during N–S followed by W–E bulk horizontal shortening. The following observations strongly support this:

(1) Porphyroblasts preserving W–E FIA in their cores that have N–S FIA defined by the foliation in their rims.

(2) The preservation of early-developed garnet porphyroblasts hosting W–E-trending FIAs that are wrapped around by staurolite porphyroblasts preserving N–S FIAs.

(3) The clear truncation and/or crenulation of the internal fabric preserved within the porphyroblasts hosting W–E FIAs by the external N–S-striking matrix foliation

(4) The crenulation of the W–E-striking matrix foliation, in transitional zones between regions dominated by W–E-and N–S-trending folds.

During O_1, deformation was strongly partitioned into the northern part of Fig. 1. During O_2 it was strongly partitioned into the Snake Creek anticline region. This resulted in a paucity of clear-cut interference geometries between N–S-and W–E-striking macroscopic folds. This same succession of overprinting was recorded by Rubenach *et al.* (2008, fig. 3) in the Selwyn Zone. Evidence for N–S shortening on all scales is widespread across the Mount Isa Inlier. A succession of nearly orthogonal foliations developed during this shortening event were described in rocks in the vicinity of Mount Isa (Winsor, 1986), adjacent to the Wonga-Duchess belt (Bell *et al.*, 1992) and west and east of Cloncurry (Lally, 1997). Porphyroblasts preserving W–E-trending inclusion trails that were developed during N–S shortening event are widespread throughout the Eastern Fold Belt (e.g., Reinhardt, 1992, in the Rosebud Syncline, Mary Kathleen area; Mares, 1998, in the Fairmile area; Adshead-Bell, 1998, in the Selwyn Range area; Sayab 2005, 2006 in the Snake Creek Anticline and White Blow areas.

7.1.2 Rotation versus non-rotation and the consistency of FIA trend

Porphyroblast rotation (e.g. Regnier *et al.*, 2003) versus non-rotation (e.g. Bell *et al.*, 2004) is still debated in the literature. The argument that non-rotation was not continuum mechanically possible is no longer valid and different approaches to modelling produce no rotation of porphyroblasts provided the anastomosing bulk shortening strain fields in which porphyroblasts grow are reproduced (e.g., Fay *et al.*, 2008, 2009; Sanislav, 2010). The assumption that the porphyroblasts rotate during the successive deformation phases involving non-coaxial deformation must always be quantitatively tested before it is applied. The quantitative data on FIAs in this region reveals that the porphyroblasts here did not rotate. Successions of FIAs can be dated and provide strongly independent confirmation of the age succession (Cao, 2009; Ali, 2010; Sanislav and Shah, 2010; Shah, 2010 a and b).

7. 2 Asymmetry of W–E FIA

The asymmetry of steeply dipping foliations overprinted by gently dipping ones preserved in porphyroblasts with W–E-trending FIAs is dominantly top-to-the-north, indicating that thrusting during N–S shortening orogenesis in this region was directed to the north. This accords with the Wonga Duchess Belt being a large scale transfer fault that separates thrusting to the south in the Mount Isa region from thrusting to the north in the Cloncurry region.

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CHANGES IN RELATIVE PLATE MOTION DURING THE ISAN OROGENY FROM 1670 TO 1490 MA

CONTENTS OF SECTION C

Changes in relative plate motion during the Isan Orogeny from 1670 to 1490 Ma

Abstract

Foliation Inflexion/Intersection Axes preserved in porphyroblasts (FIAs) that grew throughout Isan orogenesis reveal four significant changes in the direction of bulk horizontal shortening between 1670 and 1500 Ma from SW–NE, N–S, W–E to NW–SE. This anticlockwise change in the direction of bulk horizontal shortening implies an anticlockwise shift in relative plate motion with time during the long lasted 1670–1500 Ma Isan orogeny. Dating monazite grains amongst the foliations defining three of the four FIAs enabled an age for the periods of relative plate motion that produced these structures to be determined. Averaging the ages from monazite grains defining each FIA set revealed 1649±12 Ma for SW–NE shortening, 1645±7 Ma for N–S shortening, and 1591±10 Ma for that directed W–E. Inclusion trail asymmetries indicating shear senses of top to the SW for NW–SE FIAs and dominantly top to the N for W–E FIAs reflect thrusting towards the SW and N. No evidence for tectonism related to early SW–NE bulk horizontal shortening has previously been detected in the Mount Isa Inlier. Amalgamation of the Broken Hill and possibly the Gawler provinces with the Mount Isa province may have taken place during these periods of NE–SW-and N–S-directed thrusting as the ages of tectonism are similar. The possibility of an AUSWUS linkage as part of Rodinia is increased in that 1670–1500 Ma period of tectonism in the Mt Isa province exactly spans the gap between two periods of extended tectonism within the USA.

Key words: Foliation Intersection/Inflexion axes (FIA), tectono-metamorphic, porphyroblasts, bulk horizontal shortening, Isan Orogeny.

1. Introduction

Multiply deformed and metamorphosed rocks are characterized by the growth of different generations of porphyroblasts as the rocks within their host terrains were affected by a succession of tectonic pulses (Fig. 1). Textural relationships among different prograde metamorphic minerals can shed light on the relative time constraint of the metamorphic and deformational events. However, it is now known that deformation always partitions such that no portion of a terrane records the impact of every deformation event (Bell *et al*., 2004). Consequently, textural relationships alone provide little of the history undergone (Bell *et al*., 1998). Furthermore, generally only two or three generations of porphyroblasts can be distinguished texturally in rocks preserving excellent microstructural relationships; usually far less. Consequently, the absolute age of monazite grains that formed within matrix foliations and then were overgrown by porphyroblasts commonly reveals a large spread in ages that is difficult to impossible to interpret because of the lack of quantitative information available from the study of textural relationships alone (e.g., Fig. 1). Yet the ages in many cases are precise and the range of ages obtained suggests more information is preserved if only one could distinguish more periods of porphyroblast growth (Tracy, pers. comm.). The average of all such ages usually defines the orogenic period.

Significantly, monazite is now widely-used as a geochronometer and it provides precise results (e.g., Suzuki *et al*., 1994; Suzuki and Adachi, 1998; Montel *et al*., 1996, 2000; Williams *et al*., 1999; Hanchar *et al*., 2000; Shaw *et al*., 2001). Such precision should allow different generations of porphyroblasts and the matrix to be distinguished if one could confirm the data by independently by an approach that quantifies relative timing (e.g., Montel *et al*., 2000). Monazite dating robustly constrains the age of the breakdown of the garnet at the staurolite-in isograd, for example, as this is directly responsible for a period of growth of this phase within a prograde path (Smith and Bareiro, 1990; Pyle and Spear, 2003; Kohn and Malloy, 2004). Again, the question of time constrain of different generations of the same porphyroblasts, in the absence of a clear textural relationship, arises. On which basis can such an absolute age discriminator be applied to differentiate between different generations of the same texturally-unrelated porphyroblasts?

Foliation Inflexion/Intersection Axes in porphyroblasts (FIAs) represent the trends of the intersections of overprinting foliations preserved in the porphyroblasts (Fig. 1, (e.g., Bell and Johnson, 1989; Hayward, 1992; Bell *et al*., 1998; Bell and

Bruce, 2006). It has been determined in several orogens around the world that FIA trends vary consistently with time (Bell *et al*., 1995; Aerden, 2004,; Bell and Newman, 2006) and changes from core to median to rims of porphyroblast provide a succession of porphyroblast development that cannot, in general, be distinguished texturally (Ali, 2010; Sanislav, 2009; Shah, 2010). Consequently monazite inclusions trapped within porphyroblasts preserving different FIA trends provide a precise tool for constraining their timing of growth even where there is no clear textural relationships between them (Fig. 1).

2. Regional geology

The present configuration of the Australian continent appears to be the result of amalgamation and accretion of Precambrian cratons during Palaeoproterozoic, Mesoproterozoic (Fig. 2) and Phanerozoic times during several discrete orogenies as a result of consummation of oceanic crusts along differently-dipping subduction zones (Parker and Lemon, 1982; Tyler and Thorne, 1990; Collins and Shaw, 1995; O’Dea *et al*., 1997; Blewett *et al*., 1998; Daly *et al*., 1998; MacCready *et al*., 1998; Page *et al*., 2000; Betts *et al*., 2002, 2003; Vassallo and Wilson, 2002; Scrimgeour, 2003; Bagas, 2004; Boger and Hansen, 2004; Cawood and Tyler, 2004;). Intracratonic volcano-sedimentary basins such as the Leichhardt Superbasin (ca. 1800–1750), Calvert Superbasin (ca. 1730–1670), Isa Superbasin (ca. 1668–1590) were developed contemporaneously with a succession of orogenies that resulted in the accretion of the North Australian Craton and the Western Australian Craton. The Isan orogeny (1600–1500 Ma), together with other orogenies, appears to have resulted from collision of the Eastern Australian Craton with the Northern and Western Australian Cratons along a west-dipping subduction zone leading to cessation of basin development.

Most of these events have been preserved in the Mount Isa Inlier of northwest Queensland.

The Mount Isa Inlier is differentiated into three N–S-trending tectono-stratigraphic belts juxtaposed along major tectonic contacts called the Eastern Fold Belt, Kalkadoon-Leichhardt Belt and Western Fold Belt. The Soldiers Cap Group, located in the eastern portion of the Eastern Fold Belt (Fig. 3), contains Mesoproterozoic metasedimentary and metavolcanic rocks that were metamorphosed to the greenschist to amphibolites facieses (Foster and Rubenach, 2006; Rubenach *et al*., 2008). Peak metamorphism occurred around 1595–1580 Ma (Page and Sun, 1998; Giles and Nutman, 2003; Duncan *et al*., 2006; Foster and Rubenach, 2006; Rubenach *et al*., 2008). This region is characterized by three structural domains dominated by a group of meso to macroscopic folds with specific trend (Fig. 3). The northern domain is dominated by NW–SE-trending folds and located around the abandoned Gilded Rose Mine. The southern domain contains the major N–S-trending Snake Creek anticline. The central domain is dominated by the W–S-trending Toole Creek and Davis synclines, and Mountain Home anticline. The Soldiers Cap Group is divided into three metamorphic units, which from base to top are *the Llewellyn Creek Formation*, a pelitic to psammopelitic, porphyroblastic-rich turbiditic unit, *The Mount Norna quartzite*, a psammitic unit with few pelitic intercalations hosting few porphyroblasts, and *the Toole Creek volcanics*, which mainly contain metadolerite and amphibolite. Rubenach *et al*. (2008) dated a large gabbroic to tonalitic sill, ~700-m-thick, intruding the Llewellyn Creek Formation at ~1686±8 Ma, which suggests that at least the lower parts of this formation bears a depositional history earlier than that age.

3. Addressing the problem

One of the main problems regarding the Soldiers Cap Group in the Eastern Fold Belt is the relative timing of W–E-trending folds in relation to the N–S-trending folds that dominate the entire grain of the Mount Isa province. Whether or not the N–S horizontal shortening predates the W–E shortening was controversial in the literature (Bell, 1983, 1991; Reinhardt, 1992; Bell and Hickey, 1998; Lister *et al.*, 1999; Sayab, 2005, 2006; Giles *et al.*, 2006). Similarly, whether or not the W–E-and N–S-trending folds represent a continuum or non-continuum deformational phases still controversial. Bell (1983, 1991) suggested that both fold trends represents two separate non-continuum tectonic events and the first event to affect the Mount Isa province was related to a period of N–S shortening that resulted in the W–E-trending folds, which are very obvious in the Soldiers Cap Group relative to any other portions of the Inlier. Looseveld (1989), Loosveld and Etheridge (1990), Giles *et al.* (2006) believe that the W–E-and N–S-trending folds represent one continuum event and the W–E-trending folds were developed as a crumpled frontal zone of a north to northwest propagating overturned nappe and consequently they argue that no folding events prior to the N–S-trending ones in the Snake Creek anticline region. Based mainly on the FIA trends preserved within the porphyroblasts that grew during the different tectonic events, supported by monazite dating, this paper aims to trace the directions of horizontal shortening throughout the Isan Orogeny, figure out whether or not the W–E horizontal shortening was the earlier contractional tectonic event in the Orogeny and then propose a tectonic history of the region in plate tectonic framework.

4. Porphyroblastic phases

The metamorphic index minerals encountered include Grt, St, And, Bt, Ms, Crd, Sil, a few Cld and rarely Ky (mineral abbreviation symbols follow Kretz, 1983). Some porphyroblasts preserve evidence for two or more phases of growth in the form of a change of the grain size and/or composition of the inclusions (which are mainly quartz) from the core to the rim.

4.1 FIA measurement

FIA measurements were made from 65 oriented samples representative of the porphyroblastic rock units cropping out in the area. The FIA axes were measured by cutting six vertical thin sections per sample striking at 0°, 30°, 60°, 90°, 120°, and 150° around the compass and observing the flip of the asymmetry of the inclusion trails from clockwise to anticlockwise when viewed in one direction (Fig. 4a). Intervening thin sections were cut for many samples 10° apart between the two thin sections where the flip occurred. The FIA trend is located where the flip took place (e.g., Bell *et al*., 1998).

4.2 FIAs

Three FIA sets trending NW–SE, W–E and N–S were measured from the inclusion trails entrapped within the different generations of porphyroblasts. A fourth SW–NE-trending FIA was measured but not dated (Abu Sharib and Bell, unpublished data).

4.2.1 NW–SE-trending FIA

Six samples contain garnet and cordierite porphyroblasts entrapping inclusion trails that preserve a 120º–150º trending FIA (Table 1, Fig. 4b). Spiral-shaped inclusion trails in garnet consist of a succession of up 5 foliations; 2 sub-vertical and 3 sub-horizontal. Each of these foliations is truncated and/or crenulated by the succeeding one. Where 5 are present, the first is sub-horizontal foliation (Fig. 5). The inclusion trails preserving this FIA trend consist of foliations that are truncated by that in the matrix (Fig. 5).

4.2.2 W–E-trending FIA

This is the most dominant FIA trend in the region. 35 out of 65 samples containing garnet, staurolite and andalusite porphyroblasts preserve inclusion trails contain a FIA trending between 85º–110º (Table 1, Fig. 4b). Porphyroblasts with this FIA trend are characterized by commonly sigmoidal (Fig. 6a and b) and less stair case (Fig. 7) or spiral-shaped inclusion trails. The inclusion trails of these porphyroblasts define a succession of four nearly orthogonal foliations in two cycles that begin with a sub-vertical cleavage in the core that is crenulated by a sub-horizontal differentiated crenulation cleavage (Figs. 7 and 8). In low strain zones the inclusion trails entrapped within the porphyroblasts preserving this FIA trend are continuous with the dominant W–E-striking matrix foliation (Figs. 6b and 7). Porphyroblasts in some samples collected around the Gilded Rose Mine preserve inclusion trails that are continuous with the matrix and record stage 3-4 of differentiated crenulation cleavage development (Fig. 9) of Bell and Rubenach (1983).

4.2.3 N–S-trending FIA

Garnet, staurolite and andalusite porphyroblasts preserve 165º–195° trending FIA (Table 1, Fig. 4b). The internal foliations within the porphyroblasts contain one cycle of sub-vertical-sub-horizontal foliation beginning with a sub-vertical cleavage in the cores of the porphyroblasts that is crenulated by a differentiated crenulation cleavage in the rims (Figs. 10). The inclusion trails within these porphyroblasts are continuous with the dominant N–S-striking matrix foliation (Figs. 10) especially in the Snake Creek anticline.

4.2.4 Relative time relationships between the different FIAs

The relative time relationships among the different FIA trends was determined using the following criteria: (1) the FIA trend expressed by the inclusion trails preserved in core of the porphyroblasts must be older than the FIA trend preserved in the rims, (2) truncated inclusion trails versus those continuous with the matrix (e.g., Adshead-Bell and Bell, 1999; Sayab, 2005), and (3) prograde metamorphic mineral succession whereby garnet is preserved within staurolite and cordierite is replaced by andalusite. Sample Sc 855.3 hosts cordierite porphyroblasts preserving NW–SE-trending FIA together with andalusite porphyroblasts preserving the W–E-trending FIA and evidence for a partial to complete progression of cordierite into andalusite (Fig. 11 a, b). No porphyroblasts preserving a NW–SE-trending FIA have internal inclusion trails continuous with the external matrix foliation and in all the examined thin sections the outer W–E-or N–S-striking matrix foliation truncates the internal foliation in the porphyroblasts. Samples G3, G390 and N17 (Table 1) show the relationship between W–E-and N–S-trending FIAs. Sample G3 hosts garnet porphyroblasts entrapping sigmoidal-shaped inclusion trails defining W–E-trending FIA and these are truncated by the N–S-striking matrix foliation (Fig. 12). Garnet porphyroblasts are locally enclosed within staurolite and andalusite porphyroblasts containing inclusion trails defining N–S-trending FIA and which are continuous with the matrix (Figs. 12 and 13). In sample G390, garnet porphyroblasts have cores and rims entrapping sigmoidal-shaped inclusion trails defining W–E-and N–S-trending FIAs, respectively (Fig. 14). In this sample, andalusite and staurolite porphyroblasts preserving inclusion trails defining N–S-trending FIAs wrap slightly around garnet porphyroblasts entrapping inclusion trails defining W–E-trending FIA (Fig. 15). Sample N17 contains garnet porphyroblasts with cores preserving W–E-trending FIAs defined by inclusion trails that curve into the rim which defines a N–S-trending FIA (Fig. 16).

4.2.5 Inclusion trail asymmetry

The differentiation asymmetry is defined as the asymmetry with which a crenulated cleavage curves into a differentiated crenulation cleavage (Bell *et al*., 2003). The succession of asymmetries preserved by the inclusion trails entrapped by successive phases of porphyroblast growth are a direct reflection of the differentiation asymmetries of the matrix foliations that accompanied each phase of growth (e.g., Bell *et al*., 2003). These structural relationships are progressively destroyed in the matrix due to the effects of reactivation of the compositional layering during each deformation event that takes place (e.g., Ham and Bell, 2004).The asymmetries of the NW–SE-, W–E-and N–S-trending FIAs were measured using vertical thin sections nearly orthogonal to the three FIA trends looking NW, W and N, respectively. The data presented in the histograms (Fig. 17) shows the frequency by which the asymmetries of the inclusion trails change from clockwise to anticlockwise and from steeply to gently-dipping and vice versa. In the case of the NW–SE-trending FIA, due to the limited number of samples (only six) relative to the two other FIA trends, the asymmetry was measured for almost all the porphyroblasts hosting this FIA trend in all the six samples.

5. Absolute ages

5.1 Monazite chemistry

The rare-earth element monazite ((Ce, La, Nd, Th, Y)PO_4) is commonly contained in metamorphic and igneous rocks as an accessory phase. When it grows it generally contains a high percentage of Th and U and no or very little Pb making it very useful for U-Pb dating (Parrish, 1990). Furthermore, the extremely slow rate of diffusion of its major and trace components (Parrish, 1990; Cherniake *et al*., 2000) allows it to preserve geochronological data through successive phases of metamorphism. Electron microprobe analysis for dating monazite is now widely-used and gives precise results (e.g., Suzuki *et al*., 1994; Montel *et al*., 1996, 2000; Suzuki and Adachi, 1998; Williams *et al*., 1999; Hanchar *et al*., 2000; Shaw *et al*., 2001). The technique depends on measuring the concentrations of Th, U and Pb and assumes that all Pb is a radiogenic product (e.g., Parrish, 1990). Monazite growth commonly accompanies the development of successive foliations after garnet has begun to form (e.g., Williams and Jercinovic, 2002) and, particularly where it is preserved within porphyroblasts, can be used to constrain the time of the deformation and metamorphic events (e.g., Suzuki and Adachi, 1998; Montel *et al*., 2000; Terry *et al*., 2000; Williams and Jercinovic, 2002; Simpson *et al*., 2000; Asami *et al*., 2002; Hibbard *et al*., 2003; Pyle and Spear, 2003; Foster *et al*., 2004; Tickyj *et al*., 2004; Goncalves *et al*., 2005).

5.2 Analytical technique

Monazite ages were determined using a Jeol JXA8200 EPMA in the Advanced Analytical Center, James Cook University. The analytical set up is shown in Table (2). An accelerating voltage of 15kv, probe current of 200nA and spot size of

1 micron were used for the measurements. The PAP method (Pouchou and Pichoir, 1984 and 1985) was used to undertake matrix corrections. Interference corrections for Th and Y on Pb and Th on U were applied as described in Pyle *et al*. (2002). For standardization of the ages, monazite from Manangotry, Madagascar (545±2 Ma; Paquette *et al*., 1994) was analyzed as an internal age standard 5 times before and after each analytical session. Age calculations have been done using the average weight method and compiled with Isoplot 3 (Ludwig, 2003). Dates were calculated for each analytical spot and the statistical precision on each point was determined via counting statistics. This then assumed to be representative of the relative error in precision for the concentration of Pb, U and Th. To reduce the error and get reliable age data (Montel *et al*., 1996; Pyle *et al*., 2005) the samples for dating were selected according to FIA set (i.e. monazite grains were analysed according to their textural setting and thus FIA set, see below). This enabled the age data obtained from the monazite grains to be quantitatively grouped together improving the counting statistics. A mean age for each FIA was determined using standard errors at the 95% confidence level for a cluster of spots analyses within a single age domain or grain.

5.3 Samples dated

Ten out of 15 samples (Table 1) contained monazite grains sufficiently large for multiple measurement and thus reliable age information. The grain size for all analyzed monazite grains ranged from ~10 to 40 microns. No compositional domains were detected in any of the analyzed monazite grains. Most of the dated monazite grains come from samples preserving W–E-and N–S-trending FIA sets. Samples AV3 and AV5 from which the dates in Table 3 were obtained were collected from the same outcrop as samples Sc 855.3 and Sc 865 from within which a NW–SE-trending FIA was measured. Their identical mineral assemblages, adjacent location and the fact that these dates gave the oldest foliation ages for identical rocks containing the first formed FIA suggests the foliations preserved in cordierite formed at the same time in all three samples. Unbiasedly, all the dated samples belong to the pelitic-rich divisions of the Llewellyn Creek Formation (Table 1).

5.4 Sample description

5.4.1 Samples Sc 855.3 and Sc 865

These samples contain plagioclase, biotite and porphyroblasts of kyanite, andalusite and cordierite. Cordierite and andalusite porphyroblasts preserve inclusion trails defining NW–SE-and W–E-trending FIAs, respectively. The inclusion trails in all the porphyroblastic phases are truncated by the matrix foliation. Geochronological data were collected from monazite grains preserved within cordierite porphyroblasts.

5.4.2 Sample O92

This sample contains a muscovite, biotite, staurolite and garnet with the latter 2 phases preserving inclusion trails defining the W–E-trending FIA that are truncated by the matrix foliation. Monazite grains preserved in both the latter phases were dated. A total of 6 and 7 monazite grains were dated from three staurolite and four garnet porphyroblasts, respectively.

5.4.3 Sample L40

This sample contains biotite, muscovite and large andalusite porphyroblasts that contain inclusion trails defining a W–E-trending FIA. A total of 3 monazite grains from two andalusite porphyroblasts were the source for the age information.

5.4.4 Sample L5

This sample contains biotite, muscovite, garnet and staurolite with W–E-trending FIAs are entrapped in the latter 2 phases. The matrix foliation appears continuous with the inclusion trails within the porphyroblasts. Age information was collected from 5 monazite grains in 2 staurolite porphyroblasts.

5.4.5 Sample N17

This sample contains chlorite, muscovite as well as garnet porphyroblasts with inclusion trails preserving a spiral-shaped geometry and defining W–E-trending FIA. N–S-trending FIA are preserved in their rims. The inclusion trails in the rim are truncated by the matrix foliation. Most of the dated monazite grains come from the rim of the garnet porphyroblasts. Only one measurement was taken from monazite grain detected in the core of one porphyroblast.

5.4.6 Sample N14

This sample contains biotite and muscovite plus staurolite porphyroblasts preserving a W–E-trending FIA. The internal foliation within the porphyroblasts is truncated by the external matrix foliation. Two monazite grains were dated from within the staurolite porphyroblasts.

5.4.7 Sample D434

This sample hosts biotite, muscovite, plagioclase and porphyroblasts of staurolite containing N–S-trending FIAs. The matrix foliation is continuous with the foliation within the porphyroblasts. Only one monazite grain was large enough for dating measurements to be made.

5.4.8 Sample D131

This sample contains staurolite porphyroblasts bearing N–S-trending FIAs. Other metamorphic minerals include biotite, muscovite and a few plagioclase grains. The matrix foliation is continuous with the inclusion trails. Dating data has been obtained from 6 monazite grains within 2 staurolite porphyroblasts.

5.4.9 Sample CC6

This sample contains biotite, muscovite and porphyroblasts of garnet and staurolite preserving N–S-trending FIAs. The porphyroblast inclusion trails are strongly truncated by the matrix foliation. One monazite grain within 1 garnet porphyroblast has been dated.

5.5 Yttrium distribution in monazite grains preserved within porphyroblasts

Monazite and garnet are the main sinks for yttrium in metamorphic rocks. During the progressive breakdown of xenotime in pelitic rocks, both garnet and monazite grow (Pyle and Spear, 1999), with the yttrium content partitioning between them such that its enrichment in one is counteracted by its depletion in the other depending on which grew first (Zhu and O'Nions, 1999). The growth of the monazite is closely-related to the garnet breakdown or decompression reactions in metamorphic rocks (Smith and Bareiro, 1990; Pyle and Spear, 2003). The loss of garnet during the staurolite-in reaction, or during decompression with the production of cordierite or plagioclase allow the growth of monazite through the release of yttrium (Smith and Bareiro, 1990; Pyle and Spear, 2003; Gibson *et al*., 2004; Mahan *et al*., 2006; Kelly *et al*., 2006). Figure 18 and Table 4 show the distribution of the yttrium in monazite entrapped in porphyroblasts preserving W–E-or N–S-trending FIAs. Samples O92 and L5 contain garnet and staurolite porphyroblasts preserving W–E-trending FIAs that entrap monazite grains showing no appreciable difference in the yttrium contents (Fig. 18a and b). No differences in the yttrium contents of the monazite grains entrapped within porphyroblasts preserving either FIA trends were detected. For example, monazite grains detected in garnet (sample N17), staurolite (samples D434 and D131) and andalusite (sample L40) show no detectable differences in the yttrium content

(Fig. 18b and c). The slightly low yttrium content in two spots in one monazite grain entrapped in the rim of a garnet porphyroblast in sample N17 containing a N–S-trending FIA (Fig. 18c) may be related to sub-millimeter scale heterogeneity in the yttrium (Martin, 2009).

6. Interpretation

6.1 The FIA succession

Figure 4b shows that the FIAs cluster into 3 groups that can be interpreted to result from a succession of FIA sets trending NW–SE, W–E, N–S. This succession, labeled FIA set 00 through 2, is apparent from the following relationships (e.g., Bell and Hickey, 1998). Samples containing NW–SE-trending FIAs (FIA set 00) in garnet or cordierite porphyroblasts are always truncated by W–E-striking matrix foliations in samples from the north of Fig. 1, and N–S-striking ones in the south. Sample P12 contains a NW–SE-trending FIA (FIA set 00) in garnet cores and a N–S-trending FIA (FIA set 2) in its rim (Table 1). Sample N17 contains a W–E-trending FIA in garnet cores (FIA set 1) and a N–S-trending FIA (FIA set 2) in its rim (Table 1). Sample E200 contains a differentiated crenulation cleavage overgrown by andalusite porphyroblasts defining an approximately N–S-trending pseudo FIA (FIA set 2) that was inflected during porphyroblast growth to define a FIA trending at 30° (FIA set 3; Table 1). Furthermore, inclusion trails defining W–E FIA are commonly truncated by a N–S-trending matrix foliation and those defining N–S FIA are generally not truncated. This succession indicates that these rocks have been affected by deformation during four cycles of orogeny.

6.2 Bulk shortening directions

The directions of bulk horizontal shortening that were prevailing at the time that the porphyroblasts grew can be deduced directly from the FIA trends defined by the inclusion trails preserved within these porphyroblasts (e.g., Bell *et al*., 1995; Sayab, 2005; Sanislav, 2009; Ali, 2010; Shah, 2010). The direction of horizontal bulk shortening must lie orthogonal to a FIA (Bell and Newman, 2006). Consequently, the direction of bulk horizontal shortening changed with time from SW–NE, N–S, W–E to finally NW–SE.

During the development of FIA set 00, SW–NE bulk shortening resulted in the development of up to five nearly orthogonal foliations due to alternating cycles of horizontal and vertical shortening producing sub-vertical and sub-horizontal foliations, respectively, with the latter accompanying periods of gravitational collapse of the thickened orogenic pile (Bell and Newman, 2006). This formed NW–SE-trending regional folds (Abu Sharib and Bell, unpublished data (see section A)). During the development of FIA set 1, N–S bulk shortening similarly resulted in the development of up to 4 nearly orthogonal foliations and producing the dominant FIA trend in the northern part of Fig. 3. This rotated original NW–SE-trending folds into more W–E trends (Abu Sharib and Bell, unpublished data). In this northern region the inclusion trails entrapped within the porphyroblasts hosting this FIA trend are commonly continuous with the W–E-striking matrix foliation. To the south in the Snake Creek anticline, where the dominant tectonic fabric is N–S, porphyroblasts preserving this FIA trend have inclusion trails that are truncated against and crenulated by the N–S-striking matrix foliation. During the development of FIA set 2 (N–S-trending FIA), W–E horizontal bulk shortening similarly resulted in the development of at least 3 nearly orthogonal foliations and produced the dominant FIA trend in the southern part of Fig. 1. Porphyroblasts preserving this FIA trend commonly have inclusion trails that are continuous with the N–S-striking matrix foliation.

6.3 Inclusion trail asymmetry

The relationship between crenulated and differentiated crenulation cleavages preserved within porphyroblasts reveals what was going on in the matrix at the time of porphyroblast growth plus preserves the direction of shearing in the form of the differentiation asymmetry (Bell *et al.*, 2003; Bell and Hobbs, 2010). The unique anticlockwise asymmetry with top-to-the-southwest for the NW–SE-trending FIA set 00 (Fig. 17) indicates transport towards the southwest. Top-to-the-north asymmetries dominate the W–E-trending FIA set 1 (Fig. 17) indicates northward transport of the rocks at this time. Similar clockwise and anticlockwise asymmetries of the inclusion trails defining the N–S-trending FIA set 2 reflect overall bulk coaxial deformation (Fig. 17).

6.4 The absolute time of the FIA succession

36 spots from 5 monazite grains in cordierite (Table 3) preserving the NW–SE-trending FIA set 00 (samples AV3 (Sc 855.3), AV5 (Sc 865)) gave an age of 1649±12 Ma (Fig. 21a, b). 135 spots have been dated from monazite grains in garnet, staurolite and andalusite porphyroblasts preserving the W–E-trending FIA set 1 and the N–S-trending FIA set 2 (Table 3). 93 of these spots from 14, 13 and 3 monazite grains in staurolite, garnet and andalusite porphyroblasts, respectively, preserving the W–E-trending FIA set 1 (Fig. 19) gave weighted mean age of 1645±7 Ma (Fig. 21c, d). The remaining 42 spots from 12 monazite grains in garnet and 7 grains in

staurolite porphyroblasts preserving the N–S-trending FIA set 2 (Fig. 20) gave a weighted mean age of 1591±10 Ma (Fig. 21 e, f)

6.5 Monazite yttrium contents of the different porphyroblasts

Monazite grains entrapped within porphyroblasts preserving either W–E-or N–S-trending FIAs showed no observable change in yttrium content for all samples analysed suggesting they are not significantly zoned. Only very small differences in yttrium contents of monazite grains within the staurolite versus garnet porphyroblasts preserving the W–E-trending FIA set 1in sample O92. This suggests that the growth of monazite during this tectono-metamorphic event occurred at garnet grade conditions rather than due to the breakdown of the garnet porphyroblasts at the staurolite-in isograd.

7. Discussion

7.1 Possible correlations between Mount Isa and other provinces

7.1.1 Correlation between tectonism in the Gawler and Mount Isa Provinces

The Gawler province, which contains Late Archaean high-grade metasedimentary rocks, underwent a number of phases of metamorphism and deformation during several different orogenies, many of which generated associated igneous activity (Daly *et al*., 1998; Swain *et al*., 2005; Jagodzinski *et al*., 2006; Hand *et al*., 2007; Neumann and Fraser, 2007). These orogenic period consist of :

(1) The Kimban orogeny (1740–1690 Ma), which was an episode of high-temperature metamorphism and multiple deformation throughout the Gawler Craton that has been interpreted to record the collision between the Archaean nucleus of the Gawler Craton and the North Australian Craton (Betts *et al*., 2002, 2003; Giles *et al*., 2004).

(2) The Ooldean event (1660–1630 Ma), which is a tectonic event intersected in drill holes in the western Gawler province (Hand *et al*., 2007) that generated high pressure metamorphism. Daly *et al*. (1998), Swain *et al*. (2005) and Thomas *et al*. (2008) described deformation that occurred around this time and which generated metamorphism up to the granulite facies within the Western and Central Gawler Craton.

(3) The Hiltaba event (1600–1560 Ma), which is a tectono-metamorphic event wherein continental scale regional high-temperature metamorphism affected the eastern Proterozoic Australian continent in South Australia.

From 1690–1670 Ma voluminous granites belonging to the Tunkillia and Ifould Suites were emplaced (Daly *et al*., 1998; Ferris and Schwarz, 2004; Fanning *et al*., 2007; Neumann and Fraser, 2007) coincident with the Kimban event. The tectonic setting for this magmatic activity is debatable with a magmatic arc to backarc environment (Ferris *et al*., 2002; Ferris and Schwarz, 2004) suggested and the western Gawler Craton occupying a supra-subduction setting (Ferris *et al*., 2002). However, based on new geochemical data, Payne (2008) favoured a late to post-tectonic setting for the suite because no mafic rocks are present within it.

From 1620–1575 Ma widespread magmatic activity in the southwestern and central Gawler Craton involved the emplacement of the 1620–1610 Ma intermediate to felsic calc-alkaline St Peter Suite with a subduction-related magmatic arc geochemical signature (Ferris *et al*., 2002; Swain *et al*., 2008), and the 1600–1575 Ma bimodal Gawler Range Volcanics-Hiltaba volcano-plutonic event (Fanning *et al*., 2007). Giles (1988), Blissett *et al*. (1993) and Creaser (1996) argued that the Gawler Range Volcanics were synchronous and genetically related to A-type felsic pluton in the Hiltaba Suite. A within plate setting has been proposed for the Gawler Range Volcanics-Hiltaba event based on geochemical data. However, a back arc environment has also been suggested (Budd and Fraser, 2004; Fanning *et al.*, 2007).

In the Mount Isa Inlier, amphibolite facies metamorphism of varying pressures occurred from 1670 to 1515 Ma (Page and Bell, 1986; Giles and Nutman, 2002, 2003; Rubenach, 2008), clearly overlapping with the Ooldean and Hiltaba events in the Gawler province. The Ooldean event (1660–1630 Ma) corresponds in age with SW–NE-and N–S-directed thrusting in the Mount Isa province, which produced spiral inclusion trails in garnet porphyroblasts and, therefore, probably involved pressures of 5 or more kbars (e.g., Sayab, 2006; Bell and Newman, 2006). The 1600 to 1550 Ma period, which generated several N–S-trending belts of high temperature and lower pressure metamorphism across the inlier (Foster and Rubenach, 2006) overlaps the Hiltaba event. Perhaps SW–NE-and N–S-directed bulk horizontal shortening orogeny was related to the tectonism that accompanied the amalgamation of the North Australian and Gawler Cratons, whereas the W–E-directed shortening orogeny correlated with the tectonic episode responsible for the extrusion of voluminous bimodal volcanics and emplacement of the Hiltaba granite 1580–1560 Ma during the Hiltaba event.

7.1.2 Correlation between the Eastern Mount Isa Block and the Curnamona province

The Mesoproterozoic Curnamona province, of which the Broken Hill terrane represents an appreciable component, is located in the South Australian Craton. It is separated from the Mount Isa province by ~ 400 km along strike by younger cover. A growing body of evidence suggests that both provinces had a shared tectonic history during the 1800–1500 Ma period (e.g., Giles *et al.*, 2004), prior to the Late

Proterozoic Albany-Fraser and Musgravian orogenies (1330–1100 Ma). Gibson *et al*. (2008) claimed that the pre-orogenic basin history of both terranes was also similar and that they originated in a similar tectonic environment. The lower part of the 1670–1640 Ma psammopelitic sediments of the Willyama Supergroup (Sundown and Broken Hill Groups) in the Broken Hill terrane can be correlated with the Soldiers Cap Group of the Mount Isa terrane (e.g., Gibson *et al*., 2008). Both terranes are characterized by bimodal magmatic activities in the form of granitic and volcanic rocks. Mafic rocks from the Willyama Supergroup yielded ages of 1690–1670 Ma (Gibson and Nutman, 2004; Butera *et al*., 2005), which are very close to the ~1686 Ma age of the mafic sill that intrudes the upper part of the Llewellyn Creek Formation (Rubenach *et al*., 2008). The locally high iron concentrations (in some cases, > 15 wt% FeO) in the amphibolites of both terranes (e.g., Williams, 1998) also suggest a common genetic link.

The Olarian Orogeny in the Broken Hill terrane (1600–1580 Ma; Giles and Nutman, 2002; Page *et al*., 2005a, b) and the Isan Orogeny in the eastern Mount Isa province (1650–1500 Ma, this study) share a common age, deformation history and metamorphic character (low-pressure/high-temperature). Furthermore, Gibson *et al*. (2004) and Forbes *et al*. (2005) obtained an age of 1620 Ma from monazite grain hosted by metamorphic garnet in sillimanite grade metasedimentary rocks from the Willyama Supergroup. Similarly, Gibson *et al*. (2004) and Gibson and Nutman (2004) suggested that the orogenesis in the Willyama Supergroup may have started as early as 1640 Ma. These data accord well with the results presented in this study whereby the Isan orogeny in the Soldiers Cap Group commenced at ~1650 Ma and strongly support the suggestion that these terranes are direct correlatives.

7.1.3 Correlation between the Eastern Mount Isa terrane and the southwest Laurentia: applicability of the AUSWUS model for Rodinia reconstruction

Reconstruction of Proterozoic Supercontinents has been the subject of many publications during the last few decades (Dalziel, 1991; Moores, 1991; Rogers, 1996; Karlstrom *et al*., 1999; Piper, 2000; Condies, 2002; Hartz and Torsvik, 2002). The Neoproterozoic “Rodinia” supercontinent existed between 1000–800 Ma and is considered to involve a number of now widely dispersed continental masses. Many hypotheses have been introduced for the Rodinian and pre-Rodinian Proterozoic configuration (Dalziel, 1991; Hoffman, 1991; Karlstrom *et al*., 1999; Karlstrom, 2001; Burrett and Berry, 2000, 2002; Condie, 2002). The AUSWUS model (Karlstrom *et al*., 1999, 2001) proposes that the eastern part of Australia represents the southwest continuation of Laurentia. This model is based on the geologic similarities in lithology, age, tectonic histories, metamorphic character, and magmatic activities between eastern Australia (the Mount Isa and Broken Hill terranes) and the southwest US (Mojave, Yavapi and Mazatzal provinces) from 1800–1000 Ma. Also, major metallogenic massive sulphide deposits districts in Broken Hill and Mount Isa in eastern Australia have counterparts in western US (Jerome and Bagdad in Arizona and the Carlin district of Nevada, respectively). The tectono-metamorphic events that took place in the Isan and Olarian orogenies in the eastern Proterozoic rocks of Australia may correlate with the Mojave, Yavapi and Mazatzal orogenies in western US (southwest Laurentia). Overlap between the ~ 1650 and 1645 Ma ages obtained from monazite inclusions within porphyroblasts that grew during the NE–SW and N–S shortening events, respectively, and the ages obtained from the southwest part of Laurentia together with the shared low-pressure/high-temperature metamorphic character of the rocks from both terranes may be interpreted in term of the AUSWUS model of Rodinia supercontinent (Karlstrom *et al*., 1999, Karlstrom, 2001). However, recent work suggests that orogenic ages from the Mount Isa and Georgetown provinces, which range from 1670 to 1500 Ma (Black *et al*., 1998; Cihan and Parsons, 2005) actually tend to lie in between the ages obtained in the USA which range from to 1760.5±9.7 Ma to 1674±11 Ma for northern Colorado (Shah, 2010) to 1506±15 Ma to 1366±20 Ma obtained from central Colorado (Cao, 2009) and 1482±48 Ma to 1394±22 Ma from northern New Mexico (Cao and Fletcher, unpublished data). This meshing of ages suggests partitioning of deformation into the US portion of Rodinia, then the Australian portion, and finally back to the US around 1500 Ma, supporting rather than detracting from the AUSWUS model for Rodinia.

8. Conclusions

The Isan orogeny was a period of contractional deformation from ~1670 to 1500 Ma (Bell, 1983; Page and Bell, 1986; O'Dea *et al*., 1997a; Blewett *et al*., 1998; MacCready *et al*., 1998; Page and Sun, 1998; Page *et al*., 2000; Boger and Hansen, 2004; Rubenach *et al*., 2008; Abu Sharib and Bell, unpublished data) characterized by medium and low pressure-high temperature metamorphism at greenschist to upper amphibolites facies conditions (Giles and Nutman, 2002, 2003; Foster and Rubenach, 2006; Rubenach *et al*., 2008). Bulk shortening and thus relative plate motion was initially directed SW–NE. It formed the NW–SE-trending FIA set 00 and was accompanied by the growth of cordierite and garnet dated at 1649±12 Ma. This period of deformation across the whole of the Mount Isa province probably began around 1670 Ma and continued to 1648 Ma (Abu Sharib and Bell, unpublished data). The direction of relative plate motion then shifted to N–S forming the W–E-trending FIA set 1 preserved in garnet, staurolite and andalusite porphyroblasts. In the area described herein, these contain monazite grains dated at 1645±7 Ma but deformation across the Mount Isa province probably continued in this direction until ~1600 Ma (Rubenach, 2008). The direction of relative plate motion then shifted to W–E forming the N–S-trending FIA set 2 preserved in porphyroblasts of garnet andalusite and staurolite. Dates for this period of orogeny have been obtained herein at 1590±10 Ma but deformation continued across the whole of the Mount Isa province in this direction until at least 1515 Ma (Page and Bell, 1986) and produced the ~N–S-trending structures that dominate the Mount Isa Inlier (Loosveld, 1989; Reinhardt, 1992; Oliver *et al.*, 1991; Sayab, 2005, 2006; Giles *et al.*, 2006; Rubenach *et al.*, 2008). The above-described succession suggests an anticlockwise shift of the plate motion with time.

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THE TECTONO-METAMORPHIC EVOLUTION OF THE SNAKE CREEK ANTICLINE, MT ISA INLIER, AUSTRALIA

CONTENTS OF SECTION D

The tectono-metamorphic evolution of the Snake Creek anticline, Mount Isa Inlier, Australia

Abstract

Mesoproterozoic low-P/high-T volcano-sedimentary rocks of the Soldiers Cap Group record a complex polymetamorphic history that accompanied four periods of bulk horizontal shortening directed NE–SW, N–S, W–E and NW–SE during the long-lived Isan Orogeny (1650–1500 Ma). Low-P/high-T metamorphism prevailed during NE–SW bulk horizontal shortening. This was followed by medium-P/high-T and high-P/high-T tectonism that accompanied the N–S and the W–E shortening periods, respectively. The sediments of the Soldiers Cap Group were deposited between 1675–1650 Ma in a tectonic setting that has the characteristics of an intra-continental rift basin. Introduction of mafic dykes and sills at different stratigraphic levels over a wide time span was a major source of heat.

Key words: volcano-sedimentary, intra-continental, Mesoproterozoic, Isan Orogeny

1. Introduction

Most orogenic belts show evidence of long-lived and complex deformation and metamorphic histories. Examples of long lived orogenesis are the Isan orogeny in Australia (Loosveld, 1989; Oliver *et al*., 1991; Foster and Rubenach, 2006; Rubenach *et al*., 2008), the Himalayan orogeny (Le Fort, 1996; Lombardo and Rolfo, 2000; Lombardo *et al*., 1993; Manickavasagam *et al*., 1999), the Pan-African orogeny (Kroner and Stern, 2004), and the Appalachian orogeny (Bradley *et al*. 1998; Bell and Welch, 2002; Sanislav, 2010). The P-T conditions that the rocks experience during long-lived periods of deformation, metamorphism and plutonism are very complex and their understanding requires a multidisciplinary approach (e.g., Ali, 2010). Very high grade metamorphic (e.g., upper sillimanite zone, sillimanite/K-feldspar zone) events can completely overprint and erase previous metamorphic and deformation histories. For example, at lower sillimanite grade, staurolite porphyroblasts can be replaced and pseudomorphed by coarse-grained muscovite and biotite. Generally, the only evidence that staurolite ever existed are appropriately shaped pseudomorphs that at higher grades (upper sillimanite zone) become unrecognizable due to matrix coarsening. However, rocks formed at lower temperatures such in the garnet, andalusite, cordierite, staurolite or kyanite zones preserve most of their metamorphic and deformation histories within porphyroblasts. At these temperatures, diffusion is slower (Tracy, 1982) and porphyroblastic index minerals can be metastably preserved through subsequent deformation and metamorphic events. In such situations accurately correlating periods of porphyroblast growth from sample to sample and across a region becomes very important.

Porphyroblasts commonly preserve inclusion trails of a fabric that predates their growth. Where they have overgrown steeply dipping foliations with similar orientations they can be interpreted to have grown during the same metamorphic event. This is not possible with gently dipping foliations as multiple phases of gravitational collapse or spreading always produce a sub-horizontal foliation (e.g., Bell *et al*., 2004). The correlation of steeply dipping foliations preserved within porphyroblasts from sample to sample across a region can provide systematic insights into previous deformation and metamorphic events. Simple observations such as the relative orientation of the internal fabric (e.g., shallow vs steeply dipping orientations) or the apparent relationship between the internal fabric and the external matrix foliation (e.g., continuous vs truncated inclusion trails) commonly will not provide sufficient correlation criteria. This is particularly true for orogenic belts that have experienced long-lived periods of deformation and metamorphism. A solution to this problem is provided by the 3D measurement of the internal fabric orientation in porphyroblasts. This can be done by determining the orientation of the foliation intersection/inflection axes within porphyroblasts (e.g., FIAs). Porphyroblasts with identical FIA trends can be interpreted to have grown during the same period of deformation and metamorphism. Foliations cannot be readily correlated across an orogen because the same foliation can be reused many times during orogenesis (e.g., Bell *et al*., 2003). However, FIAs and thus periods of porphyroblasts growth and accompanying deformation and metamorphism can be correlated from sample to sample as well as across an entire region (Bell *et al*., 2004).

The low-P/high-T Mesoproterozoic volcano-sedimentary rocks of the Soldiers Cap Group of the Eastern Fold Belt in the Mount Isa Inlier show evidence of polyphase deformation and metamorphism during the long-lived Isan orogeny (1670–1500 Ma). This paper unravels the tectono-metamorphic history of the Soldiers Cap Group using data obtained from porphyroblasts such as PT conditions, FIAs and monazite dating.

2. Regional geology

The Mount Isa Inlier comprises three N–S-trending tectonostratigraphic domains: the Western Fold Belt, the Kalkaddon-Leichhardt Belt and the Eastern Fold Belt (Fig. 1). These belts are tectonically juxtaposed along major faults and expose Lower to Middle-Proterozoic intrusive rocks, metasediments and metavolcanics metamorphosed at greenschist to upper amphibolite facies conditions. Peak metamorphic conditions occurred at 1595–1580 Ma (Page and Sun, 1998; Hand and Rubatto, 2002; Giles and Nutman, 2003; Duncan *et al*., 2006; Foster and Rubenach, 2006; Rubenach *et al*., 2008). Two main orogenic cycles affected the Mount Isa Inlier: the Baramundi Orogeny at 1900–1850 Ma (Etheridge *et al*., 1987; McDonald *et al*., 1997; Bierlein and Betts, 2004) and the Isan Orogeny at 1610–1500 Ma (Blake and Stewart, 1992; Page and Sun, 1998). These two periods of contractional orogenesis were separated by a period of extension that led to the development of intra-continental rift-related super basins (Blake and Stewart, 1992) and the deposition of three stratigraphic cover sequences (Blake, 1987) coeval to the intrusion of volcanics. These basins are interpreted to have formed in an intra-continental (O’Dea *et al*., 1997b; Betts *et al*., 1998, 1999, 2003a; Giles *et al*., 2002; Gibson *et al*., 2008) or back-arc setting (Giles *et al*., 2002). Cover sequence 1 was deposited around (~1860 Ma) and consists of felsic volcanics and the intrusion of the Kalkadoon Granite at 1870–1850 Ma (Wyborn and Page, 1983). Cover sequence 2 (1800–1740 Ma; Williams, 1989; O’Dea *et al*. 1997a; Potma and Betts, 2006) consists of bimodal volcanics, clastics and carbonate sediments. This phase of rifting was associated with the intrusion of the Wonga Granite at about 1740 Ma (Holcombe *et al*., 1991; Pearson *et al*., 1992). Cover sequence 3 was deposited from 1740 to1670 Ma (e.g., Derrick, 1992; Blake and Stewart, 1992; O'Dea *et al*., 1997a; Jackson *et al*., 2000; Page *et al*., 2000) and consists predominantly of rhyolites, dolerites, sandstones and mudstones synchronous with the intrusion of the Sybella granite at ~1670 Ma (Page and Bell, 1986).

The Mid-Proterozoic Soldiers Cap Group occupies the eastern part of the Eastern Fold Belt and consists of low-pressure-high-temperature volcano-sedimentary sequences intruded by dykes, sills and granitoids. It is made up of three distinct rock units, from base to top: Llewellyn Creek Formation, Mount Norna Quartzite and the Toole Creek Volcanics. The Llewellyn Creek Formation is a well-bedded metaturbiditic unit that consists of alternating psammitic and pelitic layers with the more pelitic divisions containing abundant garnet, staurolite, andalusite, cordierite and sillimanite porphyroblasts and relatively few kyanite and chloritoid porphyroblasts. The Mount Norna Quartzite is a porphyroblast-poor unit dominated by metamorphosed sandstone, mudstone, siltstone and dolerites. The Toole Creek Volcanics consist of metadolerite and metabasalt with some porphyroblastic pelitic intercalations. Page and Sun (1998) proposed that the Soldiers Cap Group equates with the cover sequence 3 of Blake (1987) and determined 1670 Ma as the maximum deposition age. Rubenach *et al*. (2008) obtained an age of 1686±8 from a 700-m-thick gabbroic to tonalitic sill that intruded the Llewellyn Creek Formation, which suggests that the lower part of the Soldiers Cap Group is older.

2.1 Deformation history

2.1.1 The Mount Isa

The Mount Isa Inlier of NW Queensland, Australia was multiply deformed and metamorphosed during the prolonged Isan Orogeny. Three main phases of deformation have been proposed to explain the tectonic framework of the Mount Isa Inlier (Bell, 1983; Swager, 1985; Page and Bell, 1986; Winsor, 1986; Loosveld, 1989; Bell, 1991; Nijman *et al*., 1992; Stewart, 1992). The first event, D1, accompanied a period of north–south shortening and resulted in east–west-trending regional folds and thrusts. Evidence for W–E-trending folds has been described in the Western (Loosveld and Schreurs, 1987; Bell, 1993, 1991; Stewart, 1992; Lister *et al*., 1999), Kalkaddon-Leichhardt (Reinhardt, 1992; Stewart, 1992) and Eastern (Looseveld, 1989a; Bell *et al*., 1992; Lally, 1997) fold belts. The second event, D2, accompanied an extended period of W–E shortening and produced the regional N–S-trending structural grain of the Mount Isa Inlier. This event formed the widespread N–S-trending regional folds and the generally pervasive sub-vertical S2 axial plane cleavage. The third event, D3, also resulted from W–E shortening and produced small-scale, locally-developed folds with nearly vertical axial planes. These are generally slightly oblique to those with S2 as axial plane and Bell and Hickey (1998) argued that it only is recognizable because of an intervening event with gently dipping axial planes that rotated S2 away from the vertical so that it could be refolded during D3.

2.1.2 The Eastern Fold Belt

This fold belt contains different generations of folds that include the N–S-trending Snake Creek anticline and Weatherly Creek syncline and the W–E-trending Davis and Toole Creek syncline and the Mountain Home anticline. The timing of the W–E-versus N–S-trending folds in the Eastern Fold Belt, in particular, and in the Mount Isa Inlier, in general, is controversial. Giles *et al*. (2006a,b), O'Dea *et al*. (1997a,b), Goleby *et al*. (1998), and MacCready *et al*. (1998) argued that the deformation history in the Eastern Fold Belt involved a W–E extension during D1 followed by west-verging thin-skinned or nappe-style folding during D2, followed by thick-skinned or upright folding and faulting. Ryburn *et al*. (1988) interpreted the deformation history of the Snake Creek anticline, southeastern part of the Eastern Fold Belt, as being originally a D1, W–E-trending structure that was later refolded around the D2, N–S-trending structures. Loosveld and Etheridge (1990) and Giles *et al*. (2006a) argued that the near orthogonal pattern of folding can be attributed to refolding of the D1 nappe-style folds (Snake Creek anticline) around the second generation of the D2, N–S-trending Weatherly Creek syncline. Abu Sharib and Bell (in review) claimed that the macroscopic W–E-trending folds in the Snake Creek anticline represent originally NW–SE structures that were rotated into their present orientation during a later period of N–S horizontal shortening.

3. Sample descriptions

The metamorphic assemblages encountered in the Snake Creek anticline region include garnet, staurolite, biotite, andalusite, muscovite, sillimanite, chlorite, cordierite, chloritoid and kyanite that formed during the 1.65–1.5 Ga Isan Orogeny (Rubenach and Parker, 1998; Hand and Rubatto, 2002; Foster and Rubenach, 2006; Rubenach *et al*., 2008). Accessory phases include rutile, plagioclase, albite, graphite, ilmenite, monazite, zircon and tourmaline.

3.1 Garnet

Garnet porphyroblasts are generally idioblastic to subidioblastic (0.5 to 4 mm) with inclusion trails consisting mainly of quartz and minor ilmenite that range from straight, with the curvature restricted to the rim, to sigmoidal, to spiral-shaped. Some overgrew two different generations of inclusion trails and in a few samples they are partly replaced by chlorite.

3.2 Staurolite

Idioblastic to subidioblastic staurolite porphyroblasts (0.2 to 1 cm) plus poikiloblasts containing inclusions of quartz, muscovite, garnet, and biotite are common. Inclusion trails are commonly sigmoidal. Some staurolite contains inclusion rich cores surrounded by inclusion free rims. Local partial replacement by biotite and muscovite occurs.

3.3 Andalusite

Oval-shape andalusite porphyroblasts contain abundant fine-grained quartz defining straight trails curving gently at the margins; cordierite porphyroblasts are common in their cores. Xenoblastic andalusite porphyroblasts contain coarser quartz and commonly biotite, muscovite, garnet, staurolite and chloritoid. Skeletal andalusite up to 8 cms (Fig. 2a) contains the largest variety of inclusions plus, locally, kyanite. A few andalusite porphyroblasts have been partly replaced by coarse-grained muscovite (Fig. 2b)

3.4 Cordierite

Oval-shaped, xenoblastic cordierite porphyroblasts only contain straight trails of very fine-grained inclusions of quartz and opaque minerals with weak curvature at the margins. They are confined to the core of the Snake Creek anticline (Fig. 1).

3.5 Kyanite

Uncommon idioblastic to sub-idioblastic kyanite porphyroblasts occur within and just to the north of the Snake Creek anticline and contain no quartz inclusions.

3.6 Sillimanite

Needle shaped and fibrolitic sillimanite occurs in the core of Snake Creek anticline, generally projecting into staurolite and andalusite porphyroblasts, and increasing in proportion towards the south (Fig. 1) where migmatites are common.

3.7 Chloritoid

A few samples across the region contain chloritoid porphyroblasts with sub to idioblastic shapes (0.01-0.05 mm).

4. Methods

4.1 FIAs

FIAs are the axes of the newly formed crenulations (Bell and Bruce, 2006). They are measured by cutting horizontal slabs from oriented samples from which a series of 6 vertical thin sections are cut every 30° around the compass (Fig. 3). The asymmetry (clockwise and/or anticlockwise) of the inclusion trails in each thin section is recorded and where a change in occurs, two extra thin sections, 10° apart are cut to locate the FIA within ±5°.

4.2 Monazite dating

Monazite grains were analyzed using a Jeol JXA8200 EPMA housed at the Advanced Analytical Centre, James Cook University. The measurements were taken at an accelerating voltage of 15kV, probe current of 200nA, and spot size of 1 micron. Matrix corrections were undertaken by using the PAP (Pouchou and Pichoir, 1984, 1985) method. Background positions were chosen to minimize curvature and peak overlaps based on wavelength scans from 8 monazites of known and varied composition. For each analysis, phi-rho-z matrix corrections were applied to the measured intensities of the full major and trace elements analyzed. Interference corrections of Th and Y on Pb Mα and Th on U Mβ were applied following Pyle *et al*. (2002). Monazite from Manangotry, Madagascar (545±2 Ma; Paquette *et al*., 1994) was analyzed as an internal age standard 5 times before and after each analytical session. Individual ages were calculated for each analytical spot using the matrix and interference-corrected concentrations of Pb, U, and Th by solving the monazite age equation of Montel *et al*. (1996). The statistical precision on each point was determined via counting statistics. For each point the relative standard deviation of the net peak count rate of the unknown was calculated (Pyle *et al*., 2005) for each of the 3 elements ($\varepsilon_{\text{unknown}}$). This value was then combined with the equivalent for the respective standards (ε_{std}), such that a value for the relative standard deviation of the *k*-ratio ($\varepsilon_{k\text{-ratio}}$) is determined, i.e.,

$\varepsilon_{k\text{-ratio}} = \sqrt{\varepsilon^2_{\text{std}} + \varepsilon^2_{\text{unknown}}}$. This is then assumed to be representative of the relative error in precision for the concentration of Pb, U, and Th. The concentration errors were then propagated through the age equation (Lisowiec, 2006).

4.3 Mineral Chemistry

Major elements in muscovite, biotite, chlorite, ilmenite, garnet, and staurolite were determined by spot analyses. For each grain a few spots were analysed and their average used. Data was collected as above except with a 3 µm beam diameter. For the garnet rim a beam diameter of 1µm was used. Natural materials were used as standards. X-ray compositional maps of garnet were collected by using a 23µm beam diameter, a beam current of 200-250 nA and a dwell times of 100 ms.

4.4 Pressure-Temperature pseudosections and garnet core isopleth thermobarometry

PT pseudosections were constructed using the bulk chemistry determined for each sample analyzed by XRF at JCU. Table 1 shows the bulk composition of the modeled samples. The PT pseudosections were modeled using the computer software Thermocalc (Powell and Holland, 1988) and the database of Holland and Powell (1998; with the tcd55.txt updates of 22 November, 2003). Pseudosections were modeled in the MnNCKFMASH ($MnO-Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O$) system. Mixing models (Tinkham *et al*., 2001; White *et al*., 2001), activity models (white mica, Coggon and Holland, 2002; feldspar, Holland and Powell, 2003) and calculations involving chlorite, zoisite, chloritoid, biotite, plagioclase, muscovite, garnet, staurolite, cordierite, andalusite, sillimanite and kyanite were used. The PT conditions at garnet nucleation for a specific bulk composition can be estimated by plotting the core isopleths (e.g., X_{Alm}, X_{Gr}, X_{Sp}) in the PT space (Vance and Mahar, 1998; Evans, 2004; Tinkham and Ghent, 2005; Cihan *et al*., 2006; Sayab, 2007) for the calculated pseudosection. The method requires that garnet to be compositionally zoned, the core isolated from the reacting matrix and isopleths intersecting at a single PT point. Two samples, with different FIA trends measured in the garnet, were selected to determine the PT conditions of nucleation using porphyroblasts with the minimum amount of inclusions analyzed for both core and rim compositions (Table 2). Mineral inclusions in garnet porphyroblasts were checked under the microscope and with EDS in back-scatter imaging as they may indicate the mineral assemblage from where the garnets grew.

5. Results

5.1 FIAs

FIAs were measured from cordierite, garnet, andalusite and staurolite porphyroblasts. Figure 3 shows the FIA trends determined from all porphyroblasts and Table 3 show the FIA trends for each porphyroblastic phase. Four different FIA peaks can be separated from Fig. 4 trending N–S, E–W, NE–SW and NW–SE but only the first 3 will be discussed herein. Only cordierite and some garnet porphyroblasts contain the NW–SE-trending FIA. Garnet, andalusite and staurolite porphyroblasts contain both E–W-and N–S-trending FIAs.

5.2 Monazite ages

The ages were determined of monazite grains included in cordierite, garnet, staurolite and andalusite porphyroblasts according to which FIA set they defined. For each monazite grain, single-point dates and errors were determined at a 2σ level. These data were grouped as a function of FIA set, compiled with Isoplot 3 (Ludwic, 2003) to give a weighted average age (Table 4 and Fig. 5) for each FIA set.

5.3 Mineral chemistry

Table 5 shows the mineral chemistry for biotite, muscovite, chlorite, ilmenite staurolite and garnet rims while Table 2 show the mineral chemistry for garnet cores. Tetrahedral sites in biotite contain 2.59–2.70 Al^{IV} atoms p.f.u. and 5.30–5.41 Si atoms p.f.u.. Their Ti content ranges between 0.11–0.18 atoms p.f.u.. The majority of octahedral site are filled by Fe (2.77–2.94 atoms p.f.u.) and Mg (1.85–2.04 atoms p.f.u.) while Al^{VI} varies between 0.71–0.78 atoms p.f.u.. The interlayer site in the analysed biotite is dominated by K (1.69–1.78 atoms p.f.u.) and contains small amounts of Na (0.05–0.09 atoms p.f.u.). Octahedral sites in muscovite are filled mainly by Al^{VI} (3.92–3.98 atoms p.f.u.). The remainder are filled by Fe (0.10–0.16 atoms p.f.u.) and Mg (0.06–0.08 atoms p.f.u.). The octahedral site occupancy (ideally 4.00 atoms p.f.u.) is around 4.15 atoms p.f.u., indicating a slight deviation from dioctahedral mica. The twelve fold interlayer site is filled predominantly by K (1.21–1.32 atoms p.f.u.) and by lesser amount of Na (0.16–0.31 atoms p.f.u.). Representative compositions of staurolite with calculated structural formula are presented in Table 5. The structural formula was calculated on the basis of 46 oxygens. Octahedral sites are predominantly occupied by Al^{VI} (17.32–17.40 atoms p.f.u.) and Fe (3.38–3.40 atoms p.f.u.) with little Mg (0.58–0.61 atoms p.f.u.) and Mn (~0.02 atoms p.f.u.). Table 4 shows the average composition of chlorite and the structural formula calculated from six chlorite grains; it is a combination of chamosite and clinochlore end members and contains 4.81 atoms p.f.u. Fe and 3.67 atoms p.f.u. Mg. Low Al^{VI} (2.47 atoms p.f.u.) indicates that chlorite may contain important amounts of Fe^{3+} and this may explain the incomplete occupancy of octahedral sites. Ilmenite contains between 1.97–2.24 Ti atoms p.f.u. and between 1.46–2.04 Fe atoms p.f.u. and very little Mn (0.02–0.07 atoms p.f.u.).

Representative analysis of garnet cores and rims are presented in Table 2. The cation sum generally approaches the ideal value of 8. The Al^{VI} values, close to 2 atoms p.f.u., indicate that these garnets can be considered as a solid solution of almandine-pyrope-spessartine-grossular end members. The almost constant Al^{VI} suggest that the amount of Fe^{3+} is insignificant. Garnet cores contain 0.80–0.86 almandine (X_{alm}), 0.05–0.11 spessartine (X_{spess}), 0.07–0.09 pyrope (X_{py}) and 0.01–0.02 grossular (X_{gross}). The rims contain 0.85–0.88 almandine, 0.01–0.05 spessartine, 0.08–0.09 pyrope and 0.01–0.02 grossular. It can be observed that the almandine and pyrope content increase from core to rim while the spessartine content is decreasing from core to rim. Grossular content appears to be relatively constant. X-ray compositional maps (Fig. 6) confirm the presence of small compositional variations from core to rim for almandine, spessartine and pyrope and indicate the possibility of more complex compositional zoning (Fig. 6) for the grossular content.

5.4 PT pseudosections and garnet core isopleth thermobarometry

Figures 7a and b show PT pseudosections calculated from the bulk chemistry presented in Table 1. They show also the intersection of the garnet core isopleths for samples CC6 and N17. The uncertainties concerning the location of these isopleths (as calculated with the program Thermocalc) are indicated by shading. The centre of the spread created by the intersection of the three compositional isopleths for the garnet core for these three end-members was taken as the best approximation for the PT of core growth (Tinkham and Ghent, 2005). The area defined by the intersection of all the isopleth uncertainties is considered to represent the PT error ellipse within which core growth occurred.

6. INTERPRETATION

6.1 Metamorphic mineral succession

Cordierite was the first porphyroblastic phase to grow in this region because no other porphyroblast compositions were detected within this phase. Inclusion trails within this mineral are truncated against and wrapped by W–E-or N–S-trending matrix foliations. Porphyroblasts of staurolite and/or andalusite commonly overgrew the matrix foliation that wraps around cordierite porphyroblasts (Fig. 8a and b). Growth of garnet porphyroblasts always predated staurolite and andalusite, as it never contained the latter phases. However, they commonly enclose garnet. At least two generations of staurolite growth and three of andalusite occurred. The first phase of staurolite growth occurs as relics within first generation andalusite (Figs. 8a and 9), which was in turn wrapped by a second phase of staurolite (Figs. 8, 9 and 10) containing inclusion trails that are continuous with a N–S-trending foliation in the matrix (Fig. 11). A second phase of andalusite growth has partially replaced the second phase of staurolite (Figs. 8a and 11), whereas a third generation of andalusite growth wraps around both the first and second phases of growth (Fig. 12) and contains inclusion trails that are continuous with the dominant NE–SW-trending matrix foliation. In the Gilded Rose Mine area (north of the Snake Creek anticline, Fig. 1), first generation staurolite and andalusite contain W–E-striking inclusion trails that are truncated against N–S-trending matrix foliation. Fibrolitic sillimanite has overgrown this N–S-trending matrix foliation and in some samples has partially replaced staurolite and andalusite (Fig. 13). In a few samples (Sc8 and Sc865) kyanite porphyroblasts have overgrown the N–S-trending matrix foliation and have partially replaced second generation andalusite. Kyanite with slightly irregular grain boundaries is locally enclosed and possibly partially replaced by a third phase of andalusite (Fig. 14a and b). Based on these microstructural relationships the sequence of porphyroblast growth during FIA 2 is garnet → staurolite → andalusite → kyanite → sillimanite.

6.2 FIA succession and directions of bulk horizontal shortening

Figure 4 shows that the FIAs define three different trends. Timing criteria between the different FIAs include core to rim changes in trend, inclusion trails truncated against or continuous with the matrix foliation and the sequential growth of different porphyroblastic phases. NW–SE-trending FIAs are only preserved in cordierite and garnet porphyroblasts. In some samples, either of these phases can be enclosed by andalusite containing inclusion trails defining W–E-trending FIAs (Fig. 15a and b). Andalusite and staurolite porphyroblasts, and locally garnet, can contain either N–S-or E–W-trending FIAs. Figure 16 shows garnet containing gently dipping inclusion trails in its core and steeply dipping inclusion trails in its rim that appear to be continuous to the matrix foliation. The core trails define an E–W-trending FIA while those in the rim define a N–S-trending FIA (Fig. 16). Staurolite porphyroblasts, in the same sample, preserve N–S-trending FIA and wrap around the garnet porphyroblasts. The N–S-striking matrix foliation is continuous with both staurolite inclusion trails and the garnet rim inclusion trails. Garnets preserving W–E-trending FIA are enclosed within staurolite and andalusite porphyroblasts that contain inclusion trails defining the N–S-trending FIA. Based on these observations the chronological order is FIA set 00 (NW–SE), FIA set 1 (W–E), and FIA set 2 (N–S) and they formed during SW–NE, N–S and E–W bulk horizontal shortening, respectively (e.g., Bell *et al*., 1995; Cihan, 2004).

6.3 Monazite ages and the timing of porphyroblast growth and metamorphism

Monazite grains contained as inclusions formed prior to or during development of the FIA preserved within a porphyroblast. Monazite grains included in cordierite porphyroblasts containing FIA 00 have a weighted average age of 1649±12 Ma (Table 4 and Fig. 5). The upper limit of the age for sedimentation of the Soldiers Cap Group is constrained by detrital zircons from the Mount Norna Quartzite and Toole Creek Volcanics at 1654±4 Ma (Foster and Austin, 2008) suggesting tectonism affected these rocks immediately after they were deposited. The finer grain size of inclusions trapped within cordierite versus garnet porphyroblasts with the same FIA trend suggests that cordierite may have grown prior to garnet. 93 analysed spots from 30 monazite grains within inclusion trails defining FIA 1 in garnet, staurolite and andalusite porphyroblasts yielded a weighted average age of 1645±7 Ma (Table 4 and Fig. 5). Although this age is close to the one determined for FIA 00, the microstructural relationships indicate that FIA 1 porphyroblasts not only postdate FIA 00 porphyroblasts, but also have opposite asymmetry inclusion trails. 42 analysed spots from 19 monazite grains within inclusions defining FIA 2 in garnet, staurolite and andalusite porphyroblasts have a weighted average age of 1591±10 Ma (Table 4 and Fig. 5).

6.4 P-T conditions during successive metamorphic events

Microstructural relationships indicate that cordierite was the first porphyroblastic phase to form during NE–SW shortening and monazite dating constrains the timing of this period of deformation and metamorphism to around 1650 Ma. These porphyroblasts contain very fine-grained inclusion trails (Fig. 15b) suggesting that the matrix had not experienced much coarsening prior to the heating event responsible for cordierite nucleation and growth. Experimental work (Seifert, 1970) has shown that at low pressures in the KMASH system cordierite is produced by the reaction:

Muscovite + Chlorite +Quartz = Cordierite + Phlogopite + H_2O (1)

The equilibrium temperature for this reaction is 495±10 °C at 1 kbar and 525±10 °C at 2 kbars. The source of heat required to produce cordierite was most probably provided by meta-dolerite intrusions and was probably fast acting to prevent the matrix coarsening prior to being included.

The next period of deformation and metamorphism produced garnet, staurolite and andalusite porphyroblasts that entrap inclusion trails defining the W–E-trending FIA set 1. This event followed soon after the previous one since the weighted average age of the monazite grains included in porphyroblast that contain FIA set 00 and FIA set 1 are very close. The P-T conditions during this FIA can be assessed based on garnet core isopleths thermobarometry and phase diagram relationships. Garnet porphyroblasts from sample N17 contain inclusion trails defining the W–E-trending FIA set 1. X-ray compositional maps of a garnet porphyroblast from this sample show typical prograde zoning with manganese and calcium rich cores and iron and magnesium rich rims (Fig 6). The intersection of X_{Fe}, X_{Mn} and X_{Ca} isopleths for two garnet porphyroblasts (Figs. 6a and 17a, b) show that they nucleated and grew at about 3 Kbars and 550 °C. The replacement of staurolite by andalusite in some samples suggests that following garnet growth the rock went through the staurolite stability field before entering the St+And stability field. Figure 6 shows that the staurolite and St+And stability fields are both close to the PT conditions where the garnet growth occurred. Thus during the development of this FIA set the PT conditions were around 550 °C and 3 Kbars. This indicates a slight increase in pressure and temperature from FIA 00 to FIA 1.

A second generation of garnet, staurolite and andalusite porphyroblasts, which preserve inclusion trails defining the N–S-trending FIA set 2, were interpreted to have formed during E–W bulk horizontal shortening. Andalusite commonly replaces staurolite porphyroblasts. In a few samples kyanite has partially replaced andalusite containing FIA 2 and a third generation of andalusite has partially replaced kyanite (Fig. 14). These kyanite porphyroblasts grew in crenulation hinges associated with the development of the N–S-trending cleavage suggesting growth during FIA 2. Fibrolitic sillimanite has overgrown this N–S-trending foliation and in some samples has partially replaced staurolite and andalusite porphyroblasts (Fig. 13).

Garnet core isopleth geothermobarometry reveals that this second generation of garnet growth occurred at ~ 3.2 kbars and 555 °C (Fig. 17c and d). These P-T conditions are similar to those for the staurolite and St+And stability field. Therefore, it is proposed that staurolite and andalusite formed under the same conditions as garnet. Figure 7 shows that the kyanite stability field extends to pressures higher than 6.5 kbars and 650 °C. Such P-T conditions are unrealistic for the rocks of the Snake Creek anticline and kyanite growth was possibly related to metasomatism. This is supported by the presence of some unusual kyanite crystals that are up to 30 cms long and about 3 cms wide. However, Rubenach *et al*. (2008) proposed that kyanite grew at about 5.5–6 kbars and c. 550 °C. In most samples where sillimanite is present, it has partly replaced staurolite and andalusite suggesting that the rocks experienced just the onset of the field in which this phase grows. The P-T conditions shown in Figure 7 lie close to the invariant point that separates the sillimanite field from the Sill+St and St+And stability fields and matches the observations very well. These P-T conditions are at about 4 kbars and 600 °C.

The third generation of andalusite (Fig. 12) porphyroblasts present in some samples are uncommon and a FIA trend could not be determined for them. They appear as rims on FIA 2 porphyroblasts and have partially replaced kyanite suggesting that they most probably postdate FIA 2 and reflect a drop in temperature from the sillimanite field back into the andalusite stability field.

6.5 Sedimentation, metamorphism and tectonism

Deposition of the Soldiers Cap Group took place between 1675–1650 Ma with the exception of the Llewellyn Creek Formation which appears to be older (pre-1686 Ma, Rubenach *et al*., 2008). Introduction of mafic sill-like bodies to the sedimentary basin began early during the deposition of the Llewellyn Creek Formation and continued afterwards. Monazite ages in porphyroblasts that grew during the NE–SW, N–S and W–E bulk horizontal shortening produced ages of ~ 1649, 1645 and 1590 Ma, respectively. This implies that either the first period of horizontal shortening (onset of the Isan orogeny) took place immediately after the cessation of the sedimentation or that shortening caused deposition to cease. If this was the case, then what was the source of heat during the low-P/high-T metamorphism that accompanied the first shortening event? The intrusion of mafic, sill and dike like bodies over a wide time span at different stratigraphic levels and the intra-continental rift like character of the sedimentary basin suggests that the crust was relatively thin allowing access of hot mantle material to higher levels.

7. DISCUSSION

7.1 Comparison with previous work

The Snake Creek anticline area comprises Mesoproterozoic metasedimentary and metavolcanic units that underwent polyphase metamorphism and deformation during the lengthy Isan orogeny (1650–1500 Ma). Sillimanite K-feldspar assemblages together with some migmatite development close to the Saxby granite record the peak of metamorphism during N–S bulk shortening (D_2 of Reinhardt, 1992; Rubenach, 1992; Rubenach *et al*., 2008; D_1 of Sayab, 2006). Reinhardt (1992) and Sayab (2006) claimed that high pressure-low temperature (HPLT) metamorphism accompanied N–S-oriented shortening that resulted in multiple W–E-directed fabrics. This study does not support their hypothesis. Sayab (2006) presented photomicrographs showing kyanite porphyroblasts enclosed within cordierite porphyroblasts. He claimed that these kyanite porphyroblasts grew during N–S shortening without providing any microstructural evidence while the cordierite porphyroblasts grew in response to the intrusion of the Saxby granite. The microstructural evidence suggests that kyanite grew late during E–W shortening over the N–S-trending S_2 foliation that is axial planar to the Snake Creek anticline. No evidence for kyanite porphyroblasts overgrowing an E–W-oriented fabric was found in this study or by Rubenach and Barker (1999) who published a photomicrograph of kyanite (their fig. 9) containing inclusion trails that appear to be continuous with the surrounding S_2 matrix foliation. Kyanite grew late during E–W shortening at higher pressures that do not favor the growth of cordierite. In all the studied samples, in this study, only one generation of cordierite growth is present and it preserves the earliest NW–SE-trending FIA. A second generation of cordierite growth may have occurred (Mike Rubenach personal communication) related to emplacement of the Saxby granite that entrapped earlier grown (during E–W shortening) kyanite porphyroblasts but no evidence of this was found in this study.

Garnet core isopleth thermobarometry suggest that garnet growth during N–S and E–W shortening occurred at about 3 kbars (Fig. 17). Sayab (2006) determined that garnet porphyroblasts that grew during N–S shortening nucleated at about 6 kbars close to the Cloncurry Fault. Perhaps deeper rocks were uplifted by motion on this fault as none of the data presented in this study support the existence of a metamorphic event above 4 kbars during N–S shortening. The data presented in this study is in a good agreement with the conclusions of Adshead-Bell (2000), Rubenach and Lewthwaite (2002), Rubenach (2005), Foster and Rubenach (2006) and Rubenach *et al*. (2008) regarding the metamorphic and deformation history of the Snake Creek anticline area. This study support the early growth of cordierite in the Snake Creek anticline and based on microstructural relationships, FIA data and monazite age dating, suggest that they all grew during NE–SW shortening that predates the D1 event of the above mentioned authors.

7.2 Sedimentation history

Recent U-Pb zircon age data obtained from the Soldiers Cap Group (Page and Sun, 1998; Giles and Nutman, 2003) indicate a depositional age equivalent to the Cover Sequence 3 of Blake (1987). Maximum depositional ages determined for the units of the Soldiers Cap Group were 1658±8 Ma for the Toole Creek Volcanics, 1654±4 Ma for the Mount Norna Quartzite and 1666±14 Ma for the Llewellyn Creek Formation. Rubenach *et al*. (2008) recorded SHRIMP ages of 1686±8 from zircon grains separated from a trondjhemite lens located within a 700 m mafic sill that intruded the Llewellyn Creek Formation in the Snake Creek anticline area. Therefore, they concluded that the lower part of the Llewellyn Creek Formation was deposited prior to intrusion of these mafics. The ~25 million years between the deposition of the Llewellyn Creek Formation and the overlying units (Mount Norna Quartzite and Toole Creek Volcanics) has been interpreted to represent slow sedimentation rather than a break in deposition (Foster and Austin, 2008). This idea is supported by the fact that in the Snake Creek anticline area, the three units represent a continuous depositional sequence without any evidence of internal unconformities.

7.3 The thermal budget and the cause of HT-LP metamorphism

The Mount Isa Inlier is characterized by widespread, long lasting HT-LP metamorphism. The exact mechanism responsible for elevated temperatures required to produce HT-LP metamorphism is not well understood and the tectonic setting is complicated by the absence of any suture zone. A few models have been proposed to explain these high geothermal gradients. Loosveld and Etheridge (1990) proposed that mantle delamination and thinning of the mantle lithosphere during the initial stages of shortening was responsible for the early HT-LP metamorphism in the Mount Isa province. McLaren *et al*. (1999) interpreted that the high thermal gradients were the result of the burial of granite batholiths enriched in radiogenic elements beneath the thick insulating sedimentary succession of the Mount Isa Group. Sandiford (1998), Hand and Rubatto (2002) and Giles *et al*. (2006) proposed that a thick pile of high heat producing sediments with low thermal conductivity was responsible for sustaining long term elevated temperatures. Rubenach *et al*. (2008) attributed the high thermal anomalies to advective heat transfer due to the emplacement of widespread mafic rocks throughout the history of the Inlier. This last hypothesis can not be disregarded since there is a close spatial relationship between plutonism and HT-LP metamorphism. Initial evolution of the Mount Isa Inlier as an intra-continental rift basin (e.g., Ellis and Wyborn, 1984; Williams, 1998) prior to shortening offers a simple explanation for the early high geothermal gradients. This is supported by the occurrence of wide spread, usually bimodal, igneous activity immediately pre-to-syn metamorphism (i.e. Sybella granite emplaced between 1674 and 1655 Ma and the Ernest Henry Diorite 1660±13 Ma), voluminous mafic (Toole Creek Volcanics at 1655 Ma) and felsic (Carters Bore Rhyolite) volcanism, in some places bimodal, and the emplacement of tholeitic magmas having MORB affinities in the form of sills and dyke swarms.

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CONCLUSIONS

Conclusions

Based mainly on detailed macro and mesoscopic investigations, comprehensive microstructural analysis of porphyroblasts inclusion trails and porphyroblast to matrix relationships, geochronology, geothermobarometry and phase diagram modeling, the prolonged and complex tectono-metamorphic history of the Snake Creek anticline region, Eastern Fold Belt, Mount Isa Inlier, Australia, has been determined.

Section A

Integrated macro, meso and microstructural (mainly porphyroblasts inclusion trails and the relationships between porphyroblasts and the different matrix foliations) data from the multiply deformed and metamorphosed Mesoproterozoic rocks of the Snake Creek anticline region, revealed four distinct sub-orogenic cycles, O_{00}, O_1, O_2 and O_3, during the lengthy 1670–1500 Ma Isan Orogeny. Each of these cycles accompanied periods of horizontal shortening and produced a number of phases of deformation. The NE–SW shortening orogeny (O_{00}) produced a succession of five phases of deformation, which was responsible for the NW–SE-trending first generation folds, F_{00}, together with cleavages that are only preserved within porphyroblasts that define the NW–SE-trending FIA set 00. The N–S shortening orogeny (O_1) developed at least three phases of deformation that are well preserved as W–E-trending foliations in the matrix and within the porphyroblasts that preserve W–E-trending FIA set 1. During O_1, large portions of the original NW–SE-trending folds rotated to more W–E-trending structures. The W–E shortening orogeny (O_2) was responsible for the development of the penetrative N–S-trending structures that dominate the tectonic grain of the Mount Isa province. The NW–SE shortening (O_3) produced, locally, NE–SW-trending folds and an associated weak axial planar cleavage.

The asymmetries of the steep to gently dipping inclusion trails within different porphyroblasts that grew during these orogenic cycles were used as kinematic indicators to deduce the sense of shearing and consequently the movement direction. SW directed thrusting accompanied O_{00}, whereas thrusting towards the N accompanied O_1.

Section B

In multiply deformed terrains where successive deformations are strongly partitioned into zones dominated by group of folds with perpendicular axial planes that lack proper interference and superposition criteria, the relative timing between orthogonal folding is problematic. Such problems have led some to interpret such complex fold geometries to be developed during a single tectonic event. The same problem occurs with relative timing between the N–S-trending Snake Creek anticline and the W-E-trending Toole Creek, Davis and Mountain Home folds. It was resolved by comprehensive study of the porphyroblasts inclusion trails together with FIA measurements and correlating these microstructures with the meso, macroscopic structures.

Mesoscopic, macroscopic and microscopic structures, together with FIA measurements preserved within different porphyroblasts, revealed that N–S bulk horizontal shortening preceded W–E horizontal shortening during the Isan orogeny. This is indicated by truncation of the W–E-trending matrix foliation by a N–S-trending differentiated crenulation cleavage, truncation of porphyroblasts preserving W–E-trending FIA against the dominant N–S-trending matrix foliation, and porphyroblasts with complex inclusion trails that preserve W–E-trending FIA in their cores and N–S-trending FIA in their rims. Thus the W–E-and N–S-trending folds in the region do not represent one single deformation phase, but instead resulted from distinctly different periods of bulk horizontal shortening during the Isan orogeny with W–E-trending folds predating those that trend N–S.

Section C

Deformation phases can be constrained using appropriate dating techniques. Dating of the foliations entrapped within the porphyroblasts constrain the tectono-metamorphic events that were responsible for the growth of these porphyroblasts. Foliation Inflexion/Intersection Axes preserved within porphyroblasts (FIAs) that grew throughout Isan orogenesis reveal four significant directions of bulk horizontal shortening; NE–SW,W–E, N–S and NW–SE. The first three FIA sets have been dated using monazite grains entrapped within porphyroblasts that grew during the different tectono-metamorphic events and yielded ages of 1649±12 Ma, 1645±7 Ma and 1591±10 Ma, respectively. The dominant top-to-the-SW and-N sense of shear, shown by the inclusion trails preserved within porphyroblasts that preserve NW–SE-and W–E-trending FIA, respectively, indicate movements towards the SW and the N. A possible correlation between the Mount Isa, Broken Hill and Gawler provinces and between the Isa terrane and the SW Laurentia is suggested. NE–SW-and N–S-directed shortening events in the Isa block most probably correlate with the tectonism that accompanied the amalgamation of the Gawler and North Australia cratons whereas the W–E shortening event may be correlated with the Hiltaba tectonic event that affected the eastern Proterozoic in south Australia at 1600–1560 Ma. An anticlockwise shift in relative plate motion during the Isan orogeny is suggested by the anticlockwise shift in the direction of bulk horizontal shortening indicated by the successive changes in FIA trends, supported by monazite age dating obtained from each trend.

Section D

The low-P/high-T Mesoproterozoic volcano-sedimentary rocks of the Snake Creek anticline region show evidence of polymetamorphism that accompanied multiple deformations during the lengthy Isan orogeny. A metamorphic mineral succession grew during this succession of tectono-metamorphic events. FIA measurements reveal four distinct bulk horizontal shortening events. Microstructural and textural relationships, together with FIA measurements supported by the absolute time constrain of these FIA sets, indicate that during the NE–SW shortening event, cordierite porphyroblasts followed by garnet porphyroblasts, grew and incorporated inclusion trails that define a NW–SE-trending FIA set 00, that has been dated at 1649±12 Ma. This was followed by a N–S shortening event, during which porphyroblasts of garnet, staurolite and andalusite grew sequentially and entrapped inclusion trails defining a W–E-trending FIA set 1 that has been dated at 1645±7 Ma. Around 1591±10 Ma a W–E shortening event commenced and led to the sequential growth of garnet, staurolite and andalusite porphyroblasts that preserve a N–S-trending FIA set 2. Sillimanite and kyanite porphyroblasts grew syn-to-late the period of W–E shortening. Kyanite porphyroblasts have been found in a few locations, mainly in the Snake Creek anticline and just to the north of its nose. These reflect higher pressure metamorphic conditions. Sillimanite/sillimanite-K-feldspar and local migmatization to the south of the Snake Creek anticline, close to the Saxby granite, indicate high temperature and define the peak of metamorphism in the region.

Phase diagram modeling, in the MnNCKFMASH system, of the mineral assemblages from the Snake Creek anticline rocks using THERMOCALC software matches well with the petrographical observations. Geothermobarometry using core isopleths for garnet porphyroblasts that preserve W–E-and N–S-trending FIA sets 1 and 2, respectively, show that they nucleated at higher pressure (~ 3 kbs) and a slightly higher temperature than the cordierite porphyroblasts that preserve the NW–SE-trending FIA set 00, implying an increase in metamorphic grade from low-P/high-T (during the NE–SW shortening event) to moderate-to-high P/ high T (during the W–E and N–S shortening events).