Structural and Metamorphic Evolution of the Robertson River Metamorphics with Pressure-Temperature-Deformation-Time (P-T-D-t) Path

VOLUME I

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Dedicated to my most beloved ones, whom I have never mentioned but who are in everything that I have done…

PREFACE

This thesis describes and interprets deformational and metamorphic processes and their temporal relationships through absolute time using the Robertson River Metamorphics, located in the Georgetown Inlier, NE Australia.

The thesis consists of introduction and four sections (A-D) written in a paper format for submission to international journals. Sections A and B have been submitted to the *Journal of Structural Geology*. The former is published and the latter co-authored with Allan Parsons (his contribution is 20%) is in press. Sections C and D have been submitted to the *Journal of Petrology* and *Precambrian Research*, respectively. The last section is co-authored with Nick Lisowiec and Kevin Blake, and their contribution totals around 20%.

Contents of Volume I

INTRODUCTION TO THESIS

Unravelling the tectono-metamorphic evolution of highly deformed metamorphic terranes requires a multidisciplinary approach that involves integration of microstructural, petrographical, chemical and geochronological analyses of representative rock samples. Integrating the results of these studies is essential and provides more reliable solutions for conflicts over the number, origin and nature of deformational and/or metamorphic phases. This results in a better understanding of the processes behind what we have observed in the field as an end product.

The correct and careful identification of different fabrics in the matrix and inclusion trails within porphyroblasts, which were formed during successive deformations, provides the linkage with the other studies mentioned above. Without this step, any results obtained could have been misinterpreted. Identification of such fabrics by using conventional methods has been accomplished by many studies (e.g. Zwart, 1960; Vernon et al., 1993, Williams, 1994), but would have resulted in a very simple history. Studies (e.g. Bell, 1986; Hayward, 1992; Bell et al., 2004) using the relatively new approaches described here in have provided extensive deformation and metamorphic history and show that deformation processes are much more complex than thought to be the case previously. These innovative approaches, "*Foliation Intersection Axis within porphyroblasts*" (FIA; Bell et al., 1995) and "*reactivation of bedding during successively formed foliations*" (Bell et al., 2004), provide the backbone of the approach used in the four papers in this thesis.

The fundamental difference between the old and new approaches derives from the manner in which rock samples are thin sectioned. Conventionally, structural and metamorphic geologists cut their thin sections with respect to fabric orientations in the matrix. This is called as P-N sectioning, which involves only two thin sections; one cut parallel to lineation but perpendicular to foliation (P), and the other cut perpendicular to lineation and foliation (N; Bell and Rubenach, 1983). The new method uses multiple vertical thin sectioning around the compass and provides a 3D view of the inclusion trails. Early deformations are preserved by these inclusion trails that have been erased from the rock matrix by reactivation of the bedding (e.g. Bell et al., 2004). They cannot be distinguished using P-N sections.

These two methods are compared in the first section of the thesis using the examples from the Roberson River Metamorphics, NE Australia, and the different results obtained are documented.

The Robertson River Metamorphics lie within the Georgetown Inlier, which contains one of the most extensive exposures of Precambrian rocks in north Queensland. In terms of stratigraphy and deformational patterns, it shows similarities with the other inliers such as Mt. Isa, Coen, Yambo and Woolgar (Fig. 1 in sections B-D). The temporal and spatial tectonic reconstruction of these inliers is still a problem and needs to be dealt with detailed studies in key localities. The study area (Fig. 2 in sections A-D) investigated in this thesis is suitable for that purpose. It includes a variety of metamorphic rocks, which were originally deposited around 1695-1655 Ma (Black et al., 1998). These rocks range from greenschist in the west to upper amphibolite facies in the east and contain porphyroblasts with well-preserved inclusion trails.

The relative timing of porphyroblasts with respect to matrix and macro-scale structures provides vital information about the nature and development of these structures. Through FIA analysis, the timing of the porphyroblasts on the limbs of macro-scale folds can be ascertained and correlated from limb to limb. FIAs, regardless of whether or not porphyroblasts rotate, suggest changes in tectonic transport direction with time so that studying the inclusion trails formed around these FIAs provides timing of the macro-scale folding with respect to deformation and metamorphism. This is demonstrated in section B by investigating the porphyroblasts on the limbs of E-W trending macro scale folds in the study area.

The derivation of pressure-temperature (P-T) paths using different deformation and metamorphic phases in poly-deformed metamorphic terranes is an important step for better understanding of the mountain building processes. In section C, this is achieved by utilizing pseudosections and FIAs to obtain P-T conditions during the growth of garnet porphyroblasts. This important task has classically been achieved by using conventional methods such as thermal modelling (England and Thompson, 1984), calculation of P-T points from mineral inclusions within garnet (St-Onge, 1984) and mineral zoning (Spear and Selverstone, 1983), and have usually yielded segments of a P-T path rather than the complete path.

Pseudosections (phase diagrams) are commonly used to obtain P-T points. However, such work has been limited to the core growth of garnet porphyroblasts (e.g. Vance and Mahar, 1998). Since FIAs provides relative timing of garnet porphyroblasts and each FIA represents different deformation events, the integration of these two offer complete P-T path and differentiates P-T conditions due to overprinting tectono-metamorphic events.

The last paper of the thesis, section D, combines all the methods mentioned above with the electron microprobe dating of monazites (EMP). The EMP method has been popular, despite of its limitations compared to other dating methods such as SHRIMP and IDTIMS. It is a very important technique because of its ability to determine U, Th and Pb concentrations in domains that are ~2μm in size, which is much smaller than the minimum spot size for other methods (~20μm). This characteristic makes the EMP method very attractive as it allows dating of monazites trapped as inclusion trails within porphyroblasts and thus FIAs (e.g. Bell and Welch, 2002). In addition, EMP analysis is in expensive and easy in comparison to other methods. It was shown that the precision of this technique can be improved by better counting statistics (Pyle et al., 2002).

Combining monazite age dates with detailed structural and metamorphic investigations have generated a far-reaching deformation and metamorphic history and pressure-temperature-deformation-time (P-T-D-t) path for the Robertson River Metamorphics. This, inturn, has provided striking insights for the evolution of the North Australian Craton (NAC) that could not have been recognized previously.

SECTION -A-

THE DRAWBACKS OF SECTIONING ROCKS RELATIVE TO FABRIC ORIENTATIONS IN THE MATRIX: A CASE STUDY FROM THE ROBERTSON RIVER METAMORPHICS (NORTHERN QUEENSLAND, AUSTRALIA)

SECTION -A-

THE DRAWBACKS OF SECTIONING ROCKS RELATIVE TO FABRIC ORIENTATIONS IN THE MATRIX: A CASE STUDY FROM THE ROBERTSON RIVER METAMORPHICS (NORTHERN QUEENSLAND, AUSTRALIA)

ABSTRACT

Understanding the relationships of inclusion trail geometries in porphyroblasts relative to matrix foliations is vital for unravelling complex deformation and metamorphic histories in highly tectonized terranes and the approach used to thin sectioning rocks is critically important for this. Two approaches have been used by structural and metamorphic geologists. One is based on fabric orientations with sections cut perpendicular to the foliation both parallel (P) and normal (N) to the lineation, whereas the other uses geographic orientations and a series of vertical thin sections. Studies using P and N sections reveal a simple history in comparison with studies using multiple-vertical thin sections. The reason for this is that inclusion trails exiting the porphyroblasts into the strain shadows in P and N sections commonly appear continuous with the matrix foliation whereas multiple vertical thin sections with different strikes reveal that they are actually truncated. Such truncations or textural unconformities are apparent from microstructures, textural relationships, compositional variations and FIA (Foliation Intersection Axis) trends. A succession of four FIA trends from ENE-WSW, E-W, N-S to NE-SW in the Robertson River Metamorphics, northern Queensland, Australia, suggests that these truncations were formed because of the overprint of successive generations of orthogonal foliations preserved within porphyroblasts from growth during multiple deformation events. At least four periods involving multiple phases of

porphyroblast growth can be delineated instead of just the one previously suggested from an N and P section approach.

Keywords: Robertson River Metamorphics; truncation; inclusion trails; porphyroblast growth; reactivation.

1. INTRODUCTION

Thin section examination of inclusion trails in porpyroblasts is an important tool used to elucidate the relative timing of porphyroblast growth and deformation. Establishing such relationships is vital if the complex deformation and metamorphic history of highly tectonized terranes is to be resolved. Recent studies (e.g. Vernon et al., 1993; Bell and Hickey, 1999; Paterson and Vernon, 2001) have debated conflicting interpretation of microstructures and the deformation history that in part have resulted from different approaches to thin sectioning. One is based on fabric orientations in the matrix whereas the other is based on geographic directions around the compass. Most structural and metamorphic geologists over the past thirty years have cut their thin sections with respect to fabric orientations in the matrix. This is called the P-N approach for brevity and the thin sections are cut parallel to lineation but perpendicular to foliation (P), and perpendicular to lineation and foliation (N; Bell and Rubenach, 1983; Fig. 1). A major ongoing controversy, partly raised because of these different approaches, is whether rotation or non-rotation of porphyroblasts is the applicable model. For the first model, a major factor has been continuity of inclusion trails with the matrix, suggesting the interpretation that porphyroblasts have rotated causing the internal foliation (Si) to change orientation relative to external foliation or shear plane (Se). This geometry is very typical in P and N sections but commonly does not hold true when multiple vertical thin sections have been cut. The latter commonly reveal that porphyroblast inclusion trails are truncated in 3-D by the matrix foliation and that the porphyroblasts have not necessarily rotated. Understanding which model is a more reliable paradigm regarding porphyroblast behaviour for a specific area has important inferences for solving deformation histories. This has been tested in a number of studies (e.g., Bell and Hayward, 1991; Hayward, 1992; Johnson, 1992; Johnson and Vernon, 1995; Bell et al. 1995; Bell and Hickey, 1999; Bell and Chen, 2002) by measuring the foliation intersection axes (FIAs) preserved within porphyroblasts. The reason for this difference between the interpretations resulting from the two thin sectioning approaches is that P and N sections generally contain strain shadows around the porphyroblasts relative to the matrix foliation in which the inclusion trails exiting the porphyroblasts appear continuous with the matrix foliation. This problem is illustrated using the Robertson River Metamorphics where early studies using P and N sections revealed a relatively simple history of porphyroblast growth.

Multiple vertical thin sections with different strikes have revealed a far more complex history than expected from the relative apparent continuity of inclusion trails with the matrix foliations initially observed.

2. ROBERTSON RIVER METAMORPHICS

The Robertson River Metamorphics lie within the Georgetown Inlier, which is one of the largest exposures of Precambrian rocks in Northern Queensland (Fig. 2a). It is separated by Phanerozoic rocks from other inliers such as the Yambo, Coen, Woolgar and Mt. Isa. These inliers have been linked to similar sequences in North America that drifted apart nearly one billion years ago during the break-up of the supercontinent Rodinia (Blewett et al., 1998; Karlstrom et al., 1999). The area described herein includes intrusive rocks as well as highly deformed metamorphic rocks such as phyllites, pelitic schists, quartzites and amphibolites, which underwent prograde metamorphism (Fig.2c). These metamorphic rocks contain a greenschist to amphibolite facies metamorphic transition that has resulted in extensive porphyroblast growth with well-developed inclusion trails. The two stratigraphic units including Dead Horse Metabasalt and Cobbolt Metadolerite outline the major structural features, which are ENE-WSW to E-W trending overturned antiform and synform. N-S and NE-SW trending folds refolded these structures, which indicates polyphase deformation in the study area.

Bell and Rubenach (1983) proposed that there were six deformational events in the Robertson River Metamorphics. The first two events, dated as D_1 1570 ± 20 Ma, D_2 ~1550 Ma (Black et al, 1979; Black et al, 1998), created penetrative foliations associated with prograde metamorphism, whereas the last four produced local crenulations and are commonly associated with retrograde metamorphism. Bell and Rubenach (1983) used P and N sections and claimed that porphyroblasts grew over S1 during D2 since curving inclusion trails exiting the porphyroblasts appeared continuous with the penetrative schistosity they called S2 in the matrix (Davis, 1995). They recognized that in some sections S1 was a differentiated crenulation cleavage and, therefore, that there was potential for an extra deformation pre S1. Subsequent comparison of P-N sections with multiply oriented vertical thin sections has revealed that many inclusion trails exiting porphyroblasts, which appear to be continuous with matrix foliation, are in fact truncated in 3-D and a much more extensive history of porphyroblast growth has now been recognized.

3. STUDY METHODS

Sixty-eight spatially oriented samples collected from the study area were reoriented in the laboratory and horizontal rock slabs were marked and cut. Multiple vertical blocks around the compass were cut from these slabs (Fig. 3a). The matrix-porphyroblast relationships were examined using

8 to 10 thin sections cut by this approach. The FIAs were measured for each rock sample from these thin sections as described by Hayward (1990) and Bell et al. (1995, 1998). Initially these sections were cut from blocks with 30° increments and then two more were prepared at 10° intervals between the two in which the curvature of inclusions (clockwise / anticlockwise) switched one to another when viewed from the one direction. The FIAs were then determined as lying between the 10° sections where the asymmetry changed (Fig. 3b). This is shown in Fig. 4 where vertical thin sections cut from the same rock sample are presented. When they are examined from the one direction, inclusion trails indicate same clockwise asymmetries within the core of the garnet porphyroblasts in all but the 170° section (Fig. 4g), which contains some symmetric shaped inclusions and the 180° striking thin section (opposite view of 000° section; Fig. 4h), which shows an anticlockwise symmetry. The FIA should lie around 170° or very close to it; for this sample the FIA was determined to be at 175°. FIA trends are detached from the assumption of whether porphyroblasts rotate or not. If the porphyroblasts rotate, the FIA will be a rotation axis and perpendicular to shearing direction (Rosenfeld, 1970; Schonefeld, 1979). If they do not, the FIA trend will lie perpendicular to the direction of bulk shortening (Bell et al., 1995). P and N sections were also prepared from representative rock samples where the matrix truncates the inclusion trails of early porphyroblasts in vertical thin section orientations. In addition to

these, a representative garnet porphyroblast was analysed to check compositional anomalies across the truncation boundary or textural disconformity. This analysis is based on X-ray maps plus line traverses across the porphyroblast. X-ray maps were generated on a JxA-8200 electron microprobe. These maps were created by a 512x512 stage scan analysis made with both WDS and EDS spectrometers at 100nA beam current, 15kV and 80 ms count times. Line traverses include 54 analyses taken at 20μm spacing. These were acquired with EDS by JxA-840A microprobe.

4. FIA DATA

112 FIA measurements (Table 1) were determined from both garnet and staurolite porphyroblasts in 68 spatially oriented rock samples. The succession of FIAs was decided based on the changes in trend from the core to rim of porphyroblasts plus the textural link between garnet and staurolite porphyroblasts in places where the former is preserved as inclusions within the latter. The core must grow earlier than the rim and the growth of garnet must occur earlier than staurolite in all rock samples. This usually provides relative timing for the two or three different FIA trends present in the same rock sample. Four dominant peaks (Fig. 5a) with ENE-WSW, E-W, N-S and NE-SW directions can be distinguished on a rose diagram. The Watson's U^2 (1961; Freedman, 1981; Upton and Fingleton, 1989) statistical test was

applied to see whether these trends are composed of non-random multimodal data as suggested by the rose diagram. Since the resulting value of U^2 (0.526) exceeds the upper 0.1% critical value (0.268; Table 2), the FIA distribution cannot be the result of sampling a random population. These data were also separated into garnet versus staurolite FIAs (Fig. 3b,c). The nearly ENE-WSW (FIA1) and E-W (FIA2) trending FIAs were observed dominantly in the core and rim of the earliest garnet porphyroblasts, whereas only in a few samples were FIA2 (E-W) trends recorded within staurolite porphyroblasts. FIA1 (ENE-WSW) trends range from 50° to 70° but FIA2 (E-W) trends vary between 80º and 130º. This is followed by nearly N-S (FIA3; 170°-020°N) trending FIAs that are common in both garnet and staurolite porphyroblasts. The last FIA trend (FIA4; NE-SW, 20° to 45°) is only present within staurolite porphyroblasts. To determine whether the trends observed within both porphyroblasts are from the same population statistically, the X^2 test (e.g. Bell et al., 1998; Upton, 1992) was also applied. The X^2 values (55.2; 37.3) for this comparison are far higher than the critical values of 5.99 and 9.49 for two and four degree of freedom respectively (Table 3). This suggests that these two groups of data contain two different populations.

5. COMPOSITIONAL DATA

Compositional maps of a garnet porphyroblast from sample mc37 include the Xgrs (Ca), Xpyr (Mg), Xsps (Mn) and Xalm (Fe) components. The typical zoning patterns (Fig. 6) suggest a boundary between the core and rim of the porphyroblast. Xpyr and Xalm distinctly increase in the rim, whereas other components, Xsps and Xgrs decrease. The boundary between core and rim is marked by a sharp decrease in Xsps from core to rim, yet an increase in Xpyr and Xgrs, as shown with the vertical dash lines that refer to a truncation zone on the line traverses (Fig. 6). This boundary is characterized by zoning reversals (e.g. Xalm, Xgrs, Xpyr in Fig. 6) and steepened compositional gradients (e.g. Xsps in Fig. 6). The typical zonation patterns are generally attributed to growth zoning and/or diffusion zoning (e.g. Spear, 1993). The growth zoning occurs where compositional differences arise during the growth of a crystal due to changing external conditions such as changing P-T conditions, or a change in the local bulk composition of the rock. The diffusion zoning, on the other hand, requires modification of the pre-existing garnet composition in the absence of growth or consumption of the crystal by the volume diffusion because of the external conditions. Although the examples presented here classically suggest growth rather than diffusion, requiring a more homogeneous distribution and gradient of the compositions throughout the porphyroblasts, diffusion effects cannot be completely excluded but should be negligible (Cihan, 2004).

6. INCLUSION TRAILS IN PORPHYROBLASTS

The inclusion trails, which are well preserved in garnet and staurolite porphyroblasts, include mainly elongate quartz grains as well as plagioclase, graphite, mica and epidote. These inclusion trails are usually sigmoidally shaped and truncated by the matrix foliations (Fig. 4c-f). These textural discontinuities are very common within garnet porphyroblast between the core and the rim as well (Figs. 7 and 8). In some thin section orientations especially the ones that are parallel to the FIA, more symmetric shaped inclusions (Fig. 4g) are present. Garnet is commonly overgrown by staurolite porphyroblasts that contain inclusion trails. These trails truncate those within the garnet or parallel to the rim inclusions (Fig. 8). Although they look continuous in P-N sections with the matrix foliation (Fig. 9) in other thin section orientations they are truncated or partly continuous (Fig. 4). Since the inclusion trails in staurolite porphyroblasts are continuous with the matrix, they can be correlated with matrix foliations. There are three types of inclusion trail geometries trapped in staurolite porphyroblasts, which are characterized by different generations of staurolite growth and which are only recognizable with the help of multiple vertical thin sections. One type is preserved as differentiated crenulation cleavages, the long limbs of which are generally curved and continuous with the dominant matrix foliation (Fig. 10). The second type is slightly sigmoidal or curved defining the crenulation hinge (Fig. 11), and the last type is usually straight and parallel to the matrix foliation (Fig. 8).

7. TRUNCATION OR TRUNCATION ZONES

Truncation zones or truncations in porphyroblasts and/or at the matrix – porphyroblast boundary have been described as a textural "hiatus" or "unconformity" (Rosenfeld, 1968; Karabinos, 1984) or as truncational foliations (Bell and Hayward, 1991) that are the result of overprinting relationships between two sets of inclusion trails and/or foliations. There is a general consensus that these truncations or truncation zones can form in two ways. The first is as older foliations preserved in the porphyroblast core that are surrounded by the younger matrix foliation, which is then overgrown in a subsequent event. The second is as crenulations in microfold hinges, bounded by differentiated crenulation cleavages overgrown by porphyroblast rims during a younger event (Bell and Johnson, 1989; Bell and Hayward, 1991; Jones, 1994; Passchier and Speck, 1994; Williams, 1994; Spiess and Bell, 1996; Bell et al., 1997). Truncations can be distinguished based on smooth (partly continuous) or sudden changes in orientation, texture, composition and asymmetry of inclusions. Bell and Johnson (1989) suggested that inclusion trails are commonly not continuous but truncated from core to rim of garnet porphyroblasts generating complex, staircase or spiral shaped trails and are arranged orthogonally or near orthogonally in cross-section. This was supported by the pitch measurements of the truncations in absolute orientations (Bell and Hayward, 1991; Hayward, 1992; Aerden, 2003). Similar observations can be seen in Figs. 4 and 7, where orthogonal relationships between the inclusion trails in the core and rim of the porphyroblasts are visible. In Fig. 4c, the gently dipping core inclusions smoothly curve towards the steeply dipping rim inclusions. A truncation boundary can also be observed with the matrix foliation, in this case with a more sharply defined character. In another example inclusion trails suddenly change their orientation from core to rim (Figs. 7a, b, c). In these examples textural changes are also recognizable at the truncation zones. Fine-grained quartz and opaque minerals in the rim are orthogonally arranged with respect to the coarser quartz grains in the core. It has been reported that these relationships can be coincident with compositional zoning patterns in garnets (Powell and Vernon, 1979; Bell and Johnson, 1989; Hayward, 1992; Stallard and Hickey, 2002). Indeed, compositional X ray maps of these samples (Figs. 6) showed that the compositional modification from core to rim is consistent with the microstructural truncations and also textural relationships, as evident from Fig. 7. This suggests that following the growth of a core, a hiatus in the growth accompanied by garnet dissolution (e.g. Karabinos, 1984; Ikeda,

1993) occurred at the boundary with the older matrix. After that, growth continued in a subsequent deformation event, which developed orthogonal in cross-section to the previous one. Such characteristics result in FIA trends that can change from core to rim for a sample such as shown in Figs. 4, 7 and 8 (see Table 1).

8. IMPLICATIONS OF FIA TRENDS

One contribution of FIA data is that it enables one to test whether the porphyroblasts have been rotated in a specific area. This illuminates the nature of the mechanism of truncation and the different porphyroblast growth phases. The four FIA trends formed successively in NNE-SSW, E-W, N-S and NE-SW and suggest that the porphyroblasts have not been rotated during the deformation. If they had been rotated, they would have random trends rather than a succession of dominant orientations observed. For example, if E-W FIA2 trend was formed after an NNE-SSW FIA1 trend, and if rotation of the porphyroblasts were the cause, the FIA1 trend should have been rotated around the E-W axis as shown in Fig. 12a. In the same way, if both FIA1 (NNE-SSW) and FIA2 (E-W) porphyroblasts were rotated around the N-S trending FIA3 axis, they could have lain in any direction individually based on the amount of apparent rotation with respect to a fixed matrix (Fig. 12a), depending on the size of the porphyroblasts and type of flow (Williams and Jiang, 1999). If FIA4 (NE-SW) was a rotation axis, they could be oriented in any direction from N to E and S to W (Fig. 12b). Since this is not the case, it is not possible to claim porphyroblast rotation in the area investigated.

9. MULTIPLE PHASES OF PORPHYROBLAST GROWTH IN THE ROBERTSON RIVER METAMORPHICS

The Four FIA trends signify a sequence of porphyroblast growth with time. The earliest garnet porphyroblasts preserve FIA1 (NNE-SSW) and FIA2 (E-W), whereas FIA3 (N-S) was observed in both garnet and staurolite porphyroblasts. The FIA4 (NE-SW) was only found in staurolite porphyroblasts where the inclusions are continuous with and sub-parallel to the matrix. These different generations of FIAs indicate at least four periods of multiple phases of episodic porphyroblast growth that accompanied multiple deformation events and this is supported in single garnet porphyroblasts by the microstructures and compositional maps (Figs. 6, 7). This also suggests bulk shortening direction has changed in time from NNW-SSE to N-S to E-W and finally to NW-SE, which produced macro-scale structures mimicking the FIA trends as shown in Fig. 2.

10. DISCUSSION

10.1. Implications of compositional and FIA data for truncational relationships and phases of porphyroblast growth and their mechanisms

Consistency between microstructures and compositional variation has been previously reported from other metamorphic terrains (e.g. Karabinos, 1984; Ikeda, 1993; Stallard and Hickey, 2002). In these studies, zoning reversals observed at the truncation boundaries were attributed to resorption due to exchange reactions (e.g. Spear, 1993) producing chlorite and mica minerals in the expense of garnet. During these reactions because of Fe/Mg exchange, Xalm and Xpyp within the garnet porphyroblasts commonly increase from core to rim. Fig. 6 shows that just after the core formed, these components suddenly and then gradually increased. This suggests episodic growth of the porphyroblast because, following the growth of the core, mica and chlorite minerals were formed in earlier mica domains during the resorption and then these minerals were dissolved to grow the rim during the subsequent deformation event. The resorption or dissolution of the porphyroblasts apparently occurred against the limbs of crenulations or differentiated crenulation cleavages (mica domains) where high progressive shearing strain was active (e.g. Marlow and Etheridge, 1977; Bell et al., 1986). This indicates that the first phase of porphyroblast growth occurred on the hinge of a crenulation cleavage at the beginning of deformation during stage 2 of crenulation cleavage development (fig. 4 in Bell and Rubenach, 1983; Bell et al, 1986). Porphyroblasts growth occurs in zones of progressive shortening (Bell, 1981; Bell et al., 1986; Bell and Hayward, 1991) early in the deformation history when the strain is relatively low in the matrix (Bell et al., 2003, 2004). As the deformation intensifies, these hinges are generally destroyed unless they are trapped within porphyroblasts (Bell et al., 1992). As the porphyroblasts nucleate and grow in the progressive shortening sites (Fig. 13a), shearing becomes more active along the progressive shearing domains and porphyroblasts may begin to dissolve (Bell et al., 1986). A new phase of growth occurs only when a differently oriented phase of deformation is partitioned through the rock (e.g. Bell and Hayward, 1991; Bell and Welch, 2002; Bell et al., 2003). This is supported by the FIA trends, which change from core to rim of the porphyroblasts for some of the rock samples (e.g. Fig 7). These changes in FIA trend suggest that the direction of the bulk shortening causing orogenesis changed with time. Around the same FIA trends more than two successively formed near vertical and near horizontal foliations can develop (see Table 1; Bell and Welch, 2002) and this is common in staircase and spiral garnets (e.g. Bell and Chen, 2002). In this case the growth continues episodically during the early stages of deformation partitioning accompanying successive phases of deformation (Bell and Hayward, 1991; Bell et al., 2003).

During repartitioning of the deformation, earlier formed foliations in the matrix may rotate around the porphyroblasts towards compositional layering because of the reactivation of the bedding (e.g. Bell et al., 2003). Where this happens, the near orthogonal foliations observed within porphyroblasts have rotated closer towards parallelism in the matrix (e.g. Figs. 11, 13b). This geometry is one of the main reasons why porphyroblasts were originally suggested to be a product of rotation when one just used P-N sections (Fig. 9).

10.2. Reactivation and rotation of the earlier foliations around porphyroblasts

In multiply deformed terrains, old or intermediate events are commonly obscured by the effects of younger deformations due to reactivation of the bedding or old foliations, unless they are trapped as inclusion trails in porphyroblasts. Reactivation (Bell, 1986) is simply antithetic shear occurring on pre-existing foliations and bedding where it has an orientation compatible for this to occur in conjunction with synthetic shear on a newly developing axial plane cleavage (e.g. Bell, 1986; Bell et al., 2003). During reactivation, synthetic progressive shear on the developing foliation (S_2 in Fig. 14a) switches to antithetic shear on compositional layering (S_0 in Fig. 14a,b). At this stage, the newly formed foliation (e.g. S_2 in Fig. 14a, b) is destroyed, and remnants of earlier oblique foliations such as S_1 are rotated towards the bedding (e.g. $S_{0,1}$ in Fig. 14b). For instance, in Fig. 11 the two adjacent staurolite porphyroblasts preserve between them a differentiated crenulation cleavage that has been destroyed in the matrix elsewhere by reactivation. These porphyroblasts formed early during the development of the deformation that produced steep crenulation cleavage on which anticlockwise shear was acting.

10.3. Timing of porphyroblast growth through P-N and multiple-vertical thin sectioning approaches

Correct interpretation of the timing of porphyroblasts relative to deformational history is derived from correct identification of foliations trapped as inclusions in porphyroblasts. Reactivation of foliations around porphyroblasts and the continuity of inclusion trails into strain shadow regions relative to the matrix foliation will result in conflict in the timing of porphyroblast growth relative to deformation events unless they are observed in multiple vertical sections. For instance, P and N sections in Fig. 15 suggest porphyroblasts grew during D2 since they overgrow S1 and the inclusions appear continuous with S2. What appear to be the effects of D2 and S2 are actually those of D3 and S3 when viewed using a series of vertical thin sections (Fig. 15c).

The garnet porphyroblasts in Fig. 4 have undergone at least two phases of growth. Yet in P-N sections (Fig. 9) this growth appeared to occur as one or more phases during the formation of the matrix foliation. Clearly, P and N sections reveal little of the growth history because of the strain shadow caused by the matrix foliation and this appears to be the case elsewhere such as California (Bell and Hickey, 1999 versus Paterson and

Vernon, 2001), and the Appalachian Orogen in southeast Vermont (Rosenfeld versus Bell et al. 1998; Bell and Welch, 2002).

It is also worthwhile to note that the lack of critical geometrical relationships between inclusion trails in porphyroblasts and matrix in P and N sections can lead to misinterpretation of the shear senses used for the kinematic analysis within an orogen. The main reason here is that both shear senses can be obtained if porphyroblasts predate the matrix and if the FIA axis is sub-parallel to the P-section orientation.

11. CONCLUSIONS

Inclusion trail geometries in porphyroblasts, which are vital for understanding the deformation history in highly tectonized rocks, can only be fully analysed using multiple-vertical thin sections. Studies of the inclusion trails using a P-N section approach will regularly result in the misinterpretation of the timing of porphyroblast growth and the number of deformational and metamorphic events. The Robertson River Metamorphics contain at least four periods of porphyroblast growth accompanying different deformation events compared with the one phase proposed previously. Such multiple phases of growth versus simple histories have been recognized in other highly deformed terranes such as the Foothills of the Sierra Nevada in California (Bell and Hickey, 1999; Paterson and Vernon, 2001), Haast Schist, New Zealand (Johnson, 1990), Cooma Complex (Johnson, 1992; Johnson and Vernon, 1995) and the Appalachian Orogen in southeast Vermont (Rosenfeld, 1968; Bell et al. 1998; Bell and Welch, 2002), where multiple vertical thin section approaches have revealed much more complex deformation histories than proposed previously where sections were cut only orthogonal to the matrix foliation.

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SECTION -B-

THE USE OF PORPHYROBLASTS TO RESOLVE THE HISTORY OF MACRO-SCALE STRUCTURES: AN EXAMPLE FROM THE ROBERTSON RIVER METAMORPHICS, NORTH EASTERN AUSTRALIA

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ABSTRACT

A succession of four foliation intersection/inflection axes preserved in porphyroblasts (FIAs) trending ENE-WSW, E-W, N-S and NE-SW has been distinguished in the Proterozoic Robertson River Metamorphics (Georgetown Inlier, Queensland, Australia) based upon relative timing plus inclusion texture and orientation. The successions of asymmetries of inclusion trails defining these FIAs document the geometry of deformation associated with folding and fabric development during discreet episodes of bulk shortening. The successions of asymmetries bear no relationship to the geometry of macroscale folds present in the area suggesting that these folds predate porphyroblast growth, the widespread metamorphism and matrix fabric development. The onset of regional macro-scale folding may have begun soon after the deposition at around 1655 Ma in Georgetown Inlier. These folds were then amplified, overturned and refolded during NNW-SSE, N-S, E-W and NW-SE regional bulk shortening. Earlier deformations were erased from the matrix because of bedding-induced shearing (reactivation) on the limbs of pre-existing macro-scale folds. Four foliations, S_1 to S_4, identified in the matrix provided information about the youngest deformations preserved in these rocks.

Key words: Georgetown Inlier, Robertson River Metamorphics, FIA, porphyroblasts, inclusion trails.

1. INTRODUCTION

Solving the relationships between matrix foliations and those preserved in porphyroblasts in highly tectonized terrains is vital for the development of a complete understanding of the deformation and metamorphic history and has been highlighted in numerous studies (e.g. Zwart, 1960; Vernon, 1978, 1989; Williams, 1985; Williams, 1994; Bell and Johnson, 1989). However, a new quantitative technique including the analysis of inclusion trails in 3D (e.g. Bell et al. 2003 and references therein) has resulted in insights that challenge these earlier approaches. This technique enables the measurement of foliation intersection/inflection axes preserved within the porphyroblasts (FIAs) that have resulted from the overprinting of successively formed foliations (e.g. Bell et al., 1995) or the rotation of porphyroblasts (e.g. Rosenfeld, 1970). The FIA method is completely independent of whether porphyroblasts rotate or not and enables one to test rotation versus non-rotation models. If the porphyroblasts have rotated, the FIA represent the rotation axis and reveal the main direction of shearing or tectonic transport in an area (Rosenfeld, 1970; Schonefeld, 1979). If they have not rotated, the FIA lie perpendicular to the direction of bulk shortening that caused orogenesis (e.g. Bell et al., 1995).

Inclusion trails in porphyroblasts commonly provide information about early deformation events that are obliterated from the matrix.

Porphyroblasts are generally more competent than the matrix and preserve early formed foliations from the effects of younger deformation and metamorphism. In the matrix these foliations are destroyed or rotated towards the compositional layering due to reactivation and shearing along S_0 (Bell et al., 2003). Consequently, the matrix foliations provide information on only the very youngest deformation events (Bell et al., 2003, 2004). Measurement of FIAs and associated inclusion trails asymmetries can potentially supply useful information on the timing and mechanism of development of regional folds (e.g. Visser and Mancktelow, 1992; Bell and Chen, 2002). They also allow correlation of the orogenic history across large regions (Bell et al., 2004) and determination of P-T paths that have been obliterated elsewhere in the rock (Cihan, 2004b). These approaches have been applied in the Robertson River Metamorphics, Georgetown Inlier, which is an important metamorphic terrain that preserves a prolonged Proterozoic tectono-metamorphic history in northeast Australia.

2. GEOLOGICAL SETTING

The Georgetown Inlier contains one of the most extensive exposures of Precambrian rocks in north Queensland, Australia (Fig. 1). Other Precambrian Inliers the Coen, Yambo, Woolgar and Mount Isa are separated from the Georgetown Inlier and one another by Phanerozoic rocks, and have been related to one another based on deformational pattern and isotopic ages (Withnall, 1996; Black et al., 1998). This region (Fig. 2) contains intrusive rocks such as the Carboniferous-Permian rhyolite, dacite and microgranite, the Proterozoic Cobbolt Metadolerite and Digger Creek Granite, as well as the Proterozoic Robertson River Metamorphics (White, 1965). The latter rocks include six highly deformed units ranging from low metamorphic grade in the east to high in the west. These units have been named the Lane Creek and Corbett Formations, Thin Hill Quartzite Member, Dead Horse Metabasalt, Daniel Creek Formation and Mount Helpman Member and consist of highly deformed phyllite, pelitic schist, amphibolites, quartzites and rare calc-silicate gneiss (Withnall, 1985). Based on the absolute dating of intrusive rocks bounding the top and bottom of these units, the depositional age lies between 1695.8 ± 1.5 Ma and 1655 ± 2.2 Ma (Black et al., 1998). Previous studies (Black et al., 1979; Bell and Rubenach, 1983) proposed two major tectono-thermal events for the Proterozoic Georgetown Inlier. These were dated as D_1 1570 ± 20 Ma and D_2 1553 ± 3 Ma (Black et al., 1979; Black et al., 1998).

3. METHODS

Fieldwork involved the measurement of matrix foliations and lineations and the collection of sixty-eight oriented samples from the staurolite and sillimanite zones (Fig. 2) in which well-developed porphyroblasts are present. For each rock sample, six vertical thin sections were cut in 30° increments around the compass to determine the geometry of the structures in 3D (Cihan, 2004a). Inclusion trails within staurolite and garnet porphyroblasts were examined in each thin section together with matrix foliations. Extra thin sections at 10° intervals were cut between the two sections where the asymmetry (clockwise or anticlockwise) of curvature of single or overprinting inclusion trails switched. The FIA was determined as lying between the 10° sections where the asymmetry flips (e.g., Bell et al., 1995). FIAs were measured for each oriented rock sample relative to both geographic coordinates and the normal to the earth surface. Multiple FIA trends were distinguished in some samples using changes in trend from core to rim as well as from early garnet to younger staurolite porphyroblasts.

4. DEFORMATION EVENTS

Evidence for multiple deformations was observed microscopically and macroscopically. Structures associated with successive deformation events in the matrix were correlated from sample to sample and outcrop to outcrop using consistency in the orientation and the overprinting succession of folds, foliations and crenulations, and four deformations were differentiated. However, detailed analysis of microstructures trapped in porphyroblasts suggests that there were several deformation events that preceded the ones preserved in the matrix.

4.1. Deformation events recorded in the matrix

The deformation events preserved in the matrix consist of S_1, S_2, S_3 and S_4. S_0, in the porphyroblastic schists, is characterized by mm to cm scale compositional layering that has resulted from a changing percentage or grain size of the minerals. The stereonet plot of poles to S_0 suggests they are folded about an approximately NNW trending axes (Fig. 3) on a smaller scale than the larger scale ENE-WSW and E-W trending fold outlined by mappable compositional layering such as the Dead Horse Metabasalt and Cobbold Metadolerite (Fig. 2). The latter structures are west plunging and consist of a tight to moderate an overturned anticline and syncline (F_{1-2}; Figs. 1, 2). They seem to have been refolded around the N-S trending folds (F_3; Fig. 2). S_1 is preserved in zones where the dominant foliation is less intensely developed as a crenulated cleavage (Fig. 4). The dominant foliation represents S_1, which has been rotated towards the compositional layering because of reactivation of S_0 during D_2 (e.g., Bell et al., 2003). During this process, for instance, progressive dextral shearing acting along S_2 switched to sinistral shearing along the compositional layering and S_2 was destroyed whilst S_1 was decrenulated and rotated towards the compositional layering in the matrix (Fig. 5). Consequently, the dominant foliation is neither S_1 nor S_2. It is called $S_{1/2}$ from now on. $S_{1/2}$ is mainly E-W trending, north dipping, and folded around N-S trending axes. The intersection lineation ($L_{1/2}^0$) and the stretching lineation ($L_{1/2}^{1/2}$; Fig. 6) lies in the northern quadrants of the stereonet around N-S axis suggests these might have been distributed on the limbs of N-S folding. S_2 is preserved locally as a differentiated crenulation cleavage in porphyroblast strain shadows or as inclusion trails (Figs. 7, 8). N-S folds suggest that it might have been originally formed as a ~N-S trending steeply dipping foliation parallel to axial plane of these folds (Fig. 2). S_3 is a gently dipping weakly developed crenulation (Fig. 4) that locally intensifies to schistosity (Figs. 7, 8). The stereonet plot of poles suggests that S_3 is mainly NNW trending and NE dipping but it is also folded about an axis plunging towards the NNE (Fig. 9). This can be readily seen in outcrop to result from F_4 folds (Fig. 10). The intersection lineation, $L_3^{1/2}$, spreads in the NW and NE quadrants of the stereonet probably because of the folding of S_3 planes with low amplitudes. S_4 has developed parallel to the axial plane of these folds (Fig. 10) as the steeply dipping axial plane of crenulations (Figs. 7, 11) striking mainly towards the NNE (Fig. 9) and $L_4^{1/2}$ lies more consistently in the NE quadrant. The comparison of matrix foliations with respect to the limbs of the ENE-WSW and E-W trending folds (F_{1-2}) indicates that $S_{1/2}$ and S_3 are shallower and S_4 steeper than the limbs of these folds (Fig. 12). This suggests that these macro-scale folds were formed potentially much earlier than the currently visible matrix foliations. If this was the case, there must have been earlier deformations that have been obliterated from the matrix because of subsequent reactivation (Bell et al., 2003).

4.2. Deformation events recorded in porphyroblasts

Foliations that are no longer preserved within the matrix were trapped in garnet, staurolite, biotite, plagioclase and andalusite porphyroblasts as inclusion trails. Garnet and staurolite porphyroblasts were especially useful since they are abundant in most rock samples and contain well-preserved inclusion trails consisting of elongated quartz, ilmenite, epidote and rarely biotite. In garnet porphyroblasts these trails usually have sigmoidal geometries defining microfold hinges (Figs. 4, 7, 11), but some samples contain spiral (Fig. 13) and staircase shaped geometries (Fig. 8). The matrix foliation usually truncates the inclusions in garnet porphyroblasts, but it is also possible to observe textural discontinuities between core and rim inclusion trails (Figs. 4, 7, 8, 11, 13; Cihan, 2004). Staurolite porphyroblasts commonly contain garnet porphyroblasts as inclusions that are wrapped by inclusion trails that are sigmoidal (Fig. 4), straight with curvature at the rim that continues into the matrix (Fig. 11), or differentiated crenulations (Figs. 4, 14). The continuity of inclusions enables correlation between different growth phases of staurolite porphyroblasts versus development of the matrix foliations (Figs. 4, 11, 14). Based on these relationships, staurolite porphyroblasts overgrew successively formed S_1, S_2 and S_3 foliations that are usually observed as the hinges of crenulations or parallel to the matrix (Fig. 4, 11, 14). Pre-S_1 foliations could only be correlated and characterized based on FIAs since they are truncated by the matrix foliations.

A total of 112 FIAs were measured from successively formed foliations trapped as inclusion trails in garnet and staurolite porphyroblasts in the rock samples (Fig. 2). Four FIAs (Fig. 15) were determined (Cihan, 2004a) and these are tabulated with respect to individual samples in Table 1 and their trends are plotted on rose diagrams (Fig. 16).

The earliest formed FIA (FIA1) trends approximately ENE-WSW and is found in the cores of the garnet porphyroblasts. FIA2 occurs in an E-W orientation and in the core and the rims of garnet porphyroblasts. It is also present in some samples within staurolite porphyroblasts (Fig. 16a-b). The FIA3 is N-S trending and is equally distributed between porphyroblast phases as the dominant trend (Fig. 16a-b). FIA4, trending between 30° and 50°N, is only visible in staurolite porphyroblasts (Fig. 16c). FIA1 (ENE-WSW) and FIA2 (E-W) are described by pre-S_1 foliations whereas FIA3 (N-S) and FIA4 (NE-SW) are typified by S_{1-2} and S_{3-4} respectively, which are rotated towards main schistosity in the matrix. Significantly, the FIA1 and FIA2 trends are consistent with E-W folds (F_{1-2}), whereas FIA3 and FIA4 are consistent with N-S (F_3) and NE-SW (F_4) folds in a larger area (Fig. 1c) including the Robertson River Metamorphics (Fig. 2). These FIA trends appear to have formed are perpendicular to the tectonic transport direction, which changed from NNW-SSE to N-S to E-W and finally to NW-SE as orogenesis continued.

Although sigmoidal and spiral inclusion trails have been interpreted as having formed by porphyroblast rotation (e.g. Rosenfeld, 1970), the preservation of a succession of four different FIAs with consistent trends requires that the earlier formed porphyroblasts were not rotated during development of the younger formed ones (Cihan, 2004a). It is argued that if refolding of the early-formed FIA trends had occurred or the porphyroblasts had rotated, then a whole range of different FIAs should have been observed with erratic relative timing. Consequently, this data set suggests non-rotational porphyroblast growth over at least four different periods in the area investigated (Cihan, 2004a-b).

5. THE IMPLICATIONS OF INCLUSION TRAIL ASYMMETRIES AND FIA ORIENTATIONS FOR MACRO-SCALE FOLDING

The curvature of inclusion trails in porphyroblasts preserves the differentiation asymmetry of a crenulated cleavage as it passes into the younger differentiated crenulation cleavage (Bell et al., 2003). This asymmetry should change across any fold hinge that the porphyroblasts grew synchronously with. For example, for an antiform, the differentiation asymmetry that formed as the fold developed should switch from anticlockwise on the northern limb to clockwise on the central limb looking west with sinistral to dextral shear senses respectively, as shown in Fig. 17a. For a synform it is the opposite (Fig. 17a). Although matrix differentiation asymmetries are routinely obliterated by younger deformation, the history of differentiation asymmetry that can potentially be related to fold development is commonly trapped within porphyroblasts (Bell et al., 2003). Differentiation asymmetries are determined while examining sections sub-perpendicular to successive FIA sets. They can be presented as histograms (Fig. 17b) separated according to limb on the E-W trending folds. For FIA1 (ENE-WSW) the asymmetry is predominantly clockwise on the northern limbs of the two antiforms (A and C in Fig. 17b) for both sub-vertical and sub-horizontal events. These asymmetries are the opposite of those expected for these limbs of the folds and hence the fold did not form during the development of FIA1 (ENE-WSW). The asymmetries for FIA 2 (E-W) in the northernmost limb are mostly clockwise for predominantly sub-horizontal events. In the central limb, they are also predominantly clockwise for sub-horizontal foliation producing events. In the southernmost limb clockwise and anticlockwise asymmetries are equally present but clockwise asymmetries for sub-horizontal events prevail. This suggests more coaxial deformation on a broader scale during the formation of FIA2 (E-W). The asymmetries for FIA3 (N-S) are primarily clockwise throughout the folds and sub-horizontal foliation producing events are dominant. However, FIA3 (N-S) is perpendicular to axial plane of these folds and since the asymmetries are viewed in thin sections parallel to the axial plane of E-W folds, they show no relationship to the folds. These asymmetries can only be related to N-S folds in the study area. For FIA4 (NE-SW) the asymmetries accord with those expected for the northern and central limbs. However, they do not accord with those for the southern limb. This could be interpreted to suggest that the northern and central limbs formed during the development of FIA4. However, if this were the case, S_4 would not overprint both limbs of this fold with the same vergence asymmetry (Fig. 12). The distribution of porphyroblast growth during the development of FIA4 (NE-SW), as shown in Fig. 15d, suggests that reactivation may have resulted in less porphyroblast growth and/or deformation was not partitioned through the northern and central limbs. Likewise, FIA1 (ENE-WSW) and FIA2 (E-W) porphyroblasts might have been dissolved more, or grown less than the southern limb because of the higher degree of reactivation through this portion of the Robertson River Metamorphics.

6. DISCUSSION

6.1 Reactivation and rotation of early-formed foliations

During reactivation, progressive synthetic shearing occurring along anastomosing foliations parallel to the axial plane switches to antithetic shearing acting along the bedding or compositional layering (fig. 1 in Bell et al. 2003). This causes de-crenulation of the older foliation and results in destruction of the developing foliation and rotation of the earlier formed one into parallelism with the compositional layering (Bell, 1986). Because of this reason $S_{1/2}$ is commonly observed nearly parallel to compositional layering. It is possible to recognize the effects of reactivation at a range of scales. For example, in Fig. 5, S_1 inclusion trails preserve a D_2 crenulation hinge in a staurolite porphyroblast. S_1 decrenulated and rotated in the matrix and the D_2 Q-domain was destroyed. During this process, originally steep, differentiated S_2 cleavages were destroyed in the matrix. As a result, neither S_1 nor S_2 are preserved as sub-horizontal and sub-vertical foliations in the matrix. The degree of reactivation may change locally based on the competency-contrast differences from one limb of a fold to another or from one layer to another. For instance, it is not possible to see relict S_1 in the matrix in Fig. 5 but in Fig. 13 is still present; hence reactivation is a heterogeneous process (Bell et al, 1986). Apart from this, the inclusion trails trapped in non-rotated porphyroblasts suggests that it is a key process in erasing the pre-existing foliations from the matrix, otherwise it may not have been possible to recognize them unless one correlate matrix foliations with respect to axial planes of folds.

6.2 Porphyroblast growths and deformation partitioning

The character of non-rotational porphyroblasts, including ones containing mainly sigmoidal shaped inclusions (e.g. Figs. 4, 5, 7, 11) suggest that these preferentially grew on crenulation hinges. These sites have been defined as discrete zones of progressive shortening (e.g. Bell et al., 1986; Hayward, 1992; Williams, 1994), whereas the crenulation limbs have been described as progressive shearing domains (e.g. Bell et al. 2004) in which the dissolution of porphyroblasts occurs against mica minerals (e.g. Fig. 5). Growth of porphyroblasts in progressive shortening domains occurs by the aid of microfracturing providing the fluid access needed for the growth reaction to take place (Bell et al., 1986). Such microfracturing happens during the earliest stages of deformation prior to development of a pervasive pattern of deformation partitioning (Fig. 19a-d; e.g. Bell et al., 2004). The domains of deformation partitioning can shift through the rock as the deformation intensifies or due to younger deformations (Fig. 19e, f). During latter events, either porphyroblasts are completely dissolved, or growth may continue on different fabric, which are new progressive shortening sites formed because of the repartitioning of deformation (Fig. 19f).

The distribution of FIA trends in the study area (Fig. 15) demostrates the effect of reactivation and deformation partitioning on a macro-scale. The total frequency of porphyroblasts containing FIA1 (ENE-WSW) and FIA2

(E-W) are lesser than the FIA3 (N-S) porphyroblasts. These first two FIAs were formed by NNW-SSE and N-S shortening respectively but FIA3 (N-S) was formed by E-W shortening, which is orthogonal to the earlier directions. In addition, the P-T conditions during the formation of FIA1 (ENE-WSW) to FIA3 (N-S) indicate progressively increasing a clockwise P-T path (Cihan, 2004b). This suggests that deformation- partitioning sites should have changed drastically because of the intensity of deformation at the time of formation of FIA3 (N-S). Hence, earlier porphyroblasts were dissolved in significant numbers since they mainly remained in the shearing domains of partitioned deformation. However, an intense degree of reactivation prior to the E-W shortening event could not be excluded since tightening of the fold limbs might have taken up more shearing along compositional layering, especially in the northern and central limbs. Likewise, FIA4 (NE-SW) porphyroblasts formed during NW-SE shortening should have grown less in the northern and central limbs in comparison to the southern limb as readily seen in Fig. 15.

6.3 Evolution of folding events in relation to regional tectonic context

Bell et al. (1992, 1995, 1998) have argued that consistent successions of FIA trends suggest that the FIAs form orthogonal to the direction of bulk shortening and changes in their trend reflect changes in this direction causing polyphase deformations. The four FIAs shifted from ENE-WSW to

E-W to N-S and to NE-SW with time, and were contemporaneous with superimposed folding observed in Georgetown Inlier (Fig. 1c). The lack of relationship between the asymmetry of inclusion trails for each FIA set and the macroscopic fold limbs suggests that the onset of folding in the area occurred before the growth of porphyroblasts and extensive metamorphism, possibly just after the depositional age of 1655 ± 2.2 Ma (Black et al., 1998). Folding was amplified and inclined towards the south by dominance of north side up and top to south, suggested by the asymmetry associated with sub-vertical and sub-horizontal foliations for FIA1 (ENE-WSW) and FIA2 (E-W; Fig. 17). Large-scale S-type intrusions in the northern part of the study area (Fig. 1c) could have been emplaced into the orogen core at this time and produced clockwise asymmetries due to uplift of the core of the orogen during crustal thickening. Collapse and further orogenic cycles probably occurred several times as multiple foliations were formed around ENE-WSW and E-W FIA trends. During the development of FIA3 (N-S), these folds were refolded, since this period of the deformation involved E-W shortening. This is supported by the N-S trending folds, as well as the distribution of bedding (S_0) and main schistosity ($S_{1/2}$) that are folded around roughly N-S axes (Figs. 3, 6). Both E-W and N-S folds (Bell, 1983; Beardsmore et al., 1988; Page and Bell, 1986; Connors and Page, 1995; Rubenach and Barker, 1998) as well as E-W and N-S FIAs (Mares, 1998) have been reported from the Mt. Isa Inlier suggesting that these are regional events that affected the bulk of the northern part of the Australia. In addition to E-W and N-S folding there was another folding event late in the deformation history contemporaneous with the development of FIA4 trends. This NE-SW folding overprinted the E-W folds as indicated by the inclusion trail asymmetries and matrix foliations S_3 and S_4.

7. CONCLUSIONS

(1) Detailed microstructural analysis and outcrop studies indicate that multiple deformation events predate the matrix foliations as currently preserved. These events are preserved as inclusion trails within porphyroblasts and have been totally destroyed and rotated by the reactivation of the bedding in the matrix.

(2) A succession of four FIA sets oriented respectively ENE-WSW, E-W, N-S and NE-SW were developed in the Robertson River Metamorphics. This FIA succession suggests that the bulk shortening direction shifted through out deformation history from NNW-SSE to N-S to E-W and to NW-SE, which creates superimposed folding in a regional scale.

(3) The asymmetry of the inclusion trails examined on the limbs of the macro-scale folds showed that the folds predated porphyroblast growth and extensive metamorphism. This suggests that the onset of

the folding must have occurred earlier than previously suggested at around ca. 1570 Ma. It is proposed here that this event must have commenced just after the depositional age of ca. 1655 Ma.

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SECTION -C-

A NEW APPROACH TO THE ESTIMATION OF PRESSURE-TEMPERATURE-DEFORMATION PATHS USING P-T PSEUDOSECTIONS COMBINED WITH FIA DATA IN THE ROBERTSON RIVER METAMORPHICS, NORTHEAST AUSTRALIA

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ABSTRACT

Contouring X_{Mn}, X_{Fe} and X_{Ca} for garnet porphyroblasts and X_{An} for plagioclase inclusions in the MnNCKFMASH system provides an estimation of the P-T variation during the growth history of these porphyroblasts. Integration of this approach with relative timing constraints obtained from successions of Foliation Intersection/Inflection Axes within porphyroblasts (FIAs) reveals a more extensive P-T-D history than previously recognised in the Robertson River Metamorphics, Georgetown Inlier (NE Australia).

A succession of four FIA trends (ENE-WSW, E-W, N-S, NE-SW) reveals three extended periods of garnet porphyroblast growth and two of staurolite growth in this region. Chemically zoned garnet porphyroblasts were selected based on successively formed FIAs in their cores from four representative rock samples. The intersection of X_{Mn}, X_{Fe} and X_{Ca} isopleths for the cores of the successively generated garnet porphyroblasts plus that of X_{Ca} and X_{An} isopleths for garnet and plagioclase inclusions suggests that pressures progressively increased from 3.2 to 5.8 kb and at temperatures from 530° to 560° C. This accompanied an orogenic progression from NNW-SSE (O_1), N-S (O_2) to E-W (O_3) shortening. The maximum pressures and temperatures achieved, around 6-7 kb at 590°-610° C, were followed by decompression and retrograde metamorphism with andalusite replacing an early formed generation of staurolite. These rocks were overprinted by NW-

SE shortening (O_4) occurring synchronously with low pressure – high temperature metamorphism, resulting in the overprint of early minerals by sillimanite and prograde muscovite. This last event was attributed to widespread granitic intrusion in all NE Australian Craton at around 1550 Ma.

Keywords: Robertson River Metamorphics, Georgetown Inlier, MnNCKFMASH, P-T pseudosections, FIA

1. INTRODUCTION

The derivation of pressure-temperature (P-T) paths, which provide useful information for understanding mountain building processes, has classically been achieved by thermal modelling (England and Thompson, 1984), calculation of P-T points from mineral inclusions with garnet (St-Onge, 1987) and mineral zoning (Spear and Selverstone, 1983). Such approaches usually yield segments of the total P-T history because the early deformations and mineral assemblages are commonly erased from the matrix (Bell et al. 2003). These early segments can only be traced if they are trapped as suitable inclusions within chemically zoned porphyroblasts such as garnet (e.g. St-Onge, 1987), but this situation is relatively uncommon. Newly developed techniques, including the construction of P-T pseudosections and the analysis of Foliation Intersection Axes preserved within porphyroblasts (FIAs), provide the possibility of quantitatively combining metamorphic and structural information with relative time to determine a comprehensive pressure-temperature-deformation (P-T-D) path.

P-T pseudosections are phase diagrams that show the stability fields of a given set of mineral assemblages in P-T space for a specific bulk rock composition. They can be constructed using the programme called THERMOCALC (Powell and Holland, 1988; Powell et al., 1998) by determining all the possible mineral equilibria relationships in P-T space based on the system utilized, for example, KFMASH, MnKFMASH or MnNCKFMASH. The P-T conditions of compositionally zoned garnet growth can potentially be estimated because diffusion rates in this mineral are slow below upper amphibolite temperatures allowing it to retain the history of chemical evolution in major elements (e.g., Chakraborty and Ganguly, 1992). Garnet commonly preserves earlier foliations as inclusion trails that are erased from the matrix by reactivation of the bedding during subsequent events (e.g., Bell et al. 2003). Measurement of the FIAs defined by these trails enables successive periods of porphyroblast growth that predate the matrix foliations to be distinguished and correlated from sample to sample. This may enable portions of the P-T path to be determined and correlated from rock to rock, in spite of the heterogeneity of deformation and metamorphism. The present research combines P-T pseudosections, calculated using THERMOCALC, with a previously determined FIA dataset (Cihan, 2004), to determine the early metamorphic and deformation history and P-T-D path followed by the Proterozoic Robertson River Metamorphics in northeastern Australia.

2. GEOLOGIC BACKGROUND

The Robertson River Metamorphics lie within the Georgetown Inlier, one of the biggest Proterozoic terrains of northern Australia. This Inlier (Fig. 1) appears to be linked to similar inliers such as those at Coen, Yambo, Woolgar and Mt. Isa, based on isotopic ages and deformation patterns (e.g., Blewett and Black 1998; Betts et al*., 2002)*. These inliers formed as back arc basins within intermittently extending continental crust in the overriding plate of a subduction system between 1800 and 1670 Ma (e.g. Giles et al., 2002). There has been some controversy over whether the first deformation involved N-S shortening followed by younger deformation events accompanying E-W directed shortening (Bell, 1983) or thin-skinned westward thrusting followed by thick-skinned E-W shortening and the formation of N-S trending folds (MacCready et al., 1998; Betts et al*., 2002*).

The study area shown in Fig. 2 hosts a variety of metamorphic rocks ranging from greenschist in the west to upper amphibolite facies in the east. The folded chlorite-chloritoid (chl-cld), staurolite-andalusite (st-and), and sillimanite (sill) isograd boundaries, separate these facies from west to east

(Fig. 2). In the *chl-cld* zone, the only porphyroblastic mineral, chloritoid (Fig. 3a), disappears in the *st-and* zone, which mainly contains garnet, staurolite and andalusite porphyrobalsts (Fig. 3b-e). In the *sill* zone, the earlier porphyroblast generations have been partially replaced by sillimanite plus prograde muscovite (Fig. 3f). The rock units included in these zones consist of highly deformed phyllite, pelitic schist, amphibolite, quartzite and rare calc-silicate gneiss (Withnall, 1996). The sedimentary precursors of these rocks were deposited between 1700 and 1650 Ma (Black et al., 1998; Blewett and Black 1998). Proterozoic granites and Carboniferous-Permian dacite and microgranite intruded these highly deformed metamorphic rocks. The major structural features are overturned E-W trending antiforms and synform, which were refolded around N-S axes and then overprinted by NE-SW folds (Fig. 2; Cihan and Parsons, 2004). These structures are mimicked by early Proterozoic metadolerite and metabasalt (Fig. 1, 2). Bell and Rubenach (1983) proposed two major tectonothermal events; D_1 and widespread granite emplacement occurring in D_2 followed by younger weaker events D_3 through D6. The only metamorphic event recognized was a low pressure – high temperature one with a gently sloping P-T path (Reinhardt and Rubenach, 1989; Withnall, 1996). D_1 and D_2 were dated as 1570 ± 20 (Black et al., 1979) and 1550 Ma (Black and McCullock, 1990) respectively.

3. METHODS

3.1 Foliation intersection axes within porphyroblasts (FIA)

Foliation intersection axes preserved within porphyroblasts (FIAs), which resulted from the overprinting of successively formed foliations (e.g. Hayward, 1990; Bell et al., 1995) or the rotation of porphyroblasts (e.g. Rosenfeld, 1970) were measured. If porphyroblasts rotate, the FIA is a rotation axis and should lie perpendicular to the shearing direction (Rosenfeld, 1970; Schonefeld, 1979). If they do not rotate, the FIA lies perpendicular to the bulk shortening direction (e.g. Bell et al., 1995). Either way, the FIA trend should provide some indication of the direction of orogenic activity (Bell et al., 1995).

FIAs were measured by studying more than 500 thin sections cut from 68 spatially oriented rock samples as shown in Fig. 4a. For each rock sample, six vertical thin sections were cut in 30° increments around the compass (Fig. 4b) to determine the geometry of the structures in 3D. Inclusion trails within staurolite and garnet porphyroblasts were examined in each thin section. Extra thin sections at 10° intervals were cut between the two sections where the asymmetry (clockwise or anticlockwise) of curvature of single or overprinting inclusion trails switched. The FIA lies between the 10° sections where the asymmetry changes (Bell et al. 1995; Cihan, 2004).

3.2 Pseudosections and P-T calculations

Ten samples of pelitic schist were selected for determination of their bulk rock major element composition (Table 1). Four of these were chosen based on their succession of FIA trends for the preparation of P-T pseudosections. The others were used for average P-T calculation via the rims of garnet porphyroblasts and the matrix to check whether these were consistent through the area. Rock compositions were obtained by XRF analysis from 100-150 g of rock powder from each sample using the analytical facilities at James Cook University. P-T pseudosections using the MnO-Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (MnNCKFMASH) system were prepared with THERMOCALC 3.2.1 (Powell and Holland, 1988; Powell et al., 1998), using the dataset of Holland and Powel (1990) and mixing models after Tinkham et al. (2001). Isopleths of garnet compositions involving X_{Mn} (spessartine), X_{Ca} (grossular) and X_{Fe} (almandine), and X_{An} of plagioclase (anorthite) were contoured to obtain P-T conditions throughout the growth phases of the garnet porphyroblasts. For this purpose, electron microprobe analyses from the core, median (med1, med2) and rim of the porphyroblasts, plus the inclusions, were obtained and correlated with their X-ray maps. Point analyses were performed using EDS operating at 15 kv and 40 ms count times on a JxA-840A microprobe. X-ray maps were generated on a JxA-8200 electron microprobe and created by a 512x512 stage scan analysis made with both WDS and EDS spectrometers at 100nA beam current, 15kV and 80ms count times. Theoretically, the isopleths of garnet components at the core should intersect at a single point in P-T space since the bulk rock composition was available for nucleation at the beginning of growth (e.g., Vance and Holland, 1993; Vance and Mahar, 1998; Foster et al., 2002). Crystal fractionation or diffusion during the later phases of garnet growth results in disequilibrium with the bulk rock composition, causing these isopleth intersections to diverge from each other, making progressively larger triangles, towards the rim. If plagioclase is present as inclusions within garnet porphyroblast, the intersection of the grossular and anorthite isopleths can reduce this uncertainty, because the diffusion rate of Ca is negligible in comparison to other components (Florence and Spear, 1991). The rim P-T conditions were estimated utilizing the average P-T mode of THERMOCALC 3.2.1 (Powell and Holland, 1988; Powell and Holland, 1994), and the thermodynamic dataset of Holland and Powell (1998), resulting in more reproducible estimates of temperature and pressure than the conventional methods (e.g. Spear, 1993; Tinkham et al., 2001). For this purpose, microprobe analyses of garnet rims and adjacent matrix minerals were used. These data were integrated using the FIA data set to distinguish the different generations of porphyroblast growth.

4. STRUCTURAL ANALYSIS INCLUDING FIA DATA SET

Macroscopic and microscopic observations indicate multiple deformation events have occurred in the study area. Four successive foliations (S_1-S_4) were differentiated in the matrix based on the correlation from sample to sample and outcrop to outcrop using consistency in the orientation and the overprinting succession of folds, foliations and crenulations (Cihan and Parsons, 2004).

S_0 (bedding) is characterized by mm to cm scale layering within metasedimentary units and emphasized at the map scale by key units such as the Dead Horse Metabasalt and Cobbold Metadolerite (Fig. 2). Although S_0 lies parallel to the limbs of ENE-WSW and E-W trending regional folds at a smaller scale it is folded around NNW trending axes (Fig. 5). S_1 and S_2 are preserved where the dominant foliation is less intensely developed as a crenulation cleavage or within porphyroblasts as inclusion trails that are continuous with the matrix foliation (Fig. 3a, c, d). Since these two foliations were decrenulated and rotated towards the compositional layering in the matrix because of the reactivation of bedding (Cihan and Parsons, 2004), the dominant foliation ($S_{1/2}$) is neither S_1 nor S_2. $S_{1/2}$ is predominantly E-W striking and moderately dipping towards the north and folded around N-S axes (Fig. 5). S_3 is a gently dipping weakly developed crenulation axial plane that locally intensifies to schistosity. It mainly trends NNW trending and dips NE but is folded about an axis plunging towards the NNE. S_4, striking predominantly NE, developed parallel to the axial plane of these folds, as the steeply dipping axial plane of crenulations.

$S_{1/2}$ and S_3 are shallower and S_4 steeper than the limbs of ENE-WSW and E-W trending folds (Fig. 5; Cihan and Parsons, 2004). This suggests that these regional folds formed earlier than the deformations currently observed in the matrix. Foliations associated with this event have been erased from the matrix by reactivation of S_0 (Cihan, 2004; Cihan and Parsons, 2004).

Such early deformations, which are no longer preserved in the matrix, are trapped as inclusion trails within porphyroblasts (Cihan, 2004). Garnet porphyroblasts contain well-preserved inclusion trails defining these early deformations. In most rock samples, the inclusion trails within garnets are truncated by the matrix foliation. In staurolite the inclusion trails are continuous with the matrix foliations and reveal these porphyroblasts progressively overgrew S_1 through S_3.

Four FIA trends oriented ENE-WSW (FIA1), E-W (FIA2), N-S (FIA3) and NE-SW (FIA4) were distinguished (Fig. 6; Cihan, 2004) based on the changing trends from core to rim of garnet porphyroblasts and from garnet to staurolite porphyroblasts. FIA1 (ENE-WSW) was only recognised in garnet porphyroblasts (Fig. 6b). FIA2 (E-W) was found predominantly in garnet but occurred in staurolite in a few rock samples (Fig. 6b, c). FIA3 (N-S) was found in both garnet and staurolite porphyroblasts but FIA4 (NE-

SW) only occurred in the latter (Fig. 6b, c). This indicates four main periods of porphyroblast growth occurred in the region (Cihan, 2004).

5. PETROGRAPY AND MINERALOGY

With the exception of one rock sample from the *sill* zone, most rock samples examined for this research were collected from the *st-and* zone, and contain zoned garnet porphyroblasts suitable for quantitative analysis. These rock samples are highly aluminous, except for a few tabulated in Table 1, compared to the average pelite rock composition (e.g., Symmes & Ferry, 1991), but with Na_2O and CaO less than in an average pelite. Yet, apart from MgO the rock compositions are very similar to that of Vance & Mahar (1998; Table 1). Since the rock samples were modelled in a complex system, the conventional AFM number may be misleading (Vance & Mahar, 1998) with more aluminium used up by non-AFM phases. Consequently, the parameter A` reflecting the degree to which aluminium is used up by micas, plagioclase and the ferromagnesian minerals, was calculated. This parameter also mirrors the stability of staurolite and chloritoid (Fig. 7). For instance, chloritoid is not stable for sample mc39, which has a lower A` number than the rest of the samples (Table 1). In addition, the staurolite stability field broadens with increasing A` number. A` is 0.37 for sample mc55 with the staurolite bearing field covering more space than mc81 (A`=0.27), mc157 (A`=0.26) and mc39 (A`=0.12; Fig. 7).

All the rock samples from the *st-and* zone show more or less the same characteristics, with garnet surrounded by staurolite porphyroblasts and andalusite replacing the older staurolite generation (Fig. 3d-e) in some samples. Sample, mc152 from the *sill* zone, contains sillimanite, biotite and prograde muscovite overprinting or replacing garnet, staurolite and andalusite (Fig. 3f). Garnet in this sample shows no growth zoning (Fig. 8) and the Fe/(Fe+Mg) ratio increases from core to rim whereas in other samples it decreases (although some reversals exist in the median; e.g., samples mc39 and mc81; Table 2). The four rock samples, mc39, mc55, mc81 and mc157, from which the P-T pseudosections were constructed, are described in detail below.

5.1 Sample mc39

This rock contains the assemblage garnet, staurolite, biotite, muscovite and quartz with accessory quantities of zircon, epidote and ilmenite. Garnet porphyroblasts range from 0.5mm to 2mm in diameter, are strongly zoned (Fig. 9), and commonly contain inclusions of quartz, epidote, zircon and ilmenite defining complex inclusion trails that are discontinuous from core to rim to matrix. These discontinuities are consistent with compositional variations or anomalies within the garnets and variation in the FIA trend. This sample contains FIA1 (ENE-WSW) in the core and FIA2 (E-W) in the rim of garnet porphyroblasts. Based on probe analyses made at equal distances from core to rim, the Fe/(Fe+Mg) ratio for garnet increases suddenly from the core (0.93) to the median (med1; 0.96; Fig. 9, Table2) and then slightly declines towards the rim (0.91). This sudden increase might be attributable to re-equilibration with matrix biotite subsequent to garnet growth and is consistent with inclusion trails changing from gently dipping in the core to steeply dipping in the med1 (Fig. 9). Although the spessartine (X_{Mn}) composition monotonously decreases from core (12.12) to rim (2.66), the grossular (X_{Ca}) and pyrope (X_{Mg}) show anomalies at med1 (Table 2). For instance X_{Mg} decreases to 2.87 from core to med1 and then increases to 5.78 at the rim whereas X_{Ca} increases to med1 (18.58) and then decreases gradually to med2. Sharp variations also occur in these components from med2 to the rim as shown on the compositional maps (Fig. 9; Table2). Large staurolite grains (up to 20mm) surrounding garnet are unzoned with an Fe/(Fe+Mg) ratio of 0.879 (Table 3). These staurolite porphyroblasts contain FIA3 (N-S). Muscovite and biotite in the matrix lie parallel to the main foliation. The Fe/(Fe+Mg) ratio of biotite (0.615) and the K/(K+Na) ratio of the muscovite (0.841) are compatible with the whole rock composition (Table 1, 4).

5.2 Sample mc55

Sample mc55 contains plagioclase and andalusite in addition to the assemblage for sample mc39. The 2-2.5mm garnet porphyroblasts usually contain sigmoidal to spiral shaped inclusion trails. In some porphyroblasts the inclusion trails at the core are truncated by the rim but in others they are semi continuous. These trails become finer grained from core to rim. They are composed predominantly of quartz with epidote and muscovite present especially at the core. These textural differences are compatible with strong zoning patterns. This sample contains FIA2 (E-W) in garnet but FIA3 (N-S) and FIA4 (NE-SW) in staurolite. The Fe/(Fe+Mg) ratios of garnet gradually increase from core (0.92) to med2 (0.93) but decrease at the rim (0.91; Fig.10; Table 2). X_{Mn} decreases uniformly from core (16.30) to the rim (2.04) whereas X_{Ca} and X_{Mg} exhibit anomalies (Table 2). X_{Ca} increases from the core (14.96) to the med1 (15.84), then decreases slightly to med2 (15.48), and drops off suddenly at the rim (12.93). X_{Mg} increases subtly from the core (5.16) to the med2 (5.59) but jumps to a higher value at the rim. This is compatible with the anomalies observed for the X_{Ca} and the Fe/(Fe+Mg) ratio (Fig.10; Table 2). Two staurolite generations are present as indicated by the FIA trends with the earlier one replaced by andalusite, as shown in Fig. 3e. The younger generation overgrows the predominant foliation ($S_{1/2}$) in the matrix. Staurolite mainly contains quartz inclusions. The Fe/(Fe+Mg) ratio for staurolite is around 0.888 (Table 3). The phyllosilicates lie parallel to the dominant foliation in the matrix. The Fe/(Fe+Mg) ratio for biotite lies around 0.524 (Table 4). The K/(K+Na) ratio is 0.885 for matrix muscovite that contains significant Na compared with muscovite inclusions at the core of the garnet porphyroblasts (Table 4). Plagioclase is abundant in the matrix and shows zoning that becomes more albitic towards the rim. The anorthite (X_{An}) mole percent changes from An_{49} in the core to An_{42} in the rim as tabulated in Table 5.

5.3 Sample mc81

Sample 81 is composed mainly of biotite, muscovite, staurolite, garnet and plagioclase with ilmenite, zircon and monazite in accessory amounts. The garnet porphyroblasts are 1-2.5mm in size and characterized by sigmoidal inclusion trails, which are composed predominantly of quartz with biotite and chlorite in minor amounts in the core (Table 4). These inclusion trails define FIA3 (N-S). The Fe/(Fe+Mg) ratio of garnet shows subtle variations from core to median to rim (Fig. 11; Table 2). Like the other rock samples, X_{Mn} decreases gradually from the core to rim. Similar anomalies in X_{Ca} and X_{Mg} to those in the other rock samples occur in this sample. The staurolite porphyroblasts, which contain FIA4 (NE-SW), are unzoned and their Fe/(Fe+Mg) ratio lies around 0.844 (Table 3). The biotite compositions are similar in both inclusions and the matrix (Table 4) with Fe/(Fe+Mg) ratios of 0.485 and 0.454 respectively. Muscovite includes a significant amount of Na with a K/(K+Na) ratio around 0.839 (Table 4). As in the other rock samples, plagioclase is zoned and X_{An} varies from An_{43} in the core to An_{36} in the rim (Table 5). Plagioclase inclusions in the median of garnet have an An_{40} that is higher than the rim of plagioclase in the matrix.

5.4 Sample mc157

Sample mc157 is composed of the same mineral assemblages as mc81. Garnet porphyroblasts ranging from 1.5 to 3.5mm are strongly zoned in their major element chemistry (Fig. 12). They contain sigmoidal inclusion trails consisting of quartz and plagioclase as well as minor ilmenite, zircon and magnetite. These trails are truncated by the matrix schistosity, and textural discontinuities are commonly present between the core and the rim. The Fe/(Fe+Mg) ratio and X_{Mn} and X_{Ca} decrease from core to rim whereas X_{Mg} increases. FIA3 (N-S) is preserved within garnet porphyroblasts. However, staurolite porphyroblasts contain both FIA3 (N-S) and FIA4 (NE-SW) suggesting two generations of staurolite growth. Andalusite replaces the earlier generation similar to sample mc81. The Fe/(Fe+Mg) ratio of staurolite at 0.831 is less than in the other samples. However, the phyllosilicates are similar in composition to the other samples. Zoned plagioclase is abundant and common as inclusions. Plagioclase located within the core of garnet porphyroblasts has a much higher X_{An} (An_{42}) than in the rim (An_{36}; Table 4). This probably resulted from Ca being used by the garnet producing equilibrium with increasing pressure (e.g., Spear, 1993). X_{An} within matrix plagioclase (An_{30}) is less than that of the inclusions.

6. PSEUDOSECTIONS AND PHASE RELATIONS

P-T pseudosections (Fig. 7) were prepared from samples mc39, mc55, mc81 and mc157 assuming quartz and a pure H_2O fluid phase were present in excess. Cordierite was not observed in any of these rock samples but was included in the pseudosections for completeness (Fig. 7). Epidote group minerals including clinozoisite and zoisite are common but only the latter was modelled since it is the most stable based on the dataset of Holland and Powell (1998). Other epidote group minerals may have been stable, if the effect of Fe^{3+} could be modelled in the MnNCKFMASH system.

Biotite appears earlier than staurolite with increasing pressure and temperature in the mc39 pseudosection but not in the others (Fig. 7). However, in all cases, biotite exists over a wide range of temperatures in the lower pressure regimes whereas staurolite grows in a limited range between 3 and 10 kb at 500º-650º C. This range is most limited in the mc39 pseudosection, which does not involve chloritoid. The position of the plagioclase - out line shifts depending on the Na_2O and CaO contents and its stability increases with increasing temperature (Fig. 7). Although garnet exists over a wide range of P-T space in each pseudosection, a small difference in MnO content significantly changes the position of garnet-in equilibria (e.g. Mahar et al., 1997). For instance, for sample mc39, which contains garnet with FIA1 (ENE-WSW) in the core and FIA2 (E-W) in the rim (Fig.7a; Table1), this phase appears above 3 kb over the temperature range 500°-700°C whereas for the others it is also present at lower pressures together with cordierite and andalusite (Fig. 7b-d). Chloritoid was never observed in any garnet-bearing sample. It may have broken down to form quartz and/or staurolite prior to garnet growth (e.g. Rubie, 1998; Water & Lovegrove, 2002). This is possible according to the pseudosections where Chl+St+Plg+Ms±Cld is followed by the Chl+St+Grt+Plg+Ms field (Fig. 7b-d). However, staurolite inclusions were never observed within garnet porphyroblasts. In all samples, the garnet porphyroblasts formed before staurolite and have been dissolved to form mainly biotite. Tri-variant and quadri-variant fields consisting of Bt+St+Grt+Plg+Ms±Chl represent these reactions (Fig.7a-d). Since these are important indicators of the P-T evolution of garnet, they are contoured for X_{Mn}, X_{Ca}, X_{Fe} and the X_{An} for representative samples (Fig. 13).

The X_{Mn} contours in all examples initially lie parallel to the zero mode of garnet in the Chl-Grt-Plg-Ms-St or Bt fields (e.g. Fig. 13a-b). Contours of X_{Mn} in all samples studied show significant inflexions at the boundaries of the St-Grt-Plg-Ms-Chl-Bt field (Figs. 7, 13a-b). The X_{Ca} contours (Fig. 13a-b) have positive slopes and get steeper with increasing pressure but decrease in amount with increasing temperature. The X_{Fe} contours initially increase with temperature and are much steeper in chlorite bearing fields at intermediate pressures. However, in the chlorite free field they are unaffected by temperature. The inflexions at the biotite/staurolite -in and chlorite -out boundaries suggest garnet is resorbed to form biotite and/or staurolite with increasing temperature across these boundaries. This suggests that garnet stability is higher in the lower pressure parts of the Chl-Grt-Plg-Ms-St or Bt fields (Figs. 7-13) and this is confirmed by the contours for X_{Mn}, X_{Ca} and X_{Fe} intersecting at high angles, providing a P-T estimate for garnet core growth as will be discussed in the next section. The X_{An} contours decrease with increasing pressure in all samples indicating that plagioclase became more albitic with increasing pressure (e.g. Spear, 1993). This pressure dependence, and the intersection of X_{An} at high angles with X_{Ca} contours, provides support for the P-T estimation of garnet growth phases.

7. P-T ESTIMATION FROM THE INTERSECTION OF ISOPLETHS

Microprobe analysis of the core and median of garnet porphyroblasts (Table 2) in each sample reveals a tight intersection of the X_{Mn}, X_{Ca} and X_{Fe} isopleths in the Chl-Grt-Plg-Ms-Bt field for sample mc39 (Fig. 14a) and in the Chl-Grt-Plg-Ms-St field for mc55, mc81 and mc157 (Fig. 14b-d). These porphyroblasts nucleated at 3.4-4.8 kb and 520°-545° C for sample mc39 (FIA1; ENE-WSW; Fig. 14a), 4.2-5.4 kb and 540°-560° C for sample mc55 (FIA2; N-S; Fig. 14b), 5-5.8 kb and 545°-555° C for sample mc81 (FIA3; N-S; Fig. 14c) and finally 4.2-5.4 kb and 535°-555° C for sample mc157 (FIA3; N-S; Fig. 14d). Although the garnet in sample mc39 formed earlier than in the other samples (based on the FIA succession), similar P-T conditions were obtained when the uncertainties are taken into account (Fig. 14a,b). However, the isopleths intersect more tightly, suggesting the P-T conditions for the core in samples mc39 and mc81 are more reliable. Garnet porphyroblasts containing FIA1 (ENE-WSW) in sample mc39 show approximately 1 kb lower core pressures than sample mc81 (Fig. 14a-d), which contains FIA3 (N-S).

From core to rim, the decrease in X_{Mn} and X_{Ca} and increase in X_{Fe} (Fig. 13; Table 2) suggests a pressure and temperature rise after core growth and this is supported by the plagioclase inclusions becoming more albitic from core to median (Table 5). The intersection of isopleths for the medians of the garnet porphyroblasts indicates higher pressures and temperatures than the core but with greater uncertainty (Fig. 15a-d). However, the intersection of X_{Ca} and X_{An} isopleths provides more reliable estimations of P-T conditions where plagioclase is present (Fig. 15a, c).

7.1. Average P-T calculations

Although garnet porphyroblasts predate the matrix foliation in most samples, a P-T estimation of their rims (Table 2) was attempted using the composition of adjacent staurolite, biotite, muscovite and plagioclase (Table 3-5). The results were then compared with the pseudosections to see whether they are consistent with the likely fields in which rim growth may occur. The average P-T calculation for rim growth occurred around 6.8 ± 2.9 kb at 610 ± 80^{o} C for sample mc39 (Table 6; Fig. 15a). The uncertainty is large for this sample since there is no plagioclase in the calculation (Table 6). The absence of plagioclase does not mean that there was no plagioclase during garnet growth. Consequently, the likely fields on the pseudosection for garnet rim growth could have been those containing Chl+Bt±St+Grt±Plg+Ms (Fig. 15a). In sample mc55 (Fig. 15b) the P-T calculated for the rim is 6.8 ± 1.0 kb at 585 ± 25^{o} C (Table 6). The resulting uncertainty ellipse plots mainly in the Chl-St-Grt-Plg-Ms field lying above the intersection of isopleths and providing a better-constrained P-T estimation. For sample mc81, the uncertainty ellipse (Fig. 15c) suggests a P-T range of 7.5 ± 1.2 kb at 619 ± 51^{o} C (Table 6). This uncertainty can be reduced with the help of the pseudosection. Although the uncertainty ellipse overlaps the kyanite-sillimanite bearing fields, these minerals do not exist in the rock samples from the *st-and* zone. In addition, there is no trace of kyanite throughout the study area. Therefore no kyanite producing equilibrium occurred and the rims appear to have grown in the hatched area in Fig. 15c including Chl+Bt±St+Grt±Plg+Ms . For sample mc157, rim growth occurred about 7.2 ±1.0 kb at 600^{o} ± 24^{o} C (Table 6). The uncertainty ellipse overlaps with the intersection of X_{Ca} and X_{An} from the med2 (Fig.15d) suggesting a consistent estimation for the rim. The average P-T calculations from other rock samples tabulated in Table 6 overprint each other within their error limits and in all the cases mentioned above (Fig. 15e). Consequently, it can be suggested that garnet rim growth occurred around 6-7 kb at 590-610º C.

8. DERIVATION OF COMPLETE P-T PATH

In the previous section the segments of P-T path obtained through garnet porphyroblast growth occurred at FIA1 (ENE-WSW), FIA2 (E-W) and FIA3 (N-S; Fig. 15e). However, the textural relationships and FIA data potentially enable the rest of the P-T history to be interpreted. As portrayed in the pseudosections, garnet rim growth occurred in the Chl-St-Grt-Plg-Ms-Bt or St-Grt-Plg-Ms-Bt fields (Figs. 7, 15) and this is supported by the rare presence of biotite inclusions in the rims of some garnet porphyroblasts. This was followed by staurolite, which overgrew S_1 during the development of FIA3 (N-S). In most samples, andalusite replaced this staurolite generation (Fig. 3d, e) suggesting that the P-T path retrogressed into the St+And bearing fields (Fig. 7) around 3 kb at 530-560º C. However, the youngest staurolite generation (Fig. 3d, e), which includes $S_{1/2}$ and S_3 fabrics and formed around FIA4 (NE-SW), is also present as the product of the last metamorphic event in the samples collected from the *st-and* zone (Fig. 2). In the *sill* zone all staurolite generations and andalusite are replaced by prograde muscovite, and garnet is replaced by sillimanite and biotite suggesting increased temperature (Fig. 3f). These textural relationships entail a clockwise P-T loop followed by a path with increasing temperature (Fig. 16). In addition to this, the average P-T calculation for the rim growth of sample mc 152 from sillimanite isograd zone suggests 6.9 ± 1.3 kb at 655 ± 61° C (Fig. 15e; Table 6). Compared to the other samples, the uncertainty ellipse for this calculation occurr towards higher temperatures where mainly sillimanite bearing equilibria are present (Fig. 15e). Although garnet growth predates the matrix, it might have been re-equilibrated with the matrix minerals in the sillimanite isograd zone during subsequent HT metamorphism. A lack of zoning in garnet supports this assumption (Fig. 8) and the P-T calculation for this sample may reflect this re-equilibrium condition.

9. DISCUSSION

9.1. Outcomes from the MnNCKFMASH system

The KFMASH system has been commonly used to model pelitic rocks in petrogenetic grids (e.g. Spear, 1993), but, as highlighted by number of studies (e.g. Powel et al., 1998; Tinkham et al., 2001), may overestimate the stability of mineral assemblages, which can change at varying P-T conditions based on the rock composition. Pseudosections provide more useful tools for theoretically estimating the most stable mineral phases in a P-T space (e.g. Powell et al., 1998). Their accuracy depends on the complexity of mineral phases and the chemical system used. The

MnNCKFMASH system includes MnO, CaO and Na_2O that can profoundly affect the stability of common pelitic mineral phases such as garnet, plagioclase and zoisite or clinozoisite (Mahar et al., 1997; Vance and Holland, 1993; Vance and Mahar, 1998; Tinkam et al., 2001). Apart from this the grossular and anorthite content provide well-constrained metamorphic pressures enabling derivation of a quantitative P-T path. In the cases shown here, these phases were particularly important for determining the evolution of P-T conditions throughout the deformation and metamorphic history because they persist in the rock samples. The textural relationships observed appear consistent with the pseudosections except that garnet appears before staurolite, the opposite of what most pseudosections suggest (Figs. 7, 14). No FIA1 (ENE-WSW) is preserved in staurolite porphyroblasts and FIA2 (E-W) is uncommon in this phase (Fig. 6). Therefore, the earliest growth of staurolite occurred well after the growth of garnet began, which is not what is shown, especially by chloritoid bearing pseudosections (Figs. 7b-d, 14b-d). If staurolite grew before garnet, it was dissolved before younger staurolite growth occurred. Alternatively, the thermodynamic data or activity models are inadequate. Pattison et al. (1999) suggested that relics of staurolite from a previous higher-pressure metamorphism could remain as a metastable phase during lower-pressure metamorphism. In the examples herein, the Chl-St-And-Bt-Plg-Ms bearing equilibrium take place just below the And-Sill stability boundary in a small field around 3kb (Figs.

7, 14) and this is in agreement with the rock samples. This equilibrium would have occurred at higher pressures if the triple point of Holland and Powel (1990), Pattison (1992) or Pattison et al. (2002) were used. A problem still exists for Cld+St bearing fields that appear at lower pressures and temperatures than the field where garnet growth was estimated to occur (Figs. 7b-d, 14b-d). Perhaps the predicted staurolite-producing reactions were overstepped because of higher nucleation energy barriers (e.g., Water and Lovegrove, 2002) for this mineral. Chloritoid is not present in these samples but appears to have been a stable phase prior to St+Grt growth as it is present in lower grade rocks. As shown in Fig. 3a, chloritoid breaks down and leaves behind quartz rich pseudomorphs. In addition, both chloritoid and earlier staurolite include S_1 as inclusion trails (Fig. 3a, d). This suggests staurolite might overgrow these much later in the equilibrium history, because the breakdown of chloritoid to staurolite is very slow, or the nucleation energy barrier is higher than for the equilibrium producing garnet (e.g., Rubie, 1998; Water and Lovegrove, 2002). By the time this was completed, garnet porphyroblasts had grown and overstepping occurred. If this was the case, the staurolite-in equilibrium was overstepped by nearly 20^o between 510^o and 550^o C (Figs. 7, 14).

9.2. Fractionation or diffusion of garnet components

The complete bulk rock composition was available for the nucleation of garnets. However, as garnet growth continued, fractionation of some components into the core altered the bulk rock composition for subsequent garnet growth (e.g. Spear, 1988; Marmo et al., 2002). This means that during the growth of garnet, the bulk rock composition was continuously evolving, and the outermost rim of garnets attempted to equilibrate with it. Because of this, P-T conditions determined using the intersection of isopleths could generally only be estimated for core growth of garnet, which is in equilibrium with the bulk rock composition (e.g. Vance and Mahar, 1998). Although isopleth intersection sets from point analyses become increasingly poorly constrained from the core to rim of garnet porphyroblasts because of fractionation (e.g. Vance and Mahar, 1998; Evans, 2004), for the examples shown here, it appears that conditions for median growth could also be estimated (Fig. 15).

The overprinting effects of lower pressure - higher temperature metamorphism may have resulted in some later internal diffusion of the components in garnet. Diffusion increases exponentially with increasing temperature (e.g. Spear, 1993), and this is confirmed by sample mc152 from the *sill* zone in which garnet porphyroblasts were partly or completely homogenized (Fig.8). Even though growth zoning is generally very well preserved in all samples from the *st-and* zone (Figs. 9-12), slight effects due to this late metamorphic event may be present because X_{Fe} and X_{Mn} are thermally more sensitive than X_{Ca}. If such diffusion had occurred, and the isopleths moved towards higher temperature-pressure sites in P-T space, any effects must be minimal because the isopleths intersect quite tightly.

9.3. Implications of FIA dataset

FIA data has been published for the last decade from highly deformed metamorphic terrains. This data has been used to (1) resolve complex deformation histories preserved in porphyroblasts within a relatively simple matrix foliation and the different phases of porphyroblast growth (Bell and Hickey, 1999), (2) reveal extended histories of deformation and metamorphism preserved in porphyroblasts but destroyed in the matrix (e.g. Bell et al., 2003) and (3) suggest metamorphism is much more complex than previously conceived and to be significantly affected and controlled by the pattern of deformation partitioning (Bell et al., 2004).

In this study FIA data have enabled the distinction of three generations of garnet and two generations of staurolite formed at different P-T conditions. This dataset allow the differentiation of an early metamorphic history from a later low pressure-high temperature period of metamorphism. Apart from this, they provide valuable information about the deformation history. The successively formed FIA trends are consistent with the trends of superimposed folding observed not only in the study area (Fig. 2) but also across the central part of the Georgetown Inlier as shown in Fig. 1. This supports the suggestion that the four FIA trends reflect significant changes in regional scale tectonic movement directions during orogenesis from NNW-SSE to N-S to E-W to finally NW-SE. Porphyroblast growth occurred episodically throughout these four distinct periods in the bulk shortening history (Cihan, 2004; Cihan and Parsons, 2004).

9.4 P-T-D evolution and its significance for the regional geology

The Robertson River Subgroup (Fig. 2) contains metabasalt (Dead Horse) and intrusions (Cobbold Metadolerite) accumulated and emplaced synchronously with deposition of the sediments (Withnall, 1985). This extrusive and intrusive activity may be an expression of convective mantle upwelling produced during a regional intra-continental extensional regime at around 1695-1655 Ma (Black et al., 1998; Blewett and Black, 1998). Such a thermally weakened area could be subject to crustal thickening (e.g. Thompson et al., 2001) once shortening began. The early garnet porphyroblasts containing FIA1 (ENE-WSW) formed during NNW-SSE (O_1) shortening during the M_1 period of prograde metamorphism, followed by N-S shortening (O_2; Fig. 16). These first two events could have resulted from north-dipping subduction at around 1800-1610 Ma to the south of the northeast Australian basins that contain the Mt. Isa and Georgetown Inliers (Fig. 17a; Giles et al., 2002). Such a long-lived subduction system may have allowed the transmission of compressive stresses to intra-continental settings (Scott et al., 2000). These events were followed by E-W shortening (O_3) with increasing pressure in the study area as shown in Fig. 16. During O_3, resorption of garnet and growth of staurolite occurred and the highest pressures and temperatures were achieved (Fig. 16). O_3 may be associated with a west-dipping subduction system that potentially occurred between North America and Australia at around 1610-1500 Ma (e.g. Karlstrom et al., 2001; Betts et al., 2002). This is consistent with monazite age dates obtained from the Robertson River Metamorphics (Cihan et al., in review). This portion of the thickened crust then began to be exhumed accompanied by retrogressive metamorphism (M_2), during which andalusite replaced staurolite porphyroblasts that had formed in O_3. Finally, during NW-SE shortening (O_4), the progressive ascent of widespread S-type granitic magma, generated throughout orogenesis (O_1-O_4), reached the crustal level of the Robertson River rocks causing heat advection (e.g. Sandiford et al., 1991). This resulted in low pressure – high temperature metamorphism (M_3) in which the youngest generation of staurolite porphyroblasts and sillimanite were formed. This last metamorphic phase has been recognized as a major tectonothermal event in northeastern Australia including the Georgetown, Mt. Isa, Coen, Woolgar and Yambo Inliers at about 1550 Ma (e.g. Blewett et al., 1998).

10. CONCLUSIONS

1. FIA data provides a means of distinguishing and correlating different phases of porphyroblast growth, without which the relative timing of the deformation and metamorphic events could not be recognized.
2. Pseudosections utilizing the MnNCKFMASH system, combined with structural analysis using FIAs, allow one to obtain a complete P-T path in rocks where the bulk of the early history has been obliterated in the rock matrix.
3. Intracratonic rifting followed by E-W thin-skinned and thick-skinned shortening (ca. 1.60-1.50 Ma) tectonic models proposed for the northeast Australian craton (e.g. MacCready et al., 1998; Betts et al., 2002) are not supported by the data presented herein. Rather, thickening of the crust was accompanied by changes in the direction of bulk shortening from NNW-SSE to N-S and to E-W, followed by exhumation and NW-SE shortening between 1655 and 1550 Ma.

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SECTION -D-

ABSOLUTE TIME CONSTRAINTS ON DEFORMATION AND ACCOMPANYING METAMORPHISM FROM IN-SITU ELECTRON MICROPROBE DATING OF MONAZITE IN THE ROBERTSON RIVER METAMORPHICS, NE AUSTRALIA

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ABSTRACT

Electron microprobe dating of monazite confirms the relative timing of a succession of Foliation Intersection Axis trends in porphyroblasts (FIAs) and two extended periods of metamorphism, revealing a lengthy history of orogenesis in the Robertson River Metamorphics (NE Australia). A complete pressure-temperature-deformation-time (P-T-D-t) path has been deciphered involving an early clockwise P-T loop (not previously recognized in the NE Australian Craton) followed by an anticlockwise P-T trajectory. Metamorphism continued episodically throughout orogenesis changing from medium pressures and temperatures to lower pressures and higher temperatures after an intervening retrogressive phase.

Successive generations of fine-grained monazite (5μm-20μm) were identified using microstructure and FIA trends and then dated. The succession of four FIAs trending ENE-WSW (FIA1), E-W (FIA2), N-S (FIA3), NE-SW (FIA4) plus four matrix structures, S_1-S_4 reveal three periods of garnet and two of staurolite growth, and suggest that monazite grains were episodically grown, dissolved and regrown due to successive periods of foliation development or reactivation.

Isopleth thermobarometery, using P-T pseudosections in the MnNCKFMASH system for garnet porphyroblasts selected based on FIA trends in their core, reveal that the pressure increased progressively from 3-4kb at 530°-550°C to 6-7kb at 600°-620°C during medium pressure-temperature metamorphism. This was accompanied by changing bulk shortening directions from NNW-SSE to N-S to E-W (perpendicular to FIAs 1,2 and 3). The development of FIA1 and FIA2 occurred between ca.1655 (depositional age) and 1592 Ma. FIA3 developed over a 30 Ma period from 1592 Ma to 1559 Ma. Retrogressive metamorphism, decompression and exhumation occurred over a 10 Ma period. Further metamorphism accompanied regional granite intrusion around ca. 1550 Ma and generated lower pressure - higher temperature metamorphism during the development of FIA4 (NW-SE bulk shortening). This period of orogenesis possibly extended for another 30-50 Ma based on the ages obtained from the youngest foliations in the matrix. Correlation of these data with other NE Australian Proterozoic Inliers suggests that they were all once part of a single orogen that developed from 1655 to 1500 Ma.

Key words: Monazite, FIA, porphyroblasts, isopleth thermobarometry, Robertson River Metamorphics

1. INTRODUCTION

During orogenesis the effects of early deformations are commonly eradicated from the matrix by shearing along bedding, and this occurs through de-crenulation and rotation of early-formed foliations towards the compositional layering (Bell, 1986; Davis, 1995; Bell et al., 2003). The intensity of this phenomenon varies throughout the crust as a function of the scale of deformation partitioning (e.g. Bell et al., 2004; Cihan and Parsons, 2004). This causes correlation of foliations to become very difficult in intensely deformed metamorphic terranes (e.g. Williams, 1994; Stallard, 1998; Ham and Bell, 2004).

Early-formed foliations that once existed in the matrix of a rock can be trapped as inclusion trails in porphyroblasts. These inclusion trails can be correlated from outcrop to outcrop using Foliation Intersection Axes preserved within porphyroblasts (FIAs). Such data, measured over the last decade from several highly deformed terrains, has mainly been used to resolve complex deformation histories preserved in porphyroblasts within a relatively simple matrix foliation (e.g.; Bell et al., 1995; Aerden, 1995; Hickey and Bell, 2001; Bell et al., 2003), plus major tectonic transport directions in multiply deformed and metamorphosed terranes (e.g. Bell et al., 1995; Cihan, 2004a; Cihan and Parsons, 2004).

FIAs allow the successions of different phases of porphyroblast growth to be identified within the deformation history. Isopleth thermobarometry can then be used by constructing pseudosections in the MnNCKFMASH system for zoned garnet porphyroblasts (e.g. Vance and Mahar, 1998). By selecting samples based on the FIA trends in garnet cores, the P-T conditions under which each generation of these porphyroblasts first grew can be determined. P-T-D paths can then be obtained by correlating FIAs and different porphyroblast growth phases (e.g. Cihan, 2004b).

Although P-T-D paths provide a great deal of information that help the understanding of tectonic processes, absolute time (t) is essential for interpreting the complete significance of the different deformations and metamorphic textures, and the testing of correlations from one area to another. Great improvements have been made in refining geochronologic techniques. U-Pb isotopic dates can now be obtained from single crystals of zircon, monazite or titanite. These ages are sufficiently precise to be integrated with the P-T-D history. The presence of multiple deformations and relic textures can lead to ambiguities unless in-situ methods are used (Williams and Jercinovic, 2002; Bell and Welch, 2002; Foster et al., 2002). Monazite is ideal for this task (e.g. Williams and Jercinovic, 2002; Bell and Welch, 2002; Foster et al., 2002; Pyle et al., 2002). This LREE phosphate is very common in intermediate to high-grade metamorphic rocks and has the capability of being reset during each deformation (Bell and Welch, 2002; Williams and Jercinovic, 2002). Monazite contains significant amounts of U and Th, but negligible concentrations of common Pb (e.g. Parrish 1990; Montel et al., 1996) and can be dated chemically. It is also highly resistant to Pb loss through volume diffusion (Cherniak et al., 2004) and radiation-induced lattice damage (e.g. Seydoux-Guillaume 2002). Using the electron microprobe (EMP) to date monazites is very effective (e.g. Suzuki and

Adachi, 1991, 1994; Montel et al., 1996; Cocherie et al., 1998; Williams et al., 1999; Scherrer et al., 2000), and the small spatial resolution allows in-situ grains with various sizes (as low as 5 μm) to be analysed. Using this technique, the early deformations trapped within porphyroblasts as inclusion trails that define FIAs can be dated (e.g. Bell and Welch, 2002).

Incorporation of this dating method with a detailed structural and metamorphic investigation can give rise to an extended deformation and metamorphic history and the pressure-temperature-deformation-time (P-T-D-t) path that rocks have followed. This approach has been used to unravel the evolution of one of the key localities, the Robertson River Metamorphics of the Georgetown Inlier, NE Australia. The correlation of the age-dates obtained from this study with neighbouring Proterozoic terranes has provided striking insights into the deformation and metamorphic history of the North Australian Craton (NAC) that could not have been recognized previously.

2. GEOLOGIC BACKGROUND

The Robertson River Metamorphics are composed of the Robertson River Subgroup (White, 1962), which is the major subdivision of Proterozoic Georgetown Inlier. This inlier is separated from the others (Coen, Yambo, Dargalong, Woolgar and Mt. Isa; Fig. 1) by the Mesozoic sedimentary rocks of Carpentaria Basin. All these inliers appear to be linked to each other based on isotopic ages and deformation patterns (e.g. Blewett et al., 1998; Betts et al., 2002). It was suggested that these terranes were formed in an intra-continental back-arc setting far from a northward dipping, long-lived subduction system that lay to the south (1800-1670 Ma; Giles et al., 2002). In all these areas the first deformation and metamorphism has been attributed to a widespread tectono-thermal event characterized by voluminous volcanic rocks and emplacement of granites (1600-1500 Ma) that caused high-temperature and low-pressure metamorphism (Blewett et al., 1998; Betts et al., 2002).

The study area (Fig. 2) hosts a variety of metamorphic rocks ranging from greenschist in the west to upper amphibolite facies in the east. The folded isograd boundaries, chlorite-chloritoid (chl-cld), staurolite-andalusite (st-and), and sillimanite (sill), separate these facies from west to east (Fig. 2). In the *chl-cld* zone, chloritoid is the only porphyroblastic mineral, whereas the *st-and* zone is characterized by garnet, staurolite and andalusite porphyroblasts. In the *sill* zone, the earlier porphyroblast generations have been partially replaced by sillimanite plus prograde muscovite. The rock units included in these zones consist of phyllite, pelitic schist, amphibolite, quartzite and rare calc-silicate gneiss (Withnal, 1996), which were intruded by Proterozoic granites and Carboniferous-Permian dacite and microgranite. The sedimentary precursors of these highly deformed metamorphic rocks were deposited between 1700 and 1650 Ma (Black et al, 1998). A multitude of sills (the Dead Horse Metabasalt and the Cobbold Metadolerite; Fig. 2) were emplaced during deposition (Withnall, 1996), and they mimic the major structural features in the area (Cihan, 2004a; Cihan and Parsons, 2004). These structures are reclined antiforms and synform, which were refolded around N-S axes and then overprinted by NE-SW folding (Fig. 2; Cihan and Parsons, 2004). Bell and Rubenach (1983) proposed two main deformation events (D_1, D_2) with the latter associated with granite emplacement. These events were considered to be responsible for the tight to isoclinal folds and prograde metamorphism in the study area (Fig. 2). The only metamorphic event recognized was of low pressure – high temperature, with a gently sloping P-T path (Reinhardt and Rubenach, 1989; Withnall, 1996). D_1 and D_2 have been dated at 1570 ± 20 (Black *et al.*, 1979) and around 1550 Ma (Black and McCullock, 1990) respectively. However, the most recent study (Cihan, M., 2004b) proposed two major metamorphic events, the first of which involved early medium pressure-temperature regional metamorphism. The second was a low pressure-high temperature event.

3. METHODS

3.1. Foliation intersection axis within porphyroblasts (FIAs)

FIAs are the axes about which foliations preserved as inclusion trails in porphyroblasts curve and/or intersect (Hayward, 1990; Bell et al., 1995).

FIA trends can be considered as linear indicators of movement. If porphyroblasts rotate, it lies perpendicular to shearing direction (e.g. Rosenfeld, 1970) but if they do not, it is perpendicular to the bulk shortening direction (Bell et al., 1995). For the determination of FIAs, 68 spatially oriented rock samples were collected from the staurolite-andalusite and sillimanite isograd zones in a single rock unit called the Corbett Formation (Fig. 2). Firstly, horizontal rock slabs were cut from each rock sample (Fig. 3a). Six vertical thin sections, orthogonal to the rock slabs, were then cut with 30° increments around the compass (Fig. 3b). From these thin sections the asymmetry of clockwise or anticlockwise inclusion trails within porphyroblasts were noted. The FIAs lie where this asymmetry changes (Fig. 3b). This is analogous to an asymmetrically folded surface cut by two vertical planes lying to either side of the fold axis. When observed from one direction, where the eye is perpendicular to the page and the sections oblique to it, the fold asymmetry switches from being anticlockwise to clockwise, and the FIA lies parallel to the surface of the page as shown in Fig. 3c. Two more thin sections, 10° increments apart were cut between those 30° apart where the asymmetry flipped (Fig. 3b). The FIA is considered to lie halfway between the thin sections, where the asymmetry switches.

3.2. Isopleth thermobarometry and average P-T calculation

A representative rock sample (mc137) containing growth-zoned garnets was selected for construction of a pseudosection. The rock composition was obtained by XRF analysis from 150 g of rock powder using the analytical facilities at James Cook University. A P-T pseudosection using the MnNCKFMASH system was constructed with THERMOCALC 3.2.1 (Powell and Holland, 1988; Powell et al., 1998), using the dataset of Holland and Powel (1990) and mixing models after Tinkham et al. (2001). Quartz and muscovite were assumed to be in excess, water activity was assumed to be one and cordierite was omitted, as it is not present in rock sample. The limitations of this approach have been outlined in a number of studies (e.g. Vance and Mahar, 1998; Tinkham et al., 2001, Cihan, 2004b) and will not be discussed here.

The P-T conditions of compositionally zoned garnet growth can potentially be estimated by contouring the garnet end member compositions (e.g. Vance and Mahar, 1998; Cihan, 2004) of X_{Mn} (spessartine), X_{Ca} (grossular) and X_{Fe} (almandine). Theoretically, the isopleths of garnet components for the core of a garnet should intersect tightly on a single point in P-T space since the full bulk rock composition was available for nucleation at the beginning of the porphyroblast growth (e.g., Vance and Holland, 1993; Vance and Mahar, 1998). Away from the core, the isopleths intersect with greater uncertainty or may not intersect at all. This occurs because of the preferential fractionation of chemical components of garnet in to the core, resulting in an effective bulk composition change within the rock. If the extent of crystal fractionation is calculated, the composition of the unfractionated rock at any stage during garnet growth can be estimated (Evans, 2004). This method applies a Rayleigh fractionation model, based on measured Mn content of garnet, to generate composition volume curves (for garnet), and uses those curves to estimate the vectors of crystal fractionation. Details of this estimation can be found in Evans (2004). Using this method, the effective bulk compositions were estimated for each probe analysis referring to different stages of garnet growth, and then were utilized to calculate isopleths to obtain P-T values other than the core. These values were plotted on a P-T pseudosection with 2σ errors. For this purpose, electron microprobe analyses from the core to rim of a garnet were made. These analyses were performed using EDS operating at 15 kv and 40 ms count times on a JEOL JXA-840A microprobe. The rim P-T conditions were estimated utilizing the average P-T mode of THERMOCALC 3.2.1 (Powell and Holland, 1988; Powell and Holland, 1994). For this, the analyses of rim composition of a garnet and adjacent matrix minerals were used.

3.3. Electron microprobe dating of monazites

Monazite grains were identified from four rock samples using backscatter electron images (BSE). These were located in different fabrics in the matrix and within porphyroblasts and analysed using a JEOL JXA-8200 electron probe micro-analyser at the Advanced Analytical Centre (AAC) at James Cook University. Individual monazites were checked for compositional domains using BSE images. Each "domain" was treated separately and analysed at 15kV at 20nA for the "major elements" (Si, P, Ca, Y, La, Ce, Pr, Nd, Sm, Gd, Dy, and Th) as part of the matrix corrections outlined below. Pb, U, Th and Y concentrations for age calculations were obtained at 15kV and 200nA with counting times of 180 seconds on peak and 180 seconds (total) for the background. Spot sizes of 2μm and 1μm were used depending on the grain size and compositional heterogeneity. X-ray lines analysed for Pb, U, Th and Y were Pb Mα, U Mβ, Th Mα, and Y Lα, and the standards used were $PbSiO_3$, ThO_2, U, and YPO_4 respectively. Standards were analysed at 15kV and 20nA. Interference corrections of Th and Y on Pb Mα and Th on U Mβ were applied as in Scherrer et al. (2000) and Pyle et al. (2001). The phi-rho-z matrix correction program was used with Pb, U, Th, and Y concentrations combined with pre-determined (fixed) values of the other elements, assigned depending on the compositional domain that was being analysed.

3.3.1. Age calculation and statistical treatment

Ages were calculated for each point 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, by calculating the relative standard deviation of the net peak count rate of the unknown (as outlined in Scott et al., 1995 and Pyle et al., 2002), for each of the three elements ($\varepsilon_{unknown}$). This value is 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.,

$$\varepsilon_{k-ratio} = \sqrt{\varepsilon_{std}^2 + \varepsilon_{unknown}^2}$$

This is then assumed to be representative of the relative error in precision for the concentration of Pb, U, and Th. A comprehensive summary of this is given in Pyle et al. (2004, in press). The concentration errors were then propagated through the age equation, via the monte-carlo type simulation of Lisowiec (2004, in review). Once single point ages and errors are determined at a 2σ level, multiple points are combined and weighted averages are determined for individual monazites (or domains, if more than one stage of growth is identified).

4. MATRIX STRUCTURES AND FIA DATA

Previously four successive foliations (S_1-S_4) were differentiated in the matrix based on the correlation from sample to sample and outcrop to outcrop using consistency in the orientation and the overprinting succession of foliations and crenulations (Cihan and Parsons, 2004). S_0 is mm to cm scale layering in pelitic schists and represented by the Dead Horse Metabasalt and Cobbold Metadolerite at the map scale (Figs. 1, 2). Although it is parallel to the limbs of ENE-WSW to E-W trending regional folds (F_{1-2}), at a smaller scale it is folded around N-S trending axes. S_1 and S_2 are preserved where the dominant foliation is less intensely developed as a crenulation cleavage (Fig. 4a) or within porphyroblasts as inclusion trails that are continuous with the matrix foliation (Fig. 4a-d). Since these were decrenulated and rotated towards the compositional layering in the matrix because of the reactivation of bedding (Fig. 4e; Cihan, 2004a; Cihan and Parsons, 2004), the dominant foliation (schistosity; $S_{1/2}$) is neither S_1 nor S_2 (Fig. 4a-d). $S_{1/2}$ is predominantly E-W striking and folded around roughly N-S axes that are parallel to the axial plane of the F_3 folds at map scale (Fig. 2; Cihan and Parsons, 2004). S_3 is a weakly developed crenulation and locally intensifies towards schistosity (Fig. 4c-d). It is folded around NNE trending axis and S_4 has developed parallel to the axial plane of these folds (F_4), as the steeply dipping axial plane of crenulations (Fig. 4d).

Evidence for early deformations that are no longer preserved in the matrix, have been trapped as inclusion trails within porphyroblasts (Cihan, 2004a). Garnet porphyroblasts contain well-preserved inclusion trails defining these early deformations (Fig. 4a, c). The continuity of inclusions in staurolite porphyroblasts with the matrix enabled correlation between different phases of staurolite growth versus development of the matrix foliations (Fig. 4b,d, e). Based on these relationships, staurolite porphyroblasts progressively overgrew successively formed S_1-S_3. Pre-S_1 deformations could only be distinguished and correlated using the FIA dataset since the foliations defining them are not continuous with the matrix foliations.

A total of 112 FIA trends (Table 1) were measured from garnet and staurolite porphyroblasts. FIAs were differentiated based on the changing trend from core to rim and from garnet to staurolite porphyroblasts. Such changes provide quantitative relative timing for at least two different FIA trends because the core of the porphyroblast must have grown earlier than the rim and staurolite postdates garnet growth in the study area (Cihan, 2004a). This allows different generations of porphyroblast growth to be identified that were otherwise indistinguishable.

Four FIA trends, ENE-WSW (FIA1), E-W (FIA2), N-S (FIA3) and NE-SW (FIA4) were differentiated (Fig. 5; Cihan, 2004a). FIA1 was only identified within the core of garnet porphyroblasts (Fig. 5b). FIA2 was measured predominantly in the core and rim of garnets, and also staurolite in a few rock samples (Fig. 5b, c). FIA3 was recognized in both porphyroblasts (Fig. 5b, c) but FIA4 only in staurolite (Fig. 5c). The last two FIA sets measured within staurolite porphyroblasts are defined by foliations that are continuous with the matrix foliations since these porphyroblasts overgrew S_1, S_2, $S_{1/2}$ and S_3.

5. SAMPLE DESCRIPTIONS

Four representative rock samples were selected for detailed determination of mineral content, microstructure and FIAs. Such data is vital for determining the link between deformation, metamorphism and monazite age dates. Samples mc152 and mc135 come from the sillimanite isograd zone, but mc137 and mc133 are from the staurolite-andalusite zone. These rock samples are all very aluminous (Table 2). The MnO content is significantly higher in mc135 (0.15 wt. %) compared to the other rock samples, and the CaO/(CaO+Na_2O) ratio is higher in mc152 and mc135 compared to samples mc137 and mc133 (Table 2).

5.1. Samples mc152 and mc135

These rock samples (Fig. 2) contain the assemblage of sillimanite, staurolite, garnet, biotite, andalusite, muscovite and quartz with accessory apatite, zircon, ilmenite and monazite. The garnet porphyroblasts contain sigmoidal, spiral and staircase type inclusion trails that are truncated by the matrix and composed of predominantly quartz and occasional biotite, chlorite, muscovite and monazite. Garnet (1.5-2 mm in size) has been partially resorbed by biotite and sillimanite and shows a lack of growth zoning (Fig. 6a). Staurolite and andalusite are present as relic minerals in the matrix that have been moderately and/or completely replaced by sillimanite, biotite and prograde muscovite (Fig. 4a, f). Both mc152 and mc135 contain biotite porphyroblasts.

In sample mc152, garnet contains FIA1 (ENE-WSW) in the core and FIA2 (E-W) in the rim. FIA3 (N-S) and FIA4 (NE-SW) are present in staurolite porphyroblasts. In the matrix, the schistosity is S_3 (Fig. 4), S_4 is present as a weak steep crenulation. S_1 and S_2 can only be observed within staurolite porphyroblasts. On the other hand, in sample mc135, garnet contains FIA2 (E-W), and relic S_1 in the hinges of a crenulation cleavage in the matrix. The dominant foliation is $S_{1/2}$ that is reactivated in the matrix (Fig. 4a).

5.2. Samples mc137 and mc133

These rock samples (Fig. 2) are composed of garnet, biotite, staurolite, muscovite and quartz with accessory monazite, zircon and apatite. Mc137 also contains andalusite that replaces staurolite porphyroblasts (Fig. 4b). Garnet porphyroblasts, 1-1.5 mm in diameter, preserve well-developed major element zonation in both samples (Fig. 6b). The inclusion trails are predominantly defined by quartz and rare mica inclusions. They have sigmoidal shapes and are semi-continuous or truncated by the rim inclusions and matrix foliations. Garnet is locally surrounded by staurolite that contains quartz rich sigmoidal inclusion trails that are continuous with the dominant matrix foliation.

Mc137 contains FIA2 (E-W) in garnet and FIA3 (N-S) in staurolite. Mc133 has FIA3 (N-S) and FIA4 (NE-SW) in garnet and staurolite porphyroblasts respectively. In both rock samples the dominant foliation is $S_{1/2}$ and staurolite porphyroblasts overgrew S_1 in mc137 (Fig. 4b) but $S_{1/2}$ in mc133 (Fig. 4e).

6. ISOPLETH THERMOBAROMETRY AND AVERAGE P-T

An MnNCKFMASH pseudosection displays the mineral stability fields for the bulk rock composition of sample mc137 (Fig.7). The fields are labelled with stable mineral assemblages and darker shades are used for higher variance fields. The pseudosection indicates that biotite appears earlier than staurolite and garnet at lower pressures. However, at medium pressures staurolite occurs first with chloritoid and/or chlorite prior to garnet and biotite (Fig. 7). The predicted stability fields on the pseudosection after the garnet-in line show consistency with the observed textural relationships showing a sequence of mineral growth from garnet to staurolite to biotite and finally andalusite.

The calculated isopleths from the micro-probe analysis of a garnet porphyroblast suggests typical growth zoning (Fig. 6b), with X_{Mn} decreasing gradually from core to rim while X_{Fe} increases. The X_{Ca} and X_{Mg} isopleths however, show anomalies from core to rim. X_{Ca} subtly increases towards the rim and suddenly drops at the core-rim boundary, whereas X_{Mg}

first decreases slightly, then increases before a sharp drop at the rim. The Fe/(Fe+Mg) ratio appears stable outward from the core, with a slight increase at the rim.

The intersection of the X_{Mn}, X_{Ca} and X_{Fe} isopleths, calculated from the core analysis (gr1) suggests the garnet nucleated at 5.2-5.6 kb, 555-560°C in the chl-st-g-pl stability field (Fig. 7). The plot of the isopleth set from the median analysis of the same garnet, indicates a progressive increase in pressure during this stage of the growth, which apparently occurred at 6.0-6.5 kb, 560-565°C (Fig. 7). For clarity, the intersections of isopleth sets between these stages were not plotted. The isopleths calculated from rim analyses did not provide constructive estimations, since there is too much uncertainty on the X_{Fe} isopleth (with 2σ errors) on the pseudosections. This is possibly due to the Fe-Mg exchange reactions between the rim and the matrix phases, which resulted in unreasonable isopleth values for P-T estimation.

Although garnet predates the matrix minerals, the P-T estimation with average P-T mode of THERMOCALC was attempted using the composition of adjacent staurolite plus biotite, muscovite and plagioclase located in its strain shadow. This estimation suggests that the rim growth occurred at 7.3 ± 1.1kb, 616 ± 50°C for the sample mc137 (Table 3, Fig. 7). The same calculations for mc133 and mc152 resulted in 7.3 ± 1.1kb, 620 ± 48°C and 6.9 ± 1.3kb, 655 ± 61°C (Table 3) respectively. When these estimations are compared with the mineral stability fields on the pseudosections, more constrained results can be obtained. For instance, the error ellipse in Fig. 7 overlaps the kyanite bearing fields. However, the mc137 does not contain kyanite mineral. Indeed, nor do any other rock samples in the study area. Therefore, the rim should have grown in hatched area shown in Fig. 7 at around 6-7kb, 600^{o}C.

7. MONAZITE AGES

Monazite grains were commonly detected in the matrix and staurolite porphyroblasts, but only rarely as inclusions within garnet. They generally tended to have patchy or complex zoning patterns, although several homogenous and rare concentric zoned grains were found. Grain size varied from 5μm to 20μm. Weighted average ages were obtained from the total analyses on each grain/domain and then compared to other monazite grains, firstly based on the structures in which they lie within the sample and then from sample to sample.

In rock sample mc152, nine monazite grains were analysed. These grains were mainly located on $S_{1/2}$ and S_3 structures (Fig. 4d) except for two that lay within staurolite and biotite porphyroblasts preserving S_1 and $S_{1/2}$ as inclusion trails. The weighted average of the ages from each grain varies between nearly 1507 and 1606 Ma. The youngest ages, which are 1507± 10 Ma and 1512 ± 15 Ma (Table 4), were obtained from the grains located on S_3.

The ages derived from the grains sitting on $S_{1/2}$ lay between 1554 and 1584 Ma (Fig.8). The grains within staurolite (characterized by FIA3 (N-S)) and biotite porphyroblasts give ages of 1589 ± 18 Ma and 1606 ± 23 Ma respectively (Table 4). Some of these grains appear to have more than one age domain, which is probably related to the compositional domains detected from the BSE images (e.g. Fig. 8a, where two domains can be identified). Two single point ages from the darker area of this monazite (152m2) yield ages of 1630 and 1634 Ma, compared to ages of 1605, 1603 and 1572 Ma from the lighter region. However due to a lack of data, the two domains cannot be statistically distinguished from each other and a weighted average was still used to represent the age of the grain. This process was followed in all similar cases. For all nine monazite grains combined, it becomes clear that there are three resolvable monazite ages (1589.8 ± 9.5, 1559 ± 7.9 and 1508.5 ± 8.3 Ma) within this rock sample (Fig. 9).

In sample mc135 six monazite grains were analysed. Except for the one grain in the rim of a FIA2 (E-W) garnet, the rest were found on S_1 and $S_{1/2}$ in the matrix. The weighted average age of the monazite from the rim of a garnet is 1592 ± 24 Ma (Table 4). This is the only grain that shows concentric zoning (Fig. 10a). The darker areas in the BSE image at the core appear older (e.g. 1627 and 1649 Ma) in comparison to lighter areas, but were unable to be resolved further. Three analyses (7, 8, 9 in Fig. 10a see also Table 4) from this monazite yield younger ages, which may also imply some additional growth. The grains located on S_1 and $S_{1/2}$ show significant differences such that the two grains on S_1 give 1601 ± 31 and 1596 ± 13 Ma whereas the ones located on $S_{1/2}$ provide the ages of 1560 ± 16 and 1566 ± 15 Ma (Table 4). When all individual grains are examined, two distinct age populations can be identified as 1595.8 ± 11 and 1557.2 ± 9.2 Ma (Fig. 11).

Seven grains (five from within staurolite porphyroblasts and two from the matrix) were analysed from sample mc137. The weighted average ages of these vary between 1561 and 1605 Ma (Table 4). More specifically, the grains found within FIA3 (N-S) staurolite porphyroblasts, overgrowing S_1 give a weighted average age of 1569 ± 13 Ma (Fig. 12). The monazite grains located on $S_{1/2}$ in the matrix give 1570 ± 21 and 1599 ± 25 Ma (Fig. 12; Table 4). As observed in the previous two rock samples, different age domains appear within individual grains. However, multiple ages for these grains have not been statistically distinguishable. They seem to designate the same age population within their errors, that is 1574 ± 16 Ma (Fig. 13a-b).

In sample mc133 two grains were analysed within FIA4 (NE-SW) staurolite porphyroblasts (Fig. 14a), and three from $S_{1/2}$ in the matrix (Fig. 14b). Since the porphyroblasts overgrew $S_{1/2}$, all these grains are interpreted to be from the same fabric. The weighted average age of these are relatively well constrained (in comparison to the other rock samples) at 1524.1 ± 6.3 Ma (Fig. 15).

8. INTERPRETATION

8.1. Deformation and metamorphism

Four successively formed FIA trends (Fig. 5) indicate that deformation occurred in four periods with changing bulk shortening directions from NNW-SSE to N-S to E-W and to NW-SE. These lie orthogonal to the FIA trends (Cihan, 2004a), which are consistent with the general trends of superimposed folding not only within the study area (Fig. 2) but also in the central part of the Georgetown Inlier (Fig. 1). This suggests porphyroblast growth occurred over at least four different periods with three different garnet and two predominant generations of staurolite growth. During porphyroblast growth between FIA1 and FIA3 (from NNW-SSE to E-W bulk shortening), the pressure increased progressively from ~3-4 to ~6-7 kb (Cihan, 2004b). This is supported by isopleth thermobarometery applied to sample mc137. This combined data shows that pressure increased during the growth of FIA2 (E-W) garnet (Fig. 7), which nucleated in N-S bulk shortening. This increase must have continued through to the time of FIA3 (N-S) staurolite growth (E-W bulk shortening), which occurred soon after garnet grew (Figs. 4, 7). Hence, the peak of this metamorphic event must have been reached by the end of E-W bulk shortening at about 6-7 kb, 600-620°C. This staurolite generation was then replaced by andalusite (Fig. 4b, c, f), a reaction that occurred at around 3kb, 510-550°C (Fig. 7) suggesting retrogressive metamorphism, decompression and exhumation at this crustal level of the Robertson River Metamorphics. This was then followed by the youngest FIA4 (NE-SW) staurolite growth. As portrayed from the rock samples mc152 and mc135, sillimanite and prograde muscovite overprinted early porphyroblast generations (Fig. 4a, c, f). Unlike the same generation of garnet porphyroblasts in the staurolite-andalusite zone, FIA1 (ENE-WSW) and FIA2 (E-W) garnets from these rocks are resorbed and show a lack of zoning (Fig. 6b), which indicates a diffusion effect related to temperature increase. Therefore, the Robertson River Metamorphics have recorded two major tectonothermal events, the first of which involved early medium pressure-temperature metamorphism, followed by later high temperature-low pressure metamorphism (Cihan, 2004b).

8.2. Timing deformation and metamorphic events

Twenty-seven monazite grains analysed from the matrix and within staurolite porphyroblasts present a variety of ages. The majority of the monazite grains in the matrix include different domains possibly inherited from earlier deformations. However, when they are examined with respect to porphyroblasts and FIA trends, these different age domains can be constrained effectively. For instance, the grains found in FIA3 (N-S) staurolite porphyroblasts give a weighted average age of 1576 ± 17 Ma, whereas the ones in FIA4 (NE-SW) staurolite porphyroblasts are 1526 ±

15Ma, which reveals appoximately 50 Ma difference between the two. If this is the case, the end of E-W shortening and early medium pressure-temperature metamorphism was around or slightly younger than 1576 Ma. The last metamorphic event and accompanying NW-SE shortening, on the other hand, occurred around 1526 Ma. The only monazite grain from the rim of a FIA2 (E-W) garnet porphyroblast is 1592 ± 24Ma in age (Fig. 10a). Although it could be older at the core, this age was interpreted as representing the time boundary between N-S and E-W shortening events, since the rim should have grown sometime between these two shortening periods. However, it is possible to obtain slightly older or younger ages from the grains lying parallel to S_1 and $S_{1/2}$ structures in the matrix. Because of this reason I pooled all the age data presented in Table 4 and distinguished three distinct age populations as 1592.2 ± 6.9, 1559.3 ± 6.3 and 1518 ± 5.6 Ma (Fig. 16). This suggests that the E-W shortening period occurred over 30 Ma between the first two age populations and the peak of the early metamorphic event took place at around 1559 ± 6.3 Ma. The second metamorphic event (lower pressure-higher temperature) was previously recognized as the only major tectonothermal event and ascribed to the Forsayth Granite that intruded around 1550 Ma (e.g. Bell and Rubenach, 1983; Withnall et al., 1996) in the Georgetown Inlier. This means that the Georgetown Inlier, including the Robertson River Metamorphics was exhumed to lower crustal levels in appoximately 10 Ma. The youngest age population should reflect this second metamorphic event and this agrees with the 1512 ± 15 Ma and 1507 ± 10 Ma (Table 4) ages, obtained from the youngest foliation, S_3, in the matrix.

9. DISCUSSION AND CONCLUSIONS

9.1. Monazite growth and resetting under the control of deformation partitioning plus reactivation

Although the petrogenesis of monazite is still under debate, there is a general consensus that its growth depends on the bulk composition (e.g. Foster and Parrish, 2003) and the stability fields of its precursors, such as allanite (Overstreet, 1967; Ferry, 2000), titanite (Pan, 1997) and Ce-poor LREE phosphates (Kingsbury et al. 1993). Several studies have attempted to locate the monazite isograd and have suggested that it is coincident with the staurolite isograd (Smith and Barreirro, 1990), the kyanite or andalusite isograds (Ferry, 2000) or the garnet isograd (Harrison et al., 1995). Apart from this, it has been documented that the P-T of the first appearance of the metamorphic monazite can vary from 4kb and 500ºC up to 7kb and 650ºC (Foster and Parrish, 2003).

In the study area monazite grains were found abundantly in the matrix of the rock samples collected from both the staurolite-andalusite and sillimanite isograds. In the staurolite-andalusite isograd they are only present within staurolite, whereas in the sillimanite isograd they exist both in staurolite and garnet porphyroblasts. For instance, in sample mc137, staurolite porphyroblasts occlude monazite grains and since staurolite growth occurred just after garnet, these monazites potentially formed at around 7kb and 570-600°C (Fig. 7). Both mc137 and mc135 are from the same stratigraphic unit (Corbett Formation) and contain FIA2 (E-W) in garnet porphyroblasts. This means that they presumably grew around the same time at similar P-T conditions during the first metamorphic event. Since mc135 includes monazite in garnet porphyroblasts, the P-T of its first appearance must be around 5kb and 550°C (Fig. 7).

Although monazite grains have the ability to reset in each deformation event, they have preserved evidence of early deformation events in their compositional domains. They provided consistent ages for S_1 rather than $S_{1/2}$, which hosts a variety of ages not only from one rock sample to another but also within individual rock samples. $S_{1/2}$ is the dominant schistosity, formed because of the rotation and decrenulation of early foliations and overprinted by the younger deformations such as S_3 and S_4. Therefore, deformation partitioning and reactivation (Fig. 17; Bell, 1986; Davis, 1995; Bell et al., 2004) have played an active role in the resetting of monazite grains.

Deformation heterogeneously partitions throughout the crust based on competency-contrast differences. Consequently, the impact of deformation varies from one area to another or even from layer to layer in a smaller scale. This phenomenon can best be understood at the scale of microstructures. Bell (1981) introduced the role of the partitioning of deformation into discreet zones of progressive shearing and shortening, that are represented by the limb and hinge of a crenulation respectively (Fig. 17). Porphyroblasts preferentially nucleate and grow in the zones of progressive shortening such as crenulation hinges (Fig. 4), and dissolve against mica minerals on the crenulation limbs described as the zones of shearing (Bell and Hayward, 1991; Williams, 1994; Aerden, 1995; Bell et al., 2004; Cihan and Parsons, 2004). These domains can shift and/or switch over through the rock as the deformation intensifies or as a result of younger deformations (e.g. Cihan and Parsons, 2004).

S_1 is preserved as the hinges of a crenulation and is overgrown by FIA3 (N-S) staurolite porphyroblasts. S_2 was the limb of a crenulation before it was destroyed and rotated into $S_{1/2}$ during the reactivation process shown in Fig. 4d-e. Reactivation takes place when progressive synthetic shearing, occurring along newly formed structures switches into antithetic shearing along the bedding or compositional layering (Figs. 4e, 17; Bell et al., 2003). This causes decrenulation of the older foliation and rotation of the earlier formed one into parallelism with the compositional layering (Fig. 17). Because of this, $S_{1/2}$ commonly lies sub parallel to the compositional layering. Relic S_1 and $S_{1/2}$ can be observed in samples mc152, mc135 and mc137, in which the monazite grains located in $S_{1/2}$ provided weighted average ages between 1600 and 1550 Ma. However, the only structure present in mc133 is $S_{1/2}$ and the monazite ages are around 1524 Ma, which is consistent with the youngest ages obtained from S_3 in sample mc152. Since relic S_1 and S_2 were entirely destroyed in the matrix, this rock sample was sheared along $S_{1/2}$ during the second metamorphic event. Deformation partitioning plus reactivation will reset monazite grains in the matrix heterogeneously during subsequent deformation and metamorphism.

9.2. Implications for regional tectonic history of Northeast Australian Craton

The Northeast Australian Proterozoic basins (the Mt Isa, Georgetown, Coen, Yambo, Dargalong and Woolgar; Fig. 1) formed during rift related subsidence or during postrift thermal subsidence far away from the north-dipping subduction zone along the southern margin of North Australian Craton between 1670 and 1650 Ma (O'Deal et al., 1997; Betts et al., 1998). Betts et al. (2002) suggested that this basin development was interrupted by Mesoproterozoic orogenesis, which commenced along the eastern margin of the Australian Proterozoic continent at around 1600-1500 Ma because of convergence with North America. However, the evidence presented here reveals that deformation began much earlier sometime between 1655 and 1592 Ma, with NNW-SSE followed by N-S shortening. This suggests that long-lived N-S subduction, which occurred between ca.

1800 and 1600 Ma, allowed transmission of compressive stresses to intra-continental settings (Scott et al., 2000). This initiated medium pressure-temperature metamorphism that continued during E-W shortening in the Georgetown Inlier, possibly as a result of convergence with North America. Based on the monazite ages presented here, this is constrained between 1592 and 1559 Ma. This 30 Ma time interval overlaps with the onset of orogenesis (1600-1580 Ma) in the eastern margin of the Mt. Isa Inlier (e.g. Page and Sun, 1998), and also D_1 in the Yambo, Dargalong and (?) Coen Inliers (Fig. 1) as suggested by Blewett et al. (1998) at around 1590 Ma. However, zircon grains from these inliers have ages around 1636-1642 Ma in their cores (Blewett et al., 1998). These much older ages might have recorded the earlier deformation events that occurred within the Robertson River Metamorphics and further research is strongly recommended for these areas.

The first metamorphic event was followed by retrogressive metamorphism resulting from decompression and exhumation. This nearly 10 Ma period may be regarded as the collapse stage of an already thickened orogen. If this is the case, the weakened crust should favour widespread granite intrusion and high heat flow and advection, which caused the low pressure and high temperature metamorphism at around 1550 Ma, as recognized in whole North Australian Craton.

As a result, the P-T-D-t path proposed is that shown in Fig. 18, which includes an early clockwise loop overprinted by a gently sloping path with increasing temperature and pressure, for the Robertson River Metamorphics, Georgetown Inlier. Since an early clockwise P-T loop has also been reported from the eastern Mt Isa Inlier (Sayab and Rubenach, 2004), this metamorphic history must have had a large regional extent and suggests that the NE Australian Inliers (the Mt Isa, Georgetown, Yambo, Coen, Dargalong and Woolgar) were once parts of a single orogen that survived from 1655 to 1500 Ma.

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