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# Tectono-metamorphic evolution of the Cambro-Ordovician Balcooma Metamorphic Group, Greenvale Province, north-eastern Australia

Volume I

(Text)

Thesis submitted by

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In October, 2009

For the degree of Doctor of Philosophy
in the School of Earth and Environmental Sciences,
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# Introduction to thesis

This research work is focused on the Balcooma Metamorphic Group in north-eastern Queensland, Australia, which consists of multiply deformed Cambro-Ordovician metasedimentary and felsic metavolcanic rocks. The Balcooma Metamorphic Group crops out as the very northernmost portion of the Thomson Fold Belt in the Greenvale Province. The Balcooma copper, lead and zinc massive sulphide deposit lies within these multiply deformed rocks. The sequential growth of metamorphic index minerals (chlorite, muscovite, biotite, garnet, staurolite, plagioclase, kyanite, andalusite, cordierite and fibrolitic sillimanite) indicates prograde metamorphism well into the amphibolite facies in the region. Five deformation events can observe in the matrix ($D_1$-$D_5$, Huston, 1990; Van Der Hor, 1990; Withnall et al., 1991; Ali, 2009 A).

Multiply deformed rocks generally contain schistosity parallel to bedding or compositional layering and locally an oblique crenulation cleavage and/or some crenulations (Bell et al., 2003, 2004; Ham & Bell, 2004; Aerden, 2004). This parallelism of compositional layering and schistosity is predominantly a function of reactivation of the bedding during younger deformation events. Reactivation destroys developing foliations and rotates pre-existing ones into parallelism with $S_0$ (Bell, 2009). Reliance on matrix foliations alone can lead to incorrect geological interpretations, lack of precision and a degree of uncertainty. Unravelling a much more complete tectono-metamorphic history of multiply deformed rocks requires a very thorough study of the microstructures preserved within porphyroblasts because they preserve earlier-formed foliations from the effects of reactivation due to continuing or younger deformation within the matrix. The measurement of Foliation Intersection Axes preserved within porphyroblasts (FIAs) provides a robust tool that allows the elucidation of a much more extensive history of deformation and metamorphism. Prior to the development of this innovative technique, this history that predates schistosity parallel to compositional layering could not be distinguished (e.g., Bell & Newman, 2006). A FIA forms perpendicular to bulk shortening direction (Cihan 2004). Therefore, the preservation of FIAs in P-T sensitive minerals such as garnet, staurolite, kyanite, andalusite and cordierite can effectively be used to constrain compression and decompression directions during orogenesis. This research work combines all applications of the FIA technique used so far to elucidate the tectono-metamorphic history of the multiply deformed Balcooma Metamorphic Group.

The thesis divided into four sections. Each section has been written in paper format. The papers presented here encompass a range of structural, metamorphic, geochronological and tectonic topics.

**Section A**

Porphyroblast growth in metapelitic rocks is generally considered to be controlled by the bulk composition and P-T conditions (Spear, 1993). Bell et al. (1986, 2004) and Williams et al. (2001) suggested that once these first 3 conditions have been met, a fourth control exists on whether a porphyroblast starts or stops growing. They argued that growth begins when deformation partitions through an outcrop such that crenulations form at the scale of a porphyroblast and ceases when a differentiated cleavage begins to develop against its margins (Bell & Bruce, 2006, 2007). If this the case, then mineral phases expected to result from one specific reaction for a particular bulk composition on any particular prograde P-T path, could grow several times rather than just once. This section of the thesis documents the role and importance of deformation partitioning during porphyroblast growth apart from appropriate bulk composition and P-T.

**Section B**

Monazite dating has proved a useful geochronological technique for determining absolute timing of deformation and metamorphism across and along an orogenic belt (Williams &

Jercinovic, 2002; Forbes et al., 2007). Monazite grains can best be used an effective tool for determining absolute timing of tectonic processes when they are overgrown by porphyroblasts and are thus protected from younger deformation within the matrix ( Bell & Welch, 2002). A succession of 5 FIA sets preserved in garnet, staurolite, plagioclase, kyanite and andalusite porphyroblasts is described in the Section A. This succession records 5 changes in the direction of bulk shortening across the Balcooma Metamorphic Group. The FIAs hosted by these porphyroblasts are partially defined by monazite inclusions that can be dated on an electron microprobe to provide a minimum age estimate of the time over which they grew. This allows the relative succession of ages determined using core, median, rim relationships in porphyroblasts to be tested against the absolute ages determined by electron microprobe dating. Furthermore it allows the timing of deformation and metamorphic events that affected this portion of the Thomson Fold Belt to be determined and compared with ages determined elsewhere.

**Section C**

Amphibolite facies metamorphism in the Greenvale Province potentially began in an extensional backarc tectonic environment that was followed by compression in the Early Silurian with exhumation in the Early Devonian (Fergusson et al., 2007). Whether such a path occurred can potentially be resolved by calculating the P-T-t-D path using the appearance and disappearance of pressure and temperature sensitive index minerals (e.g., garnet, staurolite, kyanite, andalusite and cordierite). This section uses porphyroblast growth along the P-T-t-D path, microtextures, FIAs, conventional geothermobarometry, garnet isopleth intersections for $X_{Mn}$, $X_{Fe}$ and $X_{Ca}$ on P-T pseudosections, and phase equilibria modelling using P-T pseudosections to deduce a tectonic history and P-T-t-D path for this portion of the Greenvale Province.

## Section D

The N-S trending Tasman Orogen is generally regarded as forming by a succession of periods of orogenesis that migrated from west to east along the active Pacific-margin of East Gondwanaland after the break-up of Rodinia. It includes the Early Palaeozoic Delamerian, the Early and Middle Palaeozoic Thomson and Lachlan Fold Belts, the Middle and Late Palaeozoic Hodgkinson-Broken River Fold Belt and the Late Palaeozoic to Early Mesozoic New England Fold Belt. The Northern Thomson Fold Belt is an anomalous portion of this orogenic zone because it contains well preserved W-E trending batholiths and foliations. These W-E trends potentially connect with those dominating central Australia but are poorly understood because they are covered by the younger sediments of the Eromanga Basin. This section examines the significance of W-E magnetic and age trends in the Northern Thomson Fold Belt using FIA data from the Balcooma region, Greenvale Province. This region would have lain on the northern side of the Northern Thomson Fold Belt as currently exposed prior to the effects of the younger W-E directed crustal shortening that is typically associated with the Tasman Orogenic Zone. This data suggests a new tectonic interpretation can be proposed that may aid explorers after Balcooma and Charters Towers style mineralization correlatives.

## References

Ali, A., 2009 A. Deformation partitioning and porphyroblast growth.

Aerden, D.G.A.M., 2004. Correlating deformation in Variscan NW-Iberia using porphyroblasts; implications for the Ibero-Armorican Arc. *Journal of Structural Geology* **26**, 177–196.

Bell, T.H., 1986. Foliation development and refraction in metamorphic rocks: reactivation of earlier foliations and decrenulation due to shifting patterns of deformation partitioning. *Journal of Metamorphic Geology* **4**, 421-444.

Bell, T.H. & Welch, P.W., 2002. Prolonged Acadian orogenesis: revelations from foliation intersection axis (FIA) controlled monazite dating of foliations in porphyroblasts and matrix. *American Journal of Science* **302**, 549-581.

Bell, T.H., Ham, A.P. & Hickey, K.A., 2003. Early formed regional antiforms and synforms that fold younger matrix schistosities: their effect on sites of mineral growth. *Tectonophysics* **367**, 253-278.

Bell, T.H., Ham, A.P. & Kim, H.S., 2004. Partitioning of deformation along an orogen and its effects on porphyroblast growth during orogenesis. *Journal of Structural Geology* **26**, 825-845.

Bell, T.H. & Newman, R., 2006. Appalachian orogenesis: the role of repeated gravitational collapse. In: Butler, R., Mazzoli, S. (Eds.), Styles of Continental Compression. *Special Papers of the Geological Society of America* **414**, 95-118.

Bell, T.H., 2009. Deformation partitioning, foliation successions and their significance for orogenesis: hiding lengthy deformation histories in mylonites. In: Law, R.D., Butler, R.W.H., Holdsworth, R., Krabendam, M. & Strachan R. (eds) Continental Tectonics and Mountain Building: The Legacy of Peach and Horne. Geological Society of London, Special Publications, in press (accepted Dec 24, 2008).

Cihan, M., 2004. The drawbacks of sectioning rocks relative to fabric orientations in the matrix: A case study from the Robertson River Metamorphics (Northern Queensland, Australia). *Journal of Structural Geology* **26**, 2157-2174.

Fergusson, C. L., Henderson, R. A., Withnall, I. W. & Fanning, C.M., 2007. Structural history of the Greenvale Province, north Queensland: Early Palaeozoic extension and convergence on the Pacific margin of Gondwana. *Australian Journal of Earth Sciences* **54**, *573-595.*

Forbes, C.J., Giles, D., Betts, P.G., Weinberg, R. & Kinny, P.D., 2007. Dating prograde amphibolite and granulite facies metamorphism using in situ monazite U-Pb SHRIMP analysis. *The journal of Geology* **115**, 691-705.

Ham, A.P. & Bell, T.H., 2004. Recycling of foliations during folding. *Journal of Structural Geology* **26**, 1989-2009.

Huston, D.L., 1990. The stratigraphic and structural setting of the Balcooma volcanogenic massive sulphide lenses, north Queensland. *Australian Journal of Earth Sciences* **37**, 423-440.

Spear, F.S., 1993. Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths, *Mineralogical Society of America*, Washington, D. C., 799 p.

Vander Hor, F., 1990. Structural geology of the Balcooma-Dry River area, northeast Australia, with emphasis on the inter-relation between deformation and metamorphism. PhD thesis, James Cook University Australia, pp.**139.**

Williams, M.L., Scheltema, K.E. & Jercinovic, M.J., 2001. High-resolution compositional mapping of matrix phases: implications for mass transfer during crenulation cleavage development in the Moretown Formation, western Massachusetts. *Journal of Structural Geology* **23**, 923-939.

William, L. M. & Jercinovic, J.M., 2002. Microprobe monazite geochronology: putting absolute time into microstructural analysis. *Journal of Structural Geology* **24**, 1013-1028.

Withnall, I. W., Black, L.P. & Harvey, K. J., 1991. Geology and geochronology of the Balcooma area: part of an early Palaeozoic magmatic belt in north Queensland, Australia. *Australian Journal of Earth Sciences* **38**, 15-29.

# Section A:

## Deformation partitioning and porphyroblast growth

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## Abstract

An identical succession of five foliation intersection/inflection axes preserved in porphyroblasts (FIAs) in a small scale mining pit area and the large scale Balcooma region shows that there were five changes in the direction of bulk shortening during tectonism between ~476±5 and 408.8±8.9 Ma. The E-W trending FIA set 1 in garnet porphyroblasts indicates N-S shortening. The NNW-SSE trending FIA set 2 in staurolite suggests rotation of the direction of shortening to ENE -WSW. The NNE-SSW trending FIA set 3 in staurolite, plagioclase and kyanite porphyroblasts suggests ~30° rotation of the bulk shortening direction to ESE-WNW between 443.2±3.8 Ma and 425.4±3.7 Ma. The E-W trending FIA set 4 in staurolite porphyroblasts indicates further rotation to N-S by 408.8±8.9 Ma. The NE-SW trending FIA set 5 in andalusite suggests subsequent rotation of the bulk shortening direction to NW-SE. Structural and metamorphic data from porphyroblasts reveal a continuous history of tectonism that is partitioned between samples in the mining pit as well as regionally. The succession of FIA sets and microstructural relationships between garnet, staurolite, plagioclase, kyanite, andalusite, cordierite and fibrolitic sillimanite reveal a regionally consistent pattern of growth during this progression of changes in the direction of bulk shortening. The local coexistence of kyanite, andalusite and sillimanite and a consistent succession in the timing of growth of the different porphyroblastic phases resulted from the effects of deformation partitioning relative to bulk composition and P-T path. Similarly distributed FIA sets 1, 2 and 3 across the pit as well as in the Balcooma region suggest that the partitioning of deformation was relatively pervasive at all scales across the Balcooma Metamorphic Group from ~476±5 to 425.4±3.7 Ma. The preferential development of FIA set 4 in the northern half of the region reveals more localized deformation partitioning effects during this period of bulk shortening.

**Keywords:**

Deformation partitioning; episodic porphyroblast growth; FIAs; tectonics

## 1. Introduction

Structural geologists routinely map the dominant foliations seen in rocks and correlate them from outcrop to outcrop. Regionally metamorphosed porphyroblastic rocks generally contain schistosity parallel to bedding or compositional layering and locally an oblique crenulation cleavage and/or some crenulations without well developed axial plane structures. Recent research involving the quantitative measurement of inclusion trail orientations preserved within porphyroblasts has shown that porphyroblastic rocks generally contain a lengthy history of deformation and metamorphism that predates the schistosity parallel to compositional layering. The latter schistosity is predominantly a function of reactivation of the bedding during younger events, which destroys developing foliations and rotates pre-existing ones into parallelism with $S_0$ (Bell et al., 2003, 2004; Ham & Bell, 2004; Aerden, 2004; Cihan & Parsons, 2005; Sayab, 2005; Bell, 2009). The measurement of foliation inflection/intersection axes within porphyroblasts (FIAs) have revealed that many periods of growth of the one mineral phase can be preserved, which prior to the development of this technique could not be distinguished (e.g., Bell & Newman, 2006; Yeh, 2007). This is not necessarily a problem for garnet growth as this mineral can grow at various times during a lengthy deformation history by multiple reactions in rocks with suitable bulk composition. However, it could cause problems if it occurred with other mineral phases, such as staurolite and andalusite, as the reactions from which these porphyroblasts are produced are generally expected to go to completion once they have commenced (Spear, 1993).

It has recently been suggested that a primary control on where and when a porphyroblast grows, apart from suitable bulk chemistry, temperature and pressure, is whether or not deformation partitions through an outcrop at the scale of a porphyroblast (Bell et al., 2004; Bell, 2009). If this is the case, then mineral phases such as staurolite, which are commonly produced from one specific reaction for a particular bulk composition on any particular prograde P-T path, could grow several times rather than just once. Indeed, if this occurred, the case for the control of deformation partitioning over porphyroblast growth would be immeasurably strengthened. This paper documents an example of this where staurolite grew over 3 separate periods, each involving multiple deformations. Garnet grew before every other porphyroblastic phase. Staurolite grew next and during a subsequent period was accompanied by kyanite porphyroblast growth. Andalusite and cordierite porphyroblasts formed after garnet, staurolite and kyanite growth ceased.

## 2. Geological setting

The Balcooma Metamorphic Group of north-eastern Queensland, Australia, contains multiply deformed Cambro-Ordovician metavolcanics and metasedimentary rocks. This is exposed along a 33 km long and 8 km wide (Withnall, 1989; Withnall et al., 1991) zone on the north-western margin of the Palaeozoic Tasman Fold belt in the Greenvale Province. These rocks affected by five deformation events ($D_1$-$D_5$) and contain five cleavages (Huston, 1990; Van Der Hor, 1990; Rea & Close, 1998). The pervasive $S_2$ cleavage is commonly crenulated by $S_3$, which has NNE strike and a subvertical dip (Withnall, 1982). $D_4$ locally produced an easterly tending $S_4$ cleavage, which crenulates both $S_2$ and $S_3$ was recognized in the area by Huston (1990). The regional scale structures were mainly developed during the $D_4$ and $D_5$ deformation events (Huston & Taylor, 1990; Van Der Hor, 1990; Rea & Close 1998). The $D_5$

folding event is penetrative in the Greenvale Province. Relics of $S_1$ presevered in garnet porphyroblasts were recognized in thin section by Huston (1990) and Van der Hor (1990). The Balcooma copper, lead and zinc deposit lies within these multiply deformed metapelitic rocks. The Balcooma Metamorphic Group was intruded by the Ordovician Ringwood Park Microgranite and the Early Silurian Dido Tonalite (Huston, 1990; Withnall et al., 1991). Both intrusive bodies were affected by the $D_3$ deformation event (Benambran Orogenic event (440-420 Ma); c.f. Fergusson et al., 2007). The majority of porphyroblast growth in the region was reported as having taken place during emplacement of the Dido Tonalite (Withnall et al., 1991). The Balcooma Metamorphic Group is bound on the east by this Tonalite and on the west by the Dry River Volcanics (Fig. 1). The Ringwood Park Microgranite bounds the ore body in the east. The Dido Tonalite and Ringwood Park Microgranite have intrusive contacts with both metasediments and metavolcanics. The metapelites are characterized by chlorite, muscovite, biotite, garnet, staurolite, kyanite, plagioclase, andalusite, cordierite and fibrolitic sillimanite. The porphyroblasts contain abundant inclusion trails, metamorphic textural relationships providing an excellent opportunity for studying all stages of porphyroblast nucleation, growth and structural development, which have been destroyed by later deformations in the matrix due to reactivation process (see for more detail Bell, 2009).

## 3. Sample description

79 oriented samples were collected around the Balcooma copper, lead and zinc deposit. 34 of these consisted of surface samples and 45 of oriented core samples (at an average depth of 200 meters). The core samples were collected from a 1 by 0.5 km area covering the Balcooma North and South Pits; called the pit area from now on. The remainder were collected from the surrounding region (Balcooma region) to compare the effects of

deformation partitioning heterogeneity on porphyroblast growth at different scales. 700 vertical thin sections with different strikes were made from these samples in order to be able to measure within them the foliation intersection/inflection axes preserved within porphyroblasts (FIAs) as well as all other deformation partitioning supporting microstructures during the microstructural investigation. Microstructural data were mainly collected from garnet, staurolite, plagioclase and andalusite porphyroblasts. Biotite, muscovite and chlorite were not used for microstructural analysis because they are less competent and tend to deform along (001).

## 4. FIA measurement, trends, succession and interpretation

### 4. 1. The asymmetry technique

A FIA, the axis about which the asymmetry flips of one foliation overprinting another (Hayward, 1990; Bell et al., 1998), can be determined from a series of vertically oriented thin sections with different strike viewed in the one direction around the compass (Fig. 2). Six vertical thin sections were cut 30° apart (i.e. trending 00°, 30°, 60°, 90°, 120° and 150°) from a horizontal oriented block. An additional two vertical sections were cut 10° apart between the two sections where the switch in inclusion trail asymmetry was observed, in order to locate the FIA within a 10° range. For each extra FIA found within a sample another two thin sections 10° apart were cut. The FIA was taken halfway between the additionally cut vertical thin sections.

### 4. 2. FIA trends

A total of 92 FIAs preserved in garnet, staurolite, plagioclase and andalusite porphyroblasts were determined from forty-five spatially oriented samples in the Pit area (Table 1). A total of 51 FIAs preserved in garnet, staurolite, plagioclase and andalusite porphyroblasts were determined from thirty-four spatially oriented samples in the Balcooma region (Table 1). The sample locations are shown in (Fig. 1). 16 and 8 FIAs were measured from garnet porphyroblasts in the Pit area and Balcooma region respectively. 56 and 39 FIAs were measured from samples containing staurolite in the Pit area and Balcooma region respectively. Garnet is included within biotite, staurolite, plagioclase, kyanite, andalusite and cordierite porphyroblasts in both regions suggesting that it grew before the latter phases. Respectively, 8 and 11 versus 1 and 3 FIAs were measured from plagioclase and andalusite bearing samples in the Pit area and Balcooma region. Figure 3a shows a rose plot of total FIA trends measured from all samples in the Pit area and the Balcooma region. Figures 3b and 3c show rose diagrams of FIA plots in the Balcooma region and Pit area respectively. Both regions contain four FIA peaks with E-W, NNW-SSE, NNE-SSW and NE-SW trends.

### 4. 3. FIA succession determination

Different phases of porphyroblast at the time of their growth protect multiple portions of the early deformation, metamorphic history and structures in the rock from progressive younger deformation in the matrix. This episodic growth provides quantitative relative timing of a succession of different FIA sets (Bell et al., 1998). Five FIA sets have been established in the Balcooma Metamorphic Group in both the Pit area and Balcooma regions (Table 1) on the basis of

1. Core versus rim criteria, where core of the porphyroblast must be older than the rim (Fig. 4a ),
2. The prograde metamorphic mineral succession whereby garnet is preserved as inclusions within staurolite, plagioclase, kyanite, andalusite and cordierite. Staurolite

and kyanite are replaced by andalusite and andalusite is replaced by cordierite (Fig. 4b, c),

3. Truncated inclusion trails versus those that are continuous with the matrix (e.g. Adshead- Bell & Bell, 1999; Sayab, 2005; Cihan, 2004; Fig. 4d, e).
4. Monazite grains preserved as inclusions within porphyroblasts containing this succession of FIAs have been dated by Ali (2009B). No monazite grains were found within porphyroblasts defining FIA 1 but matrix ages in such rocks reach back to 454 ±12 Ma (Table 2d) and zircon rims produced during $D_1$ amphibolite facies metamorphism have been dated at 476±5-486±5-477±6 Ma by Withnall et al. (1991) and Fergusson et al. (2007) in the Greenvale Province. FIAs 2, 3 and 4 are dated at 443.2±3.8 Ma, 425.4±3.7 Ma and 408.8±8.9 Ma respectively (Table 2a, b, c; Ali, 2009B).

For both the Pit area and Balcooma region the four peaks in the rose diagram (Fig. 3a) and multiple generations of porphyroblast growth during episodic deformations consist of a succession of five FIA sets. The earliest FIA set 1, which has E-W, orientation is preserved by garnet. The inclusion trails in garnet are truncated by the matrix foliation (Fig.5). In all samples, garnet porphyroblasts only contain FIA 1. FIA 1 was never observed in staurolite, plagioclase, kyanite, andalusite and cordierite. FIA 2 formed with a NNW-SSE trend and was only observed in staurolite porphyroblasts. The inclusion trails defining this FIA are truncated by the matrix foliation (Fig. 4d). FIA 3, which is preserved by staurolite and plagioclase, has a NNE-SSW trend. Kyanite generally has no inclusion trails and is not present around the compass; one sample (AH71) where kyanite is present around the compass contains well developed inclusion trails defining FIA 3 at 10°. The inclusion trails defining FIA 3 are continuous with (Fig. 4e) or locally truncated by a well developed horizontal foliation in the matrix. FIA 4 trends E-W and was observed in staurolite porphyroblasts; this relative timing was distinguished using samples where FIAs trending NNW-SSE and NNE-SSW lay within the core of staurolite porphyroblasts that contain the E-W FIA in their rims (Fig. 4a). The continuity of the inclusion trails defining FIA 4 with those in the matrix and its preservation in a completely different porphyroblastic phase enabled samples containing this FIA to be distinguished from those containing FIA 1, even though they have the same trend. FIA set 5 trending NE-SW is preserved by andalusite that overgrew the matrix very late in the deformation history (Fig. 6). The total succession of FIAs is shown in Table 1.

### 4.4. FIA distribution

FIA 1 in the Balcooma region versus the pit area is relatively evenly distributed relative to sample locations (Fig. 7a poor outcrop prevented sampling in the Balcooma region). FIA 2 is potentially evenly distributed regionally as it is within the pit area (Fig. 7b). FIA 3 appears to be relatively evenly distributed at both map scales (Fig. 7c). FIA 4 is coarsely partitioned both regionally and within the pit area (Fig. 7d). The number of samples containing FIA 5 is limited suggesting it may be coarsely partitioned in its distribution (Fig. 7e).

## 6. Interpretation and discussion

Samples were deliberately collected using two approaches. Firstly, they were gathered across a large region where the outcrop was relatively sparse and weathered. Secondly, they were collected in similar total numbers over a small region with dimensions 1 x 0.5kms where a large amount of oriented drill core was available from very fresh rock. These two regions are called the Balcooma region and the Pit area respectively. This was done so that the local versus regional heterogeneity of porphyroblast growth and the FIA trends preserved could be examined and any the role for deformation partitioning determined (e.g., Bell et al., 2004).

### 6. 1. Lack of porphyroblast rotation

Many structural geologists have inferred that porphyroblasts rotate (e.g. Rosenfeld, 1968; Passchier et al., 1992; Williams & Jiang, 1999). They inferred rotation from the geometry of the inclusion trails, such as spiral shapes, without mentioning the actual reference frame within which the rotation occurred. They probably assumed that it was the matrix schistosity and felt that it was not necessary to state whether the porphyroblasts rotated with respect to a foliation, with respect to the bedding, or with respect to the earth's surface (Passchier & Trouw, 2005). A well-defined reference frame is needed to quantitatively test all aspects of rotation and non-rotation models for porphyroblast behaviour in multiply deformed rocks. To evaluate the rotation of porphyroblasts, geographic north and the vertical can be used as a reference frame (Hayward, 1990; Bell et al., 1998; Fay et al., 2008, 2009). A FIA is measured for a sample, independent of assumptions concerning the timing of inclusion trails relative to matrix structures and whether or not the porphyroblast have rotated. The preservation of a consistent and non-random succession of five FIA sets both regionally and locally suggests that the porphyroblasts did not rotate as they formed. If the rotation of the porphyroblasts hosting FIAs 1 through 5 had occurred, a random distribution of FIA trends would have been produced. For example if FIA 1 was rotated up to 45° either way about FIA sets 2, 3, 4 and 5, a spread of FIA 1 around the stereonet would have developed (Fig. 8a, b, c, d) but this did not occur. The consistency in the trends of the succession of FIA sets in the different mineral phases indicates that the porphyroblasts did not rotate relative to each other during different progressive deformation events in the matrix (c.f. Ham & Bell, 2004; Sayab, 2005; Bell & Newman, 2006).

### 6. 2. FIA Succession in the Pit area versus the Balcooma region

The region is very poorly exposed due to extreme tropical weathering. However, sampling from the pit area was unaffected by this because of mining related exposure plus the availability of oriented drill core. Therefore, the distribution of FIA sets in the pit is not affected by outcrop bias whereas that of the region is. Of course, coarse scale partitioning of deformation could impact on the pit area because of its small size (1 km long). However, the succession of five FIAs in the Pit area is identical with that in the Balcooma region even though their distribution on rose diagrams is different (Fig. 3b, c). The E-W trending FIA set 1 in garnet porphyroblasts indicates N-S shortening. The NNW-SSE trending FIA set 2 in staurolite indicates rotation of the direction of shortening to WSW-ENE. The NNE -SSW trending FIA set 3 in staurolite, kyanite and plagioclase porphyroblasts indicates a ~30° rotation of the shortening direction to ESE-WNW. The E -W trending FIA set 4 in staurolite porphyroblasts indicates a further rotation in shortening to N-S. NE-SW trending FIA 5 indicates rotation of the bulk horizontal shortening direction to NW-SE.

### 6. 3. FIA distribution and deformation partitioning

#### *6. 3. 1. The effect of granite plutons*

The Ringwood Park Microgranite was emplaced between ~486 and 475 Ma (Withnall et al., 1991), possibly around the time of development of the E-W trending FIA set 1, and Fig. 3 and 7 suggests that it had no impact whatsoever on the subsequent development of FIA sets. There is no sign of any greater development of any of the FIA sets close to the appropriately oriented margins (allowing for the affect of the regionally very poor outcrop) which suggests that its fine grain size meant that it did not act as a competent body. This is supported by its shape which follows that of the regional grain. The Dido Tonalite was emplaced around 425Ma around the time of development of FIA set 3 (425.4±3.7 Ma). This coarser grained Tonalite, which crops out in the NE and SE portions of the map, has no affect on the distribution of FIA set 3. However, it does appear to have affected the distribution of FIA set 4 which predominantly lies in between these two regions, although 4 samples protected by the scalloped southern boundary of the NE portion grew porphyroblasts at this time (Fig. 7d).

### *6. 3. 2. Other effects*

Bell (2009) and subsequent workers (Bell et al., 1986; Bell & Hayward, 1991; Williams, 1994; Williams et al., 2001; Bell et al., 2004; Bell & Bruce, 2006) demonstrated that the partitioning of deformation into zones of progressive shearing and coaxial shortening can control the sites of development of crenulation cleavage versus porphyroblast nucleation and growth, respectively (Fig. 9). They argued that during progressive shortening porphyroblast growth occurs primarily in coaxially deforming crenulation hinges where as platy and fibrous minerals arrange in a way to develop differentiated crenulation cleavages due progressive shearing. The partitioning of deformation into zones of progressive shortening (essentially coaxial strain) and progressive shearing (essentially non-coaxial strain) potentially can be important on one scale (porphyroblast scale) but not on another (Bell et al., 2004). This is particularly significant for porphyroblast growth because deformation needs to partition at the scale of a porphyroblast for nucleation to occur (Spiess & Bell, 1996; Bell & Bruce, 2006). FIA set 3 dominates the Pit area (Fig. 3c) and is also dominant across the region (Fig. 3b) suggesting that deformation at this time was pervasive regionally (Fig. 7c). FIA set 2 is preserved in relatively more samples regionally but decrease in a similar manner relative to those in the pit relative to the dominant FIA set 3 (compare Fig. 7b with 7c). These data suggests that the deformation partitioned relatively pervasively at all scales across the Balcooma Metamorphic Group during the development of these three FIA sets. Bell and Hayward (1991) and Spiess and Bell (1996) have shown that the partitioning of deformation at the scale of a porphyroblast is necessary for it to grow. If their arguments are correct then the crude similarity in the proportion of the total number of samples containing each FIA set in both regions (allowing for the poor outcrop regionally) requires that the scale of partitioning of deformation in each was similar for each period of porphyroblast growth for each FIA set. Porphyroblasts containing FIA sets 4 and 5 are more unevenly distributed across both regions (Fig. 7d, e) suggesting that locally partitioned deformation occurred during these two periods of bulk shortening across the Balcooma Metamorphic Group possibly due to emplacement of the Dido Tonalite mentioned above.

### 6. 4. Porphyroblast phase distributions and deformation partitioning

The large spectrum of metamorphic index minerals (chlorite, muscovite, biotite, garnet, staurolite, plagioclase, kyanite andalusite, cordierite and fibrolitic sillimanite) in the same sample at the thin sections scale (e.g. AH 119) shows either that metamorphic mineral equilibrium was not established, or that some factors other than, or addition to, temperature and pressure was responsible for the development of these minerals. Furthermore, zones of such index minerals are said to represent differences in temperature, pressure and mineral reactions across a regionally metamorphosed terrane (Snelling, 1994). However, Bell and Bruce (2006) have shown that at appropriate P-T conditions and specific bulk composition porphyroblasts start nucleation during coaxial shortening in zones of negligible strain (hinges or Q-domain) that produced from strain partitioning at a scale of porphyroblast and stop growth once a progressive shearing is established at sites of differentiated crenulation cleavage (limbs or M-domain; Fig. 9). During porphyroblast nucleation or regrowth in these zones, the presence of a pre-existing foliation lying at a high angle to a newly developing cleavage is vital (Bell et al., 2003, Bell & Bruce, 2006). The Balcooma Metamorphic Group provides a remarkable example of this phenomenon. Samples containing garnet, staurolite, plagioclase, kyanite, andalusite cordierite and sillimanite are relatively common in some locations in the Balcooma region. Significantly, there is a FIA set control on the distribution of such samples (Table 1). This indicates that deformation partitioning was the extra factor that controlled porphyroblast growth once P-T was appropriate and suitable bulk compositions were available. Indeed, the FIA sets present within the different porphyroblast phases indicate that the growth of some of these minerals occurred at different times (see below).

Prior to the development of a technique for measuring FIAs, distinguishing or even recognizing the presence of different times of growth for the same or different phases of porphyroblasts was very complicated and confusing especially for porphyroblasts with truncated inclusion trails. Furthermore, the progressive development of deformation partitioning in multiply deformed rocks was not distinguishable apart from for much younger events that affected the matrix (Bell et al., 2004; Bell & Newman, 2006). The measurement of FIAs in many orogenic belts over the past 18 years has revealed that porphyroblasts provide the best evidence for the role of partitioning in deformation history because they preserve the included microstructures from obliteration as the deformation intensifies (c.f. Bell & Bruce, 2006; Ali, 2009B).

## 6. 5. Deformation partitioning and timing of multiple porphyroblastic phases

The presence of garnet, staurolite, plagioclase, andalusite, cordierite and sillimanite in sample AA06, garnet, staurolite, plagioclase, kyanite, andalusite, cordierite and sillimanite in sample AH 119, garnet, staurolite, plagioclase and cordierite in samples AH 105, AH 113, AH 143, AH 142 and AH 132, garnet, staurolite, plagioclase and kyanite in sample AH 146 and staurolite, kyanite, sillimanite and andalusite in samples AH 071, AH 074 and AH 116, AH 122 provide striking examples of the effects of deformation partitioning on the timing of different porphyroblastic phases. These samples lie within the 0.5 square km pit area (Fig. 1) and, therefore, followed the same P-T-t path as there are no prominent faults or younger shear zones nearby.

Textural and relative deformation constraints from this study suggest the crystallization sequence chlorite, muscovite, biotite, garnet, staurolite, plagioclase, kyanite, andalusite, cordierite and fibrolitic sillimanite. These minerals are of considerable importance in metamorphic studies, as they provide quick information about pressure-temperature (P-T) conditions and P-T paths. The coexistence of kyanite, andalusite and sillimanite is uncommon. The presence of all three $Al_2SiO_5$ polymorphs in regionally metamorphosed rocks indicates very complex tectonothermal histories (Pattison, 2001; Tinkhan et al., 2001; Whitney, 2002). Kyanite, andalusite and sillimanite are present in samples AH 071, AH074, AH 091, AH 116, AH 119 and AH 122 at the thin section scale. Kyanite is replaced by andalusite and andalusite is replaced by sillimanite (Fig. 10a, b). Differences in the nature and degree of deformation of the polymorphs confirm this sequence of crystallization rather than simultaneous crystallization at the triple point.

Variation in the timing of growth of different porphyroblastic phases in different samples results from the effects of deformation partitioning relative to their bulk composition and P-T path and readily resolves conflicts in the presence of extra phases. In the 0.5 square kilometre pit area, kyanite grew during the development of FIA 3 in the range of 6-8kbar, 617-637°C at 425.4±3.7 Ma (Ali, 2009C) and was the first $Al_2SiO_5$ polymorph to form. Andalusite, which grew during the development of FIA 5, was the second aluminosilicate phase to develop from the break down of biotite, staurolite and kyanite during decompression across the Greenvale Province (Fig. 11, 4c, 10a; Ali, 2009C). Sillimanite, which nucleated within biotite, is projecting into adjacent andalusite and kyanite porphyroblasts. It locally cross cuts the matrix indicating that it was the last $Al_2SiO_5$ polymorph to form (Fig. 12).

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## References

Ali, A., 2009 B. Protection of monazite grains from obliteration in highly tectonized terrains by porphyroblasts: microstructural approaches to tectonic reconstructions.

Ali, A., 2009 C. The tectono-metamorphic evolution of the Balcooma complex, northeastern Australia; a multidisciplinary approach.

Adshead-Bell, N.S. & Bell, T.H., 1999. The progressive development of a macroscopic upright fold pair during five near-orthogonal foliation producing events: complex microstructures versus a simple macrostructure. *Tectonophysics* **306**, 121–147.

Aerden, D.G.A.M., 2004. Correlating deformation in Variscan NW-Iberia using porphyroblasts; implications for the Ibero-Armorican Arc. *Journal of Structural Geology* **26**, 177–196.

Bell, T.H., 1986. Foliation development and refraction in metamorphic rocks: reactivation of earlier foliations and decrenulation due to shifting patterns of deformation partitioning. *Journal of Metamorphic Geology* **4**, 421-444.

Bell, T.H. & Hayward, N., 1991. Episodic metamorphic reactions during orogenesis: the control of deformation partitioning on reaction sites and duration. *Journal of Metamorphic Geology* **9**, 619–640.

Bell, T.H., Hickey, K.A. & Upton, J.G., 1998. Distinguishing and correlating multiple phases of metamorphism across a multiply region using the axes of spiral, staircase and sigmoidal inclusion trails in garnet. *Journal of Metamorphic Geology* **16**, 767–794.

Bell, T.H., Ham, A.P. & Hickey, K.A., 2003. Early formed regional antiforms and synforms that fold younger matrix schistosities: their effect on sites of mineral growth. *Tectonophysics* **367**, 253-278.

Bell, T.H., Ham, A.P. & Kim, H.S., 2004. Partitioning of deformation along an orogen and its effects on porphyroblast growth during orogenesis. *Journal of Structural Geology* **26**, 825-845.

Bell, T.H. & Newman, R., 2006. Appalachian orogenesis: the role of repeated gravitational collapse. In: Butler, R., Mazzoli, S. (Eds.), Styles of Continental Compression. *Special Papers of the Geological Society of America* **414**, 95-118.

Bell, T.H. & Bruce, M.D., 2006. Progressive deformation partitioning and deformation history: Evidence from millipede structures. *Journal of Structural Geology* **27**, 18-35.

Bell, T.H., 2009. Deformation partitioning, foliation successions and their significance for orogenesis: hiding lengthy deformation histories in mylonites. In: Law, R.D., Butler, R.W.H., Holdsworth, R., Krabendam, M. & Strachan R. (eds) Continental Tectonics and Mountain Building: The Legacy of Peach and Horne. *Geological Society of London, Special Publications*, in press (accepted Dec 24, 2008).

Cihan, M., 2004. The drawbacks of sectioning rocks relative to fabric orientations in the matrix: A case study from the Robertson River Metamorphics (Northern Queensland, Australia). *Journal of Structural Geology* **26**, 2157-2174.

Cihan, M. & Parsons, A., 2005. The use of porphyroblasts to resolve the history of macro-scale structures: an example from the Robertson River Metamorphics, North-Eastern Australia. *Journal of Structural Geology* **27**, 1027-1045.

Fay, C., Bell, T.H. & Hobbs, B.E., 2008. Porphyroblast rotation versus non-rotation: conflict resolution! *Geology* **36**, 307-310.

Fay, C., Bell, T.H. & Hobbs, B.E., 2009. Porphyroblast rotation versus non-rotation: Conflict resolution! COMMENT and REPLY. *Geology* **37**, e182-e188.

Fergusson, C. L., Henderson, R. A., Withnall, I. W. & Fanning, C.M., 2007. Structural history of the Greenvale Province, north Queensland: Early Palaeozoic extension and convergence on the Pacific margin of Gondwana. *Australian Journal of Earth Sciences* **54**, *573-595.*

Ham, A.P. & Bell, T.H., 2004. Recycling of foliations during folding. *Journal of Structural Geology* **26**, 1989-2009.

Hayward, N., 1990. Determination of early fold axis orientations within multiply deformed rocks using porphyroblasts. *Tectonophysics* **179**, 353–369.

Hayward, N., 1992. Microstructural analysis of the classic snowball garnets of southeast Vermont. Evidence for non-rotation. *Journal of Metamorphic Geology* **10**, 567-587.

Huston, D.L., 1990. The stratigraphic and structural setting of the Balcooma volcanogenic massive sulphide lenses, north Queensland. *Australian Journal of Earth Sciences* **37**, 423-440.

Huston, D. L. & Taylor, T. W. 1990. Dry River copper and lead-zinc-copper deposits. In Hughes F. E. ed. Geology of the Mineral Deposits of Australia and Papua New Guinea. *Australasian Institute of Mining and Metallurgy: Melbourne*, 1519–1526.

Passchier, C.W., Trouw, R.A.J., Zwart, H.J. & Vissers, R.L.M., 1992. Porphyroblast rotation: eppur si muove? Journal of Metamorphic Geology 10, 283–294.

Passchier, C.W. & Trouw, R.A.J., 2005. Micro-tectonics. Springer-Verlag, Berlin, 283p.

Pattison, D. R. M., 2001. Instability of Al2SiO5 “triple-point” assemblages in muscovite+ biotite+ quartz-bearing metapelites, with implications. American Mineralogist 86, 1414-1422.

Rea, P.S. & Close, R.J., 1998. Surveyor 1 copper-lead-zinc-silver-gold deposit. *The Australian Institute of Mining and Metallurgy*: Melbourne, pp. 737- 742.

Rosenfeld, J.L., 1968. Garnet rotation due to the major Palaeozoic deformation in southeast Vermont. In: Zen, E-AN, White, W.S., Hadley, J.B. (Eds.), Studies of Appalachian Geology: Northern and Maritime. Interscience publishers, New York, pp. 185–202.

Sayab, M., 2005. Microstructural evidence for N–S shortening in the Mount Isa Inlier (NW Queensland, Australia): the preservation of early W–E trending foliations in porphyroblasts revealed by independent 3D measurement techniques. *Journal of Structural Geology* **27**, 1445–1468.

Snelling, A., 1994. Towards a Creationist explanation of regional metamorphism. *Answers Magazine* **8**, 51–77.

Spear, F.S., 1993. Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths, *Mineralogical Society of America*, Washington, D. C., 799 p.

Spiess, R. & Bell, T.H., 1996. Microstructural controls on sites of metamorphic reaction: a case study of the inter-relationship between deformation and metamorphism. *European Journal of Mineralogy* **8**, 165-186.

Tinkham, DK., Zuluaga, Ca. & Stowell, HH., 2001. Metapelite phase equilibria modelling in MnNCKFMASH: The effect of variable $Al_2O_3$ and MgO/(MgO+FeO) on miner stability. Geological Material Research (*Mineralogical Society of America*) **3**, 1–42.

Vander Hor, F., 1990. Structural geology of the Balcooma-Dry River area, northeast Australia, with emphasis on the inter-relation between deformation and metamorphism. *PhD thesis*, James Cook University Australia, pp.139**.**

Whitney, D.L., 2002. Coexisting andalusite, kyanite, and sillimanite: sequential formation of three polymorphs during progressive metamorphism near the $Al_2SiO_5$ triple point, Sivrihisar, Turkey. *American Mineralogist* **84**, 405-416.

Withnall, I.W., 1982. The geology of the Greenvale-Balcooma area. *Geological Society of Australia* (Queensland Division), Brisbane, pp. 31-46.

Withnall, I. W., 1989. Precambrian and Palaeozoic geology of the south-eastern Georgetown Inlier, North Queensland. *Queensland Department of Mines, report* **2**, 1-102.

Withnall, I. W., Black, L.P. & Harvey, K. J., 1991. Geology and geochronology of the Balcooma area: part of an early Palaeozoic magmatic belt in north Queensland, Australia. *Australian Journal of Earth Sciences* **38**, 15-29.

Williams, M.L., 1994. Sigmoidal inclusion trails, punctuated fabric development, and interactions between metamorphism and deformation. *Journal of Metamorphic Geology* **12**, 1–21.

Williams, M.L., Scheltema, K.E. & Jercinovic, M.J., 2001. High-resolution compositional mapping of matrix phases: implications for mass transfer during crenulation cleavage development in the Moretown Formation, western Massachusetts. *Journal of Structural Geology* **23**, 923-939.

Williams, P.F. & Jiang, D., 1999. Rotating garnets. *Journal of Metamorphic Geology* **17**, 367-378.

Yeh, M.W., 2007. Deformation sequence of Baltimore gneiss domes, USA, assessed from porphyroblast Foliation Intersection Axes. *Journal of Structural Geology* **29**, 881-897.

# Section B:

# Protection of monazite grains from obliteration in highly tectonized terranes by porphyroblasts: microstructural approaches to tectonic reconstructions

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## Abstract

Electron microprobe monazite dating of a succession of 5 FIA sets (foliation inflection/intersection axes preserved in porphyroblasts) from the Balcooma Metamorphic Group, NE Australia reveals that these Palaeozoic rocks to the east of the Precambrian Georgetown Province have been affected by 5 orogenic cycles of different intensities. Electron microprobe dating of monazite preserved within porphyroblasts containing FIAs 2 through 4 indicates that the Delamerian, Kanimblan and Hunter Bowen Orogenies did not affect this region. The earliest 443.2±3.8 Ma phase of monazite growth within the Balcooma Metavolcanic Group is preserved in porphyroblasts containing FIA 2 whereas 425.4±3.7 Ma and 408.8± 8.9 Ma ages are preserved in those containing FIAs 3 and 4 respectively. This indicates that this region was initially affected by an Early Ordovician Orogeny but was later overprinted by the Benambran (440-420 Ma) and Tabberabberan (410-370 Ma) Orogenies. The lack of younger monazite ages shows that deformation during the Kanimblan Orogeny (360-320 Ma) partitioned such that it did not affect rocks adjacent to the Georgetown Province when it impacted on the Broken River, Hodgkinson and Charters Towers Provinces to the east, northeast and southeast respectively. Sulphide inclusions in porphyroblasts containing FIAs 2, 3, 4, 5 but not in those containing FIA 1 requires that disruption of any primary volcanogenic massive sulphide body took place after FIA 1, or that the mineralization is metamorphogenic.

*Keywords*: Monazite ages; FIAs; Orogenies; Tectonics; Sulphide mineralization

## 1. Introduction

FIAs and electron microprobe dating of monazite inclusions preserved within porphyroblasts (Bell & Welch, 2002; Cihan & Parsons, 2005; Cihan et al., 2006) are being used to assess the combined effects of deformation, orogenesis and metamorphism in complexly tectonized terranes. The discovery of regionally consistent successions of FIAs has enabled extended histories of deformation and metamorphism to be identified that predate the $S_0//S_1$ matrix foliation that is always present in regionally metamorphosed porphyroblastic rocks (Bell & Newman, 2006, Bell, 2009 and references therein). Monazite dating has proved a useful geochronological tool for determining absolute timing of deformation and metamorphism across and along an orogen (William & Jercinovic, 2002; Forbes et al., 2007). However, dating monazite grains without care can lead to misinterpretations because monazite is always susceptible to the affects of hydrothermal fluids, which dissolve or lose Pb and disrupt the Th-U-Pb system (Braun et al., 1998). Monazite grains can best be used an effective tool for determining absolute timing of tectonic processes when they are overgrown by porphyroblasts and are thus armored from younger deformation within the matrix (Bell & Welch, 2002).

Disturbance of the U-Th-Pb system may occur within porphyroblasts that host monazite grains if they are fractured or altered (Forbes et al., 2007). Such situations may yield younger ages due to ongoing deformation and metamorphism events in the matrix. Similarly, analytical problems associated with electron microprobe analysis cannot be ignored (Williams et al., 2006) and differentiation between metamorphic and detrital monazite grains is important. Therefore, relying on monazite dating alone can lead to incorrect geological interpretations, lack of precision and a degree of uncertainty. Inclusion trails in porphyroblasts that predate the visible matrix foliation, protecting early-formed foliations and associated FIAs from obliteration due to later deformation and metamorphism, are common in regionally metamorphosed rocks (Bell & Welch, 2002; Bell et al., 2004). Determining FIA successions and dating them with monazite inclusions can provide vital information on the timing of deformation, orogensis and metamorphic processes. These two approaches have been applied to the rocks from the Balcooma Metamorphic Group, which lie on the northern boundary of the Thomson Fold Belt of eastern Australia (Fig. 1).

The Thomson Fold Belt has been affected by 3 well-documented orogenies (see below; Braun & Shaw, 2001; Nishiya et al., 2003; Fergusson et al., 2007a, b). Measurement of FIAs in the Balcooma Metamorphic Group indicates a more complex history of deformation, metamorphism and associated bulk shortening directions than previously reported. A succession of FIAs sets records 5 changes in the direction of bulk shortening has affected the Greenvale Province (Ali, 2009D). Structural and microstructural relationships between biotite, garnet, staurolite, kyanite, plagioclase andalusite, cordierite and fibrolitic sillimanite show a regionally consistent pattern of progressive metamorphism and tectonism. The hosting of FIAs by these porphyroblasts, and consequent shielding of monazite inclusions from dissolution and fluid access effects of later deformations, can be used to determine the absolute timing of deformation, metamorphism and bulk shortening directions affected the region. This paper develops a close link between FIAs and electron microprobe results from the dating of monazite. FIAs enable detailed and quantitative correlation of porphyroblast growth from outcrop to outcrop. This can be confirmed by monazite dating, enabling which tectonic events have affected this region to be determined. This will constrain the combined effects of deformation, orogenesis and metamorphism within the northern portion of the Thomson Fold Belt in the Greenvale Province.

## 2. Regional geological framework

The Thomson Fold Belt of eastern Australia is located north of the Delamerian and Lachlan Fold Belts and west of the New England Fold Belt. Much of the Thomson Fold Belt is poorly exposed, being concealed under the Mesozoic sediments of the Eromanga Basin (Fig. 1). Deformation/metamorphism in the Thomson Fold Belt occurred during the Delamerian (515-

500 Ma), Benambran (440-420 Ma), Tabberaberan (410-370 Ma) plus an unnamed continental-wide Ordovician Orogeny (475-450 Ma, Braun & Shaw, 2001; Nishiya et al., 2003; Fergusson et al., 2007a, b). However, the exposed parts of the Thomson Fold Belt in the Greenvale, Charters Towers and Anakie Provinces were not uniformly affected by these orogenic events (Fergusson et al., 2007a, b). The shape of the Thomson Fold Belt has been regarded mainly as a product of the Benambran Orogenic event (c.f. Fergusson et al., 2007b).

This work is focused on the Balcooma Metamorphic Group, which is exposed in the western part of the Greenvale Province northern Queensland. This is dominated by strongly deformed interbedded metagreywackes, metapelites and felsic metavolcanics (rhyolitic to dacitic in composition; Huston, 1990; Withnall et al., 1991 Van der Hor, 1990). The main porphyroblastic phases in the Balcooma Metamorphic Group are biotite, staurolite, andalusite, garnet, plagioclase, kyanite and cordierite (Huston 1990; Ali 2009b). They are considered equivalent to the Cambro- Ordovician Seventy Mile Range in the Charters Towers Province on the basis of similar lithologies, geochronology (Henderson, 1986; Withnall et al., 1991; Fergusson et al., 2007a, b) plus the fact that they both host massive sulphide deposits containing Cu, Zn and Pb (Fig. 2). The Seventy Mile Range is located 200 km southeast of the Balcooma Metamorphic Group. The connection between the two Provinces is disrupted by Cenozoic sediments, the Siluro-Devonian Lolworth Igneous complex and the Broken River Province (Withnall et al., 1991). The Balcooma Metamorphic Group is intruded by the late Ordovician Ringwood Park Microgranite and Early Silurian (U-Pb Zircon age 431±7 Ma) Dido Tonalite (Fig. 3; Withnall et al., 1991; Bain et al., 1997). The Balcooma Massive sulphide mineralization is bound to the east by the Ringwood Park Microgranite and to the west by the quartz-feldspar porphyry of the Dry River Volcanics. Previous workers (Huston & Taylor, 1990; Rea & Close, 1998) reported five deformation events in these rocks. Early $S_1$ foliation and compositional layering are subparallel to bedding. The effects of this deformation were disguised by the effects of $D_2$ (Fergusson et al., 2007b), which along with $D_3$, are the dominant events. Pervasive $S_2$ is crenulated by NNE trending $S_3$ and both were crenulated during $D_4$. $S_4$ cleavage is locally developed and overprinted by $S_5$ (Huston, 1990). All NE-trending faults have been interpreted to be due to $D_5$ (Huston & Taylor, 1990; Rea & Close, 1998). However, Emsian age (400-392 MA) marine rocks of the Conjuboy Formation are gently dipping, unstrained and unconformable on Early Paleozoic metasediments and metavolcanics (Huston 1990; Withnall et al. 1991).

Textural and relative deformation and metamorphic features among porphyroblasts present in these rocks suggest the crystallization sequence biotite, garnet, staurolite, kyanite, plagioclase, andalusite, cordierite, and sillimanite. Microstructurally, the three aluminosillicate polymorphs formed in the sequence kyanite → andalusite → sillimanite (Van der Hor, 1990, Ali, 2009C). All porphyroblasts contain well-developed inclusion trails. Consequently, these rocks provide a key location for testing the connection between FIA succession and electron microprobe monazite dating.

## 3. Tectonic events in eastern Australia reported by previous workers

The present day eastern Australia was shaped by the following orogenic events along this margin of Gondwana.

### 3.1. **Ross - Delamerian Orogeny**

The Ross - Delamerian Fold Belt (length of 4000 km), which evolved in the Middle to Late Cambrian (520-500 Ma) after Rodinia breakup (600-800Ma), included portions of Antarctica, Australia and Tasmania. It was produced by E-W directed convergent margin tectonism along the eastern margin of Gondwana (Boger & Miller, 2004; Federico et al., 2006). U-Pb dating of intrusives and volcanics across the Delamerian Fold Belt shows a shift from passive margin sedimentation to convergent margin orogenesis (Boger & Miller, 2004).

Out crops are exposed in South Australia, Victoria, Tasmania and Queensland. Those in Queensland include the Anakie Inlier and Halls Reward Metamorphics of the Greenvale Province (Figs. 1 and 2; Withnall et al., 1996; Nishiya et al., 2003). However, the Late Cambrian-Early Ordovician Seventy Mile Range and the foliated granitoid intrusions in the Argentine Metamorphics and Cape River Metamorphics in the Charters Towers Province show no effects of the Delamerian Orogeny (Henderson, 1986; Fergusson et al., 2007c).

### 3.2. Ordovician orogeny across Australia

An Early Ordovician (475-450 Ma) orogeny has affected the Harts Range of central Australia and the Greenvale and Charters Towers Provinces in eastern Australia (Withnall et al., 1991; Hand et al., 1999, Fergusson et al., 2007a,b,c; Ali, 2009D). This orogeny resulted in initiation of amphibolite facies metamorphism in the Greenvale Province. During this time the Argentine Metamorphics and the Cape River Metamorphics were intruded by granitoids in the Charters Towers Province (Fergusson et al., 2007c).

### 3.3. Benambran Orogeny

The E –W compressional Benambran Orogeny occurred along the eastern sea-board in the Early Silurian (440-420 Ma; Braun & Shaw, 2001; Fergusson et al., 2007b). This orogeny caused regional metamorphism, deformation and N-S fabric development in the Thomson Fold Belt (Braun & Shaw, 2001; Fergusson et al., 2007a, b). It affected the Late Ordovician Ringwood Park Microgranite and the Early Silurian Dido Tonalite of the Greenvale Province and induced multiple deformational fabrics across the Thomson Fold Belt (Withnall, 1989; Fergusson et al., 2007b). Fergusson et al., (2007b) attributed the steepening of foliations and reactivation of domain-bounding faults in the Greenvale Province to this orogeny. Similarly, an $^{40}$Ar /$^{39}$Ar 440Ma age on hornblende from amphibolite in the Argentine Metamorphics reflects E-W contraction during the Benambran Orogeny in the Charters Towers Province (c.f. Fergusson et al., 2007a).

### 3.4. Tabberabberan Orogeny

Compressional deformation related to the Tabberabberan Orogeny (410-370 Ma) is more wide spread in south-eastern Australia than north-eastern Australia (Powell et al., 1990). Accretion of the eastern Lachlan Fold Belt and emplacement of Early Devonian granites took place during this orogeny (Braun & Shaw, 2001). Some affects of this orogeny have been reported in the Hodgkinson/Broken River Fold Belts and Drummond Basin in north and central Queensland respectively (Henderson, 1980, Henderson, pers comm. 2009).

### 3.5. Kanimblan Orogeny

The Early Carboniferous (360-320 Ma) Kanimblan Orogeny affected much of south-eastern Australia. The Central Victorian Magmatic complexes, which consist of widespread intrusions of granite and associated felsic volcanics, developed at this time (VandenBerg et al., 2000). This produced the last regional deformation in the Lachlan Fold Belt. The impact of this orogeny on the rocks of north-eastern Australia was not very significant although it did generate folds in the Late Devonian and Early Carboniferous rocks (Henderson, 1987).

### 3.6. Hunter-Bowen Orogeny

The presence of little disturbed Permian rocks in the Burdekin Subprovince indicates that tectonism related to the Hunter-Bowen Orogeny had little effect in this portion of north Queensland (Henderson, 2007).

## 4. Sample description

### 4.1. Samples used for FIA measurements

700 vertical thin sections with different strikes were cut from 79 spatially oriented samples for FIAs determination. These samples (Fig. 3) were collected around the Balcooma copper,

lead and zinc deposit in the Greenvale Province. Apart from FIA measurements, these samples were also used for petrographic, textural and metamorphic observations. Detailed petrography revealed that different episodes of orogenesis and accompanying metamorphism produced a complete sequence of prograde metamorphic index minerals across the region. The metapelites are characterized by growth of biotite, garnet, staurolite, plagioclase, kyanite, andalusite cordierite and fibrolitic sillimanite. FIA measurements from these porphyroblasts confirm the crystallization sequence garnet, staurolite, plagioclase and andalusite. Inclusion trails in these porphyroblasts are mostly sigmoidal. Older foliations are overgrown and shielded by these porphyroblasts from obliteration during younger deformations in the matrix.

### 4.2. Samples used for monazite dating

20 samples were selected to constrain the absolute timing of deformation and metamorphic processes related to the tectonic evolution of the Greenvale Province. The sample locations are shown in (Fig. 3). At least 4 polished thin sections were prepared per sample for each FIA set from 4 of the differently striking vertical blocks used for FIA measurement. Care was taken to avoid pits and scratches during the polishing process. The surfaces of polished thin sections were made electrically conductive with a fine coat of carbon. Half of these polished thin sections had adequate monazite inclusions for dating. These lay in porphyroblasts, in fractures in porphyroblasts and in the matrix. Monazite grains were analyzed according to their position in these thin sections. This was done to develop the relative timing between monazite grains defining inclusion trails relative to those present in younger fractures through the porphyroblasts and the matrix. Inclusions of all opaque minerals in porphyroblasts were probed to determine whether any sulphides were present.

## 5. Succession of FIA sets

Five FIA sets were distinguished from 142 FIAs measured in garnet, staurolite, plagioclase and andalusite porphyroblasts (Table 1) preserved in 79 spatially oriented samples. The FIA trend was determined for each sample by locating the axis about which the asymmetry switches of inclusion trails preserved in porphyroblasts (see for detail Hayward, 1990; Sayab, 2008; Yeh, 2007 and the references therein). The flip in asymmetry was initially observed in a series of six vertical thin sections cut from a horizontal block at $30^o$ interval around the compass (Fig. 4). Two more vertical thin sections were cut $10^o$ apart where this flip occurred. For each extra FIA found within a sample another two thin sections $10^o$ apart were cut. The FIA was taken halfway between the two thin sections between which the asymmetry flipped except where both asymmetries (clockwise and anticlockwise) were equally present in a single thin section. In the latter case the FIA trend coincided with that section orientation.

The Balcooma Metamorphic Group preserves a spectacular progression of metamorphic mineral phases that reveal a lengthy history of deformation and metamorphism (Van der Hor, 1990; Ali, 2009C). Two of the FIA sets are defined by inclusion trails that are always truncated by the matrix foliation (Fig. 5a), the third and fourth are locally truncated whereas the fifth is always continuous with the matrix (Fig. 5b), indicating that the former formed earlier than the latter. All garnet porphyroblasts contain inclusion trails truncated by the matrix foliation and define a single FIA set. Garnet porphyroblasts are commonly preserved as inclusions within biotite, muscovite, staurolite, kyanite, plagioclase, andalusite and cordierite porphyroblasts. The latter FIA trend is only preserved within staurolite porphyroblasts. These 2 FIAs are designated FIA sets 1 and 2. FIA set 3 is preserved in staurolite and plagioclase porphyroblasts. FIA set 4, which is very locally developed in the northern portion of the Balcooma Metamorphic Group, is predominantly preserved in the rims of FIAs 2 and 3 staurolites. FIA 4 appears to have resulted from the overprinting of a well developed horizontal foliation (Figs. 6 and 7). FIA set 5 is preserved in andalusite porphyroblasts that commonly also incorporate biotite, garnet, staurolite, plagioclase, kyanite and little disturbed matrix and was thus the final FIA set to form (FIA 5; Vander Hor, 1990). These five FIA sets and their four dominant peaks with W-E, NNW-SSE, NNE - SSW and NE-SW are shown in (Fig. 8).

## 6. Sulphide inclusions within porphyroblasts

At least 6 different sulphide ore minerals have been observed in the matrix and as inclusions within porphyroblasts in oriented polished thin sections using reflected light microscopy and the electron microprobe. The sulphide minerals consist of pyrite, pyrrhotite, chalcopyrite, sphalerite, galena and Cd-sulphide (Hawleyite, Fig. 9). Pyrite, pyrrhotite and chalcopyrite are the most abundant, with sphalerite and galena much less common, both in the matrix and as inclusions within porphyroblasts of different generations. Porphyroblasts containing FIAs 2, 3, 4 and 5 have inclusions of sulphide ore minerals (Fig. 10). However, porphyroblasts containing FIA 1, which consist of garnet, do not contain sulphide inclusions. The only opaque incorporated as inclusions in porphyroblasts containing FIA 1 is ilmenite. Only two examples of sulphides were found in a porphyroblasts containing FIA 1 and both of them lay on younger fractures (Fig. 11).

## 7. Micro-geochronology via monazite dating

### 7.1. Analytical procedures for Th-U-Pb monazite dating

Monazite ages were determined using a JEOL JXA-8200 Electron Probe Micro Analyser (EPMA) at the Advanced Analytical Centre, James Cook University. The analytical set up for monazite identification is given in Table 2. An accelerating voltage of 15kV, beam current 200nA and a spot size of 1 micron were used. Analyses were made in step traverses across polished monazite grains. Matrix corrections were undertaken using the PAP method

(Pouchou & Pichoir, 1984, 1985). Interference corrections for Th and Y on Pb and Th on U were used as in Pyle et al., (2002). Monazite from Manangotry, Madagascar (545±2Ma; Paquette et al., 1984) was used as an internal age standard calibration, five times before and after each analytical sitting. The X-ray lines $M_\alpha$ are used for Th and Pb, $M_\beta$ for U and $L_\alpha$ for Y. Weighted means and probability plots were obtained using Isoplot/Ex (Ludwig, 2001). Ages calculated for monazite grains in each thin section have been reported in Table 3 and 4 at the $2\sigma$ level of confidence, while adopting the statistical method of Montel et al., (1996). Electron microprobe chemical analyses and calculated ages for each spot on a monazite grain are shown in the appendix-B (Section-B).

### 7.2. Identification of structural domains for monazite grain correlation and results

A total of 320 spots on 55 monazite grains were analysed and (Table 3 and 4). Separation of different generations of monazite grains in a rock provides important insights into the tectonic, structural and metamorphic interpretations (William & Jercinovic 2002). In this study all the monazite grains were analysed after identifying them within a particular FIA set. The succession of FIA sets provides an efficient tool for choosing structural domains for age analysis using monazite grains, which formed over the same period of time. The probability density plots and histograms for each FIA set are shown in Figure 12. The locations for monazite grain analyses relative to inclusion trails associated with FIA sets, fractures and matrix were specified on a petrographic microscope and then examined using backscattered electron microscopy. U-Th-Pb concentration measurements were made in detailed step traverses across in-situ polished monazite grains to calculate an average age for each monazite grain and to locate different age and compositional domains. Most grains preserved in porphyroblasts appeared homogeneous as shown in Figure 13.

Samples AA7 and AA23 contain FIAs 1 and 2 in garnet and staurolite porphyroblasts respectively. Inclusion trails preserved in both porphyroblasts are truncated by the matrix. Garnet is commonly included in staurolite in these samples. Analyses of 90 spots on 24 monazite grains from staurolite containing FIA 2 have a weighted mean age 443.2±3.8 Ma. Monazite grains from the matrix in sample AA7 have weighted mean ages of 419 ± 17, 444± 15 and 426±10 Ma (Table 4). Matrix monazite grains in sample AA23 have weighted mean ages of 425± 11, 424±18 and 427±14 Ma (Table 4).

Samples AA6, AH46, AH 77 and AH120 contain FIA 1 in garnet and FIA 3 in staurolite. In addition to FIA 1 and FIA3, sample AA6 contains FIA 5 in andalusite and sample AH 120 contains FIA 4 in the rim of staurolite. Analyses of 110 spots on 15 monazite grains within the staurolite have a weighted mean age of 425.4±3.7 Ma. One monazite grain was found inside garnet on a fracture (Fig. 14). Analyses of 9 spots from this grain have a weighted mean age of 406 ± 12 Ma. Monazite matrix grains from sample AA6 have weighted mean ages of 418±13 and 431±7 Ma (Table 4). FIA 4 in the rim of staurolite porphyroblasts in sample AH120 have a weighted mean age of 408.8± 8.9 Ma from 14 spot analyses on 2 monazite grains. Monazite matrix grains from sample AH120 yielded a weighted mean age of 415±15 Ma.

No Monazite grain was found in porphyroblasts of samples AH 145, AH 137 and AH 143. However, monazite in the matrix of sample AH145 yielded weighted mean ages of 419±12, 424±19 and 426±10 Ma (Table 4). Monazite grains in the matrix of sample AH137 have a weighted mean age of 423± 10 Ma. Sample AH 145 and AH 137 staurolite porphyroblasts contain FIA 3. Sample AH 143 contains FIA 1 and FIA3. Analyses of 11 spots on 1 monazite grain in the matrix of this sample yielded a weighted mean age of 454 ± 12 Ma (Table 4). Where andalusite is present, which is the mineral phase containing the youngest FIA, it always overgrows the matrix.

## 8. Interpretation and discussion

### 8.1. The FIA age succession

FIA 1 could not be dated. The age of monazites preserved in porphyroblasts containing FIAs 2, 3 and 4, at 443.2±3.8 Ma, 425.4±3.7 Ma and 408.8± 8.9 Ma respectively Table 3, reveal that deformation was episodic in the Greenvale Province.

### 8.2. Deformation and metamorphism across the Greenvale Province

The Greenvale Province is comprised of Early Palaeozoic metamorphics (Withnall et al., 1991; Fergusson et al., 2007b). The Lynd Mylonite Zone separates Greenvale Province rocks from the Georgetown Province. The Halls Reward Metamorphics form an eastern bounding strip to the Province (Fig. 2). Fergusson et al. (2007b) divided the Early Palaeozoic Greenvale Province from west to east into the Lynd, Balcooma, Lucky Creek, Paddys Creek and the Halls Reward metamorphic domains according to lithostratigraphy, geochronology, structure and deformation history across a W-E transect through the region (Fig. 15). Each of these domains experienced up to 4 deformation phases. The reactivation and rotation of foliations to a steeper orientation has been attributed to the Early Silurian Benambran Orogeny (Fergusson et al., 2005, Fergusson et al., 2007b). A steeply dipping intense foliation ($S_2$) in the Oasis Metamorphics, Balcooma Metamorphic and Lucky Creek Metamorphic Groups has been correlated with a low to sub-horizontal foliation in the Paddys Creek domain (Fig. 15, Fergusson et al., 2007b).

The succession of 5 FIA trends in the Balcooma domain indicates changes in the direction of bulk shortening from N-S to ENE-WSW to ESE-WNW to N-S to NW-SE during 5 main periods of tectonism. The E-W FIA set 1 and NNW-SSE FIA set 2 predates the overall NNE trending tectonic grain of the Greenvale Province. However, ENE-WSW crustal shorting during the Benambran Orogeny from 440-420 Ma formed the regional NNE fabric in the Oasis and Balcooma Metamorphic Group and is preserved in staurolite and plagioclase as FIA 3. This is consistent with the monazite dates associated with FIA set 3 (425.4±3.7 Ma). N-S shortening occurred before 443.2±3.8 Ma.

Partitioning of deformation across an orogen occurs heterogeneously at all scales during orogenesis and the timing of metamorphism and the P-T-t-D paths of the rocks can differ from place to place (Bell & Mares, 1999; Bell et al., 2004; Bell, 2009). For example, FIA 4, which formed during N-S shortening, is unevenly distributed and was observed only in the northern portion of the Balcooma Metamorphic Group (Fig. 16a). FIA 5 appears to have a very heterogeneous distribution in the Balcooma domain (Fig. 16b). It was the last FIA to form in this region and is also present in the matrix. The deformation event, which developed FIA 5 in the Balcooma Metamorphic Group is absent from the matrix in the Oasis Metamorphics but locally present in the matrix of the remaining domains of the Greenvale Province (c.f. Huston, 1990; Fergusson et al., 2007b).

### 8.3. Regional tectonic implications

The Oasis Metamorphics and Lynwater complex were previously regarded as a part of the Palaeoproterozoic-Mesoproterozoic Einasleigh Metamorphics (Withnall, 1989; Withnall et al., 1997). However, detrital zircons within them have Late Neoproterozoic to Early Palaeozoic depositional ages (Fergusson et al., 2007b). SHRIMP U-Pb zircon rim weighted mean age of 476±5 Ma for the Oasis Metamorphics and 486±5, 477±6 Ma ages for syntectonic granitoids intrusions in the Lynwater Complex confirm the initiation of amphibolite facies metamorphism in the region (Fergusson et al., 2007b). The Halls Reward Metamorphics were similarly interpreted to be Proterozoic craton (Withnall, 1989). However, Rb-Sr dating by Nishiya et al. (2003) of whole rock muscovite (500Ma), K-Ar dating of muscovite (500Ma) and U-Th-Pb chemical dating of crystallized monazite (510Ma) indicate that the Halls Reward Metamorphics were affected by the early Palaeozoic Delamerian Orogeny along the active margin of the Gondwana. A Cambrian to Early Ordovician age for the “primary subduction related arc volcanics” and metasediments in the Balcooma Metavolcanic Group and the Lucky Creek Metamorphics has been inferred using U-Pb zircon ages (Withnall et al., 1991; Fergusson et al., 2007b). 476±5-486±5-477±6 Ma U-Pb zircon ages (Fergusson et al., 2007b) and 471±4, 478±5 SHRIMP zircon ages (Withnall et al., 1991) indicate $D_1$ amphibolite facies metamorphism and accompanied intrusions at this time across the Greenvale Province orogenic belt respectively. The earliest phase of monazite growth within the Balcooma Metavolcanic Group at 454 ± 12 Ma in the matrix and the age of monazites preserved in porphyroblasts containing FIAs 2, 3 and 4 indicate that this part of the Greenvale Province was affected by an Early Ordovician and later overprinted by the Benambran Orogenies and possibly by the start of the Tabberaberan Orogeny. The orientation of FIA set 1 and the above ages indicates that the Greenvale Province was not affected by the Delamerian Orogeny. Combining all this data for the Greenvale Province suggest that the post Tabberabberan Orogenic cycles such as the Kanimblan and Hunter-Bowen have not affected the Greenvale Province (see below).

### 8.4. Deformation partitioning between the Greenvale, Broken River and Charters Towers Provinces

All regions were affected by the Benambran (440-420 Ma) Orogeny. A possibility for a role for the Tabberaberan Orogeny (410-370 Ma) in the Greenvale Province was not previously recognized although it is important in the Charters Towers Province (Quentin, pers comm. 2009). A regional basement-cover unconformity to the east of the Greenvale Province in the Broken River Province separates rocks intensely deformed during the Benambran (440-420 Ma) and Tabberaberan (410-370 Ma) Orogenies from a thick (~ 8km) Late Silurian to Late

Devonian sedimentary cover succession (c.f. Henderson, 1980; Henderson, 1987; Withnall, 1989). This succession was affected by Kanimblan (360-320 Ma) contractional deformation in the region (Fig. 2; Henderson, 1987). The Devonian and Early Carboniferous rocks in the Charters Towers and Hodgkinson Provinces were similarly affected by this Orogeny. However, the Kanimblan Orogeny did not affect the rocks in the Greenvale province. This is revealed by monazite dating constraints from this study (454 ± 12 Ma to 406 ± 12 Ma) and the uncleaved Emsian age (400-392 Ma) marine rocks of the Conjuboy Formation (Huston 1990; Fergusson et al., 2007b). Deformation was thus widespread in the Benambran Orogeny, preferentially partitioned into the Greenvale province during the start of the Tabberaberan orogeny, but not partitioned into this region during the Kanimblan Orogeny possibly because of major faults that bounded these regions (Figs. 2 and 15).

### 8.5. Effects of alteration and fractures on monazite dating

The presence of monazite inclusions in porphyroblasts and their precise analysis by an electron microprobe is a powerful tool for microstructural, metamorphic and tectonic analyses (Suzuki & Adachi, 1991; Suzuki et al., 1994; Bell & Welch, 2002; Williams & Jercinovic, 2002) especially since monazite grains less than 3 microns in size can be dated (Crowley & Ghent, 1999; Williams et al., 2006). Measuring monazite ages from fractured or altered porphyroblasts can yield younger ages due to subsequent deformation, metamorphism, dissolution, isotopic resetting and induction of hydrothermal solutions in the surrounding matrix (c.f. Gibson et al., 2004; Forbes et al., 2007). For example, analysis of 9 spots on 1 monazite grain from a fractured garnet in sample AA6, which contains inclusion trails defining FIA 1 (>443.2±3.8 Ma), yielded a young weighted mean age of 406 ± 12 Ma (Fig.14). Therefore, the establishment of clear connection between monazite grains and their textural setting is vital in a sample for precise conclusions.

### 8.6. Sulphide mineralization in the Balcooma Metamorphic Group

The Balcooma region consists of three massive sulphide deposits, the Balcooma, Surveyor and Dry River South deposits with the first of these being the largest. The mineralization at Balcooma consists of massive pyrite-chalcopyrite, massive magnetite and massive pyrite-sphalerite-galena. According to Huston (1990), sulphide lenses occupy the core of a $D_2$ antiform due to mechanical remobilization (ductile flow) of the sulphides during $D_2$ and $D_3$. Any primary syngenetic depositional character for the 5 bodies of sulphide mineralization hosted by the Clayhole Schist at Balcooma has been obliterated by younger deformation, but Huston (1990) suggested that sulphides were present syn or pre $D_2$. At that time, the nature of the sulphide mineralization was controversial due to the structural complexity and lack of underground exposure of the orebody (Withnall et al. 1991). Underground exposure is now available and this study is constrained by the collection of data from oriented core samples drilled through the orebody. The presence of sulphide inclusions in porphyroblasts containing FIAs 2, 3, 4, 5 and in the matrix but not in porphyroblasts containing FIA 1 is significant. Sulphides are generally aligned parallel to the cleavage trapped in porphyroblasts that formed from FIA 2 onwards and in the matrix. FIA 1 is preserved in rocks that spread throughout the Balcooma Metamorphic Group. The lack of sulphides in porphyroblast that formed during FIA 1 strongly suggests that the lenses of ore were emplaced into their current location along foliations, faults or thrusts after the development of FIA 1. This would help resolve the distribution of ore lenses, which currently make no sense in terms of redistribution from a primary volcanogenic massive sulphide body. Alternatively, the absence of sulphides in FIA 1 garnets suggests that no sulphides were present at all in the study area during FIA 1. Otherwise, sulphides would have been partially dissolved, transported along foliations, and included in garnets. The sulphides must have been introduced from elsewhere after FIA 1 along faults, thrusts or shear zones (either mechanically or dissolved). This may be related to the ~ 200 km northward transport of the study area along steep shear zones during the development of FIA 2 and FIA 3 as proposed in section D. They could still have come from host rocks present within the same stratigraphic sequence.

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## References

Ali, A., 2009 C. The tectono-metamorphic evolution of the Balcooma complex, northeastern Australia; a multidisciplinary approach.

Ali, A., 2009 D. W-E trending Ordovician orogenesis in Northern Australia: an example of changes in orogenic behaviour across an Euler pole?

Bell, T. H. & Mares, V. M., 1999. Correlating deformation and metamorphism around arcs in orogens. *American Mineralogist* **84**, 1727-1740.

Bell, T.H. & Welch, P.W., 2002. Prolonged Acadian orogenesis: revelations from foliation intersection axis (FIA) controlled monazite dating of foliations in porphyroblasts and matrix. *American Journal of Science* **302**, 549-581.

Bell, T.H. & Chen, A., 2002. The development of Spiral-shaped inclusion trails during multiple metamorphism and folding. *Journal of Metamorphic Geology* **20**, 397-412.

Bell, T.H., Ham, A.P. & Kim, H.S., 2004. Partitioning of deformation along an orogen and its effects on porphyroblast growth during orogenesis. *Journal of Structural Geology* **26**, 825-84

Bell, T. H. & Newman, R., 2006. Appalachian orogenesis: the role of repeated gravitational collapse. In: Butler, R., Mazzoli, S. (Eds.), Styles of Continental Compression. *Special Papers of the Geological Society of America* **414**, 95-118.

Bell, T.H., 2009. Deformation partitioning, foliation successions and their significance for orogenesis: hiding lengthy deformation histories in mylonites. In: Law, R.D., Butler, R.W.H., Holdsworth, R., Krabendam, M. & Strachan R. (eds) Continental Tectonics and Mountain Building: The Legacy of Peach and Horne. *Geological Society, London, Special Publications*, **in press** (accepted Dec 24, 2008).

Bain, J. H. C., Machenzie, D. E., Withnall, I.W. & Champion D. C., 1997. Silurian-Devonian. In: Bain J.H.C. and Draper J.J. eds. North Queensland Geology, pp. 35-36.*Australian geological Survey Organisation Bulletin 240 and Queensland Geology* **9**.

Boger, S. D. & Miller, J. McL., 2004. Terminal suturing of Gondwana and the onset of the Ross-Delamerian Orogeny: the cause and effect of an Early Cambrian reconfiguration of plate motions. *Earth and Planetary Sciences Letters* **219**, 35-48.

Braun, I., Montel, J.-M. & Nicollet, C., 1998. Electron microprobe dating of monazites from high-grade gneisses and pegmatites of the Kerala Khondalite Belt, southern India. *Chemical Geology* **146**, 65–85.

Braun, J. & Shaw, R., 2001. A thin-plate model of Palaeozoic deformation of the Australian lithosphere: implications for understanding the dynamics of intracratonic deformation. In: Miller J. A., Holdsworth R. E., Buick I. S. and Hand M. eds.

Continental Reactivation and Reworking. G*eological Society of London Special Publication* **184**, 165-193.

Cihan, M. & Parsons, A., 2005. The use of porphyroblasts to resolve the history of macro-scale structures: an example from the Robertson River Metamorphics, North-Eastern Australia. *Journal of Structural Geology* **27**, 1027-1045.

Cihan, M., Evins, P.M., Lisowiec, N.J. & Blake K.L., 2006. Time constraints on deformation and metamorphism from EPMA dating of monazite in the Proterozoic Robertson River Metamorphics, NE Australia. *Precambrian Research* **145**, 1 – 23.

Crowley, J.L. & Ghent E.D., 1999. An electron microprobe study of the U–Th–Pb systematics of metamorphosed monazite: the role of Pb diffusion versus overgrowth and recrystallization. *Chemical Geology* **157**, 285–302.

Federico, L., Capponi, G., Crispini, L. & Bradshaw, J. D., 2006. The Ross - Delamerian Orogeny: a Cambrian belt along the paleo-pacific convergent margin of Gondwana. *Geophysical Research Abstracts European Geosciences Union* **8**, 00317.

Fergusson, C. L., Henderson, R. A., Lewthwaite, K. J., Phillips, D. & Withnall, I. W., 2005. Structure of the Early Palaeozoic Cape River Metamorphics, Tasmanides of north Queensland: evaluation of the roles of convergent and extensional tectonics. *Australian Journal of Earth Sciences* **52**, 261 – 277.

Fergusson, C.L., Henderson, R.A., Withnall, I.W., Fanning, C.M. & Phillips, D., 2007a. Structural, metamorphic, and geochronological constraints on alternating compression and extension in the Early Palaeozoic Gondwanan Pacific margin, northeastern Australia. *Tectonics* **26**, 1-20.

Fergusson, C. L., Henderson, R. A., Withnall, I. W. & Fanning, C.M., 2007b. Structural history of the Greenvale Province, north Queensland: Early Palaeozoic extension and convergence on the Pacific margin of Gondwana. *Australian Journal of Earth Sciences* **54**, *573-595.*

Fergusson, C. L., Henderson, R. A., Fanning, C.M. & Withnall, I. W., 2007c. Detrital Zircon ages in Neoproterozoic to Ordovician siliciclastic rocks, northeastern Australia: implications for the tectonic history of the East Gondwana continental margin. *Journal of the Geological Society of London* **164**, 215-225.

Forbes, C.J., Giles, D., Betts, P.G., Weinberg, R. & Kinny, P.D., 2007. Dating prograde amphibolite and granulite facies metamorphism using in situ monazite U-Pb SHRIMP analysis. *The journal of Geology* **115**, 691-705.

Gibson, H.D., Carr, S.D., Brown, R.L. & Hamilton, M.A., 2004. Correlations between chemical and age domains in monazite, and metamorphic reactions involving major pelitic phases: an integration of ID-TIMS and SHRIMP geochronology with Y-TH-U X-ray mapping. *Chemical Geology* **211**, 237-260.

Gray, D.R. & Foster, D.A., 2004. Tectonic evolution of the Lachlan Orogen, southeast Australia: historical review, data synthesis and modern perspectives. *Australian Journal of Earth Sciences* **51**, 773-817.

Hand, M., Mawby, J., Kinny, P. & Foden, J., 1999. U– Pb ages from the Harts Range, central Australia: Evidence for early Ordovician extension and constraints on Carboniferous metamorphism. *Journal of the Geological Society of London* **156**, 715-730.

Hayward, N., 1990. Determination of early fold axis orientations within multiply deformed rocks using porphyroblasts. *Tectonophysics* **179**, 353–369.

Henderson, R. A., 1980. Structural outline and summary geological history for northeastern Australia. In: Henderson R. A. & Stephenson P. J. eds. The Geology and Geophysics of Northeastern Australia, pp. 1 – 26. *Geological Society of Australia*, Queensland Division, Brisbane.

Henderson, R. A., 1986. Geology of the Mt Windsor Subprovince-A lower Palaeozoic volcano-sedimentary terrane in the northern Tasman Orogenic Zone. *Australian Journal of Earth Sciences* **33**, 343-364.

Henderson, R. A., 1987. An oblique subduction and transform faulting model for the evolution of the Broken River Province, northern Tasman Orogenic Zone. *Australian Journal of Earth Science* **34**, 237 – 249.

Henderson, R.A., 2007. Crustal history and tectonics of the northern Tasman Orogenic Zone. Unpublished Economic Geology Research Unit short course, James Cook University, 1-24.

Huston, D.l., 1990. The stratigraphic and structural setting of the Balcooma volcanogenic massive sulphide lenses, northern Queensland. *Australian Journal of Earth Sciences* **37**, 423-440.

Huston, D. L. & Taylor, T. W., 1990. Dry River copper and lead-zinc-copper deposits. In Hughes F. E. ed. Geology of the Mineral Deposits of Australia and Papua New Guinea. *Australasian Institute of Mining and Metallurgy*: **Melbourne**, 1519-1526.

Ludwig, K. R., 2001. Isoplot/Ex (rev 2.49): a geochronological toolkit for Microsoft Excel. Berkeley geochronology Centre Special Publication 1 (revised).

Montel, J.M., Foret, S., Veschambre, M., Nicollet, C. & Provost, A., 1996. Electron microprobe dating of monazite. *Chemical Geology* **131**, 37-53.

Nishiya, T., Watanabe, T., Yokoyama, K. & Kuramoto, Y., 2003.New isotopic constraints on the age of the Halls Reward Metamorphics, north Queensland, Australia: Delamerian metamorphic ages and Greenville detrital zircons. *Gondwana Research* **6**, 241-249.

Paquette, J.L., N´ed´elec, A., Moine, B. & Rakotondrazafy, M., 1984. U-Pb, single zircon Pb-evaporation, and Sm-Nd isotopic study of a granulite domain in SE Madagascar. *J. Geol.* **102**, 523–538.

Pouchou, J. L. & Pichoir, F., 1984. A new model for quantitative X-ray microanalysis. Part I: application to the analysis of homogeneous samples. *La Recherche Aerospatiale* **3**, 13–38.

Pouchou, J.L. & Pichoir, F., 1985. “PAP” phi-rho-Z procedure for improved quantitative microanalysis. In: Armstrong, J.L., Editor, 1985. Microbeam Analysis, San Francisco Press Inc, San Francisco, pp. 104–106.

Powell, C. McA, Li, Z. X., Thrupp, G. A. & Schmidt P. W., 1990. Australian Palaeozoic palaeomagnetism and tectonics-I. Tectonostratigraphic terrane constraints from the Tasman Fold Belt. *Journal of Structural Geology* **12**, 553-565.

Pyle, J.M., Spear, F.S., Rudnick, R.I. & McDonough, W.F., 2002. Monazite-xenotime-garnet equilibrium in metapelites and a new monazite garnet thermometer. *Journal of Petrology* **42**, 2083-2107.

Rea, P.S. & Close, R.J., 1998. Surveyor 1 copper-lead-zinc-silver-gold deposit. The Australian Institute of Mining and Metallurgy: **Melbourne**, pp. 737- 742.

Sayab, M., 2008. Correlating multiple deformation events across the Mesoproterozoic NE Australia using foliation intersection axes (FIA) preserved within porphyroblasts. *Gondwana Research* **13**, 331-351.

Suzuki, K. & Adachi, K., 1991. Precambrian provenance and Silurian metamorphism of the Tsunosawa paragneiss in the South Kitakami terrane, Northeast Japan, revealed by the chemical Th–U-total Pb-isochron ages of monazite, zircon and xenotime. *Geochem. J.* **25**, 357–376.

Suzuki, K. & Adachi, M., 1994. Middle Precambrian detrital monazite and zircon from the Hida gneiss on Oki-Dogo Island, Japan: their origin and implications for the correlation of basement gneiss of Southwest Japan and Korea. *Tectonophysics* **235**, 277–292.

Vander, Hor F., 1990. Structural geology of the Balcooma-Dry River area, northeast Australia, with emphasis on the inter-relation between deformation and metamorphism. *PhD thesis, James Cook University Australia*, pp.139**.**

Vandenberg, A. H. M., Willman, C. E., Maher, S., Simons, B. A., Cayley R. A., Taylor, D. H., Morand, V. J., Moore, D. H. & Radojkovic A., 2000. The Tasman Fold Belt System in Victoria. *Geological Survey of Victoria Special Publication.*

William, L. M. & Jercinovic, J.M., 2002. Microprobe monazite geochronology: putting absolute time into microstructural analysis. *Journal of Structural Geology* **24**, 1013-1028.

William, L. M., Jercinovic, J.M., Goncalves, P. & Mahan, K., 2006. Format and philosophy for collecting, compiling, and reporting microprobe monazite ages. *Chemical Geology* **225**, 1-15.

Withnall, I. W., 1989. Precambrian and Palaeozoic geology of the south-eastern Georgetown Inlier, North Queensland. *Queensland Department of Mines,* **Report 2**, 1-102.

Withnall, I. W., Black, L.P. & Harvey, K. J., 1991. Geology and geochronology of the Balcooma area: part of an early Palaeozoic magmatic belt in north Queensland, Australia. *Australian Journal of Earth Sciences* **38**, 15-29.

Withnall, I. W., Golding, S. D., Rees, I. D. & Dobos, S. K., 1996. K– Ar dating of the Anakie Metamorphic Group: evidence for an extension of the Delamerian Orogeny into central Queensland. *Australian Journal of Earth Sciences* **43**, 567 – 572.

Withnall, I. W., Hutton, L. J., Garrad, P. D. & Rienks, I. P., 1997. Pre-Silurian rocks of the Lolworth-Pentland area, North Queensland. Queensland Geological Record 1997/6.

Yeh, M.W., 2007. Deformation sequence of Baltimore gneiss domes, USA, assessed from porphyroblast Foliation Intersection Axes. *Journal of Structural Geology* **29**, 881-897.

# Section C:

# Tectono-metamorphic evolution of the Balcooma Metamorphic Group, northeastern Australia; a multidisciplinary approach

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## Abstract

The sequential growth of biotite, garnet, staurolite, kyanite, andalusite, cordierite and fibrolitic sillimanite, their microstructural relationships, Foliation Intersection Axes preserved in porphyroblasts (FIAs), P-T conditions of garnet core growth, P-T pseudosection (MnNCKFMASH system) modeling and geothermobarometry provide evidence for a P-T-t-D path that changes from clockwise to anticlockwise with time for the Balcooma Metamorphic Group. Growth of garnet at approximately 530°C and 4.6±0.1kbar during the N-S shortening event that formed FIA 1 was followed by staurolite, plagioclase and kyanite growth. The inclusions of garnets in staurolite porphyroblasts that formed during the development of FIAs 2 and 3 plus kyanite growth during FIA 3 reflect continuous crustal thickening from ~ 443.2Ma to 425.4Ma during the Early Silurian Benambran period of orogeny. The temperature and pressure increased during this time from ~530°C and 4.6±0.1kbar to 623-637°C and 6.2±0.3kbar. The overprinting of garnet, staurolite and kyanite bearing mineral assemblages by low-pressure andalusite and cordierite assemblages implies ~ 4kbar decompression in the belt during Early Devonian exhumation of the Greenvale Province. P-T pseudosection constraints, textural relationships and relative deformation features for rocks containing all three $Al_2SiO_5$ polymorphs suggest a kyanite-andalusite-sillimanite crystallization sequence in separate tectonic events rather than synchronous nucleation at the aluminosillicate triple point.

**Key words:**

FIAs; MnNCKFMASH; geothermobarometry; pseudosections; $Al_2SiO_5$ triple point

## 1: Introduction

Pressure-temperature pseudosections show the stability fields of mineral assemblages of pelitic rocks in P-T space for a given rock bulk-composition (Tinkham & Ghent, 2005;

White et al., 2008). Delineating a P-T path on such pseudosections for multiply deformed rocks requires quantitative knowledge of porphyroblast microstructures, mineral assemblages, textural relationships and conventional geothermobarometry (Pattison, 2001; Zeh & Holness, 2003; Johnson & Brown, 2004; Zeh et al., 2005; Tinkham & Ghent, 2005; Rubenach et al., 2008; Powell & Holland, 2008; Vernon et al., 2008; White et al., 2008). To fully achieve this is difficult.

With the development of a method for routinely measuring FIAs (foliation intersection/inflection axes preserved within porphyroblasts) it was realized that various generations of porphyroblast growth along the P-T path could be quantitatively distinguished (Kim & Bell, 2005; Sayab, 2006). Successions of FIAs allow the PT path to be directly connected to bulk movement directions in the earth's crust both in terms of directions of relative plate motion and shear sense (Bell & Newman, 2006). Furthermore, they allow successive stages along the path to be dated using monazite grains present as inclusions amongst the foliations defining each of the FIAs in a succession (e.g., Bell & Welch, 2002; Cihan et al., 2006). This paper uses porphyroblasts, microtextures, FIAs, conventional geothermobarometry and garnet $X_{Mn}$, $X_{Fe}$ and $X_{Ca}$ isopleth intersections on P-T pseudosections to deduce the tectono-metamorphic evolution and P-T-t-D path of the Balcooma Metamorphic Group in Lower Palaeozoic rocks that border the Precambrian of northeastern Australia.

## 2: Regional geological background

The Early Paleozoic Greenvale Province, north Queensland, eastern Australia is divided into the Lynd, Balcooma, Lucky Creek, Paddys Creek and the Halls Reward metamorphic domains (Fig. 1; Withnall, 1989; Withnall et al., 1997; Fergusson et al., 2007a). SHRIMP U-Pb metamorphic zircon rim weighted mean ages of 476±5 Ma and 486±5, 478±5, 477±6, 471±4 Ma (Withnall et al., 1991; Fergusson et al., 2007a) indicate D1 amphibolite facies metamorphism accompanied granitoid intrusion during the Early Ordovician across the Greenvale Province. A Rb-Sr whole rock isotopic age of 408±6 Ma has been obtained for the youngest folding event in the Balcooma Metamorphic Group (Van Der Hor, 1990; Withnall et al., 1991).

The Balcooma Metamorphic Group crops out in the western part of the Greenvale Province (Fig. 2) and consists of multiply deformed metasedimentary (Ordovician Clayhole Schist) and felsic metavolcanics rocks (rhyolitic to rhyo-dacitic in composition; Huston, 1990). The metasedimentary sequence was divided into three units by Huston (1990). Quartz-albite-biotite schist is overlain by staurolite schist, which is overlain by quartz-muscovite-biotite schist. The lower and upper units are fine grained and rarely contain staurolite porphyroblasts. The middle unit is dominated by staurolite and biotite porphyroblasts with locally present garnet, andalusite, kyanite, and cordierite porphyroblasts and fibrolitic sillimanite. It hosts the Balcooma Cu, Zn and Pb massive sulphide deposit. The metavolcanic rocks, which are up to 3 km thick, consist of several volcaniclastic lenses that are abundant within the lower unit of quartz-albite-biotite schist and lower part of the staurolite bearing schist (Huston, 1990). They contain phenocrysts of quartz, plagioclase and K-feldspar in a very fine ground mass of feldspar and quartz with lesser muscovite and biotite (Withnall et al., 1991).

The Balcooma Metamorphic Group is intruded by the Late Ordovician fine-grained felsic Ringwood Park Microgranite and the Early Silurian medium to coarse grained biotite and biotite-hornblende bearing Dido Tonalite pluton (Huston, 1990; Withnall et al., 1991). The Dido Tonalite has U-Pb Zircon age of 431±7 Ma (Bain et al., 1997). The Balcooma Metamorphic Group is bound on the east by the Dido Tonalite and on the west by the quartz-feldspar porphyry Dry River Volcanics (Fig. 2). Both the Ringwood Park Microgranite and the Dido Tonalite have been affected by the Early Silurian W-E contractional Benambran

Orogenic event (Fergusson et al., 2007a). The Dido Tonalite was emplaced synchronous with the Benambran Orogenic event (Withnall et al., 1991; Fergusson et al., 2007a). The majority of porphyroblast growth and deformation in the region has been related to the emplacement of the Early Silurian Dido Tonalite (Withnall et al., 1991). These multiply deformed rocks are unconformably overlain by uncleaved Emsian age (400-392 Ma) marine rocks of the Conjuboy Formation. A 0.1 $km^2$ outcrop of this formation is exposed 2 km to the northeast of the Balcooma Cu, Zn and Pb massive sulphide deposit (Fig. 2, Huston, 1990; Withnall et al., 1991). Therefore, cleavage development in the Balcooma Metamorphic Group must be pre-Emsian (Huston, 1990; Van Der Hor, 1990; Withnall et al., 1991; Fergusson et al., 2007a).

Five microscopic, mesoscopic to macroscopic deformation events ($D_1$ to $D_5$) have been recognized in these rocks (Huston, 1990; Van Der Hor, 1990; Withnall et al., 1991; Ali, 2009a). An early $S_1$ foliation that is only preserved in garnet porphyroblasts has been obliterated by $S_2$ foliation in the region (Huston, 1990; Van Der Hor, 1990; Ali, 2009a). $D_2$ developed pervasive $S_2$ across the Balcooma region; the presence of $S_2$ was recognized by Huston (1990). $D_3$ generated a NNE trending subvertical $S_3$ and crenulated $S_2$ across the region. The folds related to $D_2$ are tight to isoclinal while those related to $D_3$ are upright and open. $D_4$ produced an easterly trending $S_4$ cleavage, which crenulates both $S_3$ and $S_2$. Crustal thickening during $D_3$ was followed by $D_4$ decompression (Van Der Hor, 1990). $D_3$ was characterized by kyanite and staurolite growth. The regional scale structures were mainly developed during the $D_4$ and $D_5$ deformation events (Huston & Taylor, 1990; Van Der Hor, 1990; Rea & Close 1998). The $D_5$ folding event is penetrative in the Greenvale Province. Van Der Hor (1990) derived an early clockwise medium pressure P-T-t-D path for the Balcooma Metamorphic Group followed by anticlockwise path during $D_5$ by reheating at lower pressure to metamorphic peak conditions of 575±25°C and 3±0.5 kbar.

Deformation and metamorphic evidence preserved in porphyroblasts show a crystallization sequence of chlorite, muscovite, biotite, garnet, staurolite, kyanite, plagioclase, andalusite, cordierite and fibrolitic sillimanite (Huston, 1990; Van Der Hor, 1990). This extensive sequence of metamorphic index minerals, all of which occur in a restricted area, results in this being a superb location for the examination of the inter-relationships between metamorphism, deformation and tectonics.

## 3: Petrography and textural relationships

Petrographic and textural observations from 79 samples collected from the Ordovician Clayhole Schist in the Balcooma Region (Fig. 2) show that the Balcooma metapelitic rocks consist of biotite, muscovite, staurolite, andalusite, garnet, plagioclase, kyanite, cordierite and fibrolitic sillimanite (in order of relative abundance).

### 3.1: Garnet

Most garnet overgrown by other porphyroblasts is euhedral whereas those in the matrix have rounded edges against the younger foliations defined by biotite and muscovite folia. Inclusions in garnet are primarily elongate shaped quartz grains with minor chlorite, biotite, muscovite, plagioclase and ilmenite. Plagioclase inclusions in garnet were detected using an Electron Probe Micro Analyser. Garnet porphyroblasts have sigmoidal inclusion trails that are orientated at a steep angle to the matrix foliation (Fig. 5 in Ali, 2009A). The quartz inclusions are much smaller than similar grains in the matrix. Most of garnet is extensively replaced by staurolite (e.g. Fig. 3).

### 3.2: Staurolite

Staurolite porphyroblasts are poikiloblastic, idiomorphic, large in size (up to 3cm) and preserve inclusions of chlorite, muscovite, biotite, garnet, ilmenite and sulphides (pyrite, pyrrhotite and chalcopyrite). After biotite, staurolite is the most abundant porphyroblastic phase in the region. Staurolite, kyanite and andalusite pseudomorphs after biotite and muscovite occur across the region (Fig. 4).

### 3.3: Kyanite

Kyanite porphyroblasts are large in size (up to 1cm). Staurolite grew both before and after kyanite (see below) and locally replaces it (Fig. 5). Most kyanite porphyroblasts are rimmed by muscovite.

### 3.4: Plagioclase

Plagioclase porphyroblasts are sub-idiomorphic and contains inclusions of quartz, chlorite, biotite, muscovite and garnet. Plagioclase pseudomorphs after muscovite are common (Fig.6).

### 3.5: Andalusite

Andalusite is highly poikiloblastic, large in size and the internal foliations are identical to the external foliations in the matrix (Fig.6 in Ali, 2009A). The matrix schistosity is not deflected around the andalusite porphyroblasts. Andalusite contains inclusions of quartz, biotite, muscovite, garnet, plagioclase, staurolite and kyanite and appears to replace biotite, staurolite and kyanite (Fig. 7a, b, c). Andalusite pseudomorphs after staurolite were locally observed and maintain the euhedral shape of staurolite (Fig. 8). The quartz, muscovite and biotite inclusions in andalusite resemble the surrounding matrix.

### 3.6: Cordierite

Oval-shaped cordierite porphyroblasts range in size from 0.5-3cm and contain the inclusions of garnet, staurolite, plagioclase, kyanite, andalusite, biotite and muscovite (Fig. 9a, b, c, d).

### 3.7: Fibrolitic sillimanite

Fibrolitic sillimanite, which always grows in biotite (Fig. 10a), commonly projects into andalusite, staurolite, plagioclase, kyanite or cordierite porphyroblasts (Fig. 10b, c). It is randomly oriented in large sprays and locally cross cuts the matrix.

### 3.8: Chlorite, biotite and muscovite

Chlorite inclusions occurs mainly in biotite and progressively less so in garnet, staurolite, plagioclase and kyanite. Biotite and muscovite mainly define the matrix foliations. Biotite is much more abundant than muscovite in all samples. Muscovite is generally finer grained than biotite.

## 4: FIA determination

A total of 700 vertical thin sections with different strikes were made from the above 79 porphyroblast bearing oriented samples. The vertical thin sections were used for FIA measurements, microstructural and petrographic observations. A FIA was determined for each porphyroblastic phase by locating the axis about which the asymmetry of foliations flips when one foliation overprinted another (for more detail see Hayward, 1990; Cihan, 2004). For FIA determinations, six vertical thin sections were initially cut at 30° intervals of strike. Two more vertical thin sections were cut at 10° intervals between the two sections where the flip of asymmetry occurred to constrain the FIA within a 10° range (Fig. 11). For each extra FIA found within a sample another two thin sections 10° apart were cut.

143 FIAs trending E-W, SSE-NNW, NNE-SSW and NE-SW were measured from 79 samples containing a range of garnet, staurolite, plagioclase, kyanite and andalusite porphyroblasts (Fig. 12; Table 1; Ali, 2009A). A progressively formed succession of FIAs 1 through 5 has been interpreted from these by Ali (2009A) using changes in FIA trend from the core to rim of porphyroblasts and whether the inclusion trails were truncated or continuous with the matrix foliation. The E-W trend of FIA 1, which was preserved only

within garnet porphyroblasts with inclusion trails always truncated by the matrix foliation, coincides with the trend of FIA 4. The latter FIA was only preserved in staurolite porphyroblasts that contain cores bearing FIA 2 and/or FIA 3. Furthermore, the foliations defining FIA 4 were always continuous with the matrix foliation (Ali, 2009A). The electron microprobe was used to date monazite grains preserved within porphyroblasts (Ali, 2009B) because a succession of FIA sets provides a completely independent and quantitative tool for choosing monazites of equivalent age (e.g., Bell & Welch, 2002; Cihan & Parsons, 2005). FIA 1 could not be dated because no monazite was observed in garnet porphyroblasts. The age of monazite grains preserved as inclusions in porphyroblasts containing FIAs 2, 3 and 4 were dated at 443.2±3.8 Ma, 425.4±3.7 Ma and 408.8± 8.9 Ma respectively (Ali, 2009B). Garnet porphyroblasts containing FIA 1 are commonly preserved as inclusions within staurolite containing FIAs 2, 3 and 4, as well as plagioclase, kyanite, andalusite and cordierite. The SSE-NNW trending FIA 2 was only observed in staurolite porphyroblasts containing inclusion trails that are truncated by the matrix foliation across the Balcooma Region (Ali, 2009A). The NNE-SSW trending FIA 3 is preserved in staurolite, plagioclase and kyanite (Ali 2009a). The inclusion trails preserved in porphyroblasts defining FIA 3 are continuous with or locally truncated by a well developed horizontal cleavage in the matrix. In most samples, kyanite porphyroblasts contain poorly preserved inclusion trails and are not present in the 8 or more thin sections of different orientation that were cut. In one sample (AH71), kyanite porphyroblasts with well-developed inclusion trails are present in each section cut and contain the FIA 3 trend at 10°. The E-W trending FIA 4 was only locally observed in the rims of staurolite porphyroblasts. The NE-SW trending FIA 5 was only measured in andalusite and the inclusion trails are continuous with and appear near identical to the surrounding matrix (Ali, 2009A).

## 5: Mineral Chemistry

For samples AH 105, AH 146 and AH 120 the composition of garnet, biotite, plagioclase, muscovite and staurolite within the matrix were analysed using a JEOL JXA-8200 Electron Probe Micro Analyser in order to be able to determine the geothermobarometry conditions (Tables 2 and 3; accelerating voltage of 15kv, beam current 20nA, 3µm and 1µm beam diameters were used for garnet cores and rims, respectively). Each analysis in Table 2 is the average of five points analysed from the rim of each of the above minerals (Appendix-C).

Plagioclase in all samples lies in the range $An_{24-41}$ (oligoclase-andesine). The anorthite contents in samples AH 146 ($An_{31-41}$) and AH105 ($An_{32}$) are higher than AH 120 ($An_{24-27}$; Table 2; Appendix-C). The orthoclase content lies between 0.40 and 0.61 mol per cent. Ti, $Fe^{+2}$, Mn and Mg contents are negligible in all samples.

In biotite the octahedral sites are dominated by $Fe^{+2}$ (2.11-2.27 atoms p.f.u.) and Mg (2.42-2.62 atoms p.f.u.). Mn ranges from 0.02-0.03 atom p.f.u. Ti varies between 0.08 and 0.14 atoms p.f.u. Octahedral $Al^{Vi}$ (called Tschermak's substitution) ranging from 0.81-1.00 atoms p.f.u. The Mg/(Mg+Fe) and Fe/(Fe+Mg) ratios of biotite vary from 0.49 to 0.56 and 0.44 to 0.51 respectively. The interlayer sites in the analysed biotite in all samples are dominated by K (1.48-1.77 atoms p.f.u.) whereas the presence of Na does not exceed 0.11 atoms p.f.u. and the presence of Ca is negligible (Table 2; Appendix-C).

The concentration of $Al^{Vi}$ in the octahedral site of muscovite varies from 3.68-3.78 atoms p.f.u. 93.3% of the octahedral sites are filled by the Al on average while the remaining are comprised of $Fe^{+2}$ (4.34%), Mg (2.17%) and Ti (0.33%). The Mn content in all analysed muscovites is negligible. Na/K+Na ratios in muscovite range between 0.12 and 0.17; sample AH 120 contains the lowest ratio of 0.12/0.13. K/ (K+Na) ratios vary from 0.83 to 0.88 (Table 2 ; Appendix-C). The interlayer sites in all muscovites are dominated by K (1.32-1.66

atoms p.f.u). Na contents are in range of 0.20-0.32 atoms p.f.u. while Ca contents in interlayer sites are negligible (Table 2; Appendix-C).

The octahedral sites of staurolite are dominated by $Al^{Vi}$ (17.08-17.31 atoms p.f.u.), $Fe^{+2}$ (3.22-3.36 atoms p.f.u.), Mg (0.79-0.92 atom p.f.u.) and Ti (0.04-0.08 atoms p.f.u.) in order of relative abundance. Ca, Na and K contents are below detection level. The Fe/(Fe+Mg) ratios of staurolite vary between 0.75 and 0.78 with sample AH 105 the highest (Table 2; Appendix-C).

Generally garnet rims have 0.59-0.66 almandine ($X_{Fe}$), 0.15 to 0.20 spessartine ($X_{Mn}$), 0.10 to 0.13 pyrope ($X_{Mg}$) and 0.06 to 0.12 grossular ($X_{Ca}$) contents (Table 2; Appendix-C). Almandine is the most and grossular is the least common end member species in all analysed garnets. Ti, Na and K contents are negligible in all analysed garnets (Table 2; Appendix-C).

Chemical isolation of the garnet core in P-T space can be achieved using Ca, Mn and Fe isopleths (Vance & Mahar, 1998; Whitney & Bozkurt, 2002; Evans, 2004; Cihan et al., 2006; Sayab, 2006). Therefore, microprobe radial traverses were made across garnet grains to determine the best location for the core. In sample AH 146 the garnet core is enriched in Mn and Ca ($X_{Mn}$=0.21; $X_{Ca}$= 0.12) and depleted in Fe and Mg ($X_{Fe}$=0.57; $X_{Mg}$=0.09) and the rim is enriched in Fe and Mg ($X_{Fe}$=0.60; $X_{Mg}$=0.11) and depleted in Mn and Ca ($X_{Mn}$=0.17; $X_{Ca}$=0.10) contents (Fig. 13a; Table 3). In sample AH 120, reverse zonation was observed with the core enriched in Fe ($X_{Fe}$= 0.65) and Mg ($X_{Mg}$=0.12) and depleted in Mn ($X_{Mn}$=0.15) and Ca ($X_{Ca}$=0.05) and the rim enriched in Mn ($X_{Mn}$=0.0.17) and Ca ($X_{Ca}$=0.06) and depleted in Fe ($X_{Fe}$= 0.64) and Mg ($X_{Mg}$=0.11; Fig. 13b; Table 3). Another garnet from sample AH120 displays normal zoning in Fe and Mn but reverse in Ca. Ca depletes in core and increases gradually towards the middle before it depletes again in the rim (Fig. 13c; Table 3). The garnet core isopleth intersection method of Evans (2004) using the Mn, Fe and Ca isopleths was used to estimate the approximate P-T conditions at which the nucleation of this phase occurred. The values for garnet core nucleation were plotted on P-T pseudosections (see below) with uncertainties calculated with THERMOCALC (c.f. Tinkham & Ghent, 2005) indicated by different shading.

## 6: P-T pseudosections

P-T pseudosections were constructed for samples AH 146 and AH 120 to estimate P-T conditions for the Balcooma Metamorphic Group (Fig. 14). Major elements in these samples were determined using XRF at the Advanced Analytical Centre, James Cook University. Their bulk rock compositions are shown in Table 4. These samples were selected for P-T pseudosection modeling based on their mineralogy, textures and the range of FIAs. Samples AH 146 and AH 120 contain FIA 1 in garnet and FIA 3 in staurolite. Sample AH 120 also contains FIA 4 in the rim of some staurolite porphyroblasts. All the P-T pseudosections were calculated in the MnNCKFMASH (+Qtz+$H_2O$ in excess) system using THERMOCALC software (version 3.25; dataset file tcd55.txt 22 Nov 2003; Holland & Powell, 1998) and the activity models as in Tinkham et al. (2001) and White et al. (2001). Zoisite, chlorite, muscovite, biotite, plagioclase, garnet, staurolite, cordierite and all three aluminosillicates were the main phases used for these calculations. The MnNCKFMASH system was used because of the importance of MnO, $Na_2O$ and CaO for phase relations in pelitic rocks (see for more detail Tinkham et al., 2001; Johnson et al., 2003). The triple point was calculated at $550^{\circ}C$ and 4.4 ± 0.1 kbar.

## 7: Geothermometry and geobarometry

The average P-T mode of THERMOCALC (Powell & Holland 1994) was used to conduct thermobarometry calculations. This was done for samples AH 146, AH 120 and AH 105 using the bulk rock compositions and chemical analyses of minerals given in Tables 4 and 2. P-T graphs were plotted using the avept.xls program and dataset and the correlated uncertainties of Holland & Powell (1990, http://www.earth.ox.ac.uk/~davewa/pt/tools/avept.xls; Fig. 15). The average P-T mode of THERMOCALC was used after modeling oxide weight percent (Table 2) activities for garnet, biotite, muscovite, plagioclase and staurolite end-members with the Ax program of Holland (Table 5; 2004; http://www.esc.cam.ac.uk/astaff/holland/index.html). Averaging the five electron microprobe analyses from the rims of garnet, biotite muscovite, staurolite and plagioclase (Table 2) yielded a metamorphic temperature of 587±17°C at pressure 4.1± 0.4kbar for sample AH 146, 594±15°C and 4.0±0.4kbar for sample AH 120 and 573±11°C at 4.1±0.3kbar for sample AH 105 (using the average P-T mode of THERMOCALC). The P-T conditions plot within the sillimanite field and yield identical temperatures and pressures (within error).

## 8: Interpretation

Figure 14 shows the MnNCKFMASH phase equilibria for samples AH146 and AH 120. The inclusion trails in garnet in both samples, which define FIA 1, contain some chlorite, biotite, plagioclase and muscovite. The $X_{Mn}$, $X_{Fe}$, $X_{Ca}$ isopleth intersections in sample AH146 indicate that garnet first grew at ~530°C and 4.6±0.1kbar (Fig. 14). In sample AH 120, the $X_{Mn}$, $X_{Fe}$, $X_{Ca}$ isopleths did not intersect in a point. Therefore, they were not used for garnet core nucleation PT estimation; the reverse zonation in this sample suggests Fe-Ca-Mn diffusion and partial homogenization had occurred (Fig. 14; c.f. Evans, 2004; Kim & Bell, 2005).

The presence of garnet in staurolite porphyroblasts containing FIA 2 and in staurolite, plagioclase and kyanite porphyroblasts containing FIA 3 indicates a prograde P-T-t-D path from FIA 1 to FIA 3. FIA 4 was only observed in staurolite porphyroblasts. The P-T stability field of staurolite overlaps with the kyanite, sillimanite and andalusite P-T stability fields, and ranges from 548 to 633 °C and 3.3 to 8kbar. Andalusite porphyroblasts only contain FIA 5 and grew after staurolite growth ceased.

Pattison et al. (1999) and Tinkham et al. (2001) suggested that staurolite in the stability field of cordierite is metastable. They concluded that the paragenesis Ms+Bt+St+Crd±And is unstable and rare and textural relationships indicating this succession are useful for P-T path derivation. The pseudosections (Fig. 14) show the absence of staurolite and kyanite in the field of cordierite (518-650 °C and 2.3-1.5kbar). Therefore, the presence of staurolite and kyanite as inclusions in cordierite suggest that these phases are metastably present in the Balcooma Metamorphic rocks (Fig.9 b, c). The formation of staurolite (3.3-8kbar) and kyanite (6-8kbar) took place in a different tectonic setting than cordierite because andalusite containing FIA 5 is preserved as inclusions within cordierite and formed much later and during a different direction of bulk shortening. Similarly, the kyanite stability field in each P-T pseudosection occurs ~ 2 kbar and 10°C higher than the stability field of andalusite.

The P-T plots obtained by processing samples AH 146, AH 120 and AH 105 using the average P-T mode of THERMOCALC are in better agreement with the last coexisting mineral assemblages in the region plus all samples give the same P-T range within error (Fig. 15).

## 9: discussion

### 9. 1: Significance of FIAs in P-T path derivations

Before the development of a technique for FIA measurement, only porphyroblast microstructures such as core rim relationships and continuous versus truncated inclusion trails could be used as a tool to determine whether multiple periods of growth of the same mineral phase had occurred. The latter approach was seriously flawed because thin sections cut perpendicular to the matrix foliation commonly suggest inclusion trails are continuous with the matrix when in fact they are truncated by it in 3-D (Cihan, 2004). However, using inclusion trails in porphyroblasts to measure FIAs allows multiple periods of growth of the any porphyroblastic mineral phase to be distinguished and is providing important insights into orogenic processes because of the very lengthy histories of tectonism that they preserve (c.f. Bell et al., 2004 and references therein).

A succession of 5 FIAs in the Balcooma region has distinguished a single generation of garnet, two regional and one local generations of staurolite and one generation of plagioclase, kyanite and andalusite porphyroblasts. Similarly, the microstructural relationships of cordierite and sillimanite to other porphyroblasts and the matrix show single generation when they grew in the tectonic history of the area. Garnet developed at ~530°C and 4.6±0.1kbar during N-S shortening. This period of growth probably occurred around 477 Ma because SHRIMP U-Pb metamorphic zircon rim weighted mean ages of 476±5 Ma and 486±5, 478±5, 477±6, 471±4 Ma (Withnall et al., 1991; Fergusson et al., 2007a) for syntectonic granitoid intrusions suggest that the start of amphibolite facies metamorphism accompanied granitoid intrusion during the Early Ordovician across the Greenvale Province.

The majority of staurolite growth occurred during the development of FIA 3 (Table 1). This provides a strong link between the prograde P-T path and the Early Silurian E-W bulk shortening during the Benambran contractional deformation event across the eastern Australia (c.f. Withnall et al., 1991; Ali, 2009B). Local growth of staurolite occurred during the N-S shortening in the northern part of the Balcooma Metamorphic Group and accompanied the development of FIA 4. The break down of staurolite to andalusite during FIA 5 and the replacement of this andalusite by cordierite occurred during the same decompression event. Later overgrowth by sillimanite occurred after decompression in the region.

### 9. 2: P-T-t-D path for the Balcooma Metamorphic Group

FIA analyses, garnet core isopleth intersections, geothermobarometry, monazite ages derived from staurolite of different generations, P-T pseudosection calculations in the

MnNCKFMASH system and the spectacular sequential occurrence of garnet, biotite, staurolite, kyanite, andalusite and cordierite porphyroblasts resulted a clockwise P-T-t-D path for the Balcooma Metamorphic Group (Fig. 16). Cordierite replacement by fibrolitic sillimanite at 584±13°C and 4.1±0.3Kbar calculated with the average P-T mode of THERMOCALC gave it an anticlockwise tail (Fig. 16). The MnNCKFMASH system enabled modeling of both the high and low pressure mineral assemblages in these rocks that is in excellent agreement with the history derived from the FIA succession. The presence of FIA 1, inclusions of chlorite, biotite and muscovite in garnet porphyroblasts and the Mn, Ca and Fe garnet core isopleth intersection at ~530°C and 4.6±0.1kbar suggest the initiation of amphibolite facies metamorphism around 477 Ma during N-S shortening. The incorporation of garnet in staurolites containing FIA 2 and FIA 3 and synchronous growth of kyanite during FIA 3 suggests a clockwise prograde path up to the metamorphic peak at 623-637°C and 6.2 ± 0.3 kbar. The kyanite-in line indicates an average of 635°C and 6.2 ± 0.3 kbar during the Early Silurian Benambran Orogenic event. The break down of staurolite, kyanite and biotite to andalusite and the absence of fibrolitic sillimanite inclusions in andalusite suggest that peak metamorphic conditions during the Early Silurian Benambran Orogenic event in the region followed by decompression to about 2 kbar. The replacement of staurolite by andalusite, which requires high decompression, occurred at ~450°C and 3.5kbar (c.f. Johnson & Brown, 2004). A similar situation was described by Pattison et al., (1999) and Sayab (2006) where the growth of staurolite was followed by andalusite and cordierite in a low-pressure regional metamorphic terrane. The overprinting of andalusite by cordierite before the overprinting by fibrolitic sillimanite occurred can alternatively be explained by metastable persistence of andalusite into the sillimanite-cordierite stability field during an isobaric heating path (Figs. 14a &16).

### 9. 3: Regional Tectonic implications

Inclusion trails preserved in porphyroblasts and the metamorphism of pelitic rocks has been used to interpret the tectono-metamorphic evolution of orogenic belts (Spear, 1993; Whitney, 2002; Kim & Bell, 2005). The early presence of staurolite and its replacement by cordierite suggests decompression in multiply deformed orogenic belts (Pattison et al., 1999; Sayab, 2006). In active orogenic belts, crustal thickening and associated pressure and temperature increases are commonly followed by decompression and lower temperatures during exhumation of the crust (Whitney & Dilek, 1998).

The inferred P-T results and FIA analyses provide evidence that barrovian metamorphic condition across the Greenvale Province initiated around the Early Ordovician N-S shortening during the development of FIA 1. Further crustal thickening and heating occurred during development of FIAs 2 and 3 in the Early Silurian Benambran Orogenic event (c.f. Withnall et al., 1991; Fergusson et al., 2007a). Decompression/exhumation during the Early Devonian was followed by development of FIAs 4 and 5, granitoid emplacement and further heating. Due to exhumation in the Greenvale Province to the north a thick regional basement-cover unconformity developed to the south in the Broken River Province during the Early Devonian from erosion of the exhumed rocks (Fig. 1; c.f. Henderson, 1987; Fergusson et al., 2007a).

### 9. 4: Garnet overstepping in pelitic rocks

Thermodynamics and kinetics are two important factors for the evolution of different sets of mineral assemblages in metamorphic rocks (Spear, 1993; Zeh & Holness, 2003). The growth of garnet in metapelitic rocks is strongly influenced by P-T conditions, bulk composition and Mn content (Spear, 1993). Bell et al., (1986, 2004) and Williams et al., (2001) also favor a significant role for deformation partitioning in controlling the sites and timing of porphyroblast nucleation and growth. The garnet-in line in a chlorite, biotite, plagioclase and muscovite bearing assemblage in the above P-T pseudosections demonstrates different temperatures for the first appearance of garnet in the assemblage. The tight isopleth intersections in sample AH 146 shows garnet core growth at ~530°C and 4.6±0.1kbar. This is significantly overstepped in temperature and pressure relative to the garnet-in line for this mineral assemblage. Spiess & Bell (1996) have argued that partitioning deformation through a sample and crenulation development at the scale of a porphyroblast is essential for garnet nucleation and/or growth. Curving inclusion trails in the narrow rims of porphyroblasts and intensification of the deformation in the adjacent matrix in the form of cleavage development or some rotation of the included foliation relative to that outside suggests that porphyroblasts only grow early during deformation in zones of progressive coaxial or slightly non-coaxial shortening and cease to grow as soon as zones of progressive shearing partition against their boundaries (Bell & Bruce, 2007). The garnet porphyroblasts in this sample have inclusion trails that are sub-vertically dipping. If the sub-vertical foliation preserved in these FIA 1 garnet porphyroblasts was the first to form, then this rock could have been taken to ~530°C and 4.6±0.1kbar during this first period of horizontally directed N-S shortening without garnet growth being possible because no crenulations could develop (Bell et al., unpublished data). If Spiess & Bell (1996) are correct, no garnet growth may have been possible until crenulations developed during a subsequent deformation in this rock (Fig. 17).

### 9. 5: Coexistence of $Al_2SiO_5$ “triple point” polymorphs in metapelites

$Al_2SiO_5$ polymorphs in metapelitic rocks are of considerable importance because they give a quick measure of metamorphic P-T conditions. Several attempts have been made to determine the location of the invariant point in P-T space where the three aluminosillicate polymorphs can coexist in stable equilibrium (Hodges & Spear, 1982; Spear, 1993). The invariant point of $Al_2SiO_5$ polymorphs in P-T space has been constrained at 500°C and 3.8 kbar by Holdaway (1971) and 550°C and 4.5 kbar by Pattison (2001). The coexistence of

$Al_2SiO_5$ phases in regionally metamorphosed rocks appear to most commonly record a crystallization sequence along a P-T path rather than involving nucleation at specific invariant point "$Al_2SiO_5$ triple point" (Pattison, 2001; Tinkham et al., 2001;Whitney, 2002). This is also the case in the Balcooma Metamorphic Group. Textural and P-T pseudosections constrain indicate that $Al_2SiO_5$ phases appeared in more than one tectonic event. Kyanite was the first polymorph to appear in the range of 617-637$^\circ$C and 6-8kbar at 425.4±3.7 Ma during the Benambran Orogenic event. Kyanite then broke down remaining metastably as inclusions in andalusite that formed during a younger period of FIA development. Andalusite and kyanite were overgrown by fibrolitic sillimanite very late in tectonic history of the Balcooma Metamorphic Group.

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## References

Ali, A., 2009 A. Deformation partitioning and porphyroblast growth.

Ali, A., 2009 B. Protection of monazite grains from obliteration in highly tectonized terrains by porphyroblasts: microstructural approaches to tectonic reconstructions.

Bell, T. H., Rubenach, M.J. & Fleming, P.D., 1986. Porphyroblast nucleation, growth and dissolution in regional metamorphic rocks as a function of deformation of partitioning during foliation development. *Journal of Metamorphic Geology* **4**, 37-67.

Bell, T.H., & Welch, P.W., 2002. Prolonged Acadian orogenesis: revelations from foliation intersection axis (FIA) controlled monazite dating of foliations in porphyroblasts and matrix. American Journal of Science **302**, 549-581.

Bell, T.H., & Chen, A., 2002. The development of Spiral-shaped inclusion trails during multiple metamorphism and folding. *Journal of Metamorphic Geology* **20**, 397-412.

Bell, T.H., Ham, A.P. & Kim, H.S., 2004. Partitioning of deformation along an orogen and its effects on porphyroblast growth during orogenesis. *Journal of Structural Geology* **26**, 825-845.

Bell, T.H. & Kim, H.S., 2004. Preservation of Acadian deformation and metamorphism through intense Alleghanian shearing. *Journal of Structural Geology* **26**, 1591-1613.

Bell, T.H. & Newman, R., 2006. Appalachian orogenesis: the role of repeated gravitational collapse. In: Butler, R., Mazzoli, S. (Eds.), Styles of Continental Compression. *Special Papers of the Geological Society of America* **414**, 95-118.

Bell, T.H., & Bruce, M.D., 2007. Progressive deformation partitioning and deformation history: Evidence from millipede structures. *Journal of Structural Geology* **27**, 18-35.

Bell, T.H., Rieuwers, M., Cihan, M., Evan, T.P., Ham, A. P. and Welch, P.W., 2009. Shifting patterns of deformation partitioning during mountain building and crustal channel flow. Unpublished.

Carmichael, D. M., 1969. On the Mechanism of Prograde Metamorphic Reactions in Quartz-Bearing Pelitic Rocks. *Contribution to Mineralogy and Petrology* **20**, 244-267.

Cihan, M., 2004. The drawbacks of sectioning rocks relative to fabric orientations in the matrix: A case study from the Robertson River Metamorphics (Northern Queensland, Australia). *Journal of Structural Geology* **26**, 2157-2174.

Cihan, M., & Parsons, A., 2005. The use of porphyroblasts to resolve the history of macro-scale structures: an example from the Robertson River Metamorphics, North-Eastern Australia. Journal of Structural Geology 27, 1027-1045.

Evans, T. P., 2004. A method for calculating effective bulk composition modification due to crystal fractionation in garnet-bearing schist: implications for isopleth thermobarometry. *Journal of Metamorphic Geology* **22**, 547-557.

Fergusson, C. L., Henderson, R. A., Withnall, I. W. & Fanning, C.M., 2007a. Structural history of the Greenvale Province, north Queensland: Early Palaeozoic extension and convergence on the Pacific margin of Gondwana. *Australian Journal of Earth Sciences* **54**, *573-595.*

Fergusson, C.L., Henderson, R.A., Withnall, I.W., Fanning, C.M. & Phillips, D., 2007b. Structural, metamorphic, and geochronological constraints on alternating compression and extension in the Early Palaeozoic Gondwanan Pacific margin, northeastern Australia. *Tectonics* **26**, 1-20

Hayward, N., 1990. Determination of early fold axis orientations within multiply deformed rocks using porphyroblasts. *Tectonophysics* **179**, 353-369.

Henderson, R. A. 1986. Geology of the Mt Windsor Subprovince-A lower Palaeozoic volcano-sedimentary terrane in the northern Tasman Orogenic Zone. *Australian Journal of Earth Sciences* **33**, 343-364.

Henderson, R. A., 1987. An oblique subduction and transform faulting model for the evolution of the Broken River Province, northern Tasman Orogenic Zone. *Australian Journal of Earth Science* **34**, 237 – 249.

Huston, D.L., 1990. The stratigraphic and structural setting of the Balcooma volcanogenic massive sulphide lenses, north Queensland. Australian Journal of Earth Sciences 37, 423-440.

Huston, D. L. & Taylor, T. W. 1990. Dry River copper and lead-zinc-copper deposits. In Hughes F. E. ed. Geology of the Mineral Deposits of Australia and Papua New Guinea. *Australasian Institute of Mining and Metallurgy: Melbourne*, 1519-1526.

Holland, T. J. B., & Powell, R., 1998. An internally consistent thermodynamic data set of petrological interest. *Journal of Metamorphic Geology* **16**, 309–343.

Holdaway, M.J., 1971. Stability of andalusite and the aluminium silicate phase diagram. *Am. J. Sci.* **271**, 97–131.

Hodes, K.V. & Spear, F. S., 1982. Geothermometry, geobarometry and the Al2SiO5 triple point at Mt. Moosilauke, New Hampshire. *American Mineralogist* **67**, 1118-1134.

Lang, H. M., 1996. Pressure-temperature-reaction history of metapelitic rocks from the Maryland Piedmont on the basis of correlated garnet zoning and plagioclase-inclusion composition. *American Mineralogist* **81**, 1460-1475.

Jamieson, R. A., Beaumont, C., Fullsack, P. and Lee, B., 1998. Barrovian regional metamorphism: where's the heat? In: Treloar, P. J. and O' Brien P.J. (eds) what Drives Metamorphism and Metamorphic Reactions? *Geological Society, London, Special Publication* **138**, 23-51.

Johnson, T. E., Brown, M. & Solar, G.S., 2003. Low-pressure subsolidus and suprasolidus phase equilibria in the MnNCKFMASH system: constraints on conditions of regional metamorphism in western Maine, northern Appalachians. *American Mineralogist* **88**, 624-638.

Johnson, T. E. & Brown, M., 2004. Quantitative constraints on metamorphism in the Variscides of South Brittany-a complementary pseudosection approach. *Journal of Petrology* **45**, 1237-1259.

Kim, H. S. & Bell, T.H., 2005. Combining compositional zoning and foliation intersection axes (FIA) in garnet to quantitatively determine early P-T-t paths in multiply deformed and metamorphosed schists: north central Massachusetts, USA. *Contribution to Mineralogy and Petrology* **149**, 141-163.

Kretz, R., 1983. Symbols for rock-forming minerals. *AM Miner* **68**, 277-279.

Pattison, D.R.M., Spear, F.S. & Cheney, J.T., 1999. Polymetamorphic origin of muscovite+cordierite+staurolite+biotite assemblages: implications for the metapelitic petrogenetic grid and for P-T paths. *Journal of Metamorphic Geology* **17**, 685-703.

Pattison, D. R. M., 2001. Instability of $Al_2SiO_5$ “triple-point” assemblages in muscovite+biotite+quartz-bearing metapelites, with implications. *American Mineralogist* **86**, 1414-1422.

Powell, R. & Holland, T. J. B., 1994. Optimal geothermometry and geobarometry. *American Mineralogist* **79**, 120–133.

Powell, R. & Holland, T. J. B., 2008. On thermobarometry. *Journal of Metamorphic Geology* **26**, 155-179.

Rea P.S. & Close R.J. 1998. Surveyor 1 copper-lead-zinc-silver-gold deposit. *The Australian Institute of Mining and Metallurgy: Melbourne*, pp. 737- 742.

Reche, J., Martinez, F. J. & Arboleya, M. L., 1998. Low to medium-pressure Variscan metamorphism in Galicia (NW Spain): evolution of a kyanite-bearing synform and associated bounding antiformal domains. In: Treloar, P. J. and O’ Brien P.J. (eds) what Drives Metamorphism and Metamorphic Reactions? *Geological Society, London, Special Publication* **138**, 61-79.

Rubenach, M. J., Foster, D.R.W, Evins, P.M., Blake, K. L. & Fanning, C. M., 2008. Age constraints on the tectonothermal evolution of the Selwyn Zone, Eastern Fold Belt, Mount Isa Inlier. *Precambrian Research* **163**, 81-107.

Sayab, M., 2006. Decompression through clockwise P-T path: implications for early N-S shortening orogenesis in the Mesoproterozoic Mt Isa Inlier (NE Australia). *Journal of Metamorphic Geology* **24**, 89-105.

Spear, F.S., 1993. Metamorphic phase equilibria and pressure-temperature-time paths. *Mineralogical Society of America, Washington D.C.*, 799 p.

Spiess, R. & Bell, T.H., 1996. Microstructural controls on sites of metamorphic reaction: a case study of the inter-relationship between deformation and metamorphism. *European Journal of Mineralogy* **8**, 165-186.

Tinkham, DK., Zuluaga, Ca. & Stowell, HH., (2001). Metapelite phase equilibria modelling in MnNCKFMASH: The effect of variable Al2O3 and MgO/(MgO+FeO) on miner stability. *Geological Material Research (Mineralogical Society of America)* **3**, 1–42.

Tinkham, DK & Ghent E.D., 2005. Estimating P-T conditions of garnet growth with isochemical phase-diagram sections and the problem of effective bulk-composition. *The Canadian Mineralogist* **43**, 35-50.

Vander Hor, F., 1990. Structural geology of the Balcooma-Dry River area, northeast Australia, with emphasis on the inter-relation between deformation and metamorphism. PhD thesis, James Cook University Australia, pp.**139.**

Vance, D. & Mahar EM., 1998. Pressure-temperature paths from P-T pseudosections and zoned garnets: potential, limitations and examples from the Zanskar Himalaya, NW India. *Contribution to Mineralogy and Petrology* **132**, 225-245.

Vernon, R.H., White, R. W. & Clarke, G. L., 2008. False metamorphic events inferred from misinterpretation of microstructural evidence and P-T data. *Journal of Metamorphic Geology* **26**, 437–449.

Whitney, D.L. & Dilek, Y., 1998. Characterization and interpretation of P-T paths with multiple thermal peaks. In: Treloar, P. J. and O' Brien P.J. (eds) what Drives Metamorphism and Metamorphic Reactions? *Geological Society, London, Special Publication* **138**, 53-60.

Whitney, D.L., 2002. Coexisting andalusite, kyanite, and sillimanite: sequential formation of three polymorphs during progressive metamorphism near the $Al_2SiO_5$ triple point, Sivrihisar, Turkey. *American Mineralogist* **84**, 405-416.

Whitney, D.L. & Bozkurt, E., 2002. Metamorphic history of the southern Mendres massif, western Turkey. *Geological Society of America* **114**, 829-838.

White, R.W., Powell, R. & Holland, T. J. B., 2001. Calculation of partial melting equilibria in the system $Na_2O$-CaO-$K_2O$-FeO-MgO-$Al_2O_3$-$SiO_2$-$H_2O$ (NCKFMASH). *Journal of Metamorphic Geology* **19**, 139-153.

White, R.W., Powell, R. & Baldwin, J.A., 2008. Calculated phase equilibria involving chemical potentials to investigate the textural evolution of metamorphic rocks. *Journal of Metamorphic Geology* **26**, 181-198.

Williams, M.L., Scheltema, K.E. & Jercinovic, M.J., 2001. High-resolution compositional mapping of matrix phases: implications for mass transfer during crenulation cleavage development in the Moretown Formation, western Massachusetts. *Journal of Structural Geology* **23**, 923-939.

Withnall, I. W., 1989. Precambrian and Palaeozoic geology of the south-eastern Georgetown Inlier, North Queensland. *Queensland Department of Mines Report* **2**, 1-102.

Withnall, I. W., Hutton, L. J., Garrad, P. D. & Rienks I. P., 1997. Pre-Silurian rocks of the Lolworth-Pentland area, North Queensland. *Queensland Geological Record* 1997/6.

Withnall, I. W., Black, L.P. & Harvey, K. J., 1991. Geology and geochronology of the Balcooma area: part of an early Palaeozoic magmatic belt in north Queensland, Australia. *Australian Journal of Earth Sciences* **38**, 15-29.

Zeh, A. & Holness, M. B., 2003. The effect of reaction overstep on garnet microtextures in metapelitic rocks of the Ilesha Schist Belt, SW Nigeria. *Journal of Petrology* **44**, 967-994.

Zeh, A., Klemd, R., Buhlmann, S. & Barton, J.M., 2004. Pro- and retrograde P-T evolution of granulites of the Beit Bridge Complex (Limpopo Belt, South Africa): constrains from quantitative phase diagrams and geotectonic implications. *Journal of Metamorphic Geology* **22**, 79–95.

Zeh, A., Klemd, R. & Barton, J.M., 2005. Petrological evolution in the roof of the high-grade metamorphic Central Zone of the Limpopo Belt, South Africa. Geological Magazine **142,** 229-240.

# Section D:

# East-west trending Ordovician orogenesis in Northern Australia: an example of changes in orogenic behaviour across an Euler pole?

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## Abstract

Foliation inflection-intersection axes preserved in porphyroblasts (FIAs) reveal the early history of tectonism within the Northern Thomson Fold Belt. A succession of five FIA sets in the Cambro-Ordovician Balcooma Metamorphic Group, which lie due east of the Precambrian Georgetown Block, indicates that five changes in the direction of bulk shortening occurred during Northern Thomson Fold Belt orogenesis. A progressive rotation of the horizontal bulk shortening direction occurred from FIAs 1 through 5. The E-W trending FIA set 1, which is Ordovician in age (476±5 to 454 ±12 Ma), cannot have formed with these rocks in their current geologic setting because the Precambrian rocks to the west are unaffected by this period of N-S bulk shortening. For intense N-S shortening to not affect the adjacent Precambrian to the west, these rocks must have lain approximately 200 km to the south. They were then displaced 200 km north into their current location by the E-W bulk shortening effects of the Silurian Benambran Orogeny (444-420Ma), which controlled the development of FIAs 2 (443.2±3.8 Ma) and 3 (425.4±3.7 Ma). Synchronous N-S bulk shortening orogenesis in the east in eastern Australia with N-S extensional orogenesis to the west in central Australia during the Ordovician can be explained if the Euler pole for relative plate motion was located WSW of the Mt Isa Inlier. A plate containing the southern half of Australia pivoting anticlockwise around this axis of rotation relative to one containing the northern half, would produce crustal shortening orogenesis in the east and extensional orogenesis in the west from 476±5 to 454 ±12 Ma.

**Keywords:** Northern Thomson Fold Belt, Ordovician N-S shortening, Euler poles, FIAs, Correlation of deformations.

## 1. Introduction

The Tasman Orogenic Zone, running approximately N-S (Scheibner, 1978a; Scheibner, 1978b; 1986; Coney et al., 1990; Direen & Crawford, 2003), is a Palaeozoic to early Mesozoic Fold Belt that makes up about one-third of the Australian continent. It extends over 4000 km from Tasmania in the south to Cape York in north Queensland and ranges in width to at least 1500 km. Approximately one-third of the Tasman Orogenic Zone is partially concealed beneath the Tasman and Coral seas due to the Late Mesozoic and Cenozoic rifting and sea-floor spreading (Fig. 1; Coney et al., 1990; Vos et al., 2007). This orogen is considered to have formed by a succession of periods of orogenesis that migrated from west to east along the active Pacific-facing margin of East Gondwanaland after the break-up of Rodinia (Murray, 1986; Cawood, 2005; Fergusson et al., 2007a). These are shown on (Fig. 1) and include the Early Palaeozoic Delamerian, the Early and Middle Palaeozoic Thomson and Lachlan Fold Belts, the Middle and Late Palaeozoic Hodgkinson-Broken River Fold Belt and the Late Palaeozoic to Early Mesozoic New England Fold Belt (Gray & Foster, 2004).

The Northern Thomson Fold Belt is an anomalous portion of the Tasman Orogenic Zone because it contains well preserved E-W trending batholiths and foliations (Bell, 1980). It is very poorly exposed being covered by the younger sediments of the Eromanga Basin. The significance of the overall E-W continuity of magnetic trends from central Australia to the Charters Towers region (Fig. 2) and relationship to Fold Belts to the south remains poorly understood (Fig. 1). The nature of orogenesis, magmatism, tectonic setting and degree of deformation of the Northern Thomson Fold Belt have been based on geochemistry, thermal regimes, some ages from deep drill holes, limited surface exposures, regional gravity and magnetic lineaments (Gray & Foster, 2004; Draper, 2006; Glen et al., 2007a, b). The Northern Thomson Fold Belt (including the Charters Towers and Greenvale Provinces) has been considered to be the northern continuation of the Lachlan Fold Belt even though it tends to be older (Kirkegaard, 1974; Murray & Kirkegaard, 1978; Murray, 1986; Coney et al., 1990; Fergusson et al., 2007a, b). In the Charters Towers Province (Fig. 1), granitoid intrusions and amphibolite facies metamorphism in the Argentine and Cape River Metamorphics range in age from 510 to 455Ma (Fergusson et al., 2007c). In the Greenvale Province SHRIMP U-Pb zircon rim weighted mean ages of 476±5 Ma for the Oasis Metamorphics, 486±5, 477±6 Ma for syntectonic granitoid intrusions in the Lynwater Complex (Fergusson et al., 2007b) and 471±4, 478±5 Ma for the Balcooma Metamorphic Group (Withnall et al., 1991) indicate $D_1$ amphibolite facies metamorphism and accompanied granitoid intrusions.

Basement core samples from petroleum wells located SE of the Mt Isa Inlier (Fig. 1) include granite and volcanics that have SHRIMP U-Pb ages ranging from 472.9±2.7 to 483.6±5.9 Ma (Draper, 2006). These indicate tectonic activity associated with the largest E-W trending geophysical/structural discordance in eastern Australia that truncates the Precambrian Mt Isa Inlier and Georgetown Block (Figs. 1 and 2). Similar 467±8 Ma (Hand et al., 1999) ages have been found in foliated rocks in the middle of the Arunta Block in the Harts Range of central Australia (Fig. 2). Schists and gneiss north of Hughenden (200 km southwest of Charters Towers) contain Rb-Sr whole-rock isochron 483±25 Ma ages (Paine et al., 1971) that are similar to those at Greenvale and Charters Towers Provinces as well as those from the deep drill holes to the south shown on (Fig. 1). For the period 490-460 Ma, Gray and Foster (2004) suggested that the boundary between the Thomson and Lachlan orogens may have been a collisional plate margin. However, they show basin extension occurring in central Australia at this time forming the Larapinta Seaway (Fig. 3, modified from their Fig. 25f). Throughout this period they suggest that N-S trending subduction zone continued to the east on the western edge of the Pacific (Fig. 3).

This paper examines the significance of E-W magnetic and age trends in the Northern Thomson orogen using a new type of structural data from the Balcooma region in North Queensland. This region would have lain on the northern side of the Northern Thomson Fold Belt as currently exposed prior to the effects of the younger E-W directed crustal shortening that is typically associated with the Tasman Orogenic Zone. The combinations of this data suggest a new tectonic interpretation should be considered for this region and may aid explorers after Balcooma and Charters Towers style mineralization correlatives.

## 2. Geological framework

The northern part of the Tasman Orogenic Zone in Queensland has classically been divided into three segments on the basis of rock type, metamorphic grade, geochronology and structural history; the Hodgkinson-Broken River Fold Belt in the north, the Northern Thomson Fold Belt in the southwest and the northern part of the New England Fold Belt in the southeast (Figs. 1 and 2; Murray & Kirkegaard, 1978; Day et al., 1978; Murray, 1986; Shaw et al., 1987). The Palmerville Fault (De Keyser, 1963; Henderson, 1987) separates the Hodgkinson Province from the Precambrian Georgetown to the west. The Burdekin River Fault (White, 1965; Murray, 1986) was previously regarded as the western boundary of Broken River Province with the Proterozoic Georgetown Inlier, but early Palaeozoic rocks are now known to extend much farther west, as far as Lynd Mylonite Zone (Withnall, 1989; Fergusson et al., 2007b). In the south, the eastern boundary of the Precambrian craton is covered by younger sediments (Murray, 1986).

The Balcooma Metamorphic Group, located within the northern part of the Northern Thomson Fold Belt, contain multiply deformed Cambro-Ordovician metavolcanics and metasedimentary rocks (471±4, 478±5 Ma SHRIMP U-Pb zircon ages and 454±12 Ma monazite ages; Withnall et al., 1991; Ali, 2009B). This terrane is wedged between the Early Palaeozoic Halls Reward Metamorphics (510-500 Ma, Nishiya et al., 2003) to the east and the Precambrian Georgetown Block to the west (1700-1550 Ma, Fig. 4). The Balcooma Metamorphic Group is lithologically similar to the Cambrian to Lower Ordovician Seventy Mile Range Group of the Charters Towers Province (Fig. 4; Henderson, 1986; Withnall et al., 1997; Fergusson et al., 2007b). The Balcooma Metamorphic Group is exposed in the western part of the Greenvale Province along a 33 x 8 km zone (Withnall et al., 1991; Withnall, 1989) and contains four cleavages in the rock matrix (Harvey, 1984; Huston, 1990; Huston & Taylor, 1990; Rea & Close, 1998). The pervasive $S_2$ cleavage is commonly crenulated by $S_3$, which has NNE strike and a near vertical dip (Withnall, 1982). A later crenulation deformation $D_4$ was recognized in the area by Huston (1990) that crenulated $S_2$ and $S_3$. $S_4$ is locally developed in the northern portion of the Balcooma Metamorphic Group during $D_4$ and crenulated by $S_5$ (Huston, 1990; Vander Hor, 1990; Ali, 2009 A). Relics of $S_1$, which are preserved in garnet, were recognized in thin section by Vander Hor (1990) and Ali (2009c) but this foliation is generally subparallel to bedding. The Balcooma copper, lead and zinc deposit lies within multiply deformed metagreywackes and metapelites. These rocks are bound to the east by an intrusive contact with the Ringwood Park Microgranite (Fig. 5). The sequence is approximately 7000m thick and verges to the east (Withnall et al., 1991). The metapelites are characterized by chlorite, muscovite, biotite, garnet, staurolite, plagioclase, kyanite, andalusite, cordierite and fibrolitic sillimanite. Garnet, staurolite, plagioclase and andalusite contain abundant inclusion trails and provide a wealth of information on all stages of porphyroblast nucleation, growth, dissolution and structural development that have been destroyed by reactivation of the compositional layering during later deformation in the matrix.

### 3. Sample description

79 spatially oriented porphyroblastic samples were taken systematically around the Balcooma copper, lead and zinc deposit for microstructural analysis. 45 of these were oriented core samples plus 5 surface samples from an area around the Balcooma North and South Pits. The remaining 29 samples were collected from the surrounding Balcooma region (Fig. 5). 700 vertical thin sections were cut to measure the foliation intersection/inflection axes preserved within porphyroblasts (FIAs, Table 1) as well as all other structures revealed during the detailed microstructural investigation this enabled. Deformation and accompanying metamorphism produced numerous porphyroblastic phases including biotite, garnet, staurolite, plagioclase, kyanite, andalusite and cordierite porphyroblasts plus fibrolitic sillimanite. Microstructural measurements, textural relations and relative deformation features suggest the crystallization sequence garnet, staurolite, plagioclase, kyanite and andalusite for those porphyroblasts with inclusion trails. Biotite, muscovite and chlorite, which define the matrix foliation, were not used for microstructural analysis because they are less competent and tend to deform along (001). Sillimanite was the last mineral to form. It nucleated within biotite and projecting into the adjacent porphyroblastic phases (staurolite, plagioclase, kyanite and andalusite) and overgrew the matrix foliation.

### 4. FIA determination, sets, relative timing, progressive succession and interpretation

#### 4.1. FIA determination technique

A FIA is determined for a sample by locating the axis about which the asymmetry flips of one foliation overprinting another (Hayward, 1990; Bell et al., 1995; Sayab, 2005). This technique involves observing the switch in the asymmetry of curved inclusion trails, preserved in porphyroblasts in a series of vertically oriented thin sections with different strike viewed in the one direction around the compass from the same sample (Fig. 6). Initially six vertical thin sections from a horizontal oriented block are required for a FIA trend determination cut 30° apart around the compass (i.e. trending 00°, 30°, 60°, 90°, 120° and 150°). An additional two vertical sections were cut 10° apart between the two sections in which the switch in inclusion trail asymmetry was observed to narrow the location of the FIA within a 10° range. Using multiple vertical thin sections approach was preferred because it has a very significant microstructural advantage. The inclusion trails contained in many porphyroblasts can be observed from a large range of orientations, providing a much clearer record of the inclusion trail geometry and deformation history. The P (thin section cut parallel to lineation and perpendicular to foliation)-N (thin section cut perpendicular to lineation and foliation) section approach used by most structural and metamorphic geologists over the past decades results in misinterpretation of the timing of porphyroblast growth and multiple deformational, metamorphic and tectonic events in highly tectonized terranes (for detail see Cihan, 2004).

### 4.2. FIA sets

A total of 143 FIAs preserved in garnet, staurolite, plagioclase, kyanite and andalusite porphyroblasts were determined from 79 spatially oriented samples (Table 1). The sample locations are shown in (Fig. 5). 24 FIAs were measured from garnet porphyroblasts. 95 FIAs were measured from samples containing staurolite porphyroblasts allowing three different generation of staurolite to be identified within the Balcooma region. Garnet is locally included within biotite, staurolite, plagioclase, kyanite, andalusite and cordierite porphyroblasts suggesting that it grew before the latter phases. Respectively, 9, 1 and 14 FIAs were measured from plagioclase, kyanite and andalusite bearing samples. Figure 7 presents a rose plot of total FIA trends measured from all samples in the Balcooma region. Four FIA peaks with E-W, NNW-SSE, NNE-SSW and NE-SW trends were distinguished on a rose diagram.

### 4.3. Relative timing and FIA succession determination

Extensive research work over the past decade using porphyroblasts has shown that deformation and metamorphism is far more complex than previously had been recognized using matrix foliations (Bell & Hickey, 1999). The progressive growth of different porphyroblastic phases preserves various portions of the deformation and metamorphic history and reveals more complex histories. The episodic growth of these porphyroblastic phases plus the presence of monazite grains in them can be used to establish relative timing between different FIA sets (Spiess & Bell, 1996; Bell et al., 1998; Bell & Welch, 2002; Ali, 2009B). 5 FIA sets have been established in the Balcooma Metamorphic Group (Table 1) on the basis of:-

1. Core versus rim criteria, since a foliation preserved in the core of porphyroblast must be older than that in the rim (Fig. 8a).
2. The prograde metamorphic succession where different porphyroblastic phases can preserve distinct portions of the deformation, metamorphic history and it could be determined that growth of one mineral preceded the other. For example, garnet is preserved locally within biotite, staurolite, kyanite, plagioclase, andalusite and cordierite. Staurolite and kyanite are replaced by andalusite and andalusite is replaced

by cordierite (c.f., Bell & Kim, 2004; Fig. 8 b, c, d). Therefore, the FIAs determined in garnet and andalusite formed first and last respectively.

3. Textural characteristics and the degree of continuity between the internal foliation ($S_i$) and the matrix foliation ($S_e$). For example, truncated inclusion trails versus those that are continuous with the matrix (e.g., Adshead-Bell & Bell, 1999; Cihan, 2004; Sayab, 2005; Fig. 8 e, f).
4. A total of 214 spots on 41 monazite grains preserved as inclusions within porphyroblasts were analysed by Ali (2009B) after identifying them within a particular FIA set. No monazite grains were found within porphyroblasts defining FIA 1 but locally in sample AH 143, which contains FIA 1 and FIA 3 such grains were found within the matrix with ages of 454 ±12 Ma where garnet was incorporated as inclusions in FIA 3 staurolite porphyroblasts. Note that garnet is also included as inclusions in FIA 2 staurolite porphyroblasts. SHRIMP U-Pb metamorphic zircon rim weighted mean ages of 476±5 Ma and 486±5, 478±5, 477±6, 471±4 Ma weighted mean ages for syntectonic granitoid intrusions indicate that $D_1$ amphibolite facies metamorphism accompanied granitoid intrusion during an Early Ordovician Orogeny across the Greenvale Province (Withnall et al., 1991; Fergusson et al., 2007b). Note that an Early Ordovician (475-450 Ma) orogeny has also affected the Harts Range of central Australia and Charters Towers Province in eastern Australia (Hand et al., 1999; Fergusson et al., 2007a,b,c; Ali, 2009B). FIAs 2, 3 and 4 are dated at 443.2±3.8, 425.4±3.7 Ma and 408.8±8.9 Ma respectively (Fig. 9; Ali, 2009B).

Multiple generation of porphyroblast growth during episodic deformation events preserved 5 FIA sets in the Balcooma Metamorphic Group. The earliest FIA set 1 has an E-W trend and is preserved by garnet. The foliations defining this FIA trend are completely truncated by the matrix foliation (Fig. 8e). In all samples, garnet porphyroblasts only contain FIA 1. FIA 1 was never observed in staurolite, plagioclase, kyanite, andalusite and cordierite indicating that garnet predated staurolite, plagioclase, kyanite, andalusite and cordierite. The NNW-SSE trending FIA 2 was only observed in staurolite porphyroblasts. The inclusion trails defining this FIA are truncated by the younger matrix foliation across the Balcooma region. The most distinct inclusion trails, defining a NNE-SSW trending FIA 3, are preserved by staurolite and plagioclase. Sample AH 71 contains kyanite with good inclusion trails around the compass and defining FIA 3 at $10^{o}$. These foliations are continuous with or locally truncated by a well developed horizontal foliation in the matrix. Some samples were found with FIAs trending NNW-SSE (FIA 2) and NNE-SSW (FIA 3) in the core of staurolite porphyroblasts that contain an E-W FIA in their rims. This FIA 4 trend was locally observed mainly in the rim of staurolite in the northern part of the Balcooma Metamorphic Group. The continuity of the inclusion trails defining FIA 4 with foliations in the matrix plus its preservation in different phase of porphyroblast enabled samples containing this FIA to be distinguished from those containing FIA 1, even though they have the same trend. The foliations defining FIA 4 mostly change from flat to steep pitches while those defining FIA 1 change steep to flat. FIA set 5 trending NE-SW is preserved by andalusite that overgrew the matrix very late in the deformation history. Inclusion trails preserved by andalusite are straight and continuous with foliations in the matrix (Fig. 10).

## 5. Interpretation and discussion

### 5.1. Consistent succession versus a random distribution of FIA sets

Traditionally structural geologists interpreted that porphyroblasts rotate (e.g., Rosenfeld, 1968; Passchier et al., 1992; Williams & Jiang, 1999) and spiral shaped inclusion trails in snowball garnets were used as evidence for this. However, Bell & Johnson (1989 a, b) suggested that spiral inclusion trails could be formed without porphyroblast rotation by the growth of porphyroblasts over crenulation hinges generated during successive episodes of sub-horizontal and sub-vertical directed bulk shortening. The application of techniques developed for measuring the spiral axes (Hayward, 1990; Bell et al., 1995, 1998), using a reference frame of geographical coordinates plus the vertical, resulted in a large data base that revealed consistent regional changes in the orientation of these axes from the cores to rims of porphyroblasts (Bell et al., 1998; Cihan & Parsons, 2005; Sayab, 2005, 2006, 2008; Yeh, 2007). This has been confirmed by a regular decrease in ages of monazite inclusions defining older spiral axes in the core relative to those in the rim (Bell & Welch, 2002). In spite of more than a decade of data gathered on FIAs, many structural geologists have not been convinced of their usefulness because no one had been able to experimentally reproduce non-rotation of porphyroblasts. However, the experimental work of Fay et al., (2008; 2009) has now confirmed that non-rotation is a viable mechanism in deforming rocks.

The consistent succession of 5 FIA sets on a rose diagram (Fig. 7) confirms that the porphyroblasts did not rotate as they formed. If porphyroblasts had rotated at the time of their formation or after they grew around the axis of the newly developing FIA would have generated an extremely complex distribution of FIA trends around the stereonet (Fig. 11d). The maximum curvature of inclusion trails in these rocks about any single FIA is 45°. Figure 11a, b, c and d shows the relative effects of rotating each FIA set by 45° around the next younger FIA set. The resulting distribution produces a massive spread of FIAs around the stereonet. Clearly, if the rotation of porphyroblasts had occurred, garnet porphyroblasts, which formed first and only contain FIA 1, would have been spread all over the compass (c.f., Ham & Bell, 2004; Sayab, 2005; Bell & Newman, 2006).

## 5.2. Tectonic significance of FIA data

The early history of deformation in multiply deformed rocks becomes lost because reactivational shearing of the bedding causes early formed microstructures to be destroyed in the matrix (Bell et al., 2004; Bell & Kim, 2004, Bell, 2009). Fortunately, porphyroblasts provide a tool that allows quantitative study of many of the microstructures that were destroyed in the matrix (e.g., Sayab, 2008). FIAs record a long tectonic history and allow correlation between the progressive development of microstructural features and larger scale bulk shortening directions (Bell et al., 2004; Bell & Newman, 2006). A consistent distribution and succession of FIAs potentially provides access to the changes in relative plate motion that took place during orogenesis (Bell & Welch, 2002; Bell & Newman, 2006).

The succession of FIA trends preserved within garnet, staurolite, plagioclase, kyanite and andalusite porphyroblasts in this region reveals 5 successive changes in the direction of bulk shortening during 5 main periods of tectonism across the Greenvale Province. A lengthy, more complicated and better established history of prograde metamorphic mineral assemblages has been determined than had previously been recognised in this area. Large-scale horizontal bulk shortening at a collisional plate boundary causes crustal thickening. This eventually leads to gravitational collapse of the top 30 or so kilometres of the orogenic pile, either due to over-thickening or trench rollback (Fig. 12; e.g., Bell & Newman, 2006). However, at depth, the plate motion, at such a collisional boundary, continues and eventually sufficient indirect coupling will lead again to crustal thickening. This produces successions of sub-vertical foliations and sub-horizontal ones whose intersection defines the FIA trends. Most of these phases of tectonism have been obliterated in the matrix and would not have been identified if it were not for the fact that porphyroblast growth occurred during them (e.g., Bell et al., 1998). The E-W trending FIA set 1 in garnet porphyroblasts indicates N-S shortening. Significantly, this predates the bulk shortening events that produced the overall N-S trending tectonic grain of the Tasman Orogenic Zone.

The NNW-SSE trending FIA set 2 in staurolite indicates rotation of the direction of shortening to ENE-WSW after FIA 1. The NNE-SSW trending FIA set 3 indicates a 30° rotation of the shortening direction to ESE-WNW after FIA 2. The majority of staurolite growth occurred during FIA set 3 events. This period of tectonism appears to have been responsible for the NNE-SSW trending geophysical grain that is locally visible on the eastern side of the exposed Northern Thomson Fold Belt (Fig. 4). The E-W trending FIA set 4 in staurolite indicates a further rotation in shortening back to N-S. NE-SW trending FIA 5 indicates rotation of the bulk horizontal shortening direction to SE-NW. FIA sets (2, 3 and 5) were developed during overall E-W shortening events and accord with most tectonic models of Tasman Orogenic Zone (Fergusson et al. , 2007a, b). The N-S bulk shortening during FIA 4 was very locally observed in the northern portion of the Balcooma Metamorphic Group. However, the first formed FIA set 1 (476±5 to 454±12 Ma) indicates that the first phase of orogenesis to affect the Northern Thomson Fold Belt rocks involved N-S bulk shortening (compare Figs. 2 and 3) and this has considerable significance (see below).

### 5.3. The East-west structural and tectonic grain of the Northern Thomson Fold Belt

Figure 2 shows that the E-W trending aeromagnetic grain in central Australia extends to immediately south of the Mt Isa Inlier where it fades away due to the thickness of the overlying sedimentary cover. The recognition of similar aged E-W trending tectonism in central Australia and in the Greenvale and Charters Towers Provinces, where elongate shaped plutons of Ordovician age also have a very distinct E-W trend, suggests that they were coupled orogenically and that a zone of tectonism extended between them. This E-W trend of the plutons in the Charters Towers Province is completely different to all other exposed plutons along the Tasman Orogenic Zone, which trend essentially N-S along the eastern Australian coast.

The exposed parts of the Northern Thomson Fold Belt in the Charters Towers Province and Greenvale Province to the NNW should best preserve evidence on the history of orogenesis that this orogen has undergone. As mentioned above the metamorphosed silicic volcanics and sedimentary rocks of the Greenvale Province have been correlated with the Cambrian to Early Ordovician E-W trending Seventy Mile Range in the Charters Towers Province on the basis of similar lithologies and mineralization (e.g., the Balcooma Cu-Pb-Zn deposit, Henderson, 1986; Withnall et al., 1991). A 471±4 Ma ($207^{Pb}/206^{Pb}$) age obtained by ion–microprobe analysis of zircon from the Balcooma Metamorphic Group is geochronologicaly consistent with the Seventy Mile Range in the Charters Towers Province (Withnall et al., 1991). Ion-microprobe analyses of Precambrian inherited zircons and the rhyolitic composition of the Balcooma Metamorphic Group suggests that the Ordovician volcanics formed on continental crust from the melting of cratonic crust of the Georgetown Block of the Precambrian age (Withnall et al., 1991). Thus geochemical and geochronological similarities between metavolcanics in the Balcooma and Seventy Mile Range regions (Fig. 4) imply the presence of an early Palaeozoic magmatic belt along the Precambrian cratonic margin (Withnall et al., 1991).

However, the tectonic grain of the Charters Towers Province is E-W whereas that of the Greenvale Province is NNE-SSW, similar to adjacent younger Tasman Orogenic trends (Fig. 4). This has hampered structural correlation between these two Provinces. In such situations where younger deformations have potentially obliterated previously formed structures in the matrix, FIAs provide a tool for structural correlation along an orogen (e.g., Bell & Mares, 1999). The E-W trend of FIA set 1 (Fig. 13) preserved in garnet porphyroblasts is close in orientation to the overall structural grain of the Charters Towers Province. Could the current NNE-SSW trend of the Balcooma rocks have resulted from younger orogenic shortening effects that have had less effect in the Charters Towers Province? Could the structural, lithological and geochronological similarities in each of these areas have resulted from the development of an E-W trending igneous arc produced by N-S bulk shortening with north over south subduction in the Ordovician. This would readily explain the E-W trending FIA set 1, which most significantly, cannot be explained by the current distribution of these rocks (see below).

### 5.4. The potential for correlating multiple phases of deformation across the Northern Thomson Fold Belt using FIA sets

The Northern Thomson Fold Belt has been affected by convergent margin related processes involving extensional and contractional events from the Cambrian to the late Carboniferous (Fergusson et al., 2007a, b). K-Ar dating of muscovite (500Ma), Rb-Sr dating of whole rock muscovite (500Ma) and U-Th-Pb monazite dating of (510Ma) show that the Delamerian Orogeny (520-500 Ma) has affected the Halls Reward Metamorphics of the Greenvale Province (Nishiya et al., 2003). How much this orogeny affected the rocks to the west of the Hall Rewards Metamorphics and Southern Thomson Fold Belt is unknown. U-Pb zircon SHRIMP metamorphic age of the Oasis Metamorphics at 476±5 Ma from west of the Balcooma Mylonite Zone revealed that these rocks were Ordovician in age rather than Precambrian as previously had been thought and thus identical in age to those at Balcooma (Fergusson et al., 2007b). Early Ordovician orogenesis (476-450Ma) and Silurian Orogenesis (440-420Ma - Benambran) caused regional deformation in the Charters Towers and

Greenvale Provinces (Fig. 4; Fergusson et al. , 2007a; Henderson 2007). The Late Devonian to Early Carboniferous Kanimblan Orogeny and Middle Devonian to Triassic Hunter Bowen Orogeny had the least tectonic influence on the main tectonic grain of the Northern Thomson Fold Belt (Henderson, 2007; Fergusson et al., 2007a). The exposed parts of the Northern Thomson Fold Belt do not uniformly share metamorphism and episodes of deformation related to the Delamerian, Benambran, Tabberaberan, Kanimblan and Hunter Bowen orogenies. For example the Charters Towers Province includes weakly deformed Late Cambrian to Early Ordovician rocks of the Seventy Mile Range group associated with low to high grade metasedimentary units of the Cape River, Running River and Argentine Metamorphics (Fergusson et al., 2005, 2007a, b). Due to the partitioning of deformation across an orogen, the timing of metamorphism and the P-T-t-d path of the rocks commonly differs from place to place (c.f., Bell & Mares, 1999; Bell et al., 2004). In such situations the correlation of tectonic events on the basis of overprinting structures in the matrix becomes difficult because the succession of structures and associated metamorphism commonly changes along orogenic belts (Bell & Mares, 1999). However, detailed work in the Appalachians and the Kimberley Arc in northwest Australia (Bell & Mares, 1999; Bell et al., 1998; Bell et al., 2003; Bell et al., 2004) has revealed that successions of FIA sets can remain unaffected by multiple episodes of subsequent deformation and metamorphism. The periods of orogenesis that produced the 5 FIA sets in the Balcooma region potentially have affected other regions but at different intensities. The E-W trending FIA set 1 resulted from N-S bulk shortening in the Ordovician around 476±5-454±12Ma (Ali, 2009B) and may be have generated the E-W trends preserved within the Cape River Metamorphics and the Charters Towers region (Fig. 4). Subsequent E-W shortening rotated this E-W trend to SE -NW in the Cape River Area and ENE-WSW in the Charters Towers region.

## 5.5. Significance of N-S shortening related to FIA 1 in the Balcooma Metamorphic Group

The Georgetown Block, which lies to the west of the Balcooma Metamorphic Group (Greenvale Province), contains extensive exposure of Precambrian rocks (Fig. 4). The Lynd Mylonite Zone (LMZ in Fig. 4) separates 1700-1550 Ma biotite gneiss, calc-silicate gneiss and leucocratic gneiss of the Georgetown Block from the Early Palaeozoic metamorphic rocks of the Greenvale Province (Fergusson et al., 2007b). Detailed work by Cihan and Parsons (2005) in the Georgetown Block has reported a Precambrian succession of four FIAs trending ENE-WSW, E-W, N-S and NE-SW. The last of these FIAs formed from SE-NW bulk shortening at around 1550 Ma (Black et al., 1998; Cihan and Parsons, 2005; Cihan et al., 2006). A remarkably similar FIA succession is preserved in the Mt Isa Inlier (Sayab, 2008). This FIA succession appears to have formed at the same time by the same changes in the direction of bulk shortening in each of these regions. None of these authors have reported evidence for a 476±5 to 454±12Ma E-W trending structure preserved by porphyroblasts or the matrix. The absence of an Ordovician N-S shortening direction to the west and its presence to the east of the Precambrian craton, recorded by FIA 1 in the Balcooma Metamorphic Group, is very significant. Unless a transfer or transform fault was present on the craton boundary, such a geometry is impossible. An Early Ordovician E-W trending foliations must be present in Precambrian rocks due west of Balcooma if those at the time were deformed in their current location at that time. None have been recorded although the Juntala Metamorphics, 100 km to the SW of Balcooma (Fig. 1), are affected by folds with E-W trending axial planes (Duncan, 1983). These rocks lie close to the southern edge of the Georgetown Block and could have been the northern most expression of the Northern Thomson Fold Belt prior to northwards displacement of the Balcooma and Oasis

Metamorphics. Therefore, the Balcooma and the Oasis Metamorphics to the west must have been displaced to their current location by some combination of folding and faulting that post-dated the development of FIA 1 (Fig. 14). This E-W trending Ordovician period of tectonism must have occurred along the southern boundary of the Precambrian craton to leave it unaffected. The rocks of the Greenvale Province would have been deformed on this boundary at the time of development of FIA 1 and been displaced northwards afterwards. The fold belt in which they lay would have trended E-W or ENE-WSW from south of the Mt Isa Inlier through Hughenden to Charters Towers. The bulk E-W shortening during younger orogenies that displaced them into their current location would have increased the N-S width of the Northern Thomson Fold Belt. The northwards bulging shape would have been matched by an equivalent southwards bulge and been escape structures resulting from the younger E-W shortening of initially Ordovician generated fore arc and back arc thrusts (see schematic diagrams in Fig. 15 a, b, c). This would explain the Ordovician ages obtained from volcanics and granites at the base of deep drill holes through the Eromanga Basin (Fig. 1).

### 5.6. E-W orogenesis across Australia

SHRIMP U-Pb analyses of monazite and zircon by Hand et al. (1999) indicate that the Harts Range of central Australia has been affected by an Early Ordovician (467 ± 8 Ma) regional high-grade metamorphism and deformation that produced amphibolite/granulite facies minerals assemblages (800-875 $^{O}$C and 5-7 Kbar). 445±5 and 434±6 Ma ages associated with reworking of Proterozoic granulites occur in the Eastern Arunta Block (Scrimgeour & Raith, 2001). These ages have important implications for the evolution of the cental Australia crust during the early Palaeozoic because the Ordovician has been regarded as a tectonically quiet period, characterized by slow sedimentation in a broad intracratonic Amadeus Basin (Shaw et al., 1991; Lindsay & Korsch, 1991; Hand et al., 1999). The tectonic significance of the Early Ordovician deformation in the Harts Range region is not fully understood because the Amadeus and Georgina basins contain a depositional record spanning the Neoproterozoic to Devonian (Fig. 2, Maidment et al., 2007). The major intraplate Petermann Orogeny from 550 to 520 Ma affected the southern margin of the Amadeus Basin but did not disrupt sedimentation within it (Maidment et al., 2007). Although they have no direct evidence Hand et al., (1999) suggested that the intense high metamorphic grade deformation at this time may have resulted from crustal extension associated with sedimentary basin development rather than by convergent tectonism and mountain building. Gently dipping foliations in the Anakie, Charters Towers and Greenvale areas of NE Queensland have been attributed to extension without direct structural evidence that this process was involved (Fergusson et al., 2005, 2007 a, b, c). However, the result presented herein reveals that the generation of a succession of gently dipping foliations was interspersed with the formation of sub-vertical ones during this early Ordovician time period in NE Queensland. Therefore, crustal shortening has definitely affected these rocks.

### 5.7. The Euler pole solution

The work presented herein opens a new possibility for the interpretation for the apparent E-W trend of orogens in the Ordovician across Gondwanian Australia. The E-W trending Northern Thomson Fold Belt may have resulted from an Ordovician collision zone (e.g., Glen et al., 2007a, b) along which Charters Towers Province rocks to the south were thrust northwards over basement rocks to the Broken River Province (pers. comm. Raphael Quentin 2009). The E-W trending belt of the Ordovician granites and volcanics were being emplaced concurrent with deformation forming E-W trending foliations (Bell, 1980). In the same period, the Harts Range of central Australia was being deformed to amphibolite grade metamorphism.

Compressional orogenesis in the east and extensional orogenesis in the west in the same time would have resulted if the Euler pole or rotation axis for relative plate motion at that time lay between these two regions. This is shown schematically in (Fig. 16) where the plate to the south swivels anticlockwise around the Euler pole relative to the plate to the north.

## 6. Conclusions

1. Ordovician E-W trending structures that resulted from N-S bulk shortening of rocks at the Balcooma Metamorphic Group are not present in the Precambrian craton to the west.
2. The Lower Palaeozoic orogen in which these rocks lie was displaced northwards from its original location during E-W directed Benambran shortening of the Northern Thomson Fold Belt.
3. The Early Ordovician E-W grain of the Charters Towers region is primary rather than secondary and this orogen extended westwards south of the Mt Isa Inlier towards central Australia.
4. Compressional orogenesis in NE Australia around the same time as extensional orogenesis in central Australia requires that the Euler pole for the relative motion of the two plates involved lies in between these two regions close to the Northern Territory/Queensland border.
5. This conclusion enables a dramatically different interpretation of early Palaeozoic Orogenesis in NE Australia. It suggests that the overall approximately E-W trending structural of the Charters Towers province is the relict of an originally E-W trending Cambro-Ordovician orogenic belt. This could be tested by conducting similar work to that done at Balcooma in the porphyroblastic rocks of the Charters Towers Province around the Thalanga deposit. If they preserve a similar succession of FIA trends, then the similarly aged and mineralised rocks at Thalanga and Balcooma could continue west towards Richmond

(328 km due southwest of Charters Towers). If the same orogenic history has occurred in both region then magnetics and gravity could be used to propose exactly where potentially mineralized Cambro-Ordovician rocks might occur.

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## References

Adshead-Bell, N.S. & Bell, T.H., 1999. The progressive development of a macroscopic upright fold pair during five near-orthogonal foliation producing events: complex microstructures versus a simple macrostructure. *Tectonophysics* **306**, 121-147.

Ali, A., 2009 A. Deformation partitioning and porphyroblast growth.

Ali, A., 2009 B. Protection of monazite grains from obliteration in highly tectonized terrains by porphyroblasts: microstructural approaches to tectonic reconstructions.

Bell, T.H., 1980. The deformation history of N.E. Queensland- A new framework. In Henderson, R.A., and Stephenson, P.J., (Eds), The Geology and Geophysics of Northeastern Australia, 307-313. Geological Society of Australia (Qld. Div.) Brisbane.

Bell, T.H., & Johnson, S.E., 1989a. The role of deformation partitioning in the deformation and recrystallization of plagioclase, orthoclase and microclinein the Woodroffe Thrust Mylonite Zone. *Journal of Metamorphic Geology* **7**, 151-168.

Bell, T.H., & Johnson, S.E., 1989b. Porphyroblast inclusion trails: the key to orogenesis. *Journal of Metamorphic Geology* **7**, 279-310.

Bell, T.H., A. Forde, & Wang, J., 1995. A new indicator of movement direction during orogenesis: measurement technique and application to the Alps. *Terra Nova* **7**, 500-508.

Bell, T.H., K.A. Hickey, & Upton, J.G., 1998. Distinguishing and correlating multiple phases of metamorphism across a multiply region using the axes of spiral, staircase and sigmoidal inclusion trails in garnet. *Journal of Metamorphic Geology* **16,** 767-794.

Bell, T.H., & Hickey, K.A., 1999. Complex microstructures preserved in rocks with a simple matrix: significance for deformation and metamorphic processes. *Journal of Metamorphic Geology* **17**, 521–535.

Bell, T. H., & Mares, V. M., 1999. Correlating deformation and metamorphism around arcs in orogens. *American Mineralogist* **84**, 1727-1740.

Bell, T.H., & Welch, P.W., 2002. Prolonged Acadian orogenesis: revelations from foliation intersection axis (FIA) controlled monazite dating of foliations in porphyroblasts and matrix. *American Journal of Science* **302**, 549-581.

Bell, T.H., Ham, A.P. & Hickey, K.A., 2003. Early formed regional antiforms and synforms that fold younger matrix schistosities: their effect on sites of mineral growth, Tectonophysics **367**, 253–278.

Bell, T.H., Ham, A.P. & Kim, H.S., 2004. Partitioning of deformation along an orogen and its effects on porphyroblast growth during orogenesis. *Journal of Structural Geology* **26**, 825-845.

Bell, T. H., & Kim, H.S., 2004. Preservation of Acadian deformation and metamorphism through intense Alleghanian shearing. *Journal of Structural Geology* **26**, 1591-1613.

Bell, T.H., & Newman, R., 2006. Appalachian orogenesis: the role of repeated gravitational collapse. In: Butler, R., Mazzoli, S. (Eds.), Styles of Continental Compression. *Special Papers of the Geological Society of America* **414**, 95-118.

Bell, T.H., 2009. Deformation partitioning, foliation successions and their significance for orogenesis: hiding lengthy deformation histories in mylonites. In: Law, R.D., Butler, R.W.H., Holdsworth, R., Krabendam, M. & Strachan R. (eds) Continental Tectonics and Mountain Building: The Legacy of Peach and Horne. Geological Society of London, Special Publications, in press (accepted Dec 24, 2008).

Black, L.P., Gregory, P., Withnall, I.W. & Bain, J.H.C., 1998. U-P zircon age for the Etheridge Group, Georgetown region, north Queensland: implications for relationship with the Broken Hill and Mt Isa sequences. *Australian Journal of Earth Sciences* **45**, 925-935.

Cawood, P. A., 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Palaeozoic. *Earth Sci. Rev.* **69**, 249 - 279.

Cihan, M., 2004. The drawbacks of sectioning rocks relative to fabric orientations in the matrix: A case study from the Robertson River Metamorphics (Northern Queensland, Australia). *Journal of Structural Geology* **26**, 2157-2174.

Cihan, M. & Parsons, A., 2005. The use of porphyroblasts to resolve the history of macro-scale structures: an example from the Robertson River Metamorphics, North-Eastern Australia. *Journal of Structural Geology* **27**, 1027-1045.

Cihan, M., Evins, P.M., Lisowiec, N.J. & Blake, K.L., 2006. Time constraints on deformation and metamorphism from EPMA dating of monazite in the Proterozoic Robertson River Metamorphics, NE Australia. *Precambrian Research* **145**, 1 – 23.

Coney, P. J., Edwards, A., Hine, R., Morrison, F. & Windrum, D., 1990. The regional tectonics of the Tasman Orogenic system, eastern Australia. *Journal of Structural Geology* **125**, 19-43.

Day, R. W, Murray, C. G. & Whitaker, W. G., 1978. The eastern part of the Tasman Orogenic Zone. *Tectonophysics* **48**, 327-364.

De Keyser, F., 1963. The Palmerville Fault - a “fundamental” structure in north Queensland. *Journal of the Geological Society of Australia* **10**, 273-278.

Direen, N. G. & Crawford, A. J., 2003. The Tasman Line: where is it, what is it, and is it Australia's Rodinian breakup boundary? *Australian Journal of Earth Sciences* **50**, 491-502.

Draper, J.J., 2006. The Thomson Fold Belt in Queensland revisited, Australian Earth Sciences Convention, Melbourne, Australia, extended abstracts series AB82 (on DVD).

Duncan, A.C., 1983. On geometric analysis. *Unpublished PhD thesis*, James Cook University, 1-159.

Fay, C., Bell, T.H. & Hobbs, B.E., 2008. Porphyroblast rotation versus non-rotation: conflict resolution! *Geology* **36**, 307-310.

Fay, C., Bell, T.H. & Hobbs, B.E., 2009. Porphyroblast rotation versus non-rotation: Conflict resolution! COMMENT and REPLY. *Geology* **37**, e182-e188.

Fergusson, C. L., Henderson, R. A., Lewthwaite, K.J., Phillips, D. & Withnall, I. W., 2005. Structure of the Early Palaeozoic Cape River Metamorphics, Tasmanides of north Queensland: evaluation of the roles of convergent and extensional tectonics. *Australian Journal of Earth Sciences* **52**, 261 – 277.

Fergusson, C.L., Henderson, R.A., Withnall, I.W., Fanning, C.M. & Phillips, D., 2007a. Structural, metamorphic, and geochronological constraints on alternating compression and extension in the Early Palaeozoic Gondwanan Pacific margin, northeastern Australia. *Tectonics* **26**, 1-20.

Fergusson, C. L., Henderson, R. A., Withnall, I. W. & Fanning, C.M., 2007 b. Structural history of the Greenvale Province, north Queensland: Early Palaeozoic extension and convergence on the Pacific margin of Gondwana. *Australian Journal of Earth Sciences* **54**, 573-595.

Fergusson, C. L., Henderson, R. A., Fanning, C.M. & Withnall, I. W., 2007c. Detrital Zircon ages in Neoproterozoic to Ordovician siliciclastic rocks, northeastern Australia: implications for the tectonic history of the East Gondwana continental margin. *Journal of the Geological Society of London* **164**, 215-225.

Glen, R.A., Korsch, R.J., Costelloe, R.D., Poudjom, Y. & Mantaring, R., 2007a. Preliminary results from the Thomson-Lachlan Deep Seismic Survey, northwest New South Wales. Predictive Mineral Discovery Cooperative Research Centre, Geoscience Australia.

Glen, R. A., Poudjom, Y., Djomani, Korsch, R. J., Costello, R. D. & Dick, S., 2007b. Thomson-Lachlan seismic project-results and implications. In: Lewis P. C. (ed.)

Mines and Wines 2007, Mineral Exploration in the Tasmanides. *AIG Bulletin* **46**, 73-78. http://www.smedg.org.au/M&W2007Abs.pdf

Gray, D.R. & Foster, D.A., 2004. Tectonic evolution of the Lachlan Orogen, southeast Australia: historical review, data synthesis and modern perspectives. *Australian Journal of Earth Sciences* **51**, 773-817.

Ham, A.P. & Bell, T.H., 2004. Recycling of foliations during folding. *Journal of Structural Geology* **26**, 1989-2009.

Hand, M., J. Mawby, Kinny, P. & Foden, J., 1999. U– Pb ages from the Harts Range, central Australia: Evidence for early Ordovician extension and constraints on Carboniferous metamorphism. *Journal of the Geological Society of London* **156**, 715-730.

Harvey, K. J., 1984. The geology of the Balcooma massive sulphide deposit, north-east Queensland, *M.Sc thesis*, James Cook University of North Queensland, Townsville.

Hayward, N., 1990. Determination of early fold axis orientations within multiply deformed rocks using porphyroblasts. *Tectonophysics* **179**, 353-369.

Henderson, R. A., 1986. Geology of the Mt Windsor Subprovince-A lower Palaeozoic volcano-sedimentary terrane in the northern Tasman Orogenic Zone. *Australian Journal of Earth Sciences* **33**, 343-364.

Henderson, R. A., 1987. An oblique subduction and transform faulting model for the evolution of the Broken River Province, northern Tasman Orogenic Zone. *Australian Journal of Earth Science* **34**, 237 – 249.

Henderson, R.A., 2007. Crustal history and tectonics of the northern Tasman Orogenic Zone, Unpublished Economic Geology Research Unit short course, James Cook University, 1-24.

Huston, D.L., 1990. The stratigraphic and structural setting of the Balcooma volcanogenic massive sulphide lenses, north Queensland. *Australian Journal of Earth Sciences* **37**, 423-440.

Huston, D. L. & Taylor, T. W., 1990. Dry River copper and lead-zinc-copper deposits. In Hughes F. E. ed. Geology of the Mineral Deposits of Australia and Papua New Guinea. *Australasian Institute of Mining and Metallurgy*: **Melbourne**, 1519-1526.

Kirkegaard, A.G., 1974. Structural elements of the northern part of the Tasman Geosyncline. *Geological Society of Australia* (Queensland Division), Brisbane, pp 47-62.

Lindsay, J.F. & Korsch, R.J., 1991. The evolution of the Amadeus Basin, central Australia. In: Korsch, R.J., Kennard, J.M. (eds) Geological and geophysical studies in the Amadeus Basin, central Australia, Bureau of Mineral Resources, Geology and Geophysics, Australia Bulletin, 236, 7.32.

Maidment, D.W., Williams, I.S. & Hand, M., 2007. Testing long-term patterns of basin sedimentation by detrital zircon geochronology, Centralian Superbasin, Australia. *Basin Research* **19**, 335–360

Murray, C. G. & Kirkegaard, A. G., 1978. The Thomson orogen of the Tasman Orogenic Zone. *Tectonophysics* **48**, 299-325.

Murray, C. G., 1986. Metallogeny and tectonic development of the Tasman Fold Belt system in Queensland. *Ore Geol. Rev.* **1**, 315-400.

Nishiya, T., Watanabe, T., Yokoyama, K. & Kuramoto, Y., 2003. New isotopic constraints on the age of the Halls Reward Metamorphics, north Queensland, Australia: Delamerian metamorphic ages and Greenville detrital zircons. *Gondwana Research* **6**, 241-249.

Paine, A.G.L., Harding, R.R. & Clarke, D.E., 1971. Geology of the northeastern part of the Hughenden 1:250000 Sheet area, Queensland, Rep. Bureau of Mineral Resources. *Geology and Geophysics,* Australia 1.26.

Passchier, C.W., Trouw, R.A.J., Zwart, H.J. & Vissers, R.L.M., 1992. Porphyroblast rotation: eppur si muove? *Journal of Metamorphic Geology* **10**, 283-294.

Rea, P.S. & Close, R.J., 1998. Surveyor 1 copper-lead-zinc-silver-gold deposit. The Australian Institute of Mining and Metallurgy: Melbourne, pp. 737- 742.

Rosenfeld, J.L., 1968. Garnet rotation due to the major Palaeozoic deformation in southeast Vermont. In: Zen, E-AN, White, W.S., Hadley, J.B. (Eds.), Studies of Appalachian Geology: Northern and Maritime, Interscience publishers, New York, pp. 185-202.

Sayab, M., 2005. Microstructural evidence for N–S shortening in the Mount Isa Inlier (NW Queensland, Australia): the preservation of early W–E trending foliations in porphyroblasts revealed by independent 3D measurement techniques. *Journal of Structural Geology* **27**, 1445-1468.

Sayab, M., 2006. Decompression through clockwise P-T path: implications for early N-S shortening orogenesis in the Mesoproterozoic Mt Isa Inlier (NE Australia). *Journal of Metamorphic Geology* **24**, 89-105.

Sayab, M., 2008. Correlating multiple deformation events across the Mesoproterozoic NE Australia using foliation intersection axes (FIA) preserved within porphyroblasts. *Gondwana Research* **13**, 331-351.

Scheibner, E., 1978a. Tasman Fold Belt System or Orogenic System-Introduction. *Tectonophysics* **48**, 153-157.

Scheibner, E., (EDITOR) 1978b. The Phanerozoic structure of Australia and variations in tectonic style. *Tectonophysics* **48**, 153-427.

Scheibner, E., (EDITOR) 1986. Metallogeny and tectonic development of eastern Australia. *Ore Geology Reviews* **1**,147-412.

Scrimgeour, I. & Raith, G. J., 2001. High-grade reworking of Proterozoic granulites during Ordovician intraplate transpression, eastern Arunta Inlier, central Australia. In: Miller J. A., Holdsworth R. E., Buick I. S. & Hand M. eds. Continental Reactivation and Reworking. *Geological Society of London Special Publication* **184**, 261-287.

Shaw, R. D., Fawckner, J. F. & Bultitude, R. J., 1987. The Palmerville fault system: a major imbricate thrust system in the northern Tasmanides, north Queensland. *Australian Journal of Earth Sciences* **34**, 69 – 93.

Shaw, R.D., Etheridge, M. A. & Lambeck, K., 1991. Development of the late Proterozoic to mid-Palaeozoic intracratonic Amadeus Basin in central Australia: A key to understanding tectonic forces in plate interiors. *Tectonics* **10**, 688-721.

Spiess, R. & Bell, T.H., 1996. Microstructural controls on sites of metamorphic reaction: a case study of the inter-relationship between deformation and metamorphism. *European Journal of Mineralogy* **8**, 165-186.

Vander Hor F., 1990. Structural geology of the Balcooma-Dry River area, northeast Australia, with emphasis on the inter-relation between deformation and metamorphism. *PhD thesis*, James Cook University Australia, pp.139.

Vos, I.M.A., Bierlein, F.P. & Phillips, D, 2007. The Palaeozoic tectono-metallogenic evolution of the northern Tasman Fold Belt System, Australia: Interplay of subduction rollback and accretion. *Ore Geology Reviews* **30**, 277-296.

White, D.A., 1965. The geology of the Georgetown/ Clarke River area, Queensland, Bureau of Mineral Resources. *Geology and Geophysics Australia*, Bulletin 71.

Withnall, I. W., 1982. The geology of the Greenvale-Balcooma area. In Withnall I. W. ed. 1982 Field Conference Charters Towers-Greenvale area, pp. 31-46. *Geological Society of Australia* (Queensland Division), Brisbane.

Withnall, I. W., 1989. Precambrian and Palaeozoic geology of the south-eastern Georgetown Inlier, North Queensland. *Queensland Department of Mines, Report* **2**, 1-102.

Withnall, I. W., Black, L.P. & Harvey, K. J., 1991. Geology and geochronology of the Balcooma area: part of an early Palaeozoic magmatic belt in north Queensland, Australia. *Australian Journal of Earth Sciences* **38**, 15-29.

Withnall, I. W., Hutton, L. J., Garrad, P. D. & Rienks, I. P., 1997. Pre-Silurian rocks of the Lolworth-Pentland area, North Queensland. *Queensland Geological Record*, 1997/6.

Williams, P.F., & Jiang, D., 1999. Rotating garnets. *Journal of Metamorphic Geolog*y **17**, 367-378.

Yeh, M.W., 2007. Deformation sequence of Baltimore gneiss domes, USA, assessed from porphyroblast Foliation Intersection Axes. *Journal of Structural Geology* **29**, 881-897.

# Conclusions

## Conclusions

This study has shown that Foliation Intersection Axes preserved within porphyroblasts (FIAs) can be effectively used to unravel very complex tectono-metamorphic histories of multiply deformed rocks. The detailed conclusions are given below.

### Section A

The effect of deformation partitioning on porphyroblast growth was assessed using samples gathered across a large region where outcrop was relatively sparse and weathered versus a small region where a large number of oriented drill core samples were available from very fresh rock. A total of 143 FIAs with five identical successions were determined from 79 samples. The succession of FIA sets and microstructural relationships between garnet, staurolite, plagioclase, kyanite, andalusite, cordierite and fibrolitic sillimanite reveal a regionally consistent pattern of growth across the Balcooma Metamorphic Group. The local coexistence of kyanite, andalusite and sillimanite and a consistent succession in the timing of growth of the different porphyroblastic phases resulted from the effects of deformation partitioning relative to bulk composition and P-T path. Similarly distributed FIA sets 1, 2, and 3 across the pit as well as in the Balcooma region suggest that the partitioning of deformation from ~476±5 to 425.4±3.7 Ma was relatively pervasive at all scales across the Balcooma Metamorphic Group. The W-E trending FIA 4, which is 408.8±8.9 Ma in age, was only observed in the northern part of the Balcooma region and reveals more localized deformation partitioning effects during this period of bulk shortening. The lack of staurolite growth at this time in the southern part of the region resulted from the lack of partitioning of these events into this region at the scale of a porphyroblast. The NE-SW trending FIA 5 was more frequently observed in the Pit area rather than the Balcooma region.

### Section B

The N-S trending Tasman Orogenic Zone was shaped by the Ross-Delamerian (520-500 Ma), Early Ordovician (475-450 Ma), Benambran (440-420 Ma), Tabberaberan (410-370 Ma), Kanimblan (360-320 Ma) and Permian Hunter-Bowen Orogenies. U-Pb zircon ages, SHRIMP zircon ages, electron microprobe ages of monazite grains and the unstrained Devonian marine rocks of the Conjuboy Formation (Emsian age) indicate that the Delamerian, Kanimblan and Hunter Bowen Orogenies did not affect the Balcooma Metamorphic Group. 476±5-486±5-477±6 Ma U-Pb zircon ages (Fergusson et al., 2007b) and 471±4, 478±5 SHRIMP zircon ages (Withnall et al., 1991) indicate $D_1$ amphibolite facies metamorphism accompanied igneous intrusion during an Early Ordovician Orogeny (475-450 Ma). The earliest 443.2±3.8 Ma phase of monazite growth within the Balcooma Metavolcanics, preserved in porphyroblasts containing FIA 2, and 425.4±3.7 Ma and 408.8±8.9 Ma ages preserved in those containing FIAs 3 and 4, respectively, indicate that this region was then overprinted by the Benambran (440-420 Ma), and possibly the Tabberabberan (410-370 Ma), orogenies.

### Section C

Earlier workers thought that the Greenvale Province was deformed in an extensional backarc tectonic environment in the Ordovician, underwent compression in the Early Silurian and then exhumation in the Early Devonian. W-E trending FIA 1 is only preserved in garnet porphyroblasts. Inclusions of chlorite, biotite and muscovite and tight Mn, Ca and Fe garnet core isopleth intersections indicate that the garnet cores grew at ~ 530°C and 4.6±0.1kbar. No monazite grains were trapped within the foliations defining this FIA set but the approaches of others suggest that this period of amphibolite facies metamorphism occurred around 477 Ma. The incorporation of garnet in staurolites containing FIA 2 and FIA 3 and synchronous growth of kyanite during FIA 3 suggests a clockwise prograde path up to a metamorphic peak at 623-637°C and 6.2 ± 0.3 kbar during the Early Silurian Benambran Orogenic event. The break down of staurolite, kyanite and biotite to andalusite and the overprinting of andalusite by cordierite suggest that peak metamorphic conditions during Early Silurian Benambran orogenesis were followed by decompression. A P-T-t-D path was derived from the sequential growth of chlorite, muscovite, biotite, garnet, staurolite, kyanite, andalusite, cordierite and fibrolitic sillimanite, the FIAs, the P-T conditions of garnet core growth, P-T pseudosection modeling (MnNCKFMASH system) and geothermobarometry. It changes from clockwise to anticlockwise after the Benambran Orogenic event.

## Section D

The Precambrian Georgetown Block to the west of the Balcooma Metamorphic Group was not affected during the Early Ordovician (475-450 Ma) Orogenic event. Therefore, the W-E trending FIA 1 in the Balcooma region, which is Ordovician in age (476±5 to 454±12 Ma), cannot have formed with these Precambrian rocks in their current location or Early Ordovician W-E trending foliations would be present in Precambrian rocks due west of Balcooma. The Balcooma Metamorphic Group has to have been subsequently folded and/or faulted into this location. For intense N-S shortening to not affect the adjacent Precambrian to the west, the Balcooma

Metamorphic Group must have lain approximately 200 km to the south on the western boundary of the Charters Towers Province. They were then displaced 200 km north into their current location by the E-W bulk shortening effects of the Silurian Benambran Orogeny (440-420Ma), which controlled the development of FIAs 2 (443.2±3.8 Ma) and 3 (425.4±3.7 Ma) and post-dated the development of FIA 1. Synchronous N-S bulk shortening orogenesis in eastern Australia and N-S extensional orogenesis in central Australia during the Ordovician can be explained if the Euler pole for relative plate motion was located between these locations to the WSW of the Mt Isa Inlier. A plate containing the southern half of Australia pivoting anticlockwise around this axis of rotation relative to one containing the northern half, would produce crustal shortening orogenesis in the east and extensional orogenesis in the west from 476±5 to 454±12 Ma.