- SECTION A -

TEXTURAL DEVELOPMENT OF MICA RICH PSEUDOMORPHS AFTER CORDIERITE

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ABSTRACT

The rocks near the Lolworth batholith in NE Queensland and the Mooselookmeguntic pluton in western Maine contain mica rich pseudomorphs after cordierite that show evidence of progressive textural development under an active stress regime. The former contains complete pseudomorphs consisting of preferentially aligned or “randomly oriented” fine grained muscovite, chlorite, ± biotite. The later contains partial pseudomorphs of preferentially aligned coarser grained muscovite and biotite. The preferred orientation of micas is parallel to the orientation of the inclusion trails. The micas grew preferentially along microcracks that developed in the same direction with the inclusion trails and moved progressively from the porphyroblasts margin towards the porphyroblasts core. At least three types of microcracks can be identified with two of them being relevant for the replacement process. The first one formed by direct replacement of quartz inclusions by plagioclase and volume expansion and the second one was caused by high strain rates. X-ray maps, image analysis, electron microprobe analyses of the minerals from the pseudomorphs and the surrounding matrix were used to quantify mineral modes, mineral distribution and the PT conditions.

Keywords: pseudomorphs, cordierite, microcracks, deformation, fluids.

1 INTRODUCTION

Cordierite is a common and important metamorphic mineral typical for low pressure-high temperature terrains. Its stability field can extend from lower amphibolite facies into migmatite domains and up to granulite facies terrains. Due to its relatively high stability and occurrence in a variety of rocks and PT conditions, cordierite plays a significant role in our understanding of processes that take place during metamorphism. One particularly important process refers to fluid rock interactions, of which cordierite has been proposed to be a reliable indicator (e.g., Kalt, 2000; Harley and Carrington, 2001; Rigby and Droop, 2008). That is because the equilibrium between mineral phases and PT conditions can change drastically if fluids are present. One phenomenon directly affected by fluid infiltration and/or activity during metamorphism is the appearance of mica rich pseudomorphs (e.g. Dutrow et al., 1999; 2008). This is almost always the case near pluton contacts where cordierite is a common phase and the presence of mica rich pseudomorphs has been used as an indication of fluid infiltration in relationship with the advection of magma from deeper levels in the crust.

Pseudomorphs and pseudomorphism are common phenomena that may occur in most rock types and in a diversity of environments. They preserve direct evidence of the mineralogical and chemical changes experienced by a rock during a specific event or series of events. This is particularly important for metamorphic rocks because, most of the time, direct evidence on which factors control a specific metamorphic reaction and on the form the reaction takes is missing. Traditionally, pressure, temperature and composition were attributed with the main role in driving metamorphic reactions while fluids and deformation were attributed mainly with a secondary role. The form the metamorphic reaction takes can be inferred from reaction textures or knowledge of the position of phases and isograds in the field (Kwak, 1974). It is not uncommon for pseudomorphs to consist of a core where the initial phase is preserved unaltered and a reaction rim where most of the initial phase has been replaced. Such reaction textures provide first hand evidence on the reaction progress, reaction mechanism, phases involved in the reaction, chemical changes and textural development of the pseudomorph. Starting with the early paper of Guidotti (1968), who was the first to show that muscovite segregations found in pelites from western Maine were pseudomorphs, most authors focused mainly on the reaction mechanism, compositional evolution, the role of fluids and material transport (e.g., Guidotti, 1970; Foster, 1977, 1981, 1983; Dutrow et al., 1999; Guidotti and Johnson, 2002; Dutrow et al., 2008). However, little attention has been given to the textural development of pseudomorphs and even less attention has been paid to the role of deformation. In this contribution we attempt to document these aspects with examples of mica rich pseudomorphs after cordierite from NE Queensland and western Maine.

2 GEOLOGICAL BACKGROUND

2.1 Maine

The Central Maine Belt (Northern Appalachians; Fig. 1) is interpreted to have developed as a thrust system during dextral transpressive deformation in response to Acadian oblique convergence with deformation, plutonism, and metamorphism being contemporaneous from ~408 Ma to less than 363 Ma (Solar et al., 1998; Solar and Brown, 2001; Sanislav, 2011; Sanislav and Bell, 2011). The metamorphic grade increases along strike to the southwest, from biotite to upper-sillimanite zone conditions (Guidotti, 1989) with local migmatites suggesting metamorphic conditions above the contemporary solidus (Brown and Solar, 1999). Three metamorphic events have been distinguished; M1, producing regional greenschist-facies metamorphism was followed by a regional thermal event, M2, which produced the assemblage And+St+Bt±Grt. Late-syntectonic plutons such as the Mooselookmeguntic (~389 to 363 Ma; Solar et al., 1998; Tomascak et al., 2005) have been interpreted to produce the M3 event that erased most M2 assemblages and produced St+Bt and Sill at higher grades (Guidotti, 2000; Henry and Guidotti, 2002). This event occurred at higher pressure and is spatially associated with the plutons. Guidotti & Johnson (2002) argued that prograde or retrograde pseudomorphs of the M2 porphyroblasts were produced during M3 as a function of pluton proximity. Sanislav (2011) and Sanislav and Bell (2011) proposed a succession of five different deformation and metamorphic events that affected the region from ~420 to less than 350 Ma.

2.2 NE Queensland

The Seventy Mile Range Group (NE Queensland, Australia; Fig. 2) comprises a thick Cambro-Ordovician volcano-sedimentary sequence (Henderson, 1986). The northern part of the belt has been extensively intruded by Ordovician to Devonian granitoids of the Lolworth-Ravenswood batholith (Richards, 1980). Metamorphic grades range from prehnite-pumpellyite facies in the eastern part of the belt to greenschist facies in the central part of the belt (Berry et al., 1992). To the west the metamorphic grade increases through actinolite, hornblende, biotite and andalusite isograds to amphibolite facies and rocks are characterized by higher strain possibly resulting from simultaneous regional deformation and granitoids emplacement. Three main deformations are recognized in the Seventy Mile Range Group. The first probably produced north south trending folds difficult to recognize producing only localized S_1; the dominant structure of the area is characterized by upright east-west F_2 folds and regional cleavage (S_2) associated with D_2; these structures are overprinted by a localized S_3 slaty cleavage and F_3 tight folds associated with D_3 (Berry et al., 1992).

3 THE PSEUDOMORPHS

In this paper, for partial pseudomorphs after cordierite, the part of the cordierite porphyroblast that has been almost entirely replaced by coarse-grained micas will be referred to as “the reaction rim” and the part of the pseudomorph where cordierite is the most abundant phase and was only slightly altered will be referred to as “the cordierite core”. Thus, for partial pseudomorphs, when using the word pseudomorph, this will refer to the cordierite core plus the reaction rim.

3.1 Maine–Coarse-grained pseudomorphs

Pseudomorphs after staurolite, andalusite, garnet and cordierite are common in the proximity of the Mooselookmeguntic pluton (Fig. 1). A detailed description of garnet, staurolite and andalusite pseudomorphs is to be found in Guidotti and Johnson (2002). Towards the pluton, pseudomorphs consist mainly of coarse grained micas. Pseudomorphs after staurolite are most commonly formed by coarse-grained muscovite and biotite. Where these pseudomorphs are the most advanced only small relicts of staurolite are present in a groundmass formed mainly of muscovite. Andalusite is only partly replaced by coarse grained muscovite and usually contains relict inclusions of staurolite. Coarse biotite is present mainly on pseudomorph margins where fibrolitic sillimanite nucleated as well. Sillimanite needles within andalusite are not uncommon. Garnet porphyroblasts are partly to completely replaced by coarse biotite that appears aligned to the dodecahedral faces.

Away from the pluton staurolite and andalusite porphyroblasts are partly to completely replaced by a mass of fine grained white micas. Coarse chlorite grains are usually present within the pseudomorph and/or at the pseudomorph margin. It is not unusual for pseudomorphs to be surrounded by a thin line of graphite that follows the porphyroblast contour. Garnet porphyroblasts are partly to completely replaced by coarse chlorite that follows the dodecahedral crystal faces.

Cordierite porphyroblasts are ovoidal shaped and up to 1 cm in diameter. They usually contain straight inclusion trails that curve gently in the matrix. Cordierite porphyroblasts also contain inclusions of garnet, staurolite and andalusite. Partial pseudomorphs of coarse grained micas after cordierite are common near the pluton margin. They consist of a cordierite core surrounded by a reaction rim of coarse-grained intergrowths of biotite and muscovite (Fig. 3). Within the reaction rim small grains of cordierite remnants are common. Idioblastic garnet porphyroblasts (Fig. 3b), slightly corroded, are common within the reaction rim and porphyroblastic biotite is present as inclusion in the cordierite core, in the reaction rim and in the matrix. Away from the pluton some of the cordierite porphyroblasts contain pinite alterations and coarse grained chlorite is common near porphyroblast margin.

3.2 NE Queensland – Fine-grained pseudomorphs

Fine-grained pseudomorphs after cordierite and andalusite are common in this region. Remnants of fresh cordierite are rare and where they occur they are only preserved as small grains in the core of the pseudomorph. Cordierite pseudomorphs are commonly ovoidal or pseudo-hexagonal shaped and consist of an assemblage of micas and chlorite. It is common for the cordierite porphyroblasts to contain well preserved, sigmoidal shaped inclusion trails that are usually truncated by the matrix foliation. Based on their mineralogy and textural appearance we identified three types of cordierite pseudomorphs. The first type and the most common one consists of fine grained biotite, muscovite and chlorite that are preferentially aligned along the well preserved inclusion trails (Fig. 4a, b). The second type consists of coarser grained chlorite and muscovite only that are preferentially aligned parallel to the inclusion trails (Fig. 4c, d). The third type of pseudomorphs contains poorly defined inclusion trails and consists of what appear to be randomly oriented intergrowths of chlorite and muscovite (Fig. 4e, f). Chlorite is commonly more abundant at the pseudomorphs margins and is coarser-grained at the contact with high strain zones (Fig. 4c, d, e and f).

Some of the samples contain partial to complete pseudomorphs after andalusite porphyroblast. They consist of fine grained white mica with some remnants of andalusite present in the core of the pseudomorph (Fig. 4g, h).

The inclusion trails in cordierite and andalusite pseudomorphs consist of ellipsoidal shaped quartz and ilmenite grains. In some samples the orientation of the inclusion trails in pseudomorphs differs from core to rim (Fig.4a, b, g and h).

4 CORDIERITE MICROFABRICS

The microfabrics of cordierite porphyroblasts identified in partial pseudomorphs from Maine near the Mooselookmeguntic pluton contact are characterized by the presence of inclusion trails, subgrains and microcracks.

4.1 Inclusion trails

The inclusion trails consist mainly of aligned elongate shaped quartz and plagioclase grains and subordinate ilmenite grains (Fig. 5). The inclusion trails are mainly sigmoidal shaped and appear to be continuous and sub-parallel to the matrix foliation. Within a few samples, the inclusion trails are predominately straight curving gently into the matrix at the porphyroblast margins. Biotite and muscovite grains in the reaction rim and within the remains of cordierite are similarly oriented to the inclusion trails.

4.2 Subgrains

The cores of cordierite porphyroblasts show the effects of plastic deformation in the form of undulose extinction and subgrain development. The boundaries between subgrains are irregular and no recrystallized grains have been observed near them. In a few samples subgrains impinge into one another or into the host with cracks propagating from their tips (Fig. 5a) along which muscovite and biotite grains have grown. The orientation of these grains is similar to the inclusion trails and micas present within the reaction rim. There are a few examples where the micas nucleated and grew along the boundary between two subgrains but only when the boundary is parallel to the inclusion trails (Fig. 5b), but in most cases they grew across boundaries in the direction of the inclusion trails (Fig. 5a, c).

4.3 Microcracks

Cordierite remains contain three types of microcracks. The most common type of cracks developed with preferred orientations parallel and at a high angle to the inclusion trails with the former being dominant (Fig. 5d). This type of crack appears to nucleate and to grow around inclusions from the tips of their long axes (Fig. 5e). They can grow from one inclusion to another one, developing into a series of interconnected cracks with the same orientation with the inclusion trails (Fig. 5f). The density of this type of cracks is higher towards the cordierite margin and decreases towards the core where cracks are usually absent. A more common type of microcrack develops when plagioclase replaces quartz inclusions (Fig. 5g). This results in high volume increase and microcracking of the host cordierite. The less common type of microcrack occurs and develops when one cordierite subgrain impinges into another one (Fig. 5a). In such case the crack develops from the tip of the impinging grain into the adjacent one. The grain that contains the crack always has uniform extinction. This type of crack always contains micas that grew along them and they always have the same orientation as the inclusion trails.

5 METHODS

5.1 Analytical technique

Three representative samples that contain pseudomorphs after cordierite, one from western Maine and two from NE Queensland, were selected for compositional mapping and modal mineralogy analyses. They contain cordierite pseudomorphs with distinct boundaries, reaction rims and replacement types that are characteristic for the observed samples. Polished thin sections were examined with a JEOL JXA-8200 scanning electron microscope at the Advanced Analytical Centre, James Cook University to quantify mineral modes via image analysis. Back-scattered electron images and elemental distribution X-ray maps were obtained by energy dispersive spectroscopy with an accelerating potential of 15 kV, a beam current of 10nA, and a 15µm focused electron beam producing 16-bit grayscale (256 shades) digital images for Al, K, Fe, Mg, Ti and Ca.

5.2 Mode calculation

For all back-scattered electron images and X-Ray maps (Fig. 6) the pseudomorph and the surrounding matrix were selected and isolated using Adobe Photoshop to ensure that modes from one area would not be influenced by the modes from the surrounding area. Modal mineralogical analysis was obtained using the image-processing program ImageJ (Rasband, 1997-2009) following the method described by Lydon (2005). ImageJ allows modal mineralogical analysis to be accomplished by grayscale segmentation. A specific mineral is given a unique grayscale range by combining two or more X-Ray maps, with or without a back-scattered electron image, and then the number of pixels within this grayscale range are counted and converted to an area percentage by normalizing the pixel count to the total number of pixels in the image area. The upper and lower threshold values of the grayscale range are chosen so as to include about half the edge effect pixels associated with the mineral of interest. The threshold values are determined graphically from examination of histograms of grayscale values or profiles of grayscale values across mineral grain boundaries. Mineral phases that were too small to be recognizable optically could be identified. The modal percentage of each mineral was normalized to the total area of the pseudomorph and the matrix. Modal amounts of ilmenite, pyrrhotite, apatite, muscovite, biotite, chlorite, plagioclase, cordierite, staurolite, garnet and quartz within the pseudomorph and matrix were calculated using area percentages determined by analysis of 16-bit grayscale (256-shade) back-scattered electron and X-ray maps.

5.3 Quantitative mineral chemistry

Major elements in silicate minerals from all predefined areas, pseudomorph and matrix, were analyzed by spot analyses to record variations in chemical composition relative to location. The JEOL JXA-8200 Super-Probe was used with an accelerating potential of 15kV, a beam current of 20nA, and a beam diameter of 1 to 5µm depending on the dimensions of the area in the mineral to be analyzed. The analyzed minerals comprise muscovite, biotite, chlorite, plagioclase, staurolite, garnet and cordierite.

6 RESULTS

6.1 Mineral modal amounts

6.1.1 Maine – partial pseudomorphs: sample IS90

The modal mineralogy (Table 1; Fig. 7) was obtained using the Al, K, Fe, Mg and Ca elemental distribution X-Ray maps and the back-scattered electron image for three domains; these included the cordierite core, the reaction rim and the matrix (Fig. 6a-f). The pseudomorph comprises an ellipsoidal relic of the original cordierite porphyroblast consisting of the cordierite core and the surrounding reaction rim. Within the cordierite core, the most abundant phase is represented by cordierite (53.5%), followed by coarse-grained muscovite laths (22.8%), quartz inclusion trails (10.4%), plagioclase (3.1%), and ilmenite and apatite grains aligned parallel to the cordierite long axis; porphyroblastic biotite (9.1%) is also present as inclusions (Fig. 7a). The reaction rim consists of cordierite (1.8%), coarse-grained muscovite (51.6%) and biotite (30.4%), plagioclase (10%), quartz (4.3%) and ilmenite as poorly preserved inclusion trails, plus two sub-idioblastic garnet porphyroblasts with slightly corroded margins (Fig. 7b). The matrix consists mainly of muscovite (42.8%), quartz (22%) and biotite (16%) with minor plagioclase, staurolite, apatite, ilmenite and pyrrhotite (Fig. 7c); garnet porphyroblasts (not present in the map area) are euhedral and their margins are not corroded.

6.1.2 NE Queensland – preferentially aligned complete pseudomorphs: sample RQ30

The mineral mode (Table 2; Fig. 8) was obtained using the Al, K, Fe, Mg and Ti elemental distribution X-Ray maps (Fig. 6g-k). A pseudomorph area and a portion of matrix were used for mode calculation. The pseudomorphs area consists of a fine-grained intergrowth of biotite (36.4%) and muscovite (34.7%) aligned parallel to inclusion trails defined by small ellipsoidal shaped quartz, plagioclase and ilmenite grains; chlorite (9.4%) mainly occurs on the margins (Fig. 8a). The matrix consists of quartz (29.1%), muscovite (21.2%), biotite (20.9%), plagioclase (18%), chlorite (9.8%) and minor, ilmenite and iron oxides (Fig. 8b).

6.1.3 NE Queensland –"randomly" oriented complete pseudomorphs: sample RQ83

The mineral mode (Table 3; Fig. 9) was obtained using the Al, K, Fe, Mg and Ti elemental distribution X-Ray maps (Fig. 6l-p). A complete pseudomorph (plus portions of nearby pseudomorphs) and a portion of the matrix were used for mode calculations. The former contains an apparently randomly oriented, fan-shaped intergrowth of muscovite (33.1%) and chlorite (28%); coarse-grained quartz (24%), plagioclase (14.2%) and minor ilmenite define poorly preserved inclusion trails oblique to the long axis of the original cordierite porphyroblast (Fig. 9a). The matrix consists mainly of quartz (47.6%), plagioclase (18.3%), chlorite (18.2%), muscovite (15.2%) and minor ilmenite and other iron oxide (Fig. 9b); biotite is locally present but not in the area mapped.

6.2 Mineral distribution

The method used to calculate mineral modes involved the production of a map for every mineral phase present in the pseudomorph (± cordierite core / reaction rim) and the matrix. This allowed determination of the distribution of each single mineral phase in every textural domain within the pseudomorph and the surrounding matrix.

6.2.1 Maine – partial pseudomorphs: sample IS90

From Figure 10 the relative distribution of mineral phases within the pseudomorph and the surrounding matrix can be analyzed. Muscovite and biotite are mainly concentrated in the reaction rim where they are relatively homogenously distributed. Within the cordierite core, muscovite laths are commonly aligned parallel to the inclusion trails and to the long axis of the cordierite. It is typically present along cracks that developed in the direction of the long axis of the ellipsoidal quartz grains that define the inclusion trails. The amount of muscovite grains decreases from the margin of the cordierite core towards the middle of the cordierite core where basically is missing (Fig. 10). Similar to muscovite, biotite appears to be more abundant away from the middle of the cordierite core. It is idioblastic with undisrupted grain boundaries and occurs as inclusions that tend to lie parallel to the inclusion trails. In the reaction rim muscovite is coarser than in the cordierite core and clearly aligned parallel to the inclusion trails defined in the pseudomorph area. Biotite grains appear in two different forms, as laths and as porphyroblasts. The latter are deformed, re-crystallized and aligned parallel to the inclusion trails.

Quartz is very abundant in the middle of the cordierite core from where is decreasing steadily to the margin of the cordierite core and decreases significantly in the reaction rim. Plagioclase distribution shows an inverse relationship to quartz distribution. It is more abundant in the reaction rim and decreases until almost absent in the middle of the cordierite core.

6.2.2 NE Queensland – preferentially aligned complete pseudomorphs: sample RQ30

Within the pseudomorphs, fine-grained biotite and muscovite grains that have replaced cordierite are aligned along well-preserved inclusion trails. This is apparent in the biotite map where these grains lie parallel to quartz grains (Fig. 11) defining inclusion trails that curve clockwise in the margins of the pseudomorph. Chlorite occurs rarely in the centre of the pseudomorph. It is more commonly localized in the margins of the pseudomorphs and is coarser-grained at the contact with high strain zones defined by aligned muscovite and biotite in the matrix (Fig. 11). Asymmetric high strain zones occur on both sides of the pseudomorph where segregation between muscovite and biotite has occurred. The latter phase dominates away from the pseudomorph while the former is more abundant towards it (Fig. 11). Both muscovite and biotite are absent within the strain shadow. Chlorite, which is homogeneously present in the matrix away from the pseudomorph, is absent within the high strain zones but tends to occur within the strain shadows together with quartz or at the interface between the strain shadow and muscovite within the inner portion of the high strain zone (Fig. 11).

6.2.3 NE Queensland –"randomly" oriented complete pseudomorphs: sample RQ83

Within these pseudomorphs, replacement of cordierite occurs by medium-grained intergrowth of muscovite and chlorite, homogeneously distributed, that is fan-shaped in predominantly two directions (Fig. 12). One is parallel to the inclusion trails and the second one is at high angle to the inclusion trails. Quartz grains tend to display a slight preferential alignment oblique to the long axis of the original cordierite porphyroblast and curve clockwise at the margins. This alignment probably reflects the original inclusion trail but coarser-grained quartz disrupts these trails. Coarse-grained chlorite only occurs within the matrix at the interface with the pseudomorph. All other mineral phases are homogeneously distributed within the matrix (Fig. 12).

6.3 Mineral chemistry

Major elements in silicate minerals from the pseudomorphs and matrix within samples IS90, RQ30 & RQ83 were analyzed to record variations in chemical composition relative to location. For comparison, an extra sample (IS104) from the Maine region was analyzed. This sample lies within the sillimanite zone and contains coarse grained pseudomorphs of muscovite and biotite after staurolite. This comparison provides a better understanding of changes in the replacement mechanism between higher and lower metamorphic grade samples. Representative analyses of the main phases are presented in Tables 4, 5, 6 and 7.

6.3.1 Muscovite

Tables 4, 5 and 6 show representative electron microprobe analyses of muscovite grains with respect to their textural setting (i.e. pseudomorph, matrix). The composition of muscovite grains from the lower grade rocks (e.g. RQ30 & RQ83) shows more variations than that of muscovite grains from higher grade rocks (IS90 & IS104). Figure 13a shows an overall inverse relationship between the sum of octahedral cations and octahedral Al. Significant variations relative to the textural setting of the muscovite grain are present. For example in sample RQ30, muscovite grains from the pseudomorph have lower octahedral Al than those in the matrix muscovite. In sample RQ83 the amounts of octahedral Al in muscovite grains from the pseudomorphs and matrix are similar. In sample IS90 muscovite from the cordierite core has the highest octahedral Al while the muscovite from the reaction rim and the matrix contains similar amounts of octahedral Al. In sample IS104, which is of sillimanite grade, muscovite from staurolite pseudomorphs shows higher octahedral Al than the matrix muscovite. The calcium content of muscovite from the lower grade rocks (RQ30 & RQ83) is very low (below 0.02 cations per formula unit) while in the higher grade rocks (IS90 & IS104) calcium is absent. The main substitution in the twelve fold interlayer site is between K and Na. Muscovite grains from different textural setting show characteristic K/Na ratios (Fig. 13b). For example, in sample RQ30, muscovite from the cordierite pseudomorph contains higher amounts of K and Na than muscovite from the matrix while in sample RQ83 higher K and Na is present in the matrix muscovite. In sample IS90 muscovite grains from the cordierite core have the lowest K and Na content followed by muscovite grains from the reaction rim while matrix muscovite has the highest K and Na content. In sample IS104 muscovite from the staurolite pseudomorphs and muscovite from the matrix have similar K content but matrix muscovite has a higher Na content.

6.3.2 Biotite

Biotite compositions relative to their textural setting from four different samples are presented in Tables 4, 5 and 6. In sample RQ83 biotite is present only in the matrix. Similar to muscovite, the Al-Tschermak's substitution (Fe, Mg)SiAl$^{VI}_{-1}$Al$^{IV}_{-1}$ in biotite defines the main compositional variation (Fig. 13c). Thus the ratio of the sum of the octahedral cations versus the octahedral Al has a negative slope. In sample RQ30 the ratio between octahedral cations and octahedral Al appears to be similar for biotite within both matrix and cordierite pseudomorphs. In sample IS90 octahedral Al in biotite increases from the matrix to the reaction rim and to the cordierite core with the corresponding decrease in the sum of octahedral cations. A similar trend is observed for sample IS104 where the octahedral Al in biotite increases from the matrix to the staurolite pseudomorph. In the twelve fold sites, calcium is missing in the biotite from the higher grade samples (IS90 & IS104) while in the lower grade samples (RQ30 & RQ83) there is usually less than 0.07 cations per formula unit. The highest K content is shown by the matrix biotite from sample RQ83. Figure 13d shows that biotite from the higher grade samples have higher Na content than biotite from the lower grade samples. In sample RQ30 the ratio between K and Na in biotite tends to increase from the matrix to the cordierite pseudomorph. This tendency is very clear in sample IS104 where the biotite from the matrix and the staurolite pseudomorphs clearly can be differentiated by their K/Na ratio. In sample IS90 the K/Na ratio appears to be relatively similar in biotite grains from the matrix, the reaction rim and the cordierite core.

6.3.3 Chlorite

Chlorite compositions with respect to their textural location from samples RQ30 and RQ83 are presented in Tables 5 and 6. Similar to muscovite and biotite, the main substitutions that affect chlorite involves the replacement of octahedral cations by octahedral Al (Fig. 13e). In sample RQ83 chlorite from the pseudomorph and from the matrix appear to have similar compositions. In sample RQ30 chlorite from the pseudomorph is characterized by high octahedral Al and low octahedral cations while chlorite in the matrix shows the opposite. Few matrix chlorite analyses located near pseudomorphs show similar compositional trends to the chlorite from the pseudomorph.

6.3.4 Plagioclase

Plagioclase core and rim compositions from samples RQ30 and IS90 with respect to their textural location are shown in Table 5 and 7. The plagioclase solid solution series can be described by the substitution NaSi=CaAl. This is illustrated by the negative slope of Si content vs. anorthite content in Figure 13f. The anorthite content of the two samples is clearly distinct; An_{25}-An_{30} in sample RQ30 vs. An_{19}-An_{25} in sample IS90. The change in anorthite content from core to rim of plagioclase grains relative to their textural setting is exactly opposite for samples RQ30 and IS90. In sample RQ30 plagioclase grains from the pseudomorph show a decrease in anorthite content from core to rim; plagioclase grains from the matrix and the matrix-pseudomorph boundary show an increase in the anorthite content from core to rim. In contrast, plagioclase grains from the cordierite in sample IS90 show an increase in anorthite content from core to rim; plagioclase grains from the reaction rim and from the matrix show a decrease in anorthite content from core to rim.

6.3.5 Cordierite

The composition of the cordierite core and of relicts located in the mica rich reaction rim is presented in Table 4. All cordierite analyses show a small excess of Si and the corresponding deficiency in Al. Cordierite relicts from the reaction rim tend to show complete occupancy of tetrahedral sites while all cores show a small deficiency which, at least partly, can be attributed to the presence of Fe^{3+}. The octahedral sites in cordierite are mainly occupied by Mg and to a lesser extent by Fe. Figure 13g shows that analyses of the cordierite relicts from the reaction rim have slightly lower Si content and higher Mg/Mg+Fe+Mn ratios than analyses from the cordierite core. Cordierite usually contains water and alkali ions located in the channels formed by six-membered rings. Na appears to be the only important alkali constituent of cordierite from western Maine and increases with the Si content being higher in the cordierite core than in cordierite relics from the reaction rim (Fig. 13f).

6.3.6 Garnet and staurolite

Tables 7 show core and rim analyses of a garnet porphyroblast located in the mica rich reaction rim developed around the cordierite porphyroblast and of a garnet porphyroblast located in the matrix. The almandine and spessartine content of both porphyroblasts decreases slightly from the core to the rim while the pyrope content increases. The spessartine content of the matrix garnet appears to be similar in the core and in the rim while in the spessartine content of the garnet from the mica rich reaction rim appears to be slightly higher in the rim than in the core. Chemical analyses and structural formulae for staurolite are presented in Table 4.

7 GEOTHERMOBAROMETRY ESTIMATES

7.1 Petrogenetic grids of Pattison et al. (2002)

Due to the lack of sufficient phases for precise thermobarometry calculations in the low grade RQ30 and RQ83 samples, the petrogenetic grids of Pattison et al. (2002), contoured for Mg/(Mg+Fe) in biotite as a function of pressure, were used (Fig. 14). They thermodynamically modeled petrogenetic grids in the system KFMASH using both the Pattison (1992) and the Holdaway (1971) aluminum silicate triple points. These satisfy most of the natural and experimental constraints for the low pressure assemblage muscovite + cordierite + andalusite + biotite + quartz and were then contoured in terms of X_{Mg} of biotite. Sample RQ30 has X_{Mg} values ranging from 0.465 to 0.565 which corresponds to pressures between 3.3 and 3.7 kbars and temperatures between 570 and 660°C using the Pattison (1992) triple point and to pressures between 2.3 and 2.7 kbars and temperatures between 560 and 630°C using the Holdaway (1971) triple point. Sample RQ83 has X_{Mg} values ranging from 0.308 and 0.526 which corresponds to pressures between 2.7 and 3.5 kbars and to temperatures between 560 and 660°C using the Pattison (1992) triple point and to pressures between 1.7 and 2.5 kbars and temperatures between 540 and 630°C using the Holdaway (1971) triple point. Sample IS90 has X_{Mg} values between 0.54 and 0.57 which correspond to pressures between 3.5 to 4 kbars and to temperatures between 580 to 660°C using the Pattison (1992) triple point and to pressures between 2.5 to 3 kbars and temperatures between 570 to 630°C using the Holdaway (1971) triple point.

7.2 Ti-in-biotite geothermometer

A temperature estimate was obtained using the Ti-in-biotite geothermometer of Henry et al., (2005) on samples from Maine (IS90) and NE Queensland (RQ30 & RQ83). This geothermometer is best used for graphitic, peraluminous metapelites that contain ilmenite or rutile and have equilibrated around 4-6 kbars. The temperature is given by the following equation:

$$T = \left\{\frac{\left[\ln(Ti) - a - c\left(X_{Mg}\right)^3\right]}{b}\right\}^{0.333}$$

where T is the temperature in °C, Ti is the number of atoms per formula unit (apfu) normalized on the basis of 22 O atoms, X_{Mg} is Mg/(Mg + Fe), a = –2.3594, b = 4.6482 × 10^{-9} and c = –1.7283. The calibration range for this expression is X_{Mg} = 0.275–1.000, Ti = 0.04–0.60 apfu, and T = 480–800 °C. Precision of the Ti-in-biotite geo-thermometer is estimated to be ±24 °C at the lower temperature range (<600°C) and improves to ±12 °C at higher temperatures (>700°C).

All biotite grains analyzed were plotted on the Ti/X_{Mg} diagram shown in Figure 15 using the isotherms of Henry et al. (2005) except for two analyses from RQ83 where X_{Mg} was too low to enter within the calibration range defined above. The criteria required for the application of this thermometer are present except in RQ30 and RQ83, which do not contain graphite and were probably equilibrated at the lower pressure limit.

7.2.1 Sample IS90

Analyses are well grouped around the 550°C isotherm (Fig.15a). An average composition from the fifteen biotite grains analyzed yield an average Ti content of 0.150 apfu and an X_{Mg} of 0.559. This results in a temperature using the above expression of 548±24°C.

7.2.2 Sample RQ30

Analyses are well grouped around the 450°C isotherm (Fig. 15a). An average composition from the fourteen biotite grains analyzed yield an average Ti content of 0.105 apfu and an X_{Mg} of 0.541 resulting in a temperature estimate of 434±24°C.

7.2.3 Sample RQ83

Analyses are dispersed due to a variable X_{Mg} around the 500°C isotherm (Fig. 15a). An average composition from the five biotite grains used yield an average Ti content of 0.143 apfu and an X_{Mg} of 0.460 resulting in a temperature estimate of 501±24°C.

8 INTERPRETATION

8.1 Replacement mechanism, model

8.1.1 Replacing minerals

The progressive replacement of cordierite occurs inwards from the porphyroblast margins (Fig. 16). Cordierite is primarily replaced by narrow preferentially aligned laths of muscovite as visible within the cordierite core in partial pseudomorphs (Figs. 3, 10 and 16). The coarsening of these muscovite laths and the progressive appearance of biotite as a replacing mineral forms the reaction rim where the pseudomorphic reaction is almost complete (Figs. 3, 10 and 16). Porphyroblastic biotite is common in both the remaining cordierite core and the reaction rim as well as in the matrix. The one included in the remaining cordierite core is undeformed while the one present in the pseudomorph reaction rim and in the matrix is sheared. The former suggests that the porphyroblastic biotite grew prior to cordierite growth while the later indicates that deformation was active during cordierite breakdown (Fig. 16). Quartz inclusions are progressively replaced by plagioclase during pseudomorphism; the cordierite core is quartz rich whereas the reaction rim is plagioclase rich (Fig. 10 and 16).

Even though samples from NE Queensland are of lower metamorphic grade, one can assume that the replacement mechanisms are similar. The complete pseudomorphs observed within these rocks must have started with an initial partial replacement inwards from the margin of the old porphyroblast, probably by muscovite followed by biotite and/or chlorite. The replacing material remained fine-grained compared to the rocks from Maine. The timing of the appearance of chlorite is difficult to evaluate; it could be synchronous with the development of the pseudomorphs or could have formed later by replacing the biotite after the cordierite porphyroblast was entirely replaced. Figure 11 shows the localization of chlorite at the interface between the quartz rich strain shadow and the muscovite rich high strain zone. This might be the product of vertical stress producing a very weak crenulation at this interface allowing fluids to circulate and the precipitation of chlorite. When reaching the cordierite pseudomorph, the fluid would circulate preferentially along inclusion trails and replace biotite with chlorite.

8.1.2 Role of cracks, types, nucleation and propagation

Microfabrics present within cordierite porphyroblasts provide a key to understanding pseudomorphic replacement mechanisms. Internal plastic deformation producing subgrains within cordierite porphyroblasts does not control the replacement pattern. Indeed most commonly mica grains grew across subgrain boundaries (Figs. 5a and c). In a few examples mica grains grew along a subgrain boundary but only when the latter is parallel to the direction of inclusion trails. A type of impingement microcrack can be produced by the impingement of one subgrain in another one. The crack develops and propagates from the grain tip and is filled by muscovite and biotite grains that lie parallel to the inclusion trails and to micas within the reaction rim. This is the less common type of microcrack observed. Another type of microcrack is produced by the replacement of quartz grains, present within cordierite porphyroblasts as inclusions, by plagioclase. This transformation involves a significant volume increase that may produce microcracks in the host cordierite. These cracks commonly form at the tip of an elongate shaped inclusion and propagate in the direction of the inclusion's long axis. They are filled with muscovite and biotite that thus lie parallel to the original inclusion trail direction. These phase transformation induced cracks commonly occur at the margin of the cordierite core near the reaction rim (Fig. 16). The inclusions almost exclusively consist of unaltered quartz within the cordierite core and are progressively replaced by plagioclase closer to the reaction rim (Figs. 5g and 10). Plagioclase grains are more abundant than quartz within the reaction rim where almost all of the quartz grains have been replaced. The most common is the third type of microcrack which was produced by brittle-plastic deformation of cordierite and by strain incompatibilities due to inclusions (mainly quartz). The cracks propagate from one inclusion to another forming an interconnected network that progressively develops inwards from the porphyroblast margin. Cracks develop predominantly parallel and at high angle to the inclusion trails (Fig. 5d). Most develop in the same direction with the inclusion trails. Within the cordierite cores of partial pseudomorphs, replacement occurs only within cracks parallel to the inclusion trails. This could be explained by a stress field sub-perpendicular to inclusion trails during replacement allowing the propagation of fluids/diffusion within the cordierite parallel to the inclusion trails. The continuation of such process is most probably responsible for the "preferentially alignment of complete pseudomorphs" of NE Queensland.

8.1.3 PT conditions

Most authors agree that the maximum pressures in western Maine must have been around or just above 4 kbars and the maximum temperatures were high enough to produce melting of the metasediments (e.g., Henry and Guidotti, 2002; Johnson et al., 2003; Sanislav and Bell, 2011). Near the Mooselookmeguntic pluton, peak metamorphic conditions are represented by the lower sillimanite zone at ~ 4 kbars and 600°C. However, cordierite porphyroblasts occur only within the staurolite zone. Henry and Guidotti (2002) proposed that at 3.3 kbars the temperatures in the staurolite zone ranged between 550°C and 590°C while Sanislav and Bell (2011) proposed that the staurolite stability field in the absence of chlorite and sillimanite extended between 2.7 to 4 kbars and 534 to 578°C. The later calculated that the stability field of the Bt+Mu+Pl+Grt+St+Crd assemblage lies between 2.2 and 3.2 kbars and 530 and 560°C. The temperature results of ~ 548±24°C obtained with the Ti in biotite thermometer of Henry et al. (2005) fit well with the previous observations while the PT values obtained using X_{Mg} in biotite and the petrogenetic grid of Patisson et al. (2002) are too high and do not fit the observations.

The PT conditions for the rocks from NE Queensland are difficult to estimate due to the lack of sufficient phases for precise thermobarometry calculations. The X_{Mg} isopleths in biotite for the reaction muscovite + cordierite = biotite + andalusite + quartz using the petrogenetic grids of Pattison et al. (2002) suggest a pressure ranging between 2.5 and 3.5 kbars and a temperature between 550 and 650°C for sample RQ30 and a similar temperature and a slightly lower pressure, between 2 and 3 kbars, for sample RQ83. We consider that the maximum pressures experienced by the rocks from NE Queensland must have been around 3 kbars and the maximum temperatures did not exceed 600°C, most probably lying near the 550°C isotherm.

The Ti-in biotite thermometer of Henry et al. (2005) indicates temperatures of 435 and 500°C for RQ30 and RQ83 respectively which may correspond to the retrograde path, the initiation of cordierite breakdown and the appearance of chlorite.

9 DISCUSSION

9.1 The role of P-T conditions

The partial and complete pseudomorphs after cordierite described herein offer an opportunity to reflect on the mechanisms that are involved in driving metamorphic reactions. Pressure, temperature, fluid infiltration and deformation are the main factors that affect the stability of mineral assemblages in metamorphic rocks. However, it is difficult to almost impossible to quantitatively assess how much each of these factors participates in the observed changes. The sensitivity of existing geothermobarometers is one limiting factor in determining the relevance of temperature or pressure changes for a particular observation. For example, in the case of partial pseudomorphs from western Maine, the Ti-in-biotite thermometer yields 548±24°C when applied to biotite analyses from the reaction rim and 569±24°C when applied to biotite analyses from the matrix (Fig. 13b). Similarly in complete pseudomorphs from NE Queensland this thermometer yields a temperature of 425±24°C for biotites within the pseudomorph and a temperature of 462±24°C for biotites within the matrix (Fig. 13b). Since geothermometers are chemical equilibrium sensitive they may be used to monitor the degree of equilibration. The temperature obtained for the matrix may reflect equilibration of the latter, which presumably occurred prior to the initiation of the pseudomorphing of cordierite by mica. The temperature obtained for the reaction rim may reflect that at which pseudomorphing initiated. Such an approach implies that the metamorphic reactions are localized to the volume occupied by the cordierite and that there is no material exchange between the site of reactions and the matrix. Alternatively, coupled metamorphic reactions where material transfer occurs between discrete portions of the rock where the local equilibrium was achieved (e.g., Carmichael, 1969; Foster, 1983; Dutrow et al., 2008) may have occurred. Such a reaction mechanism better explains the errors implied by Ti-in-biotite thermometer (±24°C). However, it does not eliminate the limitations of geothermobarometers where a small change in temperature or pressure determines mineralogical changes in the whole rock.

9.2 The role of fluids

Fluid activity has been considered one of the main causes for the development of mica rich pseudomorphs after staurolite, andalusite and garnet (e.g., Foster, 1981, 1983, 1986; Dutrow et al., 1999; Guidotti and Johnson, 2002; Dutrow et al., 2008). The partial (Fig. 3) or complete replacement (Fig. 4) of cordierite by mica requires the addition of fluid to the reaction site. However, the role of fluids in the stability and kinetics of cordierite dehydration/hydration at the P-T conditions at which this phase forms and subsequently evolves is poorly understood quantitatively (Dachs and Geiger, 2008; Rigby and Droop, 2008). Although it is generally accepted that the water content of cordierite decreases with temperature and increases with pressure (e.g., Zimmermann and Anonymous, 1981; Giampaolo and Putnis, 1989; Harley et al., 2002; Dachs and Geiger, 2008), many cordierite volatiles yield water content below their saturation value at certain P-T conditions and, selective and variable leakage is common (Rigby and Droop, 2008). Analyses of cordierites from the same localities, but different textural settings, have shown volatile contents to be uniform within crystals from one textural setting, but distinct between them (Fitzsimons, 1994; Harley, 1994). This is particularly important and raises the question of the role of the cordierite fluid vs. the role of the matrix fluid in the reaction. For example in western Maine all samples that contain cordierite show similar reaction pattern even though they may have different fluid contents and composition. This may suggest a greater role for matrix fluid. If this was the case then we must consider that the matrix fluid that reacted with the cordierite did reach garnet and staurolite since the latter phases appear to be in perfect textural equilibrium with their surroundings. They are idioblastic to sub-idioblastic and have sharp contacts with the matrix. At most, the matrix fluid altered the garnet composition in the rim without affecting its stability while in the case of staurolite not even compositional effects are detectable. Most probably such a behavior can result from different reactivity of garnet, staurolite and cordierite with the matrix fluid at similar P-T conditions. Alternatively, it may suggest that even though some matrix fluid was present, it did not play a major role in the stability of cordierite.

Harley et al. (2002) suggested that if a cordierite-bearing metamorphic terrain evolved on a near-isobaric cooling path, cordierite could potentially be hydrated from any coexisting H_2O fluid. In contrast if the P–T path was at high angle to the cordierite isohydrons then cordierite would tend to lose H_2O regardless of the presence of any coexisting fluid, as the solubility of H_2O in cordierite decreases with decreasing pressure (e.g., Johannes and Schreyer, 1981; Skippen and Gunter, 1996; Harley and Carrington, 2001). While an isobaric P-T path could be consistent with most of the P-T history in many low-pressure high-temperature terrains (e.g., Pattison et al., 1999; Henry and Guidotti, 2002), in western Maine there is evidence that the last part of the P-T history was dominated by decompression (Sanislav and Bell, 2011). Neither the hydration nor dehydration of cordierite can account for the crack formation, which appears to have played an important role in the replacement of this phase by micas; the molar volume of cordierite does not change with water content Harley (Carey, 1995; Skippen and Gunter, 1996;

Harley and Carrington, 2001). Decompression on the other hand has been shown to cause micro cracking (e.g., Kruhl et al., 2007) of cordierite porphyroblasts. These microcracks can provide reaction sites where the matrix fluid will tend to migrate because of the differential stress and combine with the fluid released from cordierite, thus allowing the formation of micas along cracks aligned favorably relative to the principal stresses.

9.3 The role of deformation

Two types of crystal deformation microstructures have affected the structural integrity of the cordierite porphyroblasts. One has the characteristics of plastic deformation and produced subgrains (Figs. 5a, b and c), while the other one has the characteristics of brittle deformation and produced cracks (Figs. e, f and g). The molar volume of cordierite does not change with composition or volatile content (e.g. Skippen and Gunter, 1996; Harley and Carrington, 2001). Therefore, we can expect all deformation microstructures to be related to environmental factors such as temperature, pressure and strain rate. In many cases the cracks propagate across two neighboring cordierite subgrains suggesting that the brittle deformation postdates plastic deformation. Moreover the cracks are intimately associated with the growth of micas along the newly developed fractures suggesting an important role of crack formation in the replacement of cordierite by micas. Cordierite deformation, like other rock forming minerals, is a function of the P-T regime and strain rate (Kruhl et al., 2007). The maximum P-T conditions in the vicinity of the Mooselookmeguntic pluton must have been slightly above 4 kbars and 600°C (e.g. Guidotti and Johnson, 2002; Henry and Guidotti, 2002; Sanislav and Bell, 2011). For the Grt+St+Crd assemblage the maximum P-T conditions must have been around 3.4 kbars and 565°C and the minimum P-T conditions must have been around 2.2 kbars and 530°C (Sanislav and Bell, 2011). The minimum temperature of 540°C determined for the reaction rim by Ti-in-biotite thermometry suggests that the rocks were still in the Grt+St+Crd stability field when the replacement of cordierite by micas began. For example the beginning of quartz recrystallization is assumed to be linear in a log-log plot of temperature vs. strain rate where the quartz recrystallization temperature decreases with decreasing strain rate (Stipp et al., 2002; Kruhl et al., 2007). For this case at constant temperature, the deformation behavior becomes a function of strain rate. If we consider a minimum temperature of 530°C and a maximum temperature of 565°C then we can infer that the brittle ductile transition for cordierite occurred at strain rates between 10^{-8} to 10^{-7} s^{-1} (see Fig. 15 in Kruhl et al., 2007). These values are consistent with the regional P-T and deformation history where exhumation occurred by fast decompression along an almost isothermal PT path (Sanislav and Bell, 2011).

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- SECTION B -

THE SIGNIFICANCE OF E-W STRUCTURAL TRENDS FOR THE ALICE SPRINGS OROGENY IN THE CHARTERS TOWERS PROVINCE, NORTH QUEENSLAND

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ABSTRACT

E-W structural and igneous trends in the Charters Towers Province are highly anomalous within the overall N-S trending Tasman orogen of eastern Australia and resulted from a sequence of N-S shortening events. A succession of ~E-W trending FIAs (Foliation Intersection/Inflexion Axis preserved within porphyroblasts) dated at 474.7 ± 7.2, 413 ± 13 and 381.1 ± 8.1 Ma correspond with adjacent granite crystallization ages and E-W trending FIA ages in the Greenvale Province to the NW. The magnetic anomaly map of Australia reveals that this E-W trending portion of the Tasman orogen links with and truncates several earlier formed orogens. The E-W trend of the Charters Towers Province resulted from overprinting of the Tasman Orogen by the Alice Springs Orogeny resolving the E-W pluton shape and distribution of Cambrian to Devonian magmatic activity plus the truncational nature of aeromagnetic data from Central Australia to the East coast.

Keywords: Alice Springs orogeny; Charters Towers Province; monazite dating; FIAs; aeromagnetic truncations.

1 INTRODUCTION

The Tasman Orogenic System is a mainly north-south trending mountain belt (Fig.1) that accreted onto the Precambrian cratonic crystalline basement of Australia from Lower Paleozoic to Mesozoic times (Murray and Kirkegaard, 1978; Scheibner, 1978a, b, 1986; Coney et al., 1990; Gray and Foster, 2004; Glen, 2005). It is mostly made up of fairly deep-marine Neo-Proterozoic and Paleozoic sedimentary and volcanic rocks and Paleozoic to lower Mesozoic volcanic and plutonic material. The boundary between the Tasman orogen and the Australian craton, called the Tasman line, is exposed in northeastern Australia and in the Delamerian orogen in southeastern Australia. Elsewhere its extent is mainly inferred from gravity and magnetic maps. The Tasman System is made of a series of distinct orogenic units known as the Delamerian, the Lachlan-Thomson, the New England and the Hodgkinson-Broken River orogens (Fig. 1). The Thomson Orogen is considered to be contemporaneous with, and possibly the northern extent of, the Lachlan Orogen Coney (Murray and Kirkegaard, 1978; Coney et al., 1990) but the aeromagnetic map reveals that it becomes E-W to the south truncating the N-S trending Lachlan Orogen. The Thomson Orogen is almost totally obscured by a Mesozoic sedimentary cover but its northern part is exposed in the Charters Towers, the Greenvale and the Anakie provinces (Fig. 1).

The Charters Towers Province is geologically anomalous within eastern Australia because it is dominated by E-W rather than N-S structural and igneous trends. Although most of the province is covered by late Paleozoic and younger units, its E-W trend is well defined on the aeromagnetic map of Australia (Fig. 2). This trend aligns with one of the largest anomaly that crosses the continent. Gravity and magnetic anomalies enable the margins of basement blocks against younger terrains and their relative ages to be interpreted and combined with structural and dating information presented herein reveal a significant role for N-S shortening orogenesis in Eastern Australia.

2 GEOLOGICAL SETTING

The Charters Towers Province consists of a Neoproterozoic to Cambrian basement that was regionally deformed and metamorphosed during early Paleozoic times producing the Cape River, Charters Towers, Argentine and Running River metamorphics (Fig. 3). This regional event is interpreted to be the result of the ca. 500 Ma Delamerian Orogeny (Withnall et al., 1996; Hutton et al., 1997). To the south of the province the basement consists of a thick Cambro-Ordovician volcano sedimentary sequence called the Seventy Mile Range Group (Fig. 3) that is interpreted as the remnant of an extensive arc-back arc system (Henderson, 1986). The stratigraphy and structure of these rocks has been described by Henderson (1986) and Berry et al. (1992). The base of the Seventy Mile Range Group is characterized by a thick continent derived sediment dominated package (the Puddler Creek Formation) with subordinate mafic extrusion (principally andesites in composition) conformably overlain by the Mount Windsor volcanics, a rhyolite dominated package. The Trooper Creek Formation overlay that sequence and is characterized by rapid facies variations between basaltic, andesitic, dacitic and rhyolitic volcanic and volcaniclastic rocks. The younger Rollston Range Formation within the Seventy Mile Range Group is characterized by a dominantly volcanic-derived sedimentary sequence. Numerous Ordovician to Devonian granitoids (Reedy Spring, Lolworth and Ravenswood batholiths; Fig. 3) intruded the whole Charters Towers Province (Richards, 1980). N-S compressional deformation produced a steep east-west trending cleavage and east-west upright folds within the Seventy Mile Range Group that is regarded as being probably Mid-Ordovician to Early Silurian in age as E-W shear zones (the larger of which is the Alex Hill shear zone; Fig. 3) affected Mid-Ordovician granitoids of the region (Berry et al., 1992; Kreuzer, 2004). The volcanic and sedimentary sequence has been affected by low to moderate grade regional metamorphism. Metamorphic grades range from prehnite-pumpellyite facies in the eastern part of the belt to greenschist facies in the central part of the belt (Berry et al., 1992). In the Thalanga region the metamorphic grade reaches the amphibolite facies with higher strain possibly resulting from simultaneous regional deformation and granitoids emplacement. An equivalent sequence to the Seventy Mile Range Group, known as the Balcooma metavolcanic group (Henderson, 1986; Withnall et al., 1991), more intensely deformed and at higher metamorphic grade lies 250 km to the north-west within the NE-SW trending Greenvale Province (Figs. 2, 3). Shrimp U-Pb metamorphic zircon ages indicate early Ordovician amphibolite facies metamorphism accompanied granitoid emplacement across the Greenvale Province (Withnall et al., 1991; Fergusson et al., 2007). 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).

3 THE E-W TRENDING MAGNETIC ANOMALY ACROSS AUSTRALIA

From the Tasman Orogenic System to Central Australia in Northern Australia around only one-third of the basement rocks are not covered by younger flat lying units (Wellman, 1988, 1995). Access to information on these rocks can be provided by magnetic anomaly maps at continental scale (Milligan and Franklin, 2004) as these contain unequivocal physical data (Fig. 2). Indeed, in many cases they provide the only means for defining boundaries between structural domains distinguished by sub-parallel magnetic trends that reveal tectonic structures within deformed portions of the upper crust. Different magnetic domains (Wellman, 1992b) can be defined by:-

1. an abrupt change in the dominant trends of geological structures. The domain with younger structures has trends parallel to the boundary and the adjacent domain with older structures has its trends truncated at the boundary,

2. long wavelength geophysical anomalies resulting from a combination of domains having different mean thickness and physical properties versus rock bodies formed by boundary processes adjacent to and parallel to the boundary,

3. an older domain having a marginal band of major reworking resulting from heating and deformation.

Using this approach Wellman (1988) described major E-W domains within central Australia such as the Arunta and the Musgrave domains that extend over 800 km in length. The overall N-S trending Mount Isa domain and the overall E-W trending Arunta domain of Proterozoic age are sharply truncated at their southern and southeastern end respectively by a well developed reworked zone (Wellman, 1988, 1992a, b) interpreted as the result of development of the Tasman Orogenic System in Early Paleozoic times (Fig. 2). This truncation propagates WNW across Australia and NE towards the Charters Towers Province. Within the Tasman Orogenic System the SW-NE trends of the Greenvale Province and the E-W trending Charters Towers Province differ significantly from the N-S trends of eastern Australia and truncate the Precambrian Georgetown Block to the south-east and the south respectively (Fig. 2).

4 E-W STRUCTURAL TRENDS

Mesozoic and Cenozoic sediments in north Queensland largely obscure Neoproterozoic and Paleozoic rocks. Structural analysis (Bell, 1980) suggested that correlation between the different deformation events throughout the Hodgkinson, Broken River, Greenvale and Charters Towers provinces was possible. He interpreted the change from an overall N-S trending foliations north and south of the Charters Towers Province to an overall E-W trending ones within the Charters Towers province as the result of rotation of the latter during oroclinal orogenesis producing a large amplitude fold with vertical axis that he named the Big Bend megafold. Powell (1984) and Powell et al. (1985) interpreted these E-W structures as the result of a sinistral megakink affecting the Charters Towers region that he related with the megakinks within the southeastern Lachlan fold belt. He proposed that these megakinks were related to intracratonic thrusting in the Amadeus transverse zone in central Australia that formed during 100 to 150 km of N-S bulk shortening in the mid-Carboniferous (~360 to 320 Ma). He considered that the propagation of the deformation from central Australia to the well-foliated regions of eastern Australia where the megakinks occur was driven by movement on geophysical lineaments interpreted as faults that affect the Lachlan and Thomson Fold Belts. Kreuzer (2004) and Kreuzer et al. (2007) described two distinct deformation events that produced E-W structures in the Charters Towers region. The first produced E-W striking folds and axial cleavages prior to the emplacement of Early to mid-Ordovician granitoids. The second produced E-W striking shear zones with mylonitic fabrics over strike lengths up to 50 km such as the Alex Hill Shear Zone, which is characterized by a sinistral horizontal movement. Hutton et al. (1997) described E-W to NW-SE striking mylonites related to this event with steeply plunging lineations that they interpreted as thrust faults.

5 AGES FROM DEEP DRILL HOLES THROUGH COVER INTO THE THOMSON OROGEN

SHRIMP U-Pb ages (Draper, 2006) obtained on granites and volcanics from basement core samples located south and south east of the Mount Isa Block (Fig. 1) reveal older basement rocks than recognized previously. Rhyolitic ignimbrite basement in DIO Adria Downs 1 (south of Mount Isa Block) has an U-Pb age of 510.0 ± 2.8 Ma (Middle Cambrian). GSQ Maneroo 1 located south east of Mount Isa contains Early Ordovician porphyritic rhyolite with a U-Pb age of 472.9 ± 2.7 Ma at its base. A muscovite granite from AMX Toobrac 1 has a Middle Ordovician U-Pb age of 469.4 ± 7.7 Ma almost identical to the rhyolite in nearby Maneroo 1 suggesting that the rhyolite and granite were co-magmatic. A rhyolitic ignimbrite from AAE Towerhill 1 located further N-E relative to the last well and just east of the Mount Isa block has Middle to Late Devonian boundary U-Pb age of 385.0 ± 4.6 Ma. A younging progression of ages from south of Mount Isa towards the Charters Towers Province suggests a migration in tectonic activity with truncation of the Precambrian Mount Isa Inlier and Georgetown Block. This is the largest E-W trending geophysical/structural discordance across Australia.

6 STRUCTURAL RELATIONSHIPS, SAMPLES COLLECTED AND PORPHYROBLAST MICROSTRUCTURES

Two areas 50 km apart were mapped and sampled in deeply weathered porphyroblastic schists exposed in the Thalanga (Puddler Creek formation) and Charters Towers (Charters Towers metamorphics) regions (Fig. 4a, b). Most samples had to be coated with fiberglass in the field before ones of sufficient size (15×15×15cm minimum) for quantitative FIA (Foliation Inflexion/Intersection Axis preserved in porphyroblasts) measurement (described later) could be collected because of the degree of weathering. Hundred and one oriented samples were obtained in this way. Biotite cordierite schists and biotite cordierite andalusite schists were obtained from Thalanga and biotite cordierite schists from Charters Towers. The matrix foliations are shown on Fig. 4a, b. They trend consistently 110° at Thalanga and 120° at Charters Towers. Both porphyroblastic phases contain foliations preserved as inclusion trails (Figs. 5, 6, 7 & 8). Cordierite porphyroblasts are commonly pseudomorphed by a cryptocrystalline phyllosilicate product generally called pinite. They usually preserve a pseudo-hexagonal shape (Figs. 5 & 6) and differ from partially pseudomorphed andalusite porphyroblasts, which are replaced by very fine white mica (Fig. 7). The cores of cordierite porphyroblasts are commonly replaced by very fine-grained chlorite with well-preserved inclusion trails whereas the rims are replaced by a coarser-grained assemblage of white mica, biotite and chlorite (Figs. 5 & 8). A third type of cordierite replacement with well-preserved inclusion trails consists of coarse-grained chlorite and white mica (Fig. 6). Inclusion trails are commonly defined by small ellipsoidal shaped quartz and ilmenite grains that differ in orientation from the core to rim of the porphyroblasts suggesting at least two phases of growth (Figs. 5, 7, 8). The inclusion trails in the porphyroblasts rims commonly appear locally continuous with the matrix foliation. Two stages of growth have also been observed within andalusite porphyroblasts (Fig. 7). Ali (2010) sampled the Balcooma metavolcanic group located 250 km North-West of the Thalanga Range in the Greenvale Province (Fig. 3) and applied that same FIA measurement method on rocks containing a metamorphic assemblage of biotite, cordierite, andalusite, garnet, staurolite, sillimanite and kyanite.

7 FIA MEASUREMENT TECHNIQUE

A FIA (Foliation Inflexion/Intersection Axis preserved in porphyroblasts) represents the inflexion axis of the curvature of a foliation across or within the rims of porphyroblasts or the intersection of two generations of foliations trapped as inclusion trails. The samples were reoriented in the laboratory and then horizontal rock slabs 2.5 cm thick were marked and cut for each sample. Six oriented vertical thin sections at 30° increments relative to north were prepared from these slabs (see for details Bell et al., 1995). Using the technique described by Hayward (1990) and Bell et al. (1995; 1998), these thin sections were examined on the microscope to determine where the asymmetry of the inclusion trails preserved within porphyroblasts switched from clockwise to anticlockwise. A FIA is located between the two thin sections where this change occurs. Where multiple stages of porphyroblast growth had occurred within the same sample, some core to rim relationships revealed the presence of multi-FIA porphyroblasts (Fig. 8; Bell et al., 1998). Two more thin sections were prepared at 10° increments between those that showed an asymmetry switch allowing each FIA present to be measured within a 10° range. Of the hundred and one samples originally collected only fifty contained porphyroblasts with inclusion trails well enough preserved for FIA measurement because of the extremely weathered nature of the outcrops. Over 700 thin sections were prepared and examined.

8 FIA DATA

8.1 Thalanga and Charters Towers region

A total of 46 FIAs for cordierite and 10 for andalusite porphyroblasts at Thalanga and 19 FIAs for cordierite porphyroblasts within the Charters Towers metamorphics were measured. Five peaks are apparent in the rose diagram of FIA trends for the Thalanga region (Table1; Fig.

9) and 4 are apparent for that at Charters Towers (Table 2; Fig. 10). All FIA trends in both Thalanga and Charters Towers regions have been recorded by cordierite growing during all these events. Similar trending peaks in the rose diagrams occur in both regions. An exception is the peak in the Thalanga region that trends around W-E (85°); it is not present in the Charters Towers region. During this same event, no andalusite grew within the rocks from Thalanga. Only 19 FIAs were measured at Charters Towers compared with 56 in Thalanga region and so the ~ 10° variation in the peaks at Charters Towers from those at Thalanga could result from anastomosing of the foliations involved.

Consecutive growth of porphyroblastic phases during successive deformation events can be recorded within FIA data that display distinct groupings of FIA trends (Figs. 9 & 10; e.g., Bell et al., 1997). A succession of FIA trends can be suggested using data such as:-

1. A porphyroblast grows from core to rim and can preserve a succession of over printed foliations. Therefore, if the FIA trends differ from the core to the rim the former must pre-date the latter (e.g., data in Tables 1 & 2).

2. Samples containing the assemblage cordierite plus andalusite in the Thalanga region display microstructural relationships suggesting that cordierite grew prior to andalusite (e.g. Fig. 11). Therefore, if the FIA trends are different in these 2 phases in the one sample, the former should pre-date the latter (e.g., data in Table 1).

The succession of FIA sets suggested by this data for the Thalanga region is *E-W (85°)*, NW-SE (135°), *WNW-ESE (105°)*, WSW-ENE (65°) and SW-NE (35°); for the Charters Towers region it is NW-SE (145°), *WNW-ESE (105°)*, WSW-ENE (65°) and SW-NE (45°). Only the ~ E-W FIA trends italicized are relevant to the topic of this paper; the remainder will be described and interpreted elsewhere (Section D).

8.2 Balcooma Region

FIA data and ages for the Balcooma region have been described in detail by Ali (2010). Data from this work that are relevant to this paper consist of a first formed E-W trending FIA that is only present in garnet porphyroblasts that he interpreted must have formed at 475 Ma because this is the age obtained for the first phase of metamorphism by Withnall et al. (1991; 471 ± 4, 478 ± 5 SHRIMP zircon ages). The fourth formed FIA set in the Balcooma region has a similar trend. It is only present in staurolite porphyroblasts and was dated at 408.9 ± 8.2 Ma (EPMA monazite age; Ali, 2010).

9 MONAZITE AGES OBTAINED FROM E-W FIAS IN THE THALANGA AND CHARTERS TOWERS REGIONS

Dates were obtained from two samples from Thalanga containing the first and third formed FIA (rq13 & rq30), where Silurian and Devonian granites accompanied tectonism, and another (rq91) from Charters Towers containing the second formed FIA, where Ordovician granites were present. These FIAs in both regions trend respectively 85°, 105° and 105° and the dates were obtained using monazite preserved as inclusions within the foliations that define those FIAs within cordierite porphyroblasts. The locations of these samples are shown in Fig. 4a, b. Polished thin sections were prepared from vertical blocks previously used for measuring the FIA trend. Ages were determined using a JEOL JXA-8200 Electron Probe Micro Analyzer (EPMA) housed at the Advanced Analytical Centre, James Cook University. The analytical set-up is given in Table 3. Measurements were taken at an accelerating voltage of 15 kV, beam current of 200nA, and spot size at 1µm. Matrix corrections were undertaken using the PAP method (Pouchou and Pichoir, 1984, 1985). Interference corrections for Th and Y on Pb and Th on U were applied as described in Pyle et al. (2002). Monazite from Manangotry, Madagascar (545 ± 2 Ma; Paquette et al., 1994) was analyzed as internal age standard 5 times before and after each analytical session. The X-ray lines M_{α} are used for Th and Pb, M_{β} for U and L_{α} for Y. Weighted average and probability density plots were obtained using Isoplot/Ex 3.6 (Ludwig, 2008). Ages calculated for monazite grains in each thin section are presented in Tables 4 & 5 at the 2σ level of confidence using the statistical method of Montel et al. (1996).

A total of 87 spots from within 46 monazite grains were analyzed. For each analytical spot a chemical age was calculated, the result of which is presented in Table 4. An age was determined for each monazite grain, the result of which is presented in Table 5 and the method is shown in Figure 12. Chemical maps of in situ monazite grains preserved as inclusions within cordierite and andalusite porphyroblasts reveal that all monazites are very homogeneous except for a single grain within sample rq91 that shows zonation in Yttrium content but no difference in age within the different spots analyzed (Fig. 12). A monazite age of 474.7 ± 7.2 Ma (MSWD = 0.65) was obtained from within cordierite porphyroblasts in sample rq91 containing the E-W FIA Charters Towers (Fig.13). At Thalanga the ages obtained were 413 ± 13 Ma (MSWD = 0.81, rq13) for the 085° trending FIA and 381.1 ± 8.1 Ma (MSWD = 0.33, rq30) for that trending 105° (Fig. 13). These accord with the ages (490 ± 6 to 463 ± 3 Ma, Hutton, 1997; Hutton et al., 1997; 414 ± 5 Ma and 382 ± 5 Ma; Fanning , 1995) obtained from granites in the Charters Towers and Thalanga regions respectively (see below) as well as those obtained for the Balcooma region by Ali (2010).

10 INTERPRETATION

10.1 Correlation of FIAs

Within the Balcooma metamorphics Ali (2010) recognized a first formed E-W trending FIA which he interpreted to have formed at around 475 Ma, age of the first period of orogeny in these rocks (Withnall et al., 1991). Significantly, a similarly trending FIA is dated at 474.7 ± 7.2 Ma (this study) from within the Charters Towers metamorphics (Fig. 14a). A younger period of orogeny, which produced the fourth FIA to form in the Balcooma region, generated an E-W trending FIA dated at 408.9 ± 8.2 Ma (Ali, 2010). Significantly, this coincides in orientation and age with first period of orogeny within the Thalanga region, which produced an E-W trending FIA dated at 413 ± 13 Ma (this study). A subsequent period of orogenesis, which produced the third formed FIA (trending WNW-ESE) in the Thalanga region, is dated at 381.1 ± 8.1 Ma (this study; Fig. 14b) but was not recorded in the Balcooma metamorphics.

10.2 E-W geophysical, structural and igneous trends across Australia

The Tasman Orogenic System trends essentially N-S along the east coast of Australia and was accreted eastwards from the Precambrian craton during Paleozoic and younger times. However, it is penetrated by a strong E-W magnetic lineament extending from Central Australia to North Queensland through the Charters Towers province (Fig. 2). This lineament truncates the southeastern end of the Arunta block, the southern end of the Proterozoic N-S trending Mount Isa domain and the southern end of the Georgetown block. It is associated with a zone of reworking that extends into the Charters Towers Province parallel to structural and pluton trends (e.g., Wellman 1988, 1992, 1992b).

10.3 510 to 380 Ma ages across Australia

Foliated rocks in the middle of the Arunta Block in the Harts Range of central Australia have peak metamorphic ages of ~ 470 Ma (Hand et al., 1999; Mawby et al. 1999; Fig. 1). These ages and those for the 450-300 Ma Alice Springs orogeny (Hand et al., 1999; Mawby et al., 1999; Haines et al., 2001) overlap with those recorded in the Charters Towers and Greenvale provinces. They suggest that orogenesis extended E-W across Australia at this time. Granites and metamorphic rocks within the Greenvale Province contain U/Pb ages from 486 ± 5 Ma (orthogneiss) to 477 ± 6 Ma (tonalite; Fergusson et al., 2007) and zircon with metamorphic rims dated at 476 ± 5 Ma U/Pb (Oasis metamorphics; Fergusson et al., 2007) and 471 ± 4 Ma (Balcooma metamorphics, Withnall et al., 1991) accompanied by the development of an E-W FIA trend (Ali, 2010). Granite and metamorphic rocks within the Charters Towers Province formed at 490 ± 6 to 463 ± 3 Ma (SHRIMP $^{206}Pb/^{238}U$ crystallization of the Ravenswood batholith, Hutton & Rienks, 1997; Hutton et al., 1997) and 474.7 ± 7.2 Ma (described herein) respectively. Within the Thalanga region, SHRIMP $^{206}Pb/^{238}U$ crystallization ages of 414 ± 5 Ma and 382 ± 5 Ma (Fanning, 1995) obtained from different phases in the Lolworth batholith coincide with the deformation and metamorphic ages of 413 ± 13 and 381.1 ± 8.1 Ma that accompanied the development of FIAs trending at 085° and 105°. The E-W trending FIA 4 in staurolite in the Balcooma region has an age of 408.9 ± 8.2 Ma. SHRIMP U-Pb ages from granites and volcanics obtained from drill holes located south and south east of the Mount Isa Block range from 510.0 ± 2.8 to 469.4 ± 7.7 Ma and 385 ± 4.6 Ma (Draper, 2006).

10.4 E-W trending orogenesis across Australia

This correlation of deformation/FIA ages, FIA trends, pluton ages and trends, volcanic ages and E-W geophysical anomalies across Australia strongly support the suggestion that E-W trending orogenesis extended from at least the Harts Range to the Charters Towers Province from 475 to 381 Ma. Figure 15a shows the possible extent across Australia of N-S related deformation occurring at around 475 Ma on the aeromagnetic map of Australia. From W to E deformation occurred on the southern edge of the Arunta block to the Harts Range complex where peak metamorphism occurred at ~ 470 Ma (Hand et al., 1999; Mawby et al., 1999). The development of the orogen truncated the southern end of the Precambrian Mount Isa block. The orogen trends NE from the southern edge of the Mount Isa province with granite emplacement (Fig. 15a; AMX Toobrac 1; Draper, 2006) and rhyolite extrusion at ~ 470 Ma (GSQ Maneroo1; Draper, 2006). Orogenesis at this time affected the Greenvale and Charters Towers Provinces with granite emplacement and E-W trending FIAs forming at ~ 475 Ma (Withnall et al. 1991; Ali, 2010; this study). A later N-S shortening pulse coeval with the commonly accepted 450-300 Ma Alice Springs orogeny produced E-W trending FIAs (Fig. 15b) in the Greenvale and the Charters Towers Provinces dated at 408.9 ± 8.9 Ma (Ali, 2010) and 413 ± 13 Ma (this study). The latter is associated with adjacent granite emplacement at 414 ± 5 Ma (Fanning, 1995). The SW-NE trending reworked zone of Wellman (1988, 1992a, 1992b) at the southern end of the Mt Isa Block possibly experienced sinistral shear to accommodate deformation propagation from central Australia to the Charters Towers Province. A final ~N-S shortening event produced an ~ E-W trending FIA at 381.1 ± 8.1 Ma and adjacent granite (382 ± 5 Ma; Fanning, 1995) in the Charters Towers Province plus magmatic activity to the SW (Fig. 15c) at 385 Ma (AAE Towerhill 1; Draper, 2006) related to the long lived Alice Springs orogeny. A 510.0 ± 2.8 Ma age for granite from a deep drill hole south of Mt Isa (Fig. 1; Draper, 2006) and an ~ 300 Ma age from the E-W trending Alex Hill Shear zone SE of Townsville (Fig. 3) suggest that E-W trending orogenesis connected Central and Eastern Australia from the Petermann orogeny to the end of the Alice Springs orogeny.

11 DISCUSSION

11.1 Continuity of tectonism from Petermann orogeny times?

E-W trending magmatic activity, metamorphism and deformation occurred episodically across the Australian continent such that orogeny was almost continuous from 510 to ~ 300 Ma from Central Australia to the East Coast. Hand et al. (1999) inferred that gently dipping foliated rocks aged ~ 470 Ma in the Harts Range (Arunta Block, Central Australia) were a product of crustal extension. However, these rocks contain more than one gently dipping foliation (Hand et al., 1999) and this strongly suggests that shortening orogenesis was involved (e.g., Bell , 2010). The gentle dip would be a product of gravitational collapse rather than crustal extension in this case. Orogeny appears to have shifted northwards over this period of time in Central Australia generating separate magnetic anomalies that align with the Petermann and Alice Springs orogens until they coalesce to the east. A similar northward migration occurred in the east with granites getting progressively younger as one moves closer to the PreCambrian from south of the Mt Isa Province to south of the Georgetown Block. This parallels a northwards younging in the oldest orogenic ages from the 500 Ma Anakie Province (Withnall et al., 1996) to the 475 Ma Charters Towers Province (Fig. 1). Indeed, the main metamorphic and deformation event in the Anakie Province has been interpreted to result from the Delamerian orogeny (Withnall et al., 1996) on the basis of ~ 500 Ma ages obtained from drill hole samples containing a main foliation interpreted as an S_2 fabric. However, from within the same drill hole, Withnall et al. (1996) described a ~ 540 Ma age from samples containing a compositional layering and a non-domainal foliation. If this resulted from D_1, then early deformation and metamorphism in the Anakie Province would correlate with the Petermann orogeny. Figure 16 shows the Petermann orogen continuing to the eastern coast of Australia with associated granite emplacement at 510 Ma (DIO Adria Downs 1; Draper, 2006). The Petermann orogeny commenced around 600 Ma and lasted for at least 70 Ma (Wade et al., 2005) with peak deformation at 550-540 Ma whereas Delamerian contractional orogenesis occurred from ~ 520 to 490 Ma (Haines and Flöttmann, 1998; Foden et al., 2006). Both possibly affected the Anakie Province and similar rocks of Neoproterozoic to Cambrian age within the Charters Towers Province (Withnall, 1996). However, during the Delamerian orogeny no N-S shortening occurred in Central Australia or the Thomson Orogen.

11.2 Other evidence for N-S shortening across Australia from ca. 450 to 330 Ma

Many authors have recognized that the Lachlan orogen experienced pulses of N-S shortening in Early Silurian, Late Silurian, Mid Devonian and Mid Carboniferous times (Powell, 1984; Powell et al., 1985; Glen, 1992; Miller et al., 2001; Betts et al., 2002; Gray and Foster, 2004). Early Silurian and Mid Devonian N-S shortening events produced E-W folds, foliations and thrusts in Central and Eastern Lachlan Orogen (Glen, 1992). Miller et al. (2001) have identified WNW trending brittle faults with top to the SSW shear sense in the Stawell Zone in western Victoria. They interpret these fault structures to have formed in Middle to Late Silurian (420-414 Ma). Fold interference patterns and intersecting cleavages indicating two deformational events of N-S and NE-SW shortening during Late Silurian and Middle Devonian were recognized in the Melbourne Zone in the western Lachlan Orogen (Gray and Mortimer, 1996). The Melbourne Basement Terrane of Chappell et al. (1988) contains E-W trending granites dated at ~ 370 Ma (Richards and Singleton, 1981). In North Queensland similar evidence has previously been recognized. To explain the overall E-W foliation trends in the Charters Towers

Province Bell (1980) proposed that a megafold (orocline) formed around 330 Ma. Powell (1984) and Powell et al. (1985) rationalized it as a megakinking event that also affected the south-eastern Lachlan Orogen. They argued that this produced the same amount of shortening (~150-100km) over the same period of time (ca. 350-320 Ma) as the Alice Springs orogeny. Similar kinks and timing relationships have been observed in northern Tasmania (Goscombe et al., 1994).

11.3 Extrusion or transform bounded wedge?

Powell (1984) and Powell et al. (1985) considered that the propagation of deformation from central Australia to the well-foliated regions of eastern Australia, where the megakinks occurred, was driven by movement on geophysical lineaments interpreted as faults that affect the Lachlan and Thomson Fold Belts. Wellman (1986, 1988, 1992b) inferred that the gravity and magnetic data suggests that this E-W trending geophysical belt resulted from intense shearing and reworking from the Harts Range to the NE trending Diamantina River lineament to the Clarke River Fault zone. Most authors have proposed sinistral movement (Arnold, 1975; Harrington, 1981) for this zone that extruded the rocks of the Thomson Orogen towards the north east along the Diamantina River Lineament and towards East within the Charters Towers Province along the Clarke River Fault (Klootwijk, 2008). Klootwijk argues that the approximate N-S directed Alice Springs compressional environment in Central Australia induced N-S compression and lateral extrusion of the Thomson orogen towards East. Evidence for such extrusion is limited and dealt with elsewhere (Section D).

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- SECTION C -

IDENTIFYING AND TIMING THRUST DEVELOPMENT IN MULTIPLY DEFORMED TERRANES

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ABSTRACT

The E-W trending Charters Towers Province is an orogen that formed by overall N-S compression from Ordovician to Devonian times. Strong non-coaxial deformation in the Seventy Mile Range Group in the south of the province is revealed by the dominance of one inclusion trail asymmetry within porphyroblasts during successive FIA forming events. This asymmetry indicates top to the north thrusting and corresponds with south dipping thrusts on the seismic profile 07GA-GC01 through the Seventy Mile Range Group. Similar thrusts, all of which sole into the Moho, occur across the whole of the Charters Towers Province except where it has been intruded by the Ravenswood batholith. The competency of this coarse feldspar batholith caused partitioning of thrusting deformation around it and this is confirmed by the coaxial character of the inclusion trail geometries present within porphyroblasts within Charters Towers metamorphics surrounded by the Ravenswood batholith. Long-lived non-coaxial deformation in the Seventy Mile Range Group eventually resulted in thrust sheets being emplaced well to the north of the batholith with a window through a schistose thrust sheet within the Argentine Metamorphics exposing Devonian sediments below.

Keywords: Charters Towers Province, inclusion trail asymmetry, FIA, thrust window.

1 INTRODUCTION

Inclusion trails preserved within porphyroblasts in tectono-metamorphosed rocks provide a wealth of information regarding deformation and metamorphic events that occurred during orogenesis (Sayab, 2005). They are particularly significant for accessing the full history of deformation, which in such rocks is generally obliterated within the matrix by shearing parallel to the compositional layering producing the common S_0//S_1. Measuring the orientation of Foliation Inflection / Intersection axes (FIAs; Hayward, 1990; Bell et al., 1995) preserved within porphyroblasts allows correlation between the progressive development of microstructures, porphyroblast growth and large-scale bulk horizontal movement directions. Combined with a detailed study of inclusion trail asymmetries (Bell et al., 2003; Rich, 2005; Bruce, 2007; Yeh, 2007) FIAs allow us to determine the shear senses and movement directions that took place at specific times during the evolution of the orogen.

The curvature of inclusion trails preserved within porphyroblasts provides information on the sense of shear that occurred during deformation and metamorphism. Previous studies (Bell et al., 2003; Ham and Bell, 2004; Cihan and Parsons, 2005) have found similar distributions of both asymmetries suggesting that the deformation was relatively coaxial at the bulk scale during both sub-vertical and sub-horizontally directed bulk shortening (Bell, 1981). Indeed, most terrains record a similar abundance of clockwise and anticlockwise asymmetries of inclusion trails related to a same deformation event (Bell et al., 2003; Ham and Bell, 2004; Bell and Newman, 2006). Where the total dominance of just one asymmetry has been found, it has always been associated with regional non-coaxial deformation such as thrust sheet or nappe emplacement (Rich, 2005; Bruce, 2007; Yeh, 2007).

This study utilizes inclusion trail asymmetries preserved within porphyroblasts of the Puddler Creek Formation in the Thalanga area and shows that a lengthy period of non-coaxial deformation affected the region with an overall top to the north movement. This is supported by the seismic section 07GA-GC01 that runs N-S through the Charters Towers Province, which suggests similar thrusts lie to the north of the Ravenswood batholith. The striking dominance of the non-coaxial asymmetries described herein led to an investigation of anomalous structures within the Argentine Metamorphics that proved to result from large scale thrusting of schist over sediments.

2 GEOLOGICAL BACKGROUND

The Charters Towers Province is an anomalous E-W trending region within the overall N-S trending Tasman Orogen (Fig. 1) within which the oldest rocks comprise the Cape River, Charters Towers, Argentine, and Running River Metamorphics. These consist of continental derived and marine sediments that were deposited along the Gondwana passive margin during Neoproterozoic to Cambrian times. They are interpreted to have been deformed and metamorphosed from greenschist to amphibolite facies during the ca. 500 Ma Delamerian Orogeny (Hutton et al., 1997; Withnall et al., 1997). The common presence of sub-vertical and sub-horizontal foliations within these basement rocks has been interpreted to result from alternating convergent and extensional tectonics (Fergusson et al., 2005; Fergusson et al., 2007). The south of the province is dominated by the Cambro-Ordovician Seventy Mile Range Group, a thick volcano-sedimentary sequence interpreted to have been deposited within an extensional arc/back-arc setting (Henderson, 1986). The base of the sequence is characterized by a thick continent derived sediment dominated package (the Puddler Creek Formation) with subordinate mafic extrusion (principally andesites in composition) conformably overlain by the Mount Windsor volcanics, a rhyolite dominated package. The Trooper Creek Formation overlying this sequence is characterized by rapid facies variations between basaltic, andesitic, dacitic and rhyolitic volcanic and volcaniclastic rocks. The younger Rollston Range Formation is characterized by a dominantly volcanic-derived sedimentary sequence. The whole sequence was weakly to locally strongly deformed and preserves E-W trending upright cleavages and folds interpreted by Berry et al. (1992) as Late Ordovician or younger as it also affects Middle Ordovician granites of the region. Metamorphism ranging from sub-greenschist to amphibolite facies was contemporaneous with the emplacement of numerous Ordovician to Devonian granitoids (Richards, 1980; Berry et al., 1992). The emplacement of batholiths such as the Reedy Springs, Lolworth and Ravenswood Batholiths appears to be controlled by the steeply dipping, E-W trending structures that cross the region. The Argentine metamorphics are non-conformably overlain by and faulted against Devonian to Carboniferous volcanic and sedimentary rocks of the Burdekin Basin. An extensive NW-SE trending belt of Carboniferous to Permian granitoids sub-parallel to the coast line of eastern Queensland intruded the Eastern part of the province.

3 SAMPLE DESCRIPTIONS, STRUCTURAL RELATIONSHIPS AND SEISMIC PROFILE

3.1 Thalanga region

Eighty-four oriented samples were collected from extensively weathered porphyroblastic rocks of the Puddler Creek Formation in the Thalanga range area north of the Flinders Highway (Fig. 2). They were coated with fibreglass before sampling to prevent disintegration. This area contains the northern limb of a gently ESE plunging, WNW-ESE trending, syncline interpreted as an F_2 fold (Berry et al., 1992). The regional matrix foliation S_2 is a steeply dipping foliation trending 110° that is sub-parallel to S_0 (Berry et al., 1992). S_2 is overprinted by an E-W trending S_3 slaty cleavage. The samples contain cordierite and andalusite porphyroblasts with the latter commonly partially replaced by very fine white mica. Cordierite can preserve a pseudo-hexagonal shape and contain cores replaced by very fine-grained chlorite and rims replaced by a coarser-grained assemblage of white mica, biotite and chlorite. Alternatively they can be replaced by coarse-grained chlorite and white mica or be pinitized. Of the eighty-four samples collected thirty-seven contained porphyroblasts with well preserved inclusion trails (Fig. 3). The inclusion trails are commonly defined by small ellipsoidal shaped quartz and ilmenite grains that differ in orientation from the core to rim of the porphyroblasts suggesting at least two phases of growth (Fig. 3). The inclusion trails in the porphyroblasts rims commonly appear locally continuous with the matrix foliation (Fig. 3). Two stages of growth have also been observed within andalusite porphyroblasts (Fig. 3).

3.2 Charters Towers region

Twenty oriented highly weathered samples were collected in the manner mentioned above from within the porphyroblastic rocks of the Charters Towers metamorphics occurring as screens and relics within the Ravenswood batholith (Figs. 1, 4). The regional matrix foliation S_2 dips steeply and trends 120°. The samples consist of pelitic schists containing cordierite porphyroblasts that have been pinitized. The ovoid cordierite porphyroblasts are aligned in the matrix and contain inclusion trails oblique to the matrix foliation. Of the twenty samples collected thirteen contain porphyroblasts with well preserved inclusion trails. The inclusion trails are commonly defined by small ellipsoidal shaped quartz and ilmenite grains that differ in orientation from the core to rim of the porphyroblasts suggesting at least two phases of growth.

3.3 Seismic transect

This seismic line in Figures 1 and 5 comprises the southern portion of the deep seismic reflection line 07GA-GC1 acquired in 2007 by Geoscience Australia under the Onshore Energy Security Program, in conjunction with the Queensland Department of Mines and Energy. The line runs approximately N from the Drummond Basin to Charters Towers and then NW to the boundary between the Charters Towers Province and the Broken River Province perpendicular to the grain of the orogen. The Moho is sub-horizontal between 12.5 and 14s TWT (two-way travel time), corresponding to a depth of about 37 to 42 km. Strong reflectors suggest that the crust is affected by several S dipping structures that can be interpreted as normal faults but early top to the N thrusting cannot be excluded (Withnall et al., 2009).

4 FIA DATA

4.1 FIA trends from Thalanga and Charters Towers

A FIA (Foliation Inflexion/Intersection Axis preserved in porphyroblasts; Fig. 6) is constrained by preparing a minimum of eight differently oriented vertical thin sections and examining the inclusion trail geometries within the porphyroblasts (Hayward, 1990; Bell et al., 1995; Bell et al., 1998). Six vertical blocks are cut at a 30° intervals relative to North (i.e. 0, 30, 60, 90, 120 and 150°) from horizontal slabs and marked with a single barbed arrow showing strike and way up in such a way that the final thin sections have their long edge parallel to their strike. Each thin section is observed under a petrological microscope and inclusion trail geometries from within every porphyroblast are recorded. The FIA trend is located between the two thin sections where the curvature of inclusion trails switches from an S to Z geometry. Two thin sections are prepared 10° apart within this 30° range to constrain the FIA trend to a 10°

interval. Where multiple growth of a same porphyroblastic phase or different porphyroblastic phases within the same sample preserve differently trending FIAs, more thin sections need to be cut (e.g. multi-FIA sample; Bell et al., 1998). Three hundred and twenty-four thin sections for the Thalanga region and one hundred and fourteen for the Charters Towers region were prepared to measure the FIA trends in these two regions. At Thalanga nineteen samples show a single FIA trend recorded within a single generation of cordierite. Eighteen samples contain multiple FIAs, eleven of which contain cordierite porphyroblasts with at least two stages of growth containing different FIA trends in the cores and the rims. The seven remaining samples contain both cordierite and andalusite porphyroblasts some of them containing a core and a rim displaying different FIA trends. The results are summarized in Table 1. From the thirty-seven samples containing porphyroblasts with well preserved inclusion trails, fifty-six FIA trends were measured: forty-six from within cordierite porphyroblasts and ten within andalusite porphyroblasts. Figure 7a shows all FIA trends measured whereas Figure 7b and c show the data separated for cordierite and andalusite porphyroblasts respectively. Five peaks are apparent on the rose diagram (Fig. 7a) oriented at 35°, 60°, 85°, 105° and 135°. The 85° trend is not preserved in andalusite porphyroblasts (Fig. 7c). One single measurement obtained from the core of cordierite porphyroblast within sample rq5 has a 165° trend. Within the Charters Towers metamorphics seven samples recorded a single FIA trend and six recorded multiple FIAs within cores and rims, all recorded within cordierite porphyroblasts (results shown in Table 2). Nineteen FIA trends were measured from the thirteen cordierite bearing samples with well preserved inclusion trails. Four peaks are present trending at 45, 65, 105 and 145° (Fig. 8a).

4.2 FIA relative timing criteria

Microstructural relationships for andalusite relative to cordierite in the Thalanga region indicate that the latter phase grew first (e.g. Fig. 9; Table 1 and Fig. 7d) and they generally preserve different FIA trends (e.g. Bell and Hickey, 1999). Changes in FIA orientation also occur within the porphyroblasts of some samples from core to rim (Figs. 3, 6) allowing their relative timing to be determined (Tables 1, 2; Figs. 7d, 8b). If the relative timing is consistent for all samples then a succession of FIA sets can be determined (Bell et al., 1998). At Thalanga FIAs trending 165° (sample rq5) and 85° (samples rq15 and rq30) are preserved within the cores of cordierite porphyroblasts. In the rims of samples rq5 and rq15 the FIAs trend 135°. Cordierite cores in samples rq4, rq6, rq10, rq13b and from within andalusite cores of sample rq2 have FIAs trending 135° (rq8 has FIAs varying around 135° in both core and rim of cordierite porphyroblasts - see below). A FIA averaging 105° is preserved within andalusite rims (sample rq2), cordierite rims (samples rq4, rq6, rq13b, rq30) and cordierite cores (samples rq9, rq27). A FIA averaging 60° is preserved within cordierite rims in samples rq9, rq10 and rq27 and within andalusite cores in samples rq77 and rq78. Samples rq83, rq84 and rq85 contain cordierite and andalusite porphyroblasts with different FIA trends; cordierite FIAs trend at ~ 60° while the andalusite at 30°. The latter FIA 30° also occurs within andalusite rims of samples rq77 and rq78.

At Charters Towers, FIAs average 145° within the cores of cordierite porphyroblasts in samples rq47, rq51, rq96, rq97 and rq101. A FIA trending ~ 105° is preserved within the cordierite rims of sample rq51. The cordierite cores and rims of sample rq93 contain FIAs trending at 115° and 105° respectively. A FIA trending at 65° is preserved within cordierite rims of samples rq47, rq97 and rq101. Sample rq96 contains a FIA trending at 45° in cordierite rims.

5 INTERPRETATION

5.1 FIA succession

FIAs should form near orthogonal to the direction of horizontal bulk shortening and a succession of changes therefore may reflect changes in the direction of relative plate motion (e.g., Bell and Newman, 2006). A consistent succession can be interpreted from the FIA data mentioned above for the Thalanga region from E-W (FIA 1 ~ 85°), NW-SE (FIA 2 ~ 135°), WNW-ESE (FIA 3 ~ 105°), WSW-ENE (FIA 4 ~ 60°) to SW-NE (FIA 5 ~ 35°). The 165° FIA in sample rq5 is unique and predates that at 135° preserved within the rims. However, no constraint was obtained relative to FIA 1 above trending at 85°. Sample rq8 contains cordierite cores and rims trending respectively at 135° and 125° that both lie within the same FIA peak on Figures 7a and b. This anti-clockwise progression around the compass accords with that from FIA 2 to 3.

Similarly, in the Charters Towers region, sample rq93 contains an anticlockwise progression in FIA trends from cordierite cores (115°) to rims (105°) that lie within the same FIA peak on the rose diagram (Fig. 8a). The succession interpreted for the different FIA sets is: NW-SE (FIA1 ~ 145°), WNW-ESE (FIA 2 ~ 105°), WSW-ENE (FIA 3 ~ 65°) and SW-NE (FIA 4 ~ 45°).

5.2 FIA set inclusion trail asymmetries and evidence for thrusting

The geometry of the inclusion trails observed at high angle to the FIA trend was recorded for each FIA measurement. For example within a sample containing a FIA trending at 105°, the inclusion trail asymmetry was recorded using a vertical striking thin section striking at 30° looking NW (Fig. 10a). The curvature of the inclusion trails is recorded as clockwise (S shape) or anticlockwise (Z shape). Furthermore, the curvature of the inclusion trails towards a steep or shallow dip was recorded as V (for Vertical) and H (Horizontal) respectively (Tables 1, 2). Defining shear senses within metamorphic rocks is commonly done by examining a P section of a rock (i.e. ZX plane of finite strain), perpendicular to the schistosity/foliation and parallel to the mineral elongation. The orientation of such thin section contains the direction of movement affecting the matrix during deformation allowing the shear sense to be determined. Work done by Bell et al. (2003), Rich (2005), Yeh (2007) and Bruce (2007) shows that shear senses and whether deformation involved bulk shortening or large components of shearing can be determined for each FIA from the inclusion trail asymmetries within porphyroblasts observed at high angle to the FIA trend. High proportions of one asymmetry suggest the deformation was non-coaxial whereas similar proportions suggest it was coaxial. A strong dominance of one asymmetry suggests strongly non-coaxial deformation, such as thrusting or gravitational collapse occurring during porphyroblast growth, and allows the shear sense associated with that event to be determined (Bell et al., 2003). A steep to flat geometry (referred to as H in tables 1, 2) of inclusion trails indicates the development of horizontal shearing and a flat to steep (V in tables 1 and 2) geometry indicates vertical shearing. Tables 1 and 2 show the inclusion trail asymmetries (clockwise versus anticlockwise) and the associated kinematics (H for horizontal shear and V for vertical shear) recorded for every FIA measurement in the Thalanga and Charters Towers regions. Figures 10 b & c shows the cumulative frequency plot of asymmetry data recorded for each FIA set in the Thalanga and Charters Towers regions. At Thalanga, for FIA sets 1 to 3, the inclusion trail asymmetries are recorded looking W to NW for thin sections trending N to NE. For these FIA sets a dominance of clockwise asymmetries including both flat to steep and steep to flat geometries indicate top to the North or North East thrusting with the South or South West side up. This may not apply to FIA set 3 which is closer to being coaxial. The asymmetries for FIA sets 4 and 5 are recorded looking NE at thin sections oriented SE. The anticlockwise steep to flat dominance of inclusion trails geometries indicates top to the NW horizontal shear. At Charters Towers during all four FIA events, a similar number of both clockwise and anticlockwise asymmetries were recorded indicating that the deformation in that area was largely coaxial.

5.3 Relationship to seismic section

South of the Ravenswood batholith the seismic line cross cuts the Seventy Mile Range Group between common depth points (CDPs) 21200 and 23000 (Fig. 1). On the seismic section (Fig. 5) this group is characterised by south dipping reflectors that correspond to the dip of S_0 and/or S_2 that are affected by a series of south dipping structures that sole into the base of the upper crust. These outcrop at the Policeman Fault and other similarly trending structures within the Seventy Mile Range Group (Withnall et al., 2009) from where the surrounding rocks preserve a long-lived history of FIA events. FIAs 1 (85°), 2 (145°), 4 (65°) and 5 (35°) have consistent inclusion-trail asymmetries indicating strongly non-coaxial deformation that involved thrusting that overall is top to the north. This suggests that the south dipping structures on the seismic section that out crop at the Policeman etc Fault formed as thrusts. Data from inclusion trail asymmetries within the Charters Towers metamorphics indicate that deformation in this region was coaxial during all four FIA events and corroborates with the seismic section in this location which contains no thrust like structures (Fig. 5). Between CDPs 19000 and 21200 (Fig. 1) lies both Ordovician Ravenswood batholith which intimately surrounds and penetrates the Charters Towers Metamorphics. Such a competent plutonic body could have caused deformation to partition around it and prevented thrusts cutting through it; the seismic section shows a fault along which displacement at its upper extremity was accommodated along bedding such that it disappears below this pluton creating a blind structure. This fault soles into the Moho, in a similar fashion to one to the north, rather than into the base of the upper crust like those mentioned above (Fig. 5). Thus only the thrusts to the north and south of the Ravenswood batholith propagate to the surface resolving why the Charters Towers metamorphics are affected by coaxial deformation rather than the non-coaxial deformation apparent in the Seventy Mile Range Group. Thrusting within the Seventy Mile Range Group would have occurred from when FIA 1 formed at around 413 Ma (de Gromard, unpublished data). To the north of the Ravenswood batholith thrusts propagate to the surface affecting basement rocks represented by the Argentine metamorphics. As a result, geological maps of the Argentine Metamorphics were closely examined to see if any thrusts were present. This led to the recognition of a thrust, confirmed by field work, where schistosity in the hanging wall lies parallel to bedding in Devonian sedimentary rocks in the foot wall. This structure was domed during subsequent shortening and cut by younger faults, but is quite striking as shown in Figure 11.

6 DISCUSSION

6.1 Thrusting

Identifying the presence of thrusts and the direction of thrusting in multiply deformed terrains is commonly problematical because erosion has dramatically flattened the topography. Gently dipping structures such thrusts are difficult to recognize because of this lack of topography or because they have been overprinted by several younger deformation events, or because of the intrusion of granitoids. Within the Charters Towers Province, the metamorphics were intruded by numerous voluminous granitoids leaving thin screens rather than extensive zones of deformed rocks that can be mapped in detail. Detailed study of the metamorphic and deformation history of this province has been further hindered by a cover of sedimentary and volcanic rocks and alluvium. Fortunately, porphyroblasts from a relatively small area can preserve massive amounts of information on very extended tectonic histories (e.g., Bell and Hickey, 1999). In particular, strongly asymmetric inclusion trail asymmetries are uncommon. Indeed, where-ever they have been found they are associated with periods of significant thrust or nappe development that had been previously recognized (Rich, 2005; Bruce, 2007; Yeh, 2007). A similar pattern of inclusion trail asymmetries in the Charters Towers Province suggests that significant north directed thrusting took place during the tectonic evolution of the province, even though it has not been previously recognized.

6.2 Thrust window through the Argentine Metamorphics

This anomalous map relationship was difficult to resolve prior to the recognition of large-scale thrust displacement as is apparent from the location of the cross-section in Fergusson et al. (2007; their Fig. 4). An unconformity between the Argentine Metamorphics schists in the dome core and the overlying Devonian sedimentary sequence is obvious but the regional wrapping of metamorphics around the dome was clearly difficult to resolve. In particular, the repetition of the metamorphic sequence and the parallelism between structures on either side of the unconformity are virtually impossible to explain if consideration is not given to an overlying thrust sheet. The seismic section (Fig. 5) suggests that all large-scale thrusts sole into Moho and this probably occurs at deep crustal levels for the section shown in Fig. 11b. The doming of this structure during subsequent deformation and its revelation as a window by erosion readily explains the parallelism between the foliation trends above and bedding trends below. The mylonites recognized by Hammond (1986) probably formed at an early stage during the thrusting process and were then carried over the sediments later in the structural development of this region. This structure requires that the Argentine Metamorphics have been displaced a significant distance over Devonian sedimentary rocks. Structures with similar scales of displacement are probably present elsewhere in this province.

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- SECTION D -

PALEOZOIC EXTRUSION TECTONICS IN GONDWANALAND FORCING LARGE-SCALE STRIKE SLIP MOTION IN THE CHARTERS TOWERS PROVINCE, NORTHEASTERN AUSTRALIA

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ABSTRACT

The tectonic evolution of the Charters Towers Province (northeastern Australia) in the Paleozoic resulted from the interaction between N-S and E-W bulk shortening. The origin of N-S shortening seems to result from horizontal forces acting at the plate boundary that are possibly related to ridge-push effects due to the opening of the Paleotethys at ~450 Ma. This produced the ~450 to 300 Ma intracontinental E-W trending Alice Springs Orogen in central Australia whose effects propagated eastward to create the E-W trending Charters Towers Province. E-W shortening is interpreted to result from the long-lived west dipping subduction along the eastern margin of Australia, which was part of Gondwana at the time. FIA data reveals several discrete deformation events of interspersed ~N-S and ~E-W shortening directions. The FIA ages were obtained through in-situ monazite dating and show N-S shortening events at ~475 Ma and ~415 Ma, followed by ~E-W shortening at ~400 Ma and N-S shortening at ~380 Ma in the Charters Towers Province. The magnetic anomaly map of Australia, used to locate the lateral extensions of shear zones and domain boundaries hidden by overlying sedimentary successions, allowed the linking of deformation structures from central to northeastern Australia. Compressional orogenesis in the Charters Towers Province resulted in sinistral strike-slip extrusion of the Thomson Orogen to the east that was possibly associated with periods of slab roll-back.

Keywords: extrusion tectonics, strike-slip faults, FIAs, monazite ages, Thomson Orogen.

1 INTRODUCTION

Numerous tectonic models (White, 1961, 1965; Bell, 1980; Harrington, 1981; Powell, 1984; Powell et al., 1985; Henderson, 1987) have been proposed to explain the puzzling relationship of the E-W trending Charters Towers Province within the ~N-S trending orogens of eastern Australia. Apart from the structural work of Powell (1984, 1985), no models link the contemporaneous crustal evolution of eastern Australia with that of central Australia. Difficulties in reconciling the Paleozoic deformation of central and eastern Australia are due to two main factors (Betts et al., 2002). Firstly, the inferred shortening directions are orthogonal; south directed thrusting in the intracontinental E-W trending Alice Springs Orogen and E-W compression of the Tasman Orogenic System in eastern Australia. Secondly, geochronological data only allows for broad temporal correlations between the regions.

Only one third of north-central and northeastern Australia is not covered by younger flat-lying sedimentary successions. Consequently, regional structural interpretations are largely based on gravity and magnetic data (Wellman, 1988, 1992a, 1995). Highly magnetic domains are related to rock type and the effects result of increased temperature during metamorphism and crustal reworking (Wellman, 1992a). Consequently, magnetic trends reveal tectonic structures within deformed portions of the upper crust and the relative timing of periods of orogenesis can be inferred by the truncation of structures in older domains by those in younger ones.

Inclusion trails preserved within porphyroblasts in multiply deformed rocks provide a wealth of information regarding deformation during orogenesis. They are particularly significant for accessing the lengthy history of foliation development because early formed foliations commonly are obliterated from the matrix by subsequent deformation and associated shear parallel to the compositional layering (Bell, 1986; Ham and Bell, 2004). Porphyroblast growth occurring early during crenulation development preserves earlier formed foliations as inclusion trails while the two or three commonly present foliations in the matrix represents only the very youngest ones (Bell, 1986; Ham and Bell, 2004). The quantitative measurement of foliation intersection/inflexion axes preserved within porphyroblast (FIAs) provides access to the lengthy deformation history of a region (Bell et al., 1995; Bell et al., 1998; Bell et al., 2003). A FIA represents the orientation of the axis of curvature of a foliation affected by an overprinting event or the intersection lineation of two foliations preserved as inclusion trails within porphyroblasts. Therefore the FIA is formed near orthogonal to the shortening direction and constitutes a powerful kinematic indicator for early deformation events subsequently erased from the matrix. The relative timing of growth between different porphyroblastic phases plus core to rim relationships within them allow the establishment of a relative succession of FIAs. The EPMA dating of monazite grains preserved as inclusions within foliations defining the FIAs enables the determination of absolute timing of the successive FIA events.

This study uses granitoid spatial and temporal distributions, magnetic anomaly maps at continental scale, FIA data and in-situ monazite dating to propose a tectonic evolution model for the Charters Towers Province and its surroundings.

2 GEOLOGICAL SETTING

2.1 The Tasman Orogenic System

The Tasman Orogenic System (Murray and Kirkegaard, 1978; Scheibner, 1978a, b, 1986; Coney et al., 1990; Gray and Foster, 2004; Glen, 2005) is a mainly N-S trending mountain belt that forms the eastern third of Australia (Fig.1). It was accreted against the Precambrian cratonic crystalline basement of Australia to the west during the Paleozoic. It is mostly made up of fairly deep-marine Neo-Proterozoic and Paleozoic sedimentary and volcanic rocks and Paleozoic to lower Mesozoic volcanic and plutonic material. The boundary between the Paleozoic Tasman Orogen and the Precambrian Australian craton, called the Tasman line, is commonly interpreted to represent the Australian passive margin after the breakup of Rodinia (Li and Powell, 2001). Alternatively it is interpreted as the westernmost extent of deformation associated with the Paleozoic fold belts of eastern Australia (Scheibner, 1992). It is exposed only in northeastern and in southeastern Australia; elsewhere its extent is mainly inferred from gravity and magnetic maps. The Tasman System is made of a series of distinct orogenic units, from West to East and from old to young, the Delamerian, the Lachlan-Thomson and the New England orogens. The temporal and tectonic relationship between the Thomson Orogen and the Hodgkinson-Broken River Orogen to the North is difficult to establish because the Thomson Orogen is poorly exposed. The Thomson Orogen is almost totally obscured by a Mesozoic sedimentary cover but its northern part is exposed in the Charters Towers, the Greenvale and the Anakie provinces (Fig. 1).

2.2 The Charters Towers Province

The Charters Towers Province is an anomalous E-W trending region within the overall N-S trending Tasman Orogen (Figs. 1 & 2) within which the oldest rocks comprise the Cape River, Charters Towers, Argentine, and Running River Metamorphics. These consist of continental derived and marine sediments that were deposited along the Gondwana passive margin during Neoproterozoic to Cambrian times. They are interpreted to have been deformed and metamorphosed from greenschist to amphibolite facies during the ca. 500 Ma Delamerian Orogeny (Hutton et al., 1997; Withnall et al., 1997). The common presence of sub-vertical and sub-horizontal foliations within these basement rocks has been interpreted to result from alternating convergent and extensional tectonics (Fergusson et al., 2005; Fergusson et al., 2007). The south of the province is dominated by the E-W trending Cambro-Ordovician Seventy Mile Range Group (Fig. 2), a thick volcano-sedimentary sequence interpreted to have been deposited within an originally N-S trending extensional continental back-arc basin (Henderson, 1986). The latter is interpreted to be the remnants of an active margin terrane which extended the entire length of Eastern Australia and comprised similar rocks from the Greenvale Province (Balcooma volcanics) to the North down to the Mount Read volcanics of Tasmania to the South (Henderson, 1986). Three main deformations are recognized in the Seventy Mile Range Group. The first probably produced N-S trending folds that are difficult to recognize because they are only associated with the localized development of an S_1; the dominant structure of the area is characterized by upright E-W F_2 folds and regional cleavage (S_2) associated with D_2; these structures are overprinted by a localized S_3 slaty cleavage and F_3 tight folds associated with D_3 (Berry et al., 1992). Metamorphism ranging from sub-greenschist to lower amphibolite facies was contemporaneous with the emplacement of numerous Ordovician to Devonian granitoids (Richards, 1980; Berry et al., 1992).

Three igneous provinces are recognized throughout northeastern Queensland (Bain and Draper, 1997). The Ordovician Macrossan Igneous Province is confined within the Ravenswood batholith in the Charters Towers Province (Fig. 2); the Silurian-Devonian Pama Igneous Province extends from the Coen Inlier (Fig. 1) where it trends N-S to the Charters Towers Province where it forms the E-W trending Reedy Springs, Lolworth and parts of the Ravenswood batholiths (Fig. 2); and the Carboniferous-Permian Kennedy Igneous Province, an extensive NNW-SSE trending belt sub-parallel to the coast line of eastern Queensland intruded the Eastern part of the province. The tectonic setting of the Macrossan Province appears to be related to mafic underplating during subduction related processes and melting of a continental crust, the Pama Igneous Province is interpreted to be emplaced in a thickened crust during synchronous compression and regional metamorphism and the Kennedy Province is thought to be the result of crustal melting in a transtensional, possibly back-arc, tectonic environment (Bain and Draper, 1997).

NE-SW to N-S shortening during the Mid-Ordovician to Silurian produced ~E-W shear zones throughout the Charters Towers Province with mylonitic fabrics being traceable over strike length over 50 km and 2 km wide (Peters, 1987). The most prominent of these is the Alex hill Shear Zone (Fig. 2) characterized by a sinistral S-C fabric and a flat to gently east plunging mineral stretching lineation (Hutton and Rienks, 1997). The northern boundary of the Charters Towers Province is defined by the Clarke River Fault a steeply dipping mylonite zone with shallowly plunging stretching lineations interpreted to result from sinistral shear by Arnold (1975), Harrington (1981) and Henderson (1987). The South of the province is covered by younger sedimentary basins.

2.3 The Alice Springs Orogeny

Coeval with the development of the Lachlan-Thomson Orogen in eastern Australia, a long-lived period of deformation occurred in the Arunta Block of central Australia (Fig. 1). A granulite facies metamorphic event at ca. 475 Ma (Hand et al., 1999) has been recognized (800°C and 10.5 kbars; Mawby et al., 1999) and has been interpreted to be related to extensional tectonics. Crustal shortening of the Alice Springs Orogeny could have started as early as 450 Ma (Mawby et al., 1999) and is characterized by N-S shortening and major south directed thrusting with peak metamorphism at 380 Ma (Ballèvre et al., 2000).

3 SAMPLE DESCRIPTIONS AND STRUCTURAL RELATIONSHIPS

3.1 Thalanga region

Eighty-four oriented samples were collected from extensively weathered porphyroblastic rocks of the Puddler Creek Formation in the Thalanga range area north west of the Flinders Highway (Fig. 3). They were coated with fiberglass before sampling to prevent disintegration. This area contains the northern limb of a gently ESE plunging, WNW-ESE trending, syncline interpreted as an F_2 fold (Berry et al., 1992). The regional matrix foliation S_2 is a steeply dipping foliation trending 110° that is sub-parallel to S_0 (Berry et al., 1992). S_2 is overprinted by an E-W trending S_3 slaty cleavage. The samples contain cordierite and andalusite porphyroblasts with the latter commonly partially replaced by very fine white mica (Figs. 4a & b). Cordierite can preserve a pseudo-hexagonal shape and contain cores replaced by very fine-grained chlorite and rims replaced by a coarser-grained assemblage of white mica, biotite and chlorite (Figs. 4c & d). Alternatively they can be replaced by coarse-grained chlorite and white mica (Figs. 4e - h). Of the eighty-four samples collected thirty-seven contained porphyroblasts with well preserved inclusion trails (Fig. 4). The inclusion trails are commonly defined by small ellipsoidal shaped quartz and ilmenite grains that differ in orientation from the core to rim of the porphyroblasts suggesting at least two phases of growth (Fig. 4a - d). The inclusion trails in the porphyroblasts rims commonly appear locally continuous with the matrix foliation in the strain shadow and are truncated at the porphyroblast margins by zones of high matrix strain (Figs. 4a - h). Two stages of growth have also been observed within andalusite porphyroblasts (Figs. 4a & b).

3.2 Charters Towers region

Twenty oriented highly weathered samples were collected in the manner mentioned above from the porphyroblastic rocks of the Charters Towers metamorphics, which occur as screens and relics within the Ravenswood batholith (Figs. 2 & 5). The regional matrix foliation S_2 dips steeply and trends 120°. The samples consist of pelitic schists containing cordierite porphyroblasts that have been pinitized. The ovoid cordierite porphyroblasts are aligned in the matrix and contain inclusion trails oblique to the matrix foliation. Of the twenty samples collected thirteen contain porphyroblasts with well preserved inclusion trails. The inclusion trails are commonly defined by small ellipsoidal shaped quartz and ilmenite grains that differ in orientation from the core to rim of the porphyroblasts suggesting at least two phases of growth.

4 METHODS

4.1 FIA measurement technique

A FIA (Foliation Inflexion/Intersection Axis preserved in porphyroblasts; Fig. 6) represents the inflexion axis of the curvature of a foliation across or within the rims of porphyroblasts or the intersection of two generations of foliations trapped as inclusion trails. Two observers situated on opposite sides of a fold and looking in the direction of the fold axis see the fold curving clockwise or anticlockwise (i.e. S or Z shaped curvatures respectively; Fig. 6a). Figure 6b represents the 3D geometry of inclusion trail preserved within a porphyroblast. The observer sees the inclusion trail curving clockwise in the core and anticlockwise in the rim of the porphyroblast. Two different foliation inflexion axis trends are present within the porphyroblast named in the example 'Core FIA' and 'Rim FIA'; each FIA trend is governed by the trend of the vertical foliation preserved as inclusion trail within a porphyroblast that defines the FIA (Fig. 6b). A FIA is constrained by first preparing six vertical thin sections oriented at 30° increments relative to North (i.e. 0, 30, 60, 90, 120 and 150°; Fig. 6c) and examining the inclusion trail geometries within all porphyroblasts (Hayward, 1990; Bell et al., 1995; Bell et al., 1998). The FIA trend is located between the two thin sections where the curvature of the inclusion trails switches from clockwise to anticlockwise. In the example presented in figure 6c, the rim FIA is located between 30° and 60°, and the core FIA between 60° and 90°. Two more thin sections, 10° apart within this 30° range, are prepared for every FIA to constrain their trends within a 10° range. Figure 6d represents these FIA trends plotted on an equal area rose diagram assuming that these FIAs are located in the middle of the above 30° ranges.

4.2 Monazite dating

Ages were determined using a JEOL JXA-8200 Electron Probe Micro Analyzer (EPMA) housed at the Advanced Analytical Centre, James Cook University. The analytical set-up is given in Table 1. Measurements were taken at an accelerating voltage of 15 kV, beam current of 200nA, and spot size at 1µm. Matrix corrections were undertaken using the PAP method (Pouchou and Pichoir, 1984, 1985). Interference corrections for Th and Y on Pb and Th on U were applied as described in Pyle et al. (2002). The X-ray lines M_α are used for Th and Pb, M_β for U and L_α for Y. Monazite from Manangotry, Madagascar (545 ± 2 Ma; Paquette et al., 1994) was analyzed as internal age standard 5 times before and after each analytical session. X-Ray compositional maps for Y, Pb, U and Th and back-scattered images of the largest monazite grains were obtained to select the location of the analytical spots (Fig. 7). Individual ages were calculated for each analytical spot by solving the monazite age of Montel et al. (1996). Weighted average and probability density plots of individual ages from a same grain was obtained using Isoplot/Ex 3.6 (Ludwig, 2008) to define an average age for each monazite grain (Fig. 7). The ages of the monazite grains preserved as inclusion within cordierite porphyroblasts containing the foliation that defines a FIA were combined using weighted average and probability density plots to define an average age for each FIA event.

5 FIA DATA AND INTERPRETATION

5.1 FIA sets

From the thirty-seven samples containing porphyroblasts (or pseudomorphs) with inclusion trails sufficiently well preserved for FIA measurement, fifty-six FIA trends were measured, forty-six from cordierite and ten from andalusite porphyroblasts. Nineteen samples show a single FIA trend recorded within a single generation of cordierite or andalusite. The eighteen remaining samples show multiple FIA trends recorded either from cordierite and andalusite porphyroblast with a single stage of growth or from cordierite or andalusite porphyroblasts with two or more stages of growth containing different FIA trends in the cores and the rims. The results are summarized in Table 2. Figure 8a shows all FIA trends measured whereas Figures 8b and c show the data separated for cordierite and andalusite porphyroblasts respectively. Five peaks are apparent on the rose diagram (Fig. 8a) oriented at 35°, 60°, 85°, 105° and 135°. The 85° trend is not preserved in andalusite porphyroblasts (Fig. 8c). One single measurement obtained from the core of cordierite porphyroblast within sample RQ5 has a 165° trend.

Within the Charters Towers metamorphics seven samples recorded a single FIA trend and six recorded multiple FIAs within cores and rims, all recorded within cordierite porphyroblasts (results shown in Table 3). Nineteen FIA trends were measured from the thirteen cordierite bearing samples with well preserved inclusion trails. Four peaks are present trending at 45, 65, 105 and 145° (Fig. 9a).

5.2 FIA succession

The microstructural relationships of andalusite relative to cordierite in the Thalanga region indicate that the latter phase grew first (e.g.; Table 2 and Figs. 8d & 10) and they generally preserve different FIA trends (e.g. Bell and Hickey, 1999). Changes in FIA orientation also occur within the porphyroblasts of some samples from core to rim (Figs. 4 & 6) allowing their relative timing to be determined (Tables 2 & 3; Figs. 8d & 9b). If the relative timing is consistent for all samples then a succession of FIA sets can be determined (Bell et al., 1998). At Thalanga FIAs trending 165° (sample RQ5) and 85° (samples RQ15 and RQ30) are preserved within the cores of cordierite porphyroblasts. In the rims of samples RQ5 and RQ15 the FIAs trend 135°. Cordierite cores in samples RQ4, RQ6, RQ10, RQ13b and from within andalusite cores of sample RQ2 have FIAs trending 135° (RQ8 has FIAs varying around 135° in both core and rim of cordierite porphyroblasts - see below). A FIA averaging 105° is preserved within andalusite rims (sample RQ2), cordierite rims (samples RQ4, RQ6, RQ13b, RQ30) and cordierite cores (samples RQ9, RQ27). A FIA averaging 60° is preserved within cordierite rims in samples RQ9, RQ10 and RQ27 and within andalusite cores in samples RQ77 and RQ78. Samples RQ83, RQ84 and RQ85 contain cordierite and andalusite porphyroblasts with different FIA trends; cordierite FIAs trend at ~ 60° while the andalusite at 30°. The latter FIA 30° also occurs within andalusite rims of samples RQ77 and RQ78.

At Charters Towers, FIAs average 145° within the cores of cordierite porphyroblasts in samples RQ47, RQ51, RQ96, RQ97 and RQ101. A FIA trending ~ 105° is preserved within the cordierite rims of sample RQ51. The cordierite cores and rims of sample RQ93 contain FIAs trending at 115° and 105° respectively. A FIA trending at 065° is preserved within cordierite rims of samples RQ47, RQ97 and RQ101. Sample RQ96 contains a FIA trending at 45° in cordierite rims.

FIAs should form near orthogonal to the direction of horizontal bulk shortening and a succession of changes in trend may reflect changes in the direction of relative plate motion (e.g. Bell and Newman, 2006). A consistent succession can be interpreted from the FIA data mentioned above for the Thalanga region from E-W (FIA 1 ~ 85°), NW-SE (FIA 2 ~ 135°), WNW-ESE (FIA 3 ~ 105°), WSW-ENE (FIA 4 ~ 060°) to SW-NE (FIA 5 ~ 035°). The 165° FIA in sample RQ5 is unique and predates that at 135° preserved within the rims but its timing relative to FIA 1 at 085° is unconstrained. Sample RQ8 contains cordierite cores and rims trending respectively at 135° and 125° that both lie within the same FIA peak on Figures 8a and b. This anti-clockwise progression around the compass accords with that from FIA 2 to 3.

Similarly, in the Charters Towers region, sample RQ93 contains an anticlockwise progression in FIA trends from cordierite cores (115°) to rims (105°) that lie within the same FIA peak on the rose diagram (Fig. 9a). The succession interpreted for the different FIA sets is: NW-SE (FIA 1 ~ 145°), WNW-ESE (FIA 2 ~ 105°), WSW-ENE (FIA 3 ~ 065°) and SW-NE (FIA 4 ~ 045°).

6 MONAZITE DATA AND INTERPRETATION

Although nine polished thin sections (one for every FIA) were prepared from vertical blocks for several samples used for measuring the FIA trend, only six contained sufficiently large monazite preserved within porphyroblasts to make dating worthwhile. Out of the five FIAs present in the Thalanga region only the first four FIAs could be dated; monazite grains preserved within andalusite porphyroblasts containing the youngest FIA (FIA 5) in samples RQ83 and

RQ84 were too small to be analyzed. In the Charters Towers Metamorphics only FIA set 2 could be dated; monazite grains were too rare and too small in the other samples to be dated. All FIAs were dated using monazite grains preserved within cordierite porphyroblasts.

6.1 Samples dated

Dates were obtained from five samples from the Puddler Creek formation (Thalanga region) and from one sample from the Charters Towers Metamorphics. From the Thalanga region, sample RQ13a contains FIA 1 (085°) in both the cores and rims of cordierite porphyroblasts. This sample consists of a mineralogical assemblage Crd+Bt+Ms+Qtz where cordierite porphyroblasts are completely pseudomorphed by a coarse grained assemblage of chlorite plus muscovite (Fig. 4c & d, 7b). Sample RQ8 contains FIA 2 (135°) in both cores and rims of cordierite porphyroblasts. This sample consists of a mineralogical assemblage Crd+Bt+Ms+Qtz and retrograde chlorite, cordierite porphyroblasts are completely pseudomorphed by a fine to medium grained assemblage of biotite, muscovite and chlorite (Figs. 4c, d & 7c). Sample RQ30 contains FIA sets 1 and 3 in cores and rims of cordierite porphyroblasts respectively. Cordierite cores are small and do not contain enough monazite grains to date FIA 1, monazite grains were analyzed from cordierite rims to date FIA set 3. This sample consists of the mineral assemblage Crd+Bt+Ms+Qtz and retrograde chlorite, cordierite porphyroblasts are completely pseudomorphed by a fine to medium grained assemblage of biotite, muscovite and chlorite (Fig. 7d). Samples RQ83 and RQ84 contain FIA 4 and FIA 5 in cordierite and andalusite porphyroblasts respectively. Only FIA 4 could be dated because the andalusite porphyroblasts did not contain enough monazite grains of sufficient size. These samples consists of the mineral assemblage Crd+And+Bt+Ms+Qtz and retrograde chlorite, andalusite porphyroblasts are partially replaced by very fine grained white micas and cordierite porphyroblasts are completely replaced by coarse grained chlorite and muscovite (Figs. 4g, h & 7e). From the Charters Towers Metamorphics, sample RQ91 contains FIA 2 in cordierite porphyroblast. This sample consists of the mineral assemblage Crd+Bt+Pl+Ms+Qtz and retrograde chlorite, cordierite porphyroblasts are completely replaced by a very fine grained assemblage of chlorite, biotite and muscovite. The locations of these samples are shown in Figures 3 & 5.

6.2 Monazite ages and FIAs

A total of 147 spots from 75 monazite grains were analyzed. For each analytical spot a chemical age was calculated, the result of which is presented in Table 4. A weighted average age was calculated for monazite grains where several spots were analyzed, the result of which is presented in Table 5 and the method is shown in Figure 7. Compositional maps of in-situ monazite grains preserved as inclusions within cordierite porphyroblasts reveal that monazite grains are commonly very homogeneous; some show a small zonation in Yttrium and Thorium but the ages obtained from different zones are similar (Fig. 7). Monazite grains from cordierite porphyroblasts containing the same FIA were grouped and a single weighted average age was calculated (Fig. 11).

The oldest monazite age obtained is from sample RQ91 containing the E-W FIA set 2 from the Charters Towers Metamorphics (Fig. 11a). The calculated age is of 474.7 ± 7.2 Ma (MSWD = 0.65). This corresponds with the first episode of magmatic activity recognized in the Ravenswood batholith, which has a mainly granitic composition and ranges in age between 490 ± 6 Ma and 463 ± 3 Ma ($^{206}Pb/^{238}U$ SHRIMP age on zircon; Hutton and Rienks, 1997). The Sunburst granodiorite adjacent to the Charters Towers Metamorphics was dated at 482 ± 8Ma (206Pb/238U SHRIMP age on zircon; Fanning, 1995). Therefore, the low pressure high temperature metamorphism that produced the cordierite bearing, garnet absent rocks of the Charters Towers Metamorphics is interpreted to be contemporaneous with N-S shortening and granite emplacement at around 475 Ma. The early to mid Ordovician granites of the Ravenswood batholith were subsequently strained or recrystallized during mainly ductile deformation within well-defined shear zones. In the Balcooma metavolcanics 250 km NW of this zone, Ali (2010) recognized a N-S shortening event of similar age that also produced an E-W trending FIA.

At Thalanga, the monazite ages obtained are 413 ± 13 Ma for FIA 1 (085°), 400.6 ± 9.1 Ma for FIA 2 (135°), 381 ± 8.1 Ma for FIA 3 (105°) and 378 ± 9 Ma for FIA 4 (065°). This succession of ages confirms the FIA succession described earlier. They accord with ages obtained within the adjacent Lolworth batholith; the Hodgon and Amarra Suite were dated at 414 ± 5 Ma and 382 ± 5 Ma respectively ($^{206}Pb/^{238}U$ SHRIMP zircon age; Fanning, 1995). Therefore, it is interpreted that continuous deformation and granite emplacement occurred from Early to mid-Devonian times with three main discrete deformation and granite emplacement episodes. The first is associated with N-S shortening at around 415 Ma, the second with NE-SW shortening at ~400 Ma and the third with N-S shortening at ~380 Ma. Younger deformation is associated with NW-SE shortening but no age could be determined for this FIA in the Thalanga region.

7 GRANITOID SPATIAL DISTRIBUTION IN THE TOWNSVILLE HINTERLAND

Granitoids of the Carboniferous-Permian Kennedy Igneous Province (MacKenzie and Wellman, 1997) form a linear belt, parallel to the northeastern Queensland coastline, that trends NW-SE in the Charters Towers Province (Fig. 12) and N-S in the Hodgkinson Province to the North (Fig. 1). These rocks consist largely of I-type granites and lesser S and A-types and are interpreted to have formed as the result of crustal melting in extensional (or transtensional), possibly back-arc, tectonic environment (MacKenzie and Wellman, 1997). In contrast, granites of the Silurian-Devonian Pama Igneous Province are interpreted to be emplaced into thickened crust during a compressional regime and contemporaneous with regional metamorphism (Hutton et al., 1997). They form a discontinuous belt that trends N-S in the Coen Inlier (Fig. 1), NE-SW in the Georgetown and Greenvale regions and E-W in the Charters Towers Province, (Fig. 13). The Reedy Springs Batholith is situated where the change in the trend of exposures occurs between the Greenvale and the Charters Towers Province (Fig.13). Internal fabrics show this trend changing from E-W in the south and NW-SE in the north of the batholith (Hutton et al., 1997). The southern part of the batholith contains S-C fabrics with sinistral shear sense and a gently plunging lineation indicating a possible westward extension of the Alex Hill Shear Zone (Hutton et al., 1997; Fig. 13). Some of the Silurian-Devonian plutons in the Charters Towers Province appear to have been intruded into active shear zones. These plutons are characterized by the presence of igneous foliations, best developed near their margins, parallel to their long axis and to a similar but stronger foliation in the basement rocks (Hutton et al., 1997). This suggests that Silurian-Devonian granites in the Charters Towers Province were emplaced during N-S compression and the development and/or reactivation of E-W structures; this shortening event did not affect regions north of the Greenvale Province; a N-S trending granite belt is preserved in the Coen Inlier. The Carboniferous-Permian N-S trending linear granitoid belt, parallel to the subduction zone to the east, was emplaced during subsequent extension probably related to slab roll-back.

8 MAGNETIC TRENDS FROM NORTH CENTRAL TO NORTHEASTERN AUSTRALIA

Only around one-third of the basement rocks from northeastern Queensland to Central Australia are not covered by younger flat lying units (Wellman, 1988, 1995). Therefore, in many cases, magnetic anomaly maps at continental scale (Milligan and Franklin, 2004) provide the only means for defining boundaries between structural domains (Fig. 14). These domains are distinguished by sub-parallel magnetic trends that reveal tectonic structures within deformed portions of the upper crust. Domains with older structures have their trends truncated by domains with younger structures. Figure 14 shows the truncation of older structures by younger ones. The Precambrian Arunta, Mt Isa, Georgetown and Coen domains are truncated on their southern and/or eastern boundaries by the Paleozoic Alice Springs, Thomson (including the Charters Towers and Greenvale Provinces) and Hodgkinson-Broken River Orogens. Similarly the late Neoproterozoic-early Cambrian Petermann Orogen is truncated by the Ordovician-Devonian Alice Springs Orogen. The ~500 Ma Anakie Province is truncated by the Ordovician-Devonian Charters Towers Province, which is in turn truncated by the Carboniferous-Permian New England Orogen. The magnetic trends in the Townsville hinterland are parallel with the granitoids trends described above. The highly magnetized domains of the Greenvale and the Charters Towers Provinces, trending NE-SW and E-W respectively, are interpreted to result from crustal reworking whereby metamorphism and deformation caused the enhanced magnetization (Wellman, 1992a). The Broken River Province is poorly magnetized suggesting that no major thermal event and deformation affected this area. The Greenvale and Charters Towers Provinces connect with a major zone of reworking that truncates the southern edge of the Mount Isa domain and links with the E-W trends of the southern Arunta Block (Wellman, 1988, 1992a, b). This E-W tectonic grain is interpreted to be the result of N-S shortening during the 450-300 Ma

Alice Springs Orogeny (Fig. 14). Mapped shear zones defining domain boundaries or present within domains coincide with magnetic lineaments that allow their extent to be interpreted where covered by younger sedimentary units (Fig. 14). The extent of such structures was used to produce the time slice interpretive maps presented in Figure 15.

9 IMPLICATIONS FOR THE TECTONIC EVOLUTION OF THE CHARTERS TOWERS PROVINCE

9.1 Cambrian to Early Ordovician

The Cambrian-early Ordovician Seventy Mile Range Group is regarded as having been deposited in a back-arc basin of north south orientation with the volcanic arc located to the East (Henderson, 1986). It is interpreted to be the remnants of an active margin terrane which extended the entire length of Eastern Australia, comprising similar rocks from the Greenvale Province (Balcooma volcanics) to the North, to the Mount Read volcanics of Tasmania to the South (Henderson, 1986; Fig. 15a). This suggests that the Seventy Mile range Group experienced ~70° anticlockwise rotation during subsequent deformation to reach its present orientation.

Early to mid-Ordovician granites of the Ravenswood batholith are interpreted to have been generated in response to underplating at the base of the continental crust by basic magma possibly generated in a subduction zone (Hutton and Crouch, 1993). These granites have arc-type characteristics inherited from their source indicating the existence of a pre-early Ordovician continental margin volcanic arc which correlates with the arc proposed to explain the formation of the Seventy Mile Range Group (Henderson, 1986; Berry et al., 1992; Hutton et al., 1997).

9.2 Mid-Ordovician to Late Ordovician

Early to Mid-Ordovician granites of the Ravenswood batholith are affected by sinistral strike-slip movement as shown by sinistral S-C fabrics and flat-lying mineral stretching lineation defining the ~E-W trending Alex Hill Shear Zone (Peters, 1987; Hutton and Rienks, 1997). Hutton and Rienks interpreted that shearing and plutonism were at least partly synchronous through recognizing that igneous flow occurred parallel to tectonic foliation in Mid-Ordovician granites. Hutton et al. (1997) interpreted sinistral strike slip motion on the Clarke River Fault, contemporaneous with deformation within the Cape River Metamorphics, during the Early to Mid-Ordovician. The ~475 Ma NE-SW shortening producing the ~105° trending FIA 2 in the Charters Towers Metamorphics is interpreted to be responsible for the initiation of sinistral strike slip movement on the Alex Hill Shear Zone and the Clarke River Fault. A similar event was recognized in the Greenvale Province where Ali (2010) interpreted synchronous amphibolite facies metamorphism, granite emplacement and ~E-W FIA development at ~475 Ma.

Within the Harts Range in Central Australia, Hand et al. (1999) recognized a tectonothermal event dated at ~470 Ma associated with upper amphibolite facies metamorphism and the development of sub-horizontal shear fabrics that was interpreted as the product of crustal extension. However these rocks contain more than one gently dipping foliation (Hand et al., 1999) and this strongly suggests that shortening orogenesis was involved (e.g. Bell, 2010). The gently dipping foliations would be the product of repeated gravitational collapse during orogenesis rather than crustal extension in this case. This interpretation suggests that the Australian continent underwent from the Mid-Ordovician N-S compression producing intracontinental deformation in central Australia and the initiation of major sinistral strike slip faults in the Charters Towers Province.

9.3 Silurian-Devonian

Silurian-Devonian granites of the Pama Igneous Province are interpreted to be emplaced in a thickened continental crust during a compressional regime that was contemporaneous with regional metamorphism (Hutton et al. 1997). In the Greenvale Province, ~E-W shortening produced a NNW-SSE and NNE-SSW trending FIAs dated at ~445 Ma and ~425 Ma respectively (Ali, 2010). These reveal that Ordovician N-S shortening was followed by Silurian E-W shortening producing the ~NE structural trends of this province. Synchronous granitoids emplacement was controlled by regional structures, the long axis of the batholiths trend parallel to them. The anticlockwise evolution of the ~NE-SW trending FIA 3 and 4 in the Charters Towers Metamorphics could reflect a progressive change from N-S shortening to E-W shortening in the Late Ordovician, prior to the development of the ~445 and ~425 Ma ~N-S FIAs in the Greenvale Province.

A N-S shortening event produced the E-W FIA 4 dated at ~410 Ma in the Greenvale Province (Ali, 2010) and the E-W FIA 1 dated at ~415 Ma in the Thalanga region (Charters Towers Province) synchronous with emplacement of plutons within the Lolworth batholith. Inclusion trails preserved within porphyroblasts defining FIA 1 at Thalanga display asymmetries indicating north directed thrusting and was interpreted to affect rocks South and North of the Ravenswood batholith (e.g. Section B). ~E-W shortening produced the NW-SE FIA 2 at Thalanga dated at 400 Ma, followed by Late Devonian (dated at ~380 Ma) N-S shortening producing E-W FIA 3, top to the north thrusting (e.g. Section B) and synchronous granite emplacement in the Lolworth batholith. Magmatic and tectonic foliations in Silurian-Devonian granitoids of the Charters Towers Province indicate that they were emplaced during N-S shortening events into E-W trending shear zones. The southern part of the Silurian-Devonian

Reedy Springs batholith contains S-C fabrics with sinistral shear sense and a gently plunging lineation indicating a possible westward extension of the Alex Hill Shear Zone (Hutton et al., 1997; Figs. 13, 15b & 16). This suggests that the Alex hill Shear Zone, initiated in the Ordovician, was reactivated during the Silurian-Devonian.

The Charters Towers Province is regarded as a zone where thrusting and sinistral strike slip occurred synchronous with granite emplacement; Figure 16a shows the interpreted structures of the Charters Towers Province in the Late Devonian. The main shortening direction is to the north and was probably related to the period of major intracontinental deformation that affected central Australia were most of the transport is to the South. The reworked zone along the southern margin of the Mt Isa Inlier (Fig. 14) is interpreted to result from intense shearing along a transfer fault that allows the connection between the thrust system in the Alice Springs Orogen and the thrust and strike slip system of the Charters Towers Province (Fig. 15b). Most of the deformation in the Charters Towers Province is the result of the N-S shortening which explains the E-W tectonic grain of the Province and rotation of the originally N-S trending Seventy Mile Range Group into its present ~E-W position. The southern boundary of the Charters Towers Province is interpreted as another sinistral strike slip shear zone (Fig. 15b); the boundary between the E-W trends of the Charters Towers Province and the N-S trends of the Thomson Orogen to the South is displayed on the magnetic anomaly map. However, no field data are available to confirm this interpretation since it is all covered by younger sedimentary successions. Interspersed E-W shortening events are probably the expression of compressional episodes related to the west-dipping subduction to the East, but the sinistral strike slip motion probably occurred during episodes of slab roll-back leading to the tectonic extrusion of the Thomson Orogen. This implies that a region similar to the Charters Towers Province with opposite shear sense may occur to the south of the Thomson Orogen or within the Lachlan Orogen to accommodate the eastwards extrusion. Such a structure could be presented by the megakinks proposed by Powell (1985) in the eastern Lachlan Orogen during the Carboniferous and by the southeastern extrusion of the central Lachlan Orogen in the Silurian-Devonian as proposed by Glen et al. (1992).

9.4 Carboniferous to Permian

The Carboniferous-Permian granitoids of the Kennedy Igneous Province that intruded the eastern part of the Charters Towers Province form a continuous ~NW-SE trending belt parallel to the coast line (Fig. 12). They are interpreted to result from crustal melting in an extensional (or transtensional), possibly back-arc, tectonic environment (Bain and Draper, 1997). These granitoids are not affected by the E-W shear zones mentioned above suggesting that N-S shortening associated with the Alice Springs Orogeny is over in this region. The southeastern end of the Charters Towers Province has its E-W structural trends truncated by the northern extent of the New-England Orogen (Figs. 14 & 15c). The latter consists of arc and arc related rocks that were accreted onto the continent in the Late Devonian-Carboniferous during plate convergence associated with the long-lived West dipping subduction zone east of Gondwanaland. The New-England Orogen forms the easternmost tectonic unit of Eastern Australia and contributes to the growth of the Phanerozoic crust of Australia (Fig. 15c).

10 DISCUSSION

10.1 Limitations of monazite dating

Three main limitations arise, first the EPMA indirect dating method, second the possible resetting of the U-Th-Pb system during subsequent high temperature metamorphism and third the possible dissolution and reprecipitation of monazite grains due to fluid infiltration. These points are discussed below.

The EPMA dating of monazite involves large errors on the age for each analytical spot commonly between ±20 and ±120 Ma (Table 4). This is mainly due to the low accuracy of Pb measurement due to the impossibility to differentiate between common Pb and radiogenic Pb by this method (Montel et al., 1996). However, Parrish (1990) argues that common Pb is negligible relative to radiogenic Pb in monazite assuming that all Pb present is radiogenic. The age errors are reduced by a statistical treatment of homogeneous ages and by microstructural control of monazite grains preserved within foliation defining the corresponding FIAs, resulting in age errors of commonly ~10 Ma (Fig. 11). The EPMA dating of monazite controlled by FIAs has recently been intensively investigated; the monazite ages obtained are consistent with the FIA successions and proved to be geologically meaningful (Bell and Welch, 2002; Cihan et al., 2006; Cao, 2009; Ali, 2010; Sanislav, 2011).

The resetting of the U-Th-Pb system in monazite due to temperature increase seems unlikely in rocks from the Seventy Mile Range Group and from the Charters Towers Metamorphics where peak metamorphism is estimated at 550°C and maximum 3kbar (section A). Smith and Barreiro (1990) showed that the U-Th-Pb system in monazite is resistant to resetting up through sillimanite grade; indeed diffusion rates in monazite are very slow compared to geological processes (Gardés et al., 2006; Cherniak and Pyle, 2008). Recent experimental studies at moderate temperature and pressure show that fluid-induced dissolution-reprecipitation of monazite is a more efficient mechanism than diffusion for resetting the age (Seydoux-Guillaume et al., 2002; Williams et al., 2011). However monazite alteration textures were commonly not observed except maybe in some monazite rims; in these cases the spots analyzed were obtained from the unaltered core of monazite grains (Fig. 7).

10.2 Origin of the Paleozoic continent wide N-S compression and localization of deformation

The contemporaneous orthogonal shortening directions that resulted in the development of the Lachlan/Thomson and the Alice Springs orogens of Eastern and Central Australia respectively, hindered progress in understanding the tectonic evolution of the Charters Towers Province located at the intersection between them. E-W shortening is attributed to subduction processes along the eastern Gondwana margin during the entire Paleozoic (Scheibner, 1986; Coney et al., 1990; Li and Powell, 2001; Gray and Foster, 2004). The tectonic setting of the Australia's northern margin, as part of Gondwanaland in the Paleozoic, which resulted in the intracontinental Alice Springs Orogeny, is not well understood. It has been proposed that collision of Gondwana with North America in mid-Carboniferous time may have been responsible for the intraplate Alice Springs Orogeny (Coney et al., 1990; Coney, 1992), but this does not take into account earlier intracontinental deformation from the Early to Mid-Paleozoic. Alternatively, Pan (1994) proposed a convergent margin linking with subduction zone of eastern Gondwana and implying numerous microplates including north and south China. More recently, paleotectonic-paleogeographic reconstructions of (Stampfli and Borel, 2004) suggest the opening of the Paleo-Tethys Ocean Australia at ~450 Ma. This implies that the intraplate deformation would result from ridge-push effect associated with the opening of the Paleo-Tethys Ocean at ~450 Ma as also proposed by Gray and Foster (2004). In all cases, the synchronous Paleozoic N-S shortening in central Australia and E-W shortening in eastern Australia requires plate boundary processes along the northern and eastern margins of this part of Gondwana at that time and therefore similar plate boundary stresses to those occurring today (Betts et al., 2002). Braun and Shaw (2001) reproduced the tectonic evolution of the Australian lithosphere in a thin viscous plate thermomechanical numerical model, invoking in-plane driving forces generated at the plate margins. They concluded that "the most likely mechanism for intracratonic deformation is the concentration of strain by transmission of horizontal stress originated at plate boundaries into regions of decreased lithospheric strength". Previous intracratonic deformation or difference in lithospheric strength between zones of increased strength, such as cratons, and zones of reduced strength would cause the localization of deformation. Localization of the deformation in the Alice Springs has been suggested to result from the emplacement of highly radiogenic granitoids that weakened the crust (Sandiford and Hand, 1998; Hand and Sandiford, 1999)

10.3 Discussion of previous and proposed tectonic models

Almost all possible tectonic models were proposed for the evolution of the CTP and surrounding provinces to explain its anomalous E-W structural trends in regards to the N-S trending Tasman Orogen. It has been explained to be the result of rifting (White, 1961, 1965), a failed triple point (Harrington, 1981), a megafold (Bell, 1980; Powell, 1984, 1985) and a transform like structure associated with an oblique subduction (Henderson, 1987). Such a multitude of interpretations is possible because any orogen scale geometry can result from many different paths. The resolution level of geochronological data allowed only for broad temporal correlation between regions; the previous models were lacking absolute dating of deformation events and their associated shortening directions now accessible through in-situ monazite dating of FIA forming events. The model proposed in this study correlates the ages of successive deformation events associated with shortening directions, synchronous metamorphism and granite emplacement, with the CTP being the result of extrusion driven strike slip that displaced the Thomson Orogen to the east. SV wave azimuthal anisotropy at 100 km depth (Debayle and Kennett, 2000) reveals strong E-W anisotropy in central and eastern Australia interpreted to represent deformation frozen in the lithosphere preserved since the Alice Springs orogeny. This correlates with Klootwijk's (2008) interpretation of paleomagnetic data in the New-England Orogen also arguing for tectonic extrusion of the Thomson Orogen and the New-England Orogen due to N-S shortening in Central Australia during the Alice Springs Orogeny probably associated with slab roll-back/retreat of the East Gondwana subduction zone.

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CONCLUSIONS

This study has demonstrated that complex tectono-metamorphic histories can be accurately revealed in regions where most basement rocks are covered by sedimentary successions using a multidisciplinary approach consisting of microstructural measurements, geochronology, plus careful examination of geophysical data and geological maps. Several discrete events within an apparently continuous long-lived deformation period can be depicted by detailed analyses of microstructures preserved within porphyroblasts as inclusion trails. The principal conclusions of each section are summarized below:

Section A

The method used to calculate mineral modal amounts involved the production of a map for every mineral phase present in the pseudomorph (± cordierite core / reaction rim) and the matrix. This allowed determination of the distribution of each mineral phase in every textural domain within both the pseudomorph and the surrounding matrix. This shows that the progressive replacement of cordierite occurs inwards from the porphyroblast margins. Cordierite is primarily replaced by narrow preferentially aligned laths of muscovite. The coarsening of muscovite laths and subsequent appearance of biotite leads to the development of a reaction rim where most of the outer margin of the cordierite porphyroblast has been replaced. The continuity of this process results in the complete replacement of the original cordierite porphyroblast.

The development of microcracks is of fundamental importance in the replacement of the cordierite porphyroblast. The two relevant mechanisms for microcrack formation and propagation are:

-brittle-plastic deformation of cordierite and strain incompatibilities between inclusions (mainly quartz) and the host cordierite and,

-volume increase due to the replacement of quartz inclusions by plagioclase during pseudomorphism.

Deformation induced microcracks develop primarily at the margin of the porphyroblasts; this allows fluids to penetrate the cordierite resulting in the replacement of quartz inclusions by plagioclase, enhanced microcracking and growth of micas. Cracks propagate from one inclusion to another preferentially in the direction of the inclusion trails. Eventually an interconnected network of cracks spreads over the entire cordierite resulting in the progressive replacement of the cordierite by micas that grow in the same direction as the inclusion trails.

The PT conditions for the rocks from NE Queensland are difficult to estimate due to the lack of sufficient phases for precise thermobarometry calculations. It is interpreted that the maximum pressures experienced by these rocks were around 3 kbars and the maximum temperatures did not exceed 600°C, most probably lying near the 550°C isotherm. The temperatures obtained via the Ti-in biotite thermometer may reflect retrograde conditions rather than peak metamorphic conditions. This thermometer is strongly dependant on chemical equilibration of biotite grains. The temperatures obtained within biotites in the matrix are systemically higher than that from those in complete or partial pseudomorphs indicating that equilibration of biotites in the matrix occurred prior to pseudomorphism. This implies that the metamorphic reactions are localized to the volume occupied by the cordierite and the material exchange with the matrix is limited.

Section B

Examination of the magnetic anomaly maps of Australia reveals the truncation of N-S trending Precambrian tectonic structures of the Mt Isa Block by the E-W trending ones of the Charters Towers Province and Alice Springs Orogeny. Granite ages along the southern and eastern edges of the Mt Isa block indicate an apparent northward migration of the magmatic front from the southern edge of the Mt Isa block towards the Charters Towers Province between ~500 and 385 Ma. Three ~E-W trending FIA sets were identified from porphyroblastic rocks of the Charters Towers Province. These successive ~N-S shortening events were dated at ~475, ~415 and ~380 Ma by EPMA dating of monazite grains preserved as inclusion within foliations defining the corresponding FIAs; these events are synchronous with pluton emplacement in the Ravenswood and Lolworth batholiths. Two similar FIA sets in age and orientation were previously recognized in the Greenvale Province indicating that N-S compression affected the Charters Towers and Greenvale Provinces at ~475 and ~415 Ma; younger N-S shortening seems to have affected only the Charters Towers Province. The deformation ages obtained are consistent with the relative timing relationships observed between the development of E-W trending tectonic structures and granite emplacement and overlap with metamorphic and deformation ages in central Australia.

This correlation of deformation/FIA ages, FIA trends, pluton ages and trends, volcanic ages and E-W geophysical anomalies across Australia strongly support the suggestion that E-W trending orogenesis extended from central Australia to the Charters Towers Province from 475 to 380 Ma. The SW-NE trending reworked zone at the southern end of the Mt Isa Block possibly experienced sinistral shear to accommodate deformation propagation from central Australia to the Charters Towers Province.

Section C

The systematic recording of inclusion trail asymmetries observed in sections cut near orthogonal to each FIA set reveals that strong non-coaxial deformation involving overall top to the North thrusting affected the Seventy Mile Range Group to the South of the Charters Towers Province. This suggests that the south dipping structures observed on the N-S seismic section that out crop in the Seventy Mile Range Group formed as thrusts. Similar thrusts, all of which sole into the Moho, occur across the whole of the Charters Towers Province. These structures are not observed only where the Ravenswood batholith crops out. The competency of this coarse feldspar batholith may have caused partitioning of thrusting deformation around it. Thus only the thrusts to the north and south of the Ravenswood batholith propagate to the surface resolving why the Charters Towers metamorphics are affected by coaxial deformation rather than the non-coaxial deformation apparent in the Seventy Mile Range Group. Thrusting within the Seventy Mile Range Group would have occurred from when FIA 1 formed at around 415 Ma.

To the north of the Ravenswood batholith thrusts propagate to the surface affecting basement rocks represented by the Argentine metamorphics. As a result, geological maps of the Argentine Metamorphics were closely examined to see if any thrusts were present. This led to the recognition of a thrust, confirmed by field work, where schistosity in the hanging wall lies parallel to bedding in Devonian sedimentary rocks in the foot wall. This structure was domed during subsequent shortening and cut by younger faults.

The method proposed herein is relevant for any multiply deformed terrains where recognition of such structures can be hindered by subsequent deformation.

Section D

The tectonic evolution of the Charters Towers Province in the Paleozoic resulted from the interaction between N-S and E-W bulk shortening. The tectonic evolution model of the Province is summarized as follows. In the Cambrian to early-Ordovician, the eastern margin of Australia, which was part of Gondwana at that time, experienced the development of a N-S trending continental volcanic arc that extended the entire length of Australia in response to a west dipping subduction zone lying to the East. The sedimentary and volcanic rocks of the Seventy Mile Range Group and the Balcooma metavolcanics were deposited in the associated back-arc basin. Early to mid-Ordovician plutons of the Ravenswood batholith have volcanic arc inherited characteristic and are interpreted to have been generated in response to underplating at the base of the continental crust by basic magma generated in the subduction zone.

NE-SW shortening dated at ~475 Ma produced the 105° FIA in the Charters Towers Metamorphics and in the Greenvale Province. This event is interpreted to be responsible for the onset of the sinistral strike slip on the ~E-W trending Alex Hill Shear Zone and Clarke River Fault. Some mid-Ordovician plutons in the Ravenswood batholith were emplaced within the Alex Hill Shear Zone. Coeval with this event, upper amphibolite facies metamorphism associated with gently dipping foliations occurred in central Australia and is interpreted to result from gravitational collapse of an orogenic prism.

Ordovician N-S shortening was followed by ~E-W shortening during the Silurian, which produced in the Greenvale Province NNW-SSE and NNE-SSW trending FIAs dated at ~445 Ma and ~425 Ma respectively and contemporaneous granite intrusion. The ~NE-SW non-dated FIAs in the Charters Towers Metamorphics are interpreted to result from the progressive change from

N-S shortening to E-W shortening in the Late Ordovician prior to those that developed in the Greenvale Province.

N-S shortening dated at ~415 Ma produced the E-W trending FIAs in the Greenvale and Charters Towers Provinces synchronous with emplacement of plutons within the Lolworth batholith and northward thrusting in the Seventy Mile Range Group. Two more FIA forming events related with ~E-W followed by N-S compression were dated at ~400 and ~380 Ma respectively. N-S compression reactivated northward thrusting throughout the Province and sinistral strike slip motion on the Alex hill Shear Zone and the Clarke River Fault.

The origin of N-S shortening seems to result from horizontal forces acting at the plate boundary that are possibly related to ridge-push effects due to the opening of the Paleotethys at ~450 Ma. The localization of the deformation during this continent wide compressional event in the intracontinental Alice Springs Orogen could be due to weakening of the lithosphere by highly radiogenic granite intrusion in the region. This event tends to extrude eastward the Thomson Orogen towards the “free boundary” of eastern Australia possibly during slab roll-back episodes. This forced the formation of sinistral strike slip faults in the Charters Towers Province, a similar province with opposite shear sense may occur south of the Thomson Orogen. The interspersed E-W shortening events are probably the expression of compressional episodes related to the west-dipping subduction to the East.

Early Carboniferous tectonic accretion of the N-S trending New-England Orogen forms the last episode of continental growth of the Australian lithosphere that overprinted the E-W structures of the Charters Towers Province. Subsequent slab roll-back caused an extensional (or transtensional), possibly back-arc, tectonic environment and melting of the crust resulting in voluminous granitoid intrusion in the Carboniferous-Permian that forms the continuous ~NW-SE trending belt that lies parallel to the present coast line of northeastern Australia.

Recommendations for further investigations

It is important to investigate the poorly known structural relationships between the Charters Towers and Greenvale Provinces and the Hodgkinson-Broken River Province. The latter was probably thrust over the basement rocks of the two former during subduction related processes. Evidence from the seismic data seems to indicate a continuity of crustal blocks underneath the Broken River Province linking basement rocks of the Charters Towers and Greenvale provinces.

The evolution of the intracontinental, fault bounded, Burdekin Basin in the Charters Towers Province seems to result from conjugate movement on the E-W trending strike slip faults and the faults bounding the basin creating a local extensional environment and the formation of half graben structures during the Devonian. This idea needs to be tested by subsequent field work to investigate the temporal correlation between the evolution of the Burdekin basin and the sinistral motion on E-W strike slip faults.

Basement rocks of the Charters Towers and surrounding provinces lack of detailed microstructural studies allowing the precise dating of successive deformation and metamorphic events; together with additional geochronology of the magmatic phases, large scale tectonic correlations would be better constrained.