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

VOLUME I

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

PREFACE

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

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

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ABSTRACT

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

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

ABSTRACT

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

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

ABSTRACT

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

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

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

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

ABSTRACT

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

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

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

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

INTRODUCTION TO THESIS

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

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

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

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

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

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

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

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

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

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