The microstructural and metamorphic history preserved within garnet porphyroblasts from southern Vermont and northwestern Massachusetts

VOLUME I

Thesis submitted by

Bronwyn Patricia GAVIN BSc (Hons) *Canterbury, NZ*

in June 2004

for the degree of Doctor of Philosophy

in the School of Earth Sciences

James Cook University

STATEMENT OF ACCESS

I, the undersigned, author of this work, understand that James Cook University will make this thesis available for use within the University Library and, via the Australian Digital Theses network, for use elsewhere.

I understand that, as an unpublished work, a thesis has significant protection under the Copyright Act and I do not wish to place any further restriction on access to this work.

_____ _____

Bronwyn Gavin June 2004

STATEMENT OF SOURCES

DECLARATION

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

_____ _____

Bronwyn Gavin June 2004

ELECTRONIC COPY

I, the undersigned, the author of this work, declare that the electronic copy of this thesis provided to the James Cook University Library is an accurate copy of the print thesis submitted, within the limits of the technology available.

_____ _____

Bronwyn Gavin June 2004

ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisor, Tim Bell, for his enthusiasm and encouragement throughout this project. Tim contributed significantly to the design of this project and has provided immeasurable assistance on the microscope helping me interpret inclusion geometries and reading and discussing numerous drafts of this thesis. I would also like to thank all the other members of SAMRI, past and present, who have helped contribute to my understanding of orogenesis in general and the development of the Appalachians in particular. I am especially grateful to Tom Evans and Peter Welch for introducing me to THERMOCALC and for providing me with datafiles and other assistance as I constructed the pseudosections in this thesis.

I would like to acknowledge Kevin Blake of the Advanced Analytical Centre at James Cook University for his help in preparing compositional zoning maps and for general assistance in using the microprobe. During my fieldwork I am grateful to have been able to use the rock cutting facilities at the University of Massachusetts and I would like to thank Mike Williams and Shelia Seaman for their help. I would like to thank Paul Karabinos of Williams College for suggesting I collect samples from the Devils Den area. I am also thankful to Scott Johnson for his constructive remarks on an early version of Section A, Neil Mancktelow for his comments on a version of Section B and David Hirsch for his very helpful review of a version of Section C.

During my PhD I was initially supported by a School of Earth Sciences Scholarship and later by a James Cook University Scholarship. Financial support used to cover the cost of research was partly provided by an Australian Research Council grant given to Tim

Bell. The School of Earth Sciences is also acknowledged for financial support used to cover basic research costs.

I would like to thank my parents, Garth and Mary Gavin, for their emotional and financial support throughout my academic career. Much as I missed New Zealand while I was studying in Townsville they ensured I never felt isolated from my family. Most of all I would like to thank my husband, James Leonard, for all his help. His practical assistance was invaluable during fieldwork and rock preparation and his emotional support has kept me sane. I could not have done this without him.

ABSTRACT

Garnet porphyroblasts from southern Vermont and northwestern Massachusetts typically preserve multiple generations of inclusion trails, reflecting a potentially complex deformation and metamorphic growth history. Textural discontinuities, such as inclusion trail truncations or deflection planes, are commonly preserved within these complex inclusion trails and they are dominantly sub-vertically and sub-horizontally oriented. This observation cannot be adequately explained using the rotational model of spiral inclusion trail formation, leading to the conclusion that the trails were formed by the inclusion of multiple sub-vertical and sub-horizontal foliations during episodic garnet growth without porphyroblast rotation. Foliation inflection/intersection axes preserved within porphyroblasts (FIAs) provide important information about the kinematics of deformation, particularly the direction of bulk shortening at the time they formed. Samples from this study preserve a succession of six FIA sets resulting from a progressive change in the direction of bulk shortening through time. The distribution of these FIA sets across the field area indicates that the deformation was heterogeneously partitioned and occurred at different scales throughout orogenesis. Localization of deformation is an important control on garnet growth and repartitioning during successive deformation events resulted in a heterogeneous spatial distribution of garnet growth through time. The episodic nature of garnet growth is reflected in compositional zoning anomalies in garnet porphyroblasts from the Hoosac Formation. Zones of manganese enrichment, accompanied by calcium depletion, reveal pauses in garnet growth that may have been accompanied by fluid infiltration, garnet dissolution-reprecipitation and metasomatism at crystal or greater scales. The metamorphic history of these samples was further investigated using P-T pseudosections constructed via THERMOCALC. The mineral assemblages predicted are in good agreement with the

observed mineralogy of the samples and estimates of P-T conditions at the time of garnet core growth were made using compositional isopleths based on microprobe analyses of garnet core composition. The samples do not show a clear relationship between the P-T data and the FIA data, suggesting that the preservation of different FIAs is not simply a function of P-T conditions. In samples where initial garnet appears to have occurred at temperature and/or pressure conditions higher than the minimum P-T conditions predicted for garnet stability, deformation probably played an essential role in garnet nucleation and growth. These "overstepped" samples indicate a progressive increase in pressure through the different phases of orogenesis.

This study reveals that garnet porphyroblasts in southern Vermont and northwestern Massachusetts grew during a complex history of deformation involving the production of multiple sub-horizontal and sub-vertical foliations with garnet growth primarily controlled by deformation partitioning, resulting in a heterogeneous spatial distribution through time. FIAs allow the relative age of different phases of garnet growth to be established and provide a framework for interpreting the relationship between deformation and metamorphism. Compositional zoning anomalies reflect the episodic nature of garnet growth and P-T modelling suggests that deformation took place under conditions of increasing pressure.

TABLE OF CONTENTS

Volume I

Volume II

Appendices **X-1**

INTRODUCTION

Understanding the relationships between deformation and metamorphism is crucial to understanding the process of orogenesis as a whole. The Appalachians in southern Vermont and northwestern Massachusetts are particularly suited to a study focusing on the relationships between metamorphism and deformation because of the remarkable structural and metamorphic history recorded as inclusion trails within the garnet porphyroblasts growing in these rocks. Many important microstructural and metamorphic studies have been carried out in southern Vermont and northwestern Massachusetts (e.g. Rosenfeld, 1968; Thompson et al., 1977; Karabinos, 1984; Armstrong et al., 1992; Vance & Holland, 1993; Bell et al., 1998; Bell & Welch, 2002) and these provided an excellent background to the present study. The main difference between the present study and previous work is that the same set of samples used for microstructural analysis were also used for electron microprobe mapping of compositional zoning and thermodynamic modelling of P-T conditions during garnet growth. This allows the integration of microstructural data with petrologic observations and P-T pseudosections and highlights the inter-relationship of deformation and metamorphism in this area. The study forms part of a larger ongoing research project by the Structure and Metamorphism Research Institute (SAMRI) at James Cook University that is investigating and integrating the structural, metamorphic and tectonic history of the Appalachian orogenic belt.

Thesis Format

The thesis consists of four sections, each written as stand-alone bodies of work with the intention that they will be submitted as papers for publication. The thesis structure aims to provide a logical progression from microstructural to metamorphic interpretations

and the metamorphic history preserved in the porphyroblasts is discussed in terms of the microstructural framework established. The main text of the thesis is in Volume I and figures and tables are presented in Volume II. References are given at the end of each section in Volume I and appendices are included at the end of Volume II.

Section A

The orientation of textural discontinuities in garnets with complex spiral inclusion trails

Textural discontinuities are common within the complex inclusion trails of 'snowball' garnets in southern Vermont and northwestern Massachusetts. Textural discontinuities may be truncations, where an inner foliation is truncated by a younger foliation in the rim of the garnet, commonly at a high angle, or deflection planes, where the inner foliation bends sharply before merging with the outer foliation at a low angle, resembling the differentiated zones of crenulation cleavages. Measurement of over 500 discontinuities in six samples indicates that they are dominantly sub-vertical and sub-horizontal features. This section discusses the formation of textural discontinuities and evaluates how well the observed features are explained by the rotational and non-rotational models for spiral inclusion trail development.

Section B

Foliation Inflection/Intersection Axes in garnet porphyroblasts and the relationship between deformation and garnet growth

The complex inclusion trails preserved in garnet porphyroblasts in this area indicate a history of multiple phases of deformation and garnet growth. **F**oliation **i**nflection/**i**ntersection **a**xes preserved in garnet porphyroblasts (FIAs) show a systematic

change in the direction of principal horizontal bulk shortening across the area through time in the form of a succession of six FIA sets. This section describes the spatial distribution of the different FIA sets and discusses the fundamental controls on garnet growth indicated by the demonstrated heterogeneous and episodic distribution of garnet growth.

Section C

Chemical zoning anomalies in garnet porphyroblasts displaying multiple phases of growth: their formation and relationship to textural discontinuities

Garnet porphyroblasts from the Hoosac Formation in southern Vermont have distinct textural core and rim zones associated with anomalous chemical zoning. The core-rim boundary is marked by a narrow area where there is a spectacular increase in manganese and by changes in calcium and magnesium zoning patterns. This section describes the different styles of zoning anomaly observed in four Hoosac garnets. Using these examples, the role of open versus closed system behaviour in developing the zoning anomalies is evaluated. The relationship between zoning anomalies and the formation of textural discontinuities is also examined.

Section D

Pressure-temperature conditions during garnet growth in southeastern Vermont

P-T pseudosections are an important tool for extracting information about the pressure and temperature conditions of garnet formation. In this section, THERMOCALC is used to produce P-T pseudosections for seven samples of pelitic garnet schist from the Hoosac formation of southeastern Vermont. The mineral assemblages predicted from the modelling are generally in good agreement with the observed mineralogy of the

samples and the pseudosections successfully model the garnet core compositions measured in six out of seven samples. Core compositional isopleths are used to estimate the P-T conditions of initial garnet growth and these results are discussed in relation to the FIA sets preserved in these samples.

References

Armstrong, T. R., Tracy, R. J. & Hames, W. E. 1992. Contrasting styles of Taconian, Eastern Acadian and Western Acadian metamorphism, central and western New England. Journal of Metamorphic Geology 10, 415-426.

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

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

Karabinos, P. 1984. Polymetamorphic garnet zoning from southeastern Vermont. American Journal of Science 284, 1008-1025.

Rosenfeld, J. L. 1968. Garnet rotations due to the major Paleozoic deformations in southeast Vermont. In: Studies in Appalachian Geology (edited by Zen, E., White, W., Hadley, J. B. & Thompson, J. B.). Wiley Interscience, New York, 185-202.

Thompson, A. B., Tracy, R. J., Lyttle, P. T. & Thompson, J. B. 1977. Prograde reaction histories deduced from compositional zonation and mineral inclusions in garnet from the Gassetts Schist, Vermont. American Journal of Science 277, 1152-1167.

Vance, D. & Holland, T. 1993. A detailed isotopic and petrologic study of a single garnet from the Gassetts Schist, Vermont. Contributions to Mineralogy and Petrology 114, 101-118.