Linking Deformation and Metamorphism: Pressure-Temperature-time-deformation Paths through Quantitative Microstructural Analysis and Pseudosections

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ABSTRACT. Pressure-**T**emperature-**t**ime-**d**eformation paths have been modelled using microstructural, petrologic and geochronologic data for schists from southern Vermont, U.S.A. Microstructural evidence obtained from inclusion trail geometry reveals 4 distinct periods of garnet growth preserved in Cambrian through Devonian age schists in southeastern Vermont. These periods of mineral growth are recognised as having inclusion trail spiral axis or **f**oliation **i**ntersection **a**xes with distinct orientations, termed FIA sets 1-4. This regionally consistent succession of four different FIA trends in garnet has been dated by analysing monazite inclusions with an electron microprobe. P-T pseudosections (maps of stable mineral assemblages) were constructed using the program THERMOCALC for two samples that contain garnet porphyroblasts with numerous periods of garnet growth and known FIA succession. Thermobarometric calculations were compared with P-T pseudosections. These samples also preserve inclusion mineralogies that reveal partial mineral assemblages present during early mineral reactions. Pseudosections were calculated in the system MnKFMASH.

Pseudosections calculated in the system MnKFMASH show excellent agreement with mineral reactions observed for these two samples. Chloritoid, chlorite and muscovite remained the stable mineral assemblage to 550°C at medium to high pressure. Ages of monazite inclusions linked to this mineral assemblage suggest that this assemblage grew at or prior to 425 Ma. Garnet growth occurred by the breakdown of chlorite in the presence of chloritoid at ≈ 550°C and 9 kbar for the two samples. Monazite inclusions bracket the timing of the onset of garnet growth between 425 Ma and 405 Ma. The addition of staurolite as inclusions in garnet suggests a more complex early history evolving along an up pressure path originating below 6 kbar. Garnet growth continued along an up-pressure path reaching peak pressure of 13.5 kbar at ≈ 600°C. Garnet growth proceeded at high pressure by the breakdown of chloritoid and chlorite removing both of these phases from the matrix between 405-385 Ma. The peak temperature recorded for these two samples is 610°C at 13.6 kbar. Porphyroblastic staurolite growth began at high pressure around 385-380 Ma prior to rapid decompression. Decompression occurred between 380 and 350 Ma with very little heating indicating that initial uplift was rapid. Monazite ages from garnet rims and matrix mark the end deformation and mineral growth at 350 Ma. Staurolite, garnet rims and overprinting biotite grew along decompression part of the P-T path.

The matrix assemblage prior to porphyroblast growth involved chloritoid (sample V634A) or chloritoid and staurolite (sample V240) developing during NW-SE crustal shortening and subsequent crustal thickening. Garnet porphyroblast growth began in these two samples after a relative shift in the bulk shortening direction to N-S. Further garnet growth occurred during a shift to WSW-ENE shortening that accompanied maximum crustal loading. The final stages of porphyroblast growth as well as matrix microstructures for these samples occurred along a decompression path that records a relative WNW-ESE shortening direction.

INTRODUCTION

New approaches to modelling P-T paths utilizing large internally consistent thermodynamic datasets are becoming increasingly popular (e.g., Vance and Mahar, 1998; Stowell and others 2001). One of the more exciting methods for modelling P-T histories is the construction of P-T pseudosections. These are phase diagrams specific to a fixed bulk composition, which effectively provide a map of stable mineral assemblages in P-T space for a particular rock. They serve as an ideal tool for modelling the early mineral assemblages and reactions in high-grade metamorphic rocks where evidence of this history is commonly obscured. During orogenesis, evidence of older events are generally erased or overprinted by younger ones. Common mechanisms for this are:

1. the formation of new foliations or the reactivation of old ones, or
2. successive prograde or retrograde mineral assemblages forming from pre-existing ones.

Understanding the nature of these changes is essential for understanding the history of early events responsible for the formation of complexly deformed metamorphic belts. In certain settings the early events control what follows, for example, the formation of large-scale folds early during deformation (Hickey and Bell, 2001). Historically, researchers have focused on investigating deformation history and metamorphic evolution for such rocks independently. However, there is a link between metamorphism and the processes that drive progressive deformation at all scales and current research should strive to integrate these two areas. Understanding the processes by which orogenesis proceeds requires knowledge of the paths that rocks take through the crust along with chemical and physical behaviour along these paths. To unravel such paths, structural and metamorphic geologists need to ascertain the history of temperature and pressure changes that accompany metamorphism in direct relationship to the history of deformation that accompanies and has some control over these changes. If the structural and metamorphic paths can be linked and timed, then P-T pseudo-sections provide an ideal means to model the early mineral reactions that accompany progressive foliation development and which are commonly obscured by later deformation and mineral growth.

Porphyroblasts have been used to determine all aspects of the metamorphic and structural development of orogenic belts because they generally retain information about temperature, pressure and deformation history (Tracy, 1982; Spear, 1988; Bell and others, 1998). Garnet is the most widely used mineral for this type of research because it commonly preserves compositional zoning, which can then be used to extract information about the temperature and pressure associated with metamorphism. Additionally, it is common for garnet to contain inclusion trails that reveal early foliation development history that can be erased from the matrix by subsequent deformation. Quantitatively measuring and dating **f**oliation **i**nflection/intersection **a**xes preserved in porphyroblasts (FIAs; Bell and others, 1998; Bell and Welch, 2002) has revealed that this history can be very extensive. The FIAs provide a method for establishing the relative timing of periods of porphyroblast growth, where a single sample commonly preserves more than one episode of porphyroblast growth. This enables a more extensive metamorphic history to be integrated with the structural history that accompanied metamorphism. These events may be linked with the larger scale tectonic history resulting from changes in the directions of bulk shortening that accompany shifts in the directions of relative plate motion.

Several approaches have been utilised for the construction of P-T paths or sections of P-T paths, for example, thermal modelling (England and Thompson, 1984), calculation a series of P-T points using mineral inclusions (St Onge, 1986) and using mineral zoning (Spear and Selverstone, 1983). More recently, large internally consistent datasets have been used to constrain thermobarometric conditions of metamorphic assemblages (Berman, 1988; Holland and Powell, 1994). The advantages of the latter method are (1) that multi-equilibria techniques are used and some assessment of the equilibrium state of a mineral assemblage can be inferred from thermobarometric calculations; (2) These calculations can be compared directly with calculated equilibria that are used to construct P-T pseudosections. The program THERMOCALC is ideally suited to this, as it can be used to calculate equilibria for fixed mineral activities (thermobarometry), as well as calculating mineral equilibria for varying mineral activity (pseudosections).

If the bulk composition of a rock is known then a phase diagram specific to that rock (a pseudosection) can be constructed using the methods introduced by Hensen (1971) and more recently by Powell and others (1998) with expanded chemical system. The construction of P-T pseudosections provides a means to calculate all of the stable assemblages for a given bulk composition or rock. FIA successions can be used to separate periods of porphyroblast growth that are otherwise difficult to identify. P-T pseudosections are an invaluable tool for modelling reaction histories that can be used as a map of mineral equilibria that may be compared directly with microstructural observations. Thermobarometric calculations can then be directly compared to the stability fields for mineral assemblages present in that rock. This paper uses this approach to model P-T-t paths in rocks where the FIAs have previously been determined (Bell and others, 1998) and their ages are known from monazite dating (Bell and Welch, 2002). The microstructural and dating work has been integrated with reaction histories determined from P-T pseudosections to construct P-T-t paths that are consistent with the progressive deformation history and allow us to establish a fully quantified tectono-metamorphic history.

REGIONAL GEOLOGICAL SETTING

The succession of lithotectonic blocks in Vermont (Fig. 1) is the culmination of a prolonged history spanning 700 million years and plays a key role in tectonic reconstructions of the New England Appalachians (Stanley and Ratcliffe, 1985). The stratigraphic succession and the dominant phase of metamorphism generally gets younger from the Precambrian Grenville-affected rocks in the west (Fig. 2), through the Ordovician Taconic Orogeny that affects the Rowe-Hawley Belt to the Devonian Acadian Orogeny which affects the Connecticut Valley Trough rocks to the east. Six major parautochthonous to allochthonous lithotectonic units have been designated based on distinctive sequences that have been recognised within them (Stanley and Ratcliffe, 1985; Ratcliffe and other, 1992). Middle Proterozoic Basement Gneisses of the Green Mountain Massif (1) are unconformably overlain by Cambrian rift and passive margin metasedimentary rocks that bound the eastern edge of the Laurentian margin. Taconic allochthons (2), comprised of a deeper water facies, are in thrust contact with the more shallow water facies of the passive margin. These thrust sheets were emplaced during the Taconian orogeny. East of the Green Mountain Massif lie the Middle Proterozoic allochthonous basement gneisses of the Chester and Athens Domes (3). Late Proterozoic to Early Cambrian Hoosac Formation (4) is comprised of a transitional facies between the Taconic shelf and slope that had developed before the Taconic Orogeny. The nature of the contact between the Hoosac Formation and the underlying basement gneisses remains problematic but likely represents a zone of syn-metamorphic detachment (Ratcliffe, 1997). The Hoosac Formation has been over-thrust by the highly tectonized Cambro-Ordovician Rowe-Hawley Belt (5). The Rowe-Hawley Belt is generally recognised as the Taconic accretionary wedge and is comprised of calcareous, pelitic and semi-pelitic metasedimentary and, mainly mafic, metavolcanic and intrusive rocks of the Rowe-Moretown (or Rowe-Hawley) lithotectonic unit. The youngest of the lithotectonic belts is the thick Siluro-Devonian sequence of the Connecticut Valley Trough (6). These rocks are separated from the Rowe-Hawley belt by an angular unconformity.

In southeastern Vermont three distinct orogenies and accompanying metamorphism have been recognized as the Proterozoic Grenville, Ordovician Taconic and Devonian Acadian orogenies (Stanley and Ratcliffe, 1985; Armstrong and others, 1992). The Taconic Orogeny resulted in the collapse of the Laurentian passive margin with large-scale west-directed thrusting that was terminated with docking of an Ordovician Island Arc. The Acadian Orogeny continued with the closure of the Iapetus Ocean resulting in greatly thickened crust. This orogeny caused extensive folding of the whole Proterozoic to Devonian sequence (Bradley, 1983; Hepburn and others, 1984; Armstrong and others, 1992). Metamorphism associated with the Ordovician Taconian Orogeny dominates to the west of the Green Mountain Massif while the affects of the Acadian Orogeny dominate to the east (Laird and others, 1984; Sutter and others, 1985).

Metamorphic and Structural Setting of SE Vermont

Regionally, a subvertical N-S to SSW-NNE trending crenulation cleavage has formed as the axial plane to the domes and has been termed S_5 after Hayward (1991, 1992). This fabric locally overprints the microscopically and mesoscopically dominant crenulation cleavage, S_4, that transects the axial plane to the Spring Hill synform (Hickey and Bell, 2001). Microscopically, in areas of weaker S_5 development, S_4 has a sub-horizontal attitude and varies in intensity from open crenulations to a fully differentiated foliation that is axial planar to rootless folds in bedding and crenulations of an earlier foliation S_3 (Hickey and Bell, 2001). A sporadically developed sub-horizontal coarsely spaced crenulation, S_6, locally overprints S_5 (Hickey and Bell, 2001). Hayward (1992) argued that at least two additional foliations, which he called S_1 and S_2, are preserved in the porphyroblasts. Bell and others (1998) have demonstrated multiple early foliations are preserved in porphyroblasts and that these range in age from 425Ma to 360Ma (Bell and Welch, 2002). Most large tight folds, like the Spring

Hill Synform (Fig. 3), appear to be pre-date the formation of S_4 (Hickey and Bell, 2001). No folds or foliations of clear Taconic age have been identified in these studies although pre-Silurian lithologies must have undergone some deformation during the Taconian.

Porphyroblasts with well-preserved inclusion trails revealing a protracted deformational history are common. Early studies on the origin of inclusion trail geometries in garnet porphyroblasts from this area (Rosenfeld, 1968) have not been supported by later ones (Hayward, 1992; Bell and others, 1998). The classic 2-stage tectonic model of early nappe development followed by doming for this part of the New England Appalachians is not supported by quantitative data (Ham, 2001; Hickey and Bell, 2001). This requires further refinements to the tectonic interpretations for this area as Bell and others (1998) have identified four distinct periods of garnet growth from microstructural studies and this is supported by absolute age dates (Bell and Welch, 2002).

Several studies have examined the timing of metamorphism in southern Vermont (Sutter and others, 1985; Spear and Harrison, 1989; Vance and Holland, 1993). The first two of these studies produced Ar/Ar ages that indicate thermal peaks associated with the Acadian Orogeny. However, these ages reflect little about the early history. Vance and Holland (1993) used U/Pb and Sm/Nd methods to determine the ages for garnet growth and produced garnet rim ages that are consistent with the timing of Acadian but were unable to establish meaningful ages for garnet cores. Bell and Welch (2002) dated monazite inclusions trapped in garnet in samples with known FIAs (Bell and Hickey, 1997; Bell and others, 1998) in order to establish absolute timing of deformation and garnet growth associated with progressive shifts in relative direction of bulk shortening and potentially plate motion. Monazite populations were separated by microstructural position for garnets with multiple growth events (FIAs) so that ages could be calculated for FIAs. Ages were determined using U-Th-total Pb techniques by microprobe analysis. Monazite grains trapped as inclusions in garnets yielded ages ranging from 431 +/-2 Ma to 349 +/-3 Ma. Monazite ages are interpreted to represent the ages of successively developed foliations that were progressively trapped by episodic porphyroblast growth throughout orogenesis. The succession of 4 FIA sets (and concurrent garnet growth), began forming prior to 424 +/-3, 405 +/-6, 386 +/-6 and 366+/-4 million years ago (Bell and Welch, 2002).

Armstrong and others (1992) produced P-T paths for southern Vermont based solely on peak P-T conditions but did not use inclusion trails or mineral zoning. Vance and Holland (1993) estimated P-T-t paths for the region but did not consider the deformation history. None of these studies utilise inclusion trail geometries or compositional maps of garnet porphyroblasts. Consequently, this paper sets out to integrate the quantitative microstructural analysis and monazite dating with metamorphic studies on the P-T path in order to provide a fully quantified P-T-t-deformation path.

SAMPLES

Samples of metasedimentary, garnet bearing, non-carbonaceous quartz-mica schists and carbonaceous pelitic and semi-pelitic phyllites and schists were taken from a range of Cambrian (Proterozoic?) to Silurian stratigraphic units, mainly the Hoosac, Moretown, Cram Hill, Northfield and Waits River Formations for the microstructural work. From these samples, two high-Al or aluminous pelites (V634A, V240) and one low-Al or sub-aluminous pelite (V436B) were chosen for detailed phase analysis (locations shown in Fig. 1). All contain excellent inclusion trails in porphyroblasts, including some monazite grains, enabling a direct correlation between deformation, absolute time and mineral growth histories.

V634A, a garnet-staurolite schist from the Cram Hill formation, contains garnet porphyroblasts up to 1 cm diameter that are typically surrounded by staurolite (Fig. 4a). The garnet cores and rims can be differentiated by inclusion trail geometry and inclusion mineralogy (see Fig. 4). Cores contain inclusion trails that are dominated by quartz, but chloritoid laths are also abundant as inclusions that are oblique to the internal foliation (Fig. 4c). Chloritoid inclusions were rarely recorded in the rims, but when observed in these locations, they always lie at the core-rim interface. The inclusion trails in the rims are dominated by elongate ilmenite grains. Staurolite porphyroblasts are inter-grown with the outer edges of the garnet rims but rarely trapped as equant inclusions except in the outer portions of the rims. The matrix is dominated by quartz and muscovite with minor ilmenite, biotite and locally abundant apatite.

V240, a garnet-staurolite schist from the Hoosac Fm, contains large garnet porphyroblasts up to 2.5 cm diameter in a matrix dominated by muscovite, staurolite and to a lesser extent quartz (Fig. 5a,b). Staurolite grains in the matrix are generally equant with quartz and ilmenite inclusions and are commonly inter-grown with chlorite and biotite (Fig. 5f). The matrix also contains minor ilmenite and tourmaline. Garnet porphyroblasts preserve a complex growth history revealed by the inclusion trails and the inclusion mineralogy. Garnet cores contain sigmoidal to spiral-shaped inclusion trails that are truncated by orthogonal inclusion trails at the core/rim interface (Fig. 5c). Inclusions of chloritoid, quartz, ilmenite and tourmaline are present throughout the large garnet porphyroblasts. Chloritoid inclusions are abundant in both garnet cores and rims but are absent from the matrix. Staurolite inclusions are abundant in the garnet cores and less so in garnet rims. Rare kyanite inclusions were found in the cores (Fig. 5d) and are absent from the rims and matrix. Chlorite inclusions have only been observed in the garnet rims (Fig. 5e) and chlorite persists in the matrix, often inter-grown with biotite. Paragonite-margarite inter-growths are common in the cores but are not present in the garnet rims. Rare muscovite inclusions have also been identified throughout.

V436B, a graphitic garnet-muscovite schist from the Cram Hill Formation, contains abundant 0.5-1.0 mm diameter euhedral garnet porphyroblasts. In contrast to the previous two samples, this rock has a simple inclusion mineralogy. Inclusion trails in garnet cores are dominated by quartz and inclusions trails in the rims are dominated by graphite (Fig. 6). The matrix contains a strongly developed differentiated crenulation cleavage comprised dominantly of muscovite that has been overgrown by late biotite and chlorite. Garnet rims also contain numerous euhedral bands of graphite.

METHODS

FIAs and Microstructures

The FIA distribution for this region was described by Bell and Hickey (1997) and Bell and others (1998). They argued that multiple foliations accompany the development of each FIA trend and that each trend reflects a period of time over which the direction of bulk shortening accompanying orogenesis remains constant (Bell and others, 1998). Consequently, foliations preserved as inclusion trails in porphyroblasts cannot be readily correlated but FIAs can (Bell and Mares, 1999). They found a sequence of four differently trending FIAs that are regionally consistent oriented successively SW-NE, W-E, NNW-SSE and SSW-NNE as shown in figure 3. For consistency, the same nomenclature as Bell and others (1998) is used here with FIA set 1 through FIA set 4 representing these trends from oldest to youngest respectively.

Microstructural work and accompanying FIA measurements indicate a complex deformation history for the three samples presented here. Line diagrams outlining the interpreted garnet growth events and inclusion train geometries are shown in figures 4b, 5b and 6b. In all three cases, the inclusion trails in garnet cores are truncated by inclusion trails in the rims.

Sample V634A contains FIA set 1 as the axis of the weakly developed crenulated cleavage associated with chloritoid inclusions that lies between the differentiated crenulation cleavage seams preserved as inclusion trails in the garnet core (Fig. 4b). This foliation formed before porphyroblast growth and the differentiated crenulation cleavage seams could have been reactivated during the development of the FIA set 2. The differentiated crenulation cleavage in the core is curved around FIA set 2. The core inclusion trails are truncated by a strongly differentiated crenulation cleavage in the garnet medians (Fig. 4c) that defines FIA set 3. This cleavage is coincident with the last appearance of chloritoid. Garnet rim growth occurred during the development of FIA set 4 seen regionally across Vermont as shown in figure 3. Garnet cores in sample V240 (Fig. 5b) preserve a curved differentiated crenulation. The core inclusion trails are defined by a differentiated crenulation cleavage, which preserves the early crenulated foliation that in turn curves a younger crenulation geometry near the core-rim boundary. The foliations in the cores are dominated by elongate quartz grains and rutile needles. The inclusions in the core have been strongly truncated by a steeply pitching differentiated crenulation cleavage in the rim (Fig. 5c) that formed during the development of FIA set 3. A shallowly pitching foliation that formed against a portion of garnet that grew during development of this FIA set (Fig. 5b). Garnets in this sample do not preserve any evidence of having grown during FIA set 4. Early porphyroblastic staurolite growth commenced during the development of FIA set 3. Crenulations in the matrix and inclusion trails in most staurolite grains define FIA set 4.

A garnet porphyroblast from sample 436B is shown in figure 6a. The garnet core contains a well-preserved early curving foliation defined by elongate quartz inclusions. FIA set 3 is present in the curvature of the core foliation. The core inclusion trails are truncated by complex inclusions trails in the rims that are comprised of graphite. These trails are a mixture of euhedral bands of graphite parallel to the crystal faces and gently curving bands of graphite that crosscut them. In the outer portions of the rims the graphite bands are continuous with matrix foliations. The curving portions of these trails contain FIA set 4.

Compositional Mapping

Numerous episodes of growth have been identified in single garnet porphyroblasts across SE Vermont (Hayward, 1992; Bell and others, 1998). The samples described here are interpreted to have multiple growth events. Compositional maps were collected on the JEOL 840 microprobe at James Cook University, to see how zoning related to episodes of growth and FIA trend changes. Ca, Mg and Mn were analysed using WDS spectrometers and Si, Al Ti, Fe, P, Na, K and Ti using the EDS detector. Porphyroblasts were mapped as 512x512 pixel images with the step or pixel size determined according the size of the area being mapped. Several maps were collected for each sample to be sure that full zoning patterns were obtained. For V240, the large size of the porphyroblasts required several maps to get sufficient resolution. Representative Ca, Mg, Mn and Al maps for the three samples are shown in figures 7-10. Ca, Mg and Mn typically retain the most useful information with regard to growth zoning. In this case, Al maps were particularly useful for identification of inclusion minerals, especially when used in conjunction with the full suite of maps. An understanding of the zoning is vital before point analyses are collected if the data are going to be used for thermobarometric calculations. With complex zoning patterns such as those observed in V240, microprobe analyses can vary significantly over very short distances across a single grain.

Ca, Mg, Mn, and Al maps for V634A (Fig. 7) show zoning patterns that are consistent with garnet growth from prograde reactions (Tracy, 1982). Mn and Ca contents decrease from core to rim and Mg increases. A distinct core and rim are apparent at the change from FIA 2 to FIA 3. The zoning patterns are not continuous around the rim for growth that occurred during FIA set 3 with two distinctive areas of low Ca and Mn with correspondingly high Mg that lie adjacent to quartz rich strain shadows. The transition from FIA set 3 to FIA set 4 is not marked by a composition break. The Al map in figure 7 shows the presence of chloritoid inclusions in the core and the pattern of staurolite and garnet intergrowths at the outer edges of the garnet rims.

As mentioned above, partial maps were collected for sample V240 (Figs 8 and 9). Garnet from V240 shows a more complex zoning pattern than V634A that relates directly to the transition from FIA 2 to FIA 3. The Ca content is high in the cores and low in the rims with Mg being the reverse. In contrast to V634A, the Mn content in

V240 does not show a simple pattern that decreases from core to rim. It is flat to slightly decreasing in the cores over the portion of garnet that records the end of FIA set 2 and then sharply increases at the transition from core to rim when FIA 3 commenced. This high-Mn zone forms a patchy band of variable Mn content, similar to the composition of the cores of the porphyroblasts. A higher resolution map for this band of high Mn content is given in figure 9. This patchy band of Mn always occurs inside the rim microstructures that truncate inclusion trails in the cores. This zone also marks a shift in the composition of the inclusion minerals, most notably chloritoid (see Mg map in Fig. 9). Outside this band both Mn and Ca content drop off sharply. The transition from FIA 3 to FIA 4 in the rim is not marked by any compositional break.

Composition maps from sample V436B are shown in figure 10. Like the previous two samples, compositional maps for this sample show zoning patterns that delineate core-rim structures. The transition from the core to rim is most apparent in the Ca map. Mn content is highest in the cores and decreases outward to the rims. Mn drops very sharply from the core to the core-rim interface where the Mn content remains low to the rims. The behaviour of Mg is the reverse to that Mn with the exception of a slight increase in the cores. A prominent feature in the compositional zoning for this sample is euhedral patterns in Ca maps. The general pattern for Ca zoning is similar to Mn (decreasing from core to rim) with some additional complexity. There is a small patch in the garnet cores with lower Ca. The rims also have several thin bands of Ca enrichment. At the very outer portions of the rims there is a discontinuous band of high Ca where garnet is in contact with matrix muscovite.

Mineral and Bulk Compositions

The bulk compositions of each sample, needed to construct P-T pseudosections, were determined by XRF analysis at the Advanced Analytical Center at James Cook University. Crushed fractions from the same specimens used to make thin-sections were used to ensure that XRF analyses could be compared to the mineral assemblages observed in thin-section. Samples were homogeneous at the scale of a hand sample and were free from any visible alteration such as quartz veins or iron oxide staining. Bulk compositions for the three samples are presented in table 1 along with the bulk composition of average Littleton Formation at amphibolite grade from Shaw (1956) for comparison.

Mineral compositions were determined by electron microprobe analysis on the JEOL 840 microprobe at James Cook University. Analyses were collected by energy dispersive methods using an accelerating potential of 15 kV and a probe current of 10 nA. Standard ZAF corrections were used to determine oxide percentages. Analyses were done in triplicate for each area of interest with the mean values used for all calculations. Inclusion suites were analysed along with surrounding host (garnet) from cores through to rims. Mineral suites or assemblages were analysed for all microstructural positions and compositional domains that could be identified in garnet porphyroblasts. Matrix minerals were analysed in several locations and averages were calculated for use in thermobarometric calculations. Representative probe data are given in tables 2 and 3 for the 2 samples that were analysed in detail and a full set of microprobe data are given in the appendix. For sample V634A chloritoid-garnet pairs were analysed across two porphyroblasts. Staurolite-garnet pairs were measured at the rims and muscovite, biotite and chlorite were analysed in several places in the matrix. V240 contains more complex inclusion mineralogy. Staurolite-chloritoid-garnet pairs were analysed together and where micas were present, they were analysed as well. Sample V436B lacks the appropriate inclusion mineralogy to for P-T path determination.

MONAZITE AGES

A full discussion of monazite age determination is presented in the first chapter of this dissertation. Monazite age distributions for sample V634A were discussed in detail in the second chapter. Monazite age distributions are given in figure 11. Monazite grains were analysed for U, Th, Pb and Y by electron microprobe analysis at the University of Massachusetts. Analyses were done *in-situ* so that ages could be related directly to microstructures. Ages were then determined for individual grains using the Age equation of Montel (1996). For sample V634A, monazite grains were grouped according to microstructural position (core, median, rim, matrix) and then weighted averages were determined for those groups. Four distinct ages were determined at 425 Ma, 405 Ma, 386 Ma and 366 Ma for garnet cores, medians, rims and matrix respectively. V240 does not contain any monazites grains clearly inside garnet cores. One matrix grain, two grains from the garnet rims, and one from a pressure shadow related to garnet cores were analysed. Weighted averages were calculated for grains from garnet rims and the matrix yielding an age of 377 Ma. The grain in the strain shadow yielded an age of 423 Ma.

INTERPRETATION

Thermobarometry

Thermobarometric calculations were done using THERMOCALC V3.21 and the Holland and Powell 1998 dataset with subsequent upgrades. P-T conditions were calculated using the average P-T mode in THERMOCALC following the approach given in Powell and Holland (1994). Activities for mineral end-members were calculated using the AX software written by Tim Holland. Errors on the activities are the result of propagating a standard microprobe error of 1.5 relative percent through the activity models used by the program. Average P-T calculations were done for the full sets of independent reactions for each of the samples where sufficient numbers of end-members were present. The uncertainties in P-T calculations result from the propagation of the uncertainties of the activities of end-members used in the calculations. A full discussion of the error propagation in average P-T calculations using THERMOCALC is given in Powell and Holland (1994). Temperature and Pressure conditions along with associated errors and the end-members used in the calculations are summarised in table 4. All of the data discussed here are presented with 2-sigma confidence levels. The final P-T conditions recorded for each sample were calculated using garnet rim compositions and average compositions for matrix minerals. Core, median and rim P-T conditions that could be directly related to the FIA succession were calculated using inclusion mineral suites with corresponding garnet compositions. A single inclusion of muscovite was analysed for sample V240 and this value was used for calculations involving the garnet core and median. Ideally, the calculations should be made using a full set of inclusions thought to represent an equilibrium assemblage. However, sample V240 does contain a rich inclusion suite. Additionally, given that this is a muscovite rich rock, the muscovite compositions will be somewhat buffered during reactions. In the case of sample V634A, muscovite was not found as an included phase. Muscovite is present in both the differentiated crenulations cleavage in the matrix as well in an earlier crenulation cleavage preserved in the strain shadows around garnet porphyroblasts (see Al X-ray compositional map in Fig. 7). Muscovite composition from the strain shadow was used for the garnet core calculations and an average muscovite composition from the differentiated crenulation cleavage was used for garnet rim calculations.

Sample V634A yielded P-T estimates of 554 ± 27°C and 9.5 ± 3.6 kbar for the earliest stages of garnet growth that accompanied the development of FIA set 2; they were calculated using garnet core compositions with corresponding chloritoid composition. A second calculation using garnet and chloritoid compositions at the edge of the garnet cores that formed later during the development of FIA set 2 yielded 576 ± 26°C and 10.1 ± 3.7 kbar. Estimates for the inner portion of the rim, which formed during FIA set 3, yielded 595 ± 26°C and 11.9 ± 2.9 kbar using compositions for the last appearance of chloritoid and 610 ± 25 °C and 13.6 ± 2.6 kbar for the first appearance of staurolite. Garnet rim compositions along with staurolite, muscovite, chlorite, and biotite compositions from the matrix, which developed during FIA set 4, yielded 580 ±16°C and 5.6 ±2.2 kbar.

Sample V240 contains a larger suite of minerals trapped as inclusions in garnet than V634A. It yielded P-T estimates of 580 ± 11°C and 11.2 ± 1.3 kbar for the core, which developed during FIA set 2. The foliation microstructures in the area of patchy compositional zoning on the outer edge of the core also developed during FIA set 2. However, the patchy zoning could have developed after the microstructure by alteration to chlorite (for example) and then have been replaced by garnet as a prograde reaction continued late in the development of FIA set 2 or possibly early in the development of FIA set 3. The conditions calculated using the high Mn portions in the patchily zoned portion, are 550 ± 15°C and 9.8 ± 2.0 kbar. The inner portions of the garnet rims, where chloritoid is present, developed during FIA set 3 and yielded 584 ± 12°C and 12.8 ± 1.5 kbar. Estimates for the outer rim and matrix, which developed during development of FIA set 4, were done using compositions at the garnet rim/matrix interface and yielded 593 ± 22°C and 6.6 ± 2.6 kbar.

It should be noted that in each of these cases the temperature is more highly constrained than the pressure. The equilibria that were used are typically more sensitive to temperature than pressure. Equilibria involving plagioclase are typically more sensitive to changes in pressure however all the samples discussed here lack plagioclase.

Phase Equilibria- P-T Pseudosections

Petrogenetic grids have long been recognised as important tools for predicting the occurrence of key metamorphic minerals (for example, Hensen, 1971; Spear and Cheney, 1989). However, they can be misleading in that they show all of the univariant reactions for a given chemical system and these reactions may not "seen" by all bulk compositions. P-T pseudosections provide an ideal means for predicting the sequence of mineral assemblages in a given metamorphic rock providing the P-T path is well constrained. Conversely, if the sequence of mineral assemblages is well constrained then a P-T pseudosection should be useful for determining the P-T path for a given rock. Pseudosections are constructed using a fixed bulk composition such that all of the calculated equilibria have full “access” to all the components in the chemical system. An underlying assumption with using P-T pseudosections to model a metamorphic path is that the bulk composition is known and remains constant over the P-T space being considered. It can be assumed that the bulk composition measured by XRF adequately represents the bulk composition of the rock within the chemical system being modelled during the final stages of metamorphism. If P-T pseudosections are to be used to model the early metamorphic reactions then it must be argued that the bulk composition has not changed considerably during metamorphism. Consequently, the effects of shifting bulk composition during metamorphism need to be addressed. Ague (1991) argued that considerable volume loss occurs during progressive metamorphism and is dominated by loss of SiO_2 through the dissolution of quartz. The pseudosections herein were calculated with quartz in excess and hence their topology is not affected by the modal abundance of this phase. Ague (1991) also argued for the relative enrichment of Al_2O_3 and loss of K_2O, Na_2O and CaO. Both of the samples have a relatively high K_2O content and it is unlikely that significant loss of K_2O would have occurred .The pseudosections have also been calculated with an Al_2O_3 corrected for CaO and Na_2O on a one-to-one basis since the alkalis are commonly coupled with Al_2O_3 in mineral phases. The Al_2O_3 values used in the calculations should be considered a minimum value, as some of the CaO would be used in apatite and in the grossular component in garnet. Plagioclase was not observed in any thin sections. Therefore, modelling in an expanded system, which includes CaO and Na_2O for V634A and V436B, was not considered essential for these samples, as garnet is the only phase to incorporate significant amounts of CaO and muscovite is the only Na_2O bearing phase. V240 contains both paragonite and margarite as inclusions in garnet as well as minor paragonite in the matrix. The P-T pseudosections were modelled in the K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (KFMASH) system as well as the MnO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (MnKFMASH) system as MnO has been recognised as expanding the stability fields for garnet (Symmes and Ferry, 1992; Mahar and others, 1997). Al_2O_3 values were corrected by subtracting Al_2O_3 in proportion to $Na_2Al_2O_4$ and $CaAl_2O_4$ molecules for measured Na_2O and CaO values.

Small changes in the bulk composition can have the most significant effects on the topology of a pseudosection when the bulk composition lies on or near the g-chl tie-line on an AFM projection. The Bulk compositions for V240 and V634A are well above this tie-line and the bulk composition of V436B is below. Another consideration is that two of the samples contain chloritoid stable only as inclusions. The removal of these inclusions from the reactive portion of the rock must have some effect on the effective composition at higher grade. However, the modal proportion of inclusions in the whole rock is relatively low. Perhaps the most significant shifts to the effective bulk composition would result from fractionation by garnet growth. Ideally we are interested in modelling the early reactions that the samples would undergo so that the bulk composition of the whole rock should more closely resemble the lower grade equivalent.

All of the Fe is considered to be FeO. The KFMASH petrogenetic grid was calculated using the program THERMOCALC v3.21 and the Holland and Powell 1998 dataset (Fig. 12a). A copy of the datafile used to calculate the grids and MnKFMASH pseudosections is given in the appendix. KFMASH is not ideal in that it does not adequately represent the early garnet forming reactions. The MnKFMASH petrogenetic grid of Mahar (1997) was re-calculated using the most recent data set of Holland and Powell (1998) and is given figure 12a. Figure 12b shows all of the univariant reactions that emanate from the cordierite absent invariant point (B on Fig. 12b). The KFMASH and MnKFMASH grids are shown together as the Mn bearing univariant reactions all terminate at the KFMASH invariant points. For example, the alumino-silicate-absent univariant (reaction 2 in Fig. 12b) in MnKFMASH terminates at the alumino-silicate-absent invariant in KFMASH (location A in Fig. 12b). The pseudosections were constructed by calculating the stable portions of MnKFMASH univariant lines and then calculating the bounding surfaces to the higher variance fields from these lines using the methods of Powell and others (1998). MnKFMASH pseudosections for the three samples are shown in figures 13 to 15. Fields are labelled with stable mineral assemblages with darker shades indicating fields of higher variance. Trivariant and quadravariant fields, shown in light and dark blue respectively, dominate both pseudosections. Divariant assemblages lie to the sides of the stable portions of the univariant reactions and typically occupy very limited space on the pseudosections. Stable portions of the univariant lines are restricted to low pressure with the exception of a short segment of the ctd-ky-chl-st-g univariant stable around 13 kbar at 600°C for V240 (location A in Fig. 14a). In all three samples, the topologies of the low temperature fields (i.e., the garnet producing reactions) are determined by the cluster of divariant fields that emanate from the MnKFMASH invariant point labelled B in figure 12b. No cordierite bearing fields are shown on the pseudosections as cordierite was not found to be stable for the bulk compositions of the analysed samples.

Integration of Mineral Assemblages, Pseudosections, FIA Development and Thermobarometry

A progression of prograde mineral assemblages revealed through petrographic observations for V634A and V240 were used to model P-T paths on their respective pseudosections. The P-T path for sample V436B will not be addressed in detail here because it does not contain sufficient inclusion mineralogy, however the pseudosection is used for comparison. Thermobarometric estimates were used to constrain the evolution of the observed mineral assemblages in the context of the pseudosections and the interpreted P-T paths (Figs. 13b and 14b). Sections of the modelled P-T paths are then correlated with FIA sets, which are derived from inclusion geometries. For the high-Al samples, V240 and V634A, chloritoid is found as inclusions in garnet and was stable prior to garnet growth. For sample V634A, the chloritoid inclusions roughly lie in the hinges of an early crenulation that formed during FIA set 1. For V240, this FIA set has not been recognised. The earliest phases predate garnet growth, which preserved FIA set 2 as the earliest recognisable foliation-producing event.

On the pseudosections, the high-Al samples have a thin divariant field with chl-ctd-g-st (8 in Fig. 13a and Fig. 14a). This field is absent from the pseudosection for V436B (Fig. 15) as it is only stable for bulk compositions above the g-chl tie-line. This field is equivalent to the kyanite-absent univariant on the KFMASH grid in figure 12a. On the low temperature side of this field in figures 13a and 14a there are three different trivariant fields labelled (1) chl-ctd-st, (2) chl-ctd-g, and (3) ctd-g-st. Below 6-7 kbar staurolite becomes stable before garnet (for example, V240) and above 6-7 kbar garnet becomes stable before staurolite (for example, V634A). It is from these relationships that the phase transitions are being modelled.

Sample V634A. Chloritoid grew as porphyroblastic laths in crenulation hinges that define FIA set 1 as this mineral lies oblique to the trails defined by the other inclusions. Figure 16a and 16b compares an example of chloritoid schist from Bell and others (1986) along with an example of a chloritoid lath trapped as an inclusion in the core of V634A. Garnet growth in this sample occurred during FIA set 2 and preserves this earlier fabric. The low temperature part of the pseudosection for V634A is dominated by the chl-ctd field (4 in Fig. 13a). Chlorite is not preserved as an included phase, as would be expected if garnet growth resulted from the breakdown of chlorite rather than chloritoid. Growth of garnet would have involved the breakdown of chlorite as the sample moved across the trivariant g-chl-ctd field (2 in Fig. 13a) to the g-ctd field (5 in Fig. 13a). Modal calculations across this field (2 in Fig. 12a) show that the modal abundance of chloritoid should remain roughly constant while chlorite goes to garnet or that chloritoid is not consumed in the reaction. The P-T point calculated from the garnet core corresponds with the garnet-in line in the presence of chlorite and chloritoid. A second calculation at the outer portion of the garnet core marks the high temperature side of the chl-ctd-g field. Chloritoid became unstable during the period of garnet growth that accompanied the development of FIA set 3 as few chloritoid inclusions are preserved in this portion. However, staurolite began to grow (see Al content map in Fig. 7), possibly during the late stages of development of FIA set 3, and certainly during the development of FIA set 4. This accords well with the pseudosection as chloritoid would have been consumed and staurolite would have grown as the sample crossed the trivariant g-ctd-st field (3 in Fig. 13a) to the quadravariant g-st field (6 in Fig. 13a). This history is best explained by a heating path with increasing pressure as shown in figure 13b. The peak P-T conditions calculated for this sample is 610°C and 13.6 kbar. The point lies outside the predicted field (g-st, 6 Fig. 13a) but the path to this point is realistic as shown by the pseudosection (Fig. 13). The peak pressure is close to being within error of the calculation. The sample then underwent massive decompression to 580 ±16°C and 5.6 ±2.2 kbar in the bi-g-st field (7 in Fig. 13a) with no evidence for any significant heating. The garnet rims equilibrated with small amounts of biotite and chlorite that grew as the final phases. Pressure estimates are not well constrained for this sample as shown by the error ellipses in figure 13b.The trend of the P-T points does however, correspond well with mineral reactions as predicted by the pseudosection.

Sample V240. No chlorite is present in the cores but both staurolite and chloritoid grains are preserved within inclusion trails throughout the garnet, although the amount of staurolite decreases in the rims. Kyanite is rarely preserved as inclusions and then only in the very outer portion of two or three garnet cores from the 10 thin sections examined from this sample. This suggests the rock initially lay in the chl-ctd-st field (1 in Fig. 14a) of the pseudosection. Chloritoid and staurolite remained stable as garnet first began to grow again suggesting that they did not contribute significantly to the garnet producing reaction. This accords very well with the pseudosection and suggests the sample crossed from the chl-ctd-st field (1 in Fig. 14a) to the narrow, highly elongate chl-ctd-st-g field (8 in Fig. 14a), progressing along an up-pressure path to the ctd-st-g-ky field (5 in Fig. 14a) as chlorite was consumed. The P-T conditions calculated for the garnet cores lie in the chl-ctd-g field (2 in Fig. 14a) out of error range but not that far from conditions suggested by the ctd-st-g-ky field on the pseudosection (5 in Fig. 14b). This may suggest that the kyanite grew as a metastable phase, or that the chemistry has been slightly altered by later events. The outer portion of the core has been modified by the addition of Mn (Figs. 8 and 9) post growth. This is revealed by the patchy distribution of high Mn. The pattern strongly suggests alteration such as chloritization of the rim and then regrowth of garnet with the high Mn patches being the remains of chlorite. Possible explanations for this phenomenon are presented in the discussion. Thermobarometric estimates for this high-Mn zone are shifted to significantly lower P-T conditions (550°C and 10 kbar). However, garnet in the rim as close as possible to the high Mn core rim is back up to the high temperatures and pressures of 565.6 +/-12 C and 13.6 +/- 1.4 kbar. These conditions are in close agreement with the starting point of the P-T path for the previous sample. These peak pressure conditions, which occurred during FIA set 3, are similar in timing of development and value to V634A.

Garnet rim growth is marked by lower modal proportion of staurolite. Significantly, the remains of staurolite present just outside edge of the core tend to be elongate parallel to the remnants of the core foliation. This progressive loss of staurolite can be readily explained using the pseudosection by migration of the sample across the ctd-g-st field (3 in Fig. 14a) to the chl-ctd-g field (2 in Fig.14a). This is supported by the fact that chlorite, which is never preserved in the core, appears in the rim. The garnet rims formed during FIA set 3. Staurolite porphyroblasts also grew during FIA set 4, either interpenetrating the outer rim of the garnet, or individuals in the matrix. The Mn zoning returns to normal in the rim and combined with the disappearance and then regrowth of staurolite suggests that the sample was again moving across the pseudosection through the ctd-g-st field (3 in Fig. 14a) to the chl-ctd-g-st field (8 in Fig. 14a) and finally the chl-st-g field (6 in Fig. 14a) in the matrix where chloritoid is not present. P-T calculations for the rim (Fig. 14b) are shifted to slightly lower temperature than the predicted stability field of ctd-g-st-ky (3) but close to the range indicated by the ellipse in figure 13b.

A decompression path originating from the g-ctd-st-ky divariant field (5 in Fig. 14a) produces the observed assemblages from the outer garnet core/rim interface through to the matrix. This path crosses from the chl-g-st field (6 in Fig. 14a) to the bi-g-st field (7 in Fig. 14a). Along this path the modal proportion of biotite increases at the expense of staurolite. Textural evidence for this reaction is shown by biotite rims around staurolite (Fig. 5f), which is a common feature in thin-section of this sample. Thermobarometry suggests a greater range in P-T than the microstructural succession and pseudosection requires, but a similar path (Fig. 14b). These estimates are not exhaustive of all the preserved P-T conditions but are used to try to constrain a P-T path along with the pseudosection.

Sample V436B Sub-aluminous pelites such as V436B tend not to develop early mineral assemblages that can be trapped and remain stable as inclusions. As such, the early reactions history of these samples is often not obvious. The pseudosection for V436B has been included to show the difference in the pseudosection topology (Fig. 15) between such rocks and the more aluminous ones shown in figures 13a and 14a.

DISCUSSION

Microstructures and Mineral Zoning

Several stages of garnet growth have been recognised in the rocks mantling the Chester and Athens Domes. Microstructural work done by Bell and others (1998) indicates at least four periods of garnet growth have occurred in the Chester and Athens Dome area and that another older period is present to the north in central Vermont (Ham, 2001). A notable feature in the two samples discussed in detail here is the sharp change in inclusion trail geometry at the garnet core/rim interface indicated in figures 4 to 6. In both cases, the inclusion trails in the garnet rims truncate the trails in the cores. Such truncations suggest a hiatus in garnet growth. These geometries are the result of deformation that is partitioned around the porphyroblasts, and which controls the growth of garnet (Spiess and Bell, 1996). If the development of successive foliations does not involve a significant shift in P-T space then it would not be expected that any record of this would be present in the compositional zoning patterns that spatially correlate with microstructural truncations; zoning should remain smooth. However, the FIAs record periods of foliation development in response to ongoing deformation. There can be a significant shift in P-T conditions (position in the crust) during the time that FIAs develop regionally. If garnet growth occurred during the development of FIA set 1 and then did not re-occur until the development of FIA set 3 or 4, due to partitioning of the deformation away from those rocks, and there was a significant shift in P-T space during this period, then it would expect that there should be a significant change in compositional zoning across the boundary between the periods of growth bounding that break.

Garnet zoning patterns for V634A are consistent with two stages of garnet growth although the zoning patterns are overall continuous. Garnet cores have prograde zoning patterns with Mn content highest in the cores decreasing out to the rims. There are no sharp inflections in composition to suggest that there was a hiatus in garnet growth. Garnet porphyroblasts in V240 have more complex zoning. One feature that has been observed only in samples from the Hoosac Fm is a band of Mn enrichment at the core/rim interface. A high-resolution compositional map for a section of the core/rim interface is shown in figure 9. The area inside the microstructural truncation has the highest Mn content of the entire garnet. The high-Mn garnet does not form a euhedral shaped band but rather is comprised of patchy zones that anastomose around zones of low-Mn garnet. This pattern is interpreted to represent a garnet resorption event that postdates the garnet cores but must predate the formation of the garnet rims. In this case there must have been a second garnet growth event. The high-Mn garnet must have grown before the foliation trapped in the garnet rims formed. The rim microstructures would have formed as a foliation that was strongly partitioned around the new porphyroblasts. Thermobarometry for this resorption zone yields significantly lower temperatures than either the garnet cores or rims. These P-T conditions are outside the garnet stability field on figure 14a, which is consistent with early garnet breakdown.

The Anomalous Mn Content in Garnet

The "Gassetts" Schist, sometimes referred to as the Cavendish member of the Hoosac formation, has provided a cause celebre for metamorphic researchers for many decades (Thompson and others, 1976; 1977), initially because of the unusual preservation of a range of minerals as inclusions in garnet porphyroblasts, and more recently because of recognition of the complex zoning patterns including spessartine rich garnets that have overgrown garnets with lower spessartine content (e.g. Karabinos 1988). The high Mn band is commonly on the edge of the cores of garnet porphyroblasts present but the anomalous patchiness described herein is only locally present about the Chester and Athens Domes. Other samples from the Hoosac Schist collected some distance from the Chester and Athens domes (unpublished data from the Rayponda-Sadawga Domes, see Fig. 2) show the Mn excursion but the patterns are euhedral rather than patchy. Samples V634A and V240 show much of the same structural and reaction history and lie just 7 kms apart almost along strike from one another on the western limb of the Chester-Athens dome (Fig. 1). However, V240 comes from the "Gassetts" Schist and lies close to the gneissic basement that cores the domes and contains what appears to be a spectacular P-T path diversion that is not present in V634A. Yet in terms of the matrix foliations and structural location around the dome these rocks have undergone a very similar structural history. How is this apparent P-T path diversion possible? As mentioned above, the Mn increase on the core rim occurs in "Gassetts" schist samples that are located close to the contact with basement gneiss within different domes. The microstructural position of the Mn excursion occurs towards the end of the development of FIA set 2 and before the development of FIA set 3. No other lithologies containing garnet that developed during FIA set 2 show evidence for this Mn excursion. V240 does contain staurolite inclusions in the core that have a high Mn content (see table 3). Staurolite breaks down outside the core of the garnets and the release of Mn would shift the effective bulk composition. This possibility has been dismissed because the modal abundance of staurolite is low and some samples that contain this feature did not appear to have had staurolite as an early phase. This pattern of patchy growth in some areas and euhedral banding in others must have resulted from Mn addition to the bulk composition. To our knowledge, this feature has only been observed in "Gassetts" schist lying close to underlying gneiss within the domes.

Tectonic Significance of the Mn Excursion

All portions of the "Gassetts" schist that have recognised as containing this high Mn excursion, after growth of the garnet core, lie adjacent to the contact between the basement and cover sequence which has been interpreted as major zone of syn-metamorphic detachment (Ratcliffe and others, 1985). A tectonic scenario that would explain all of our observations is granite emplacement along this shear zone during the development of FIA set 2. Numerous Acadian granites crosscut the regional foliations and are largely interpreted to postdate major deformation (Ratcliffe, 2000) and are likely too young to have affected garnet cores. However, this feature is most easily explained as forming from fluids emanating from and moving ahead of granites along the shear zone between basement and cover sequences. This event must have post-dated growth of garnet cores which is interpreted to have formed early during the Acadian.

Integration of Metamorphic and Structural Approaches

Foliation intersection axes preserved within porphyroblasts, or FIAs, provide a geological tool that allows the complete integration of metamorphic, structural, geochronologic and tectonic research. When used in conjunction with P-T pseudosections and monazite geochronology they become particularly invaluable because:

1. They develop over a period of time during which the direction of bulk shortening within an orogen remains constant and their trend should be related in some direct manner to the relative directions of plate motion that caused orogenesis (Bell and others, 1995),
2. They allow structural time control, as they can be correlated from sample to sample as well as regionally (Bell and others 1998).
3. They record structural and metamorphic information that is directly linked through the inclusion trail and porphyroblast compositions as well compositional zoning within the latter minerals, as shown herein,
4. They allow access to an extended P-T path in a rock that can be directly linked to structural motions through the inclusion trail asymmetry.

The results reported herein attempt to fully link a metamorphic history with a structural history where an extended history of metamorphism and deformation lasting some 70 million years is preserved within the porphyroblasts that predate the matrix foliations. A summary of our tectonic interpretation, which utilizes FIAs, detailed P-T paths derived from pseudosections, and monazite geochronology is given in figure 17. The P-T paths constructed here are believed to accurately represent the thermobarometric evolution of the region and can be used to constrain the timing of mineral reactions and shifts in the direction of bulk shortening.

1) The earliest metamorphic mineral growth that has been recognised are the chloritoid grains trapped as inclusions that grew in a crenulation cleavage during FIA set 1 in sample V634A. This early crenulation cleavage resulted from NW-SE shortening post-dating the major deformation of the Taconic Orogeny. Clear microstructural evidence for mineral growth during FIA set 1 in V240 is lacking but monazite ages would suggest that the timing of the growth of the inclusion minerals is similar. Monazite grains trapped in these early foliations in V634A yielded an age of 425 Ma that is interpreted to represent the age of those early foliations. A single monazite inside the garnet rim in V240 yielded an age of 423 Ma, suggesting the timing is the same for the two samples. P-T estimates for the earliest recorded mineral growth during FIA set 2 places this region at a minimum of 9 kbar and 550°C. These thermobarometric conditions suggest that these rocks remained at depth following the Taconic orogeny as this pre-dates major Acadian collision. Although both samples contain garnets that grew during the development of FIA set 2, the P-T conditions calculated for the onset of growth are different. Inherent to the concept of FIAs is that they occur over a period of time and we should expect that growth during a single FIA could occur along a section of the P-T path rather than at a point. A further complication is that in this case V240 contains an extended history that is interpreted to have occurred during FIA set 2. If the history of V240 is considered from the position of the resorption front onward the P-T paths are in good agreement.

2-4) If these rocks remained at depth following the Taconian orogeny, continuing collision with the onset of the Acadian orogeny would have resulted in a greatly over-thickened crust. In this model there was continued crustal thickening from FIA set 2 to 3 reaching a maximum pressure of 13-14 kbar during FIA set 3. Monazite ages from the core of V634A place this peak pressure at between 405- 380 Ma. This crustal thickening would have occurred during the transition form predominantly N-S shortening to WSW-ENE- directed shortening in the transition from FIA set 2 to FIA set 3. These pressure estimates are thought to reflect the peak of crustal thickening for the region and not necessarily the thermal peak. However, maximum temperature estimate at peak pressure is 610°C, which is consistent with thermal maximum for staurolite grade rocks from the region (Armstrong and Tracy, 2000; Vance and Holland, 1993). It has been argued that the loading responsible for the peak of pressure in the region resulted from early nappe stage (Rosenfeld, 1968; Thompson and others, 1968). The peak pressures calculated here are thought to be inconsistent with nappe style deformation. A conservative estimate of 10 kbar as peak pressure would require □ 30 km of over-thrust material and perhaps locally as much as 40 km. Current stratigraphy cannot account for an overburden of that thickness. This is further complicated by pressure estimates approaching 10 kbar in the Siluro-Devonian sequence that is stratigraphically and structurally above the Chester and Athens Domes (Spear and other, 2002). The excess pressure is interpreted to be the result of homogeneous crustal thickening and perhaps partial subduction of the entire sequence in eastern Vermont leading up to 380 Ma.

5-6) This greatly over-thickened crust would have become unstable following 380 Ma resulting in rapid initial uplift rates (Hames, 1989). There is no evidence to suggest that there was considerable heating during decompression. Peak temperatures for the region do not exceed 650°C. Although there must have been continued mineral growth, as garnet rims for these samples grew at this time, as did the majority of staurolite, this was not due to significant heating but rather decompression with only minor heating. In fact, these samples show final re-equilibration temperatures (□ 590°C) lower that the peak temperatures that have been reported. This requires that heat must have been added to the crust for reaction to proceed but not enough to produce regional crustal heating. The decompression path coincided with a shift in the direction of bulk shortening from ENE-WSW to ESE-WNW. The majority of matrix microstructures that have been preserved would have formed at this time along with the growth of staurolite and locally biotite. Additionally, garnet rims for V634A would have grown during decompression as these all preserve FIA set 4. Monazite ages from matrix and garnet rims indicate that metamorphism and mineral growth continued to 350 Ma. These data suggest that total duration for the decompression from □13 kbar to □ 6 kbar would have lasted 30 m.y. This equates to approximately 20 km of unroofing over a 30 m.y. period. This relatively rapid rate of unroofing is consistent with rates predicted by Hames (1989) for similar tectonic block in southern New England. It is also likely that the initial unroofing may have been significantly faster as longer residence time at depth would produce a P-T path with heating during decompression.

In the examples presented here, the pseudosections accurately represent the early garnet producing reactions. In the case the system MnKFMASH is suited to model high-Al pelites. This system fall short in that it cannot be used to evaluate the phase relations of grossular component of garnet with plagioclase and Na-Ca micas, which are often essential for thermobarometry (Tinkham and others, 2001). However, the large number of phases preserved in these samples allows for robust estimates of temperature and pressure. Used in conjunction with microstructures and thermobarometry a detailed P-T-deformation can be established. Regardless of the system that is used the pseudosection will always provide a useful method for modelling the garnet-in reactions.

What still remains unclear from this work is that the majority of the FIAs that have been recognised by Bell and others (1998) occur quite late in the FIA succession. If our model in correct, then it would be expected that the majority of garnet growth would occur as part of the decompression path. Regardless of the bulk composition, the garnet-in reactions must be considerably over stepped or garnet was continuously growing and dissolving during the early part of this path. This is something that will require continued study if all of the microstructural and growth modelling are going to be resolved in such a way that they are consistent within tectonic models.

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