# Episodic Deformation and Metamorphism in Southeastern Vermont: New Age Constraints from Electron Microprobe and SHRIMP Analysis of Monazite Inclusions in Garnet.

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**ABSTRACT.** Five samples of garnet bearing pelitic schist from southeastern Vermont that contain monazite inclusions in garnet were examined in detail using major and trace element compositional maps in conjunction with U-Th-Pb microprobe dating. Two of these samples were further analyzed using a SHRIMP to check for consistency between isotopic ages and those determined using the electron microprobe. Monazite grains trapped as inclusions in garnet as well as grains in the matrix were analyzed for all of the samples. Compositional mapping of monazite grains and *in-situ* microprobe analyses reveal complex compositional zoning patterns that cannot be easily explained by a single monazite producing reaction. Most of the monazite grains that were analyzed preserve distinct compositional domains. Rims of monazite grains commonly have overgrowth textures revealed through Y and Th rich cores and U rich rims and in most cases these compositionally distinct domains yield different ages.

U-Th-Pb age distributions show that monazite growth and subsequent metamorphism occurred over a period at least 80 m.y from 430 Ma to 350 Ma. Every sample was found to have monazite grains with statistically distinct ages. Individual samples were found to contain distinct populations when monazite grains were grouped by microstructural positions: garnet core, garnet median, garnet rim, or matrix. A single sample yielded ages of 424 ± 2.4 Ma, 405 ± 6.0 Ma, 386 ± 6.0 Ma, 366 ± 3.8 for monazite populations analysed in the cores, medians, and rims of garnet porphyroblasts and matrix respectively. SHRIMP analyses for this sample provided inconclusive results because monazite grains were smaller than the analytical area. A second sample produced consistent results of 377 ± 4.0 by electron microprobe and 381.1 ± 3.8 by SHRIMP. Weighted averages calculated from electron microprobe ages of monazite populations for all of the samples clustered around 425 Ma, 405, Ma, 387 Ma, 377, Ma and 365 Ma and 350 Ma.

All of the examined samples contain garnet porphyroblasts that exhibit polyphase growth histories. Distinct stages of garnet growth are in part defined by truncations in inclusion trails trapped within garnet porphyroblasts. The inclusion trails commonly occur as near orthogonal sets and are interpreted to represent discrete foliations that form during ongoing deformation. The age distributions calculated from these samples are taken to represent a best estimate of the timing of deformation and accompanying mineral growth for southeastern Vermont. The nature of the zoning in monazite grains, the microstructural relationships in garnet porphyroblasts and the distribution of ages above shows that Acadian metamorphism and deformation in southeastern Vermont was both protracted and episodic.

## INTRODUCTION

Establishing an absolute time frame for geologic events is fundamentally important to understanding the processes that take place during orogenesis. The rates and timing of orogen scale processes such as collision and exhumation as well as micro-scale processes such as material transport, re-crystallization and deformation at the scale of a thin-section must be constrained before meaningful tectonic models can be constructed. This can only be achieved if the results of geochronologic studies can be linked directly to the observations used to produce those tectonic models. The development of new techniques in geochronology that focus on doing analyses *in-situ* have arisen in response to this need because these methods enable textural information that is crucial to structural and metamorphic studies to be retained. One such technique that utilizes the electron microprobe for age determination has produced a new wave of approaches to geochronology in metamorphic rocks (Suzuki and others, 1994: Montel and others, 1996; Crowley and Ghent, 1999; Williams and others, 1999, 2002). This technique of quantitative age determination has developed around the ability to precisely date monazite grains in thin-sections by analyzing U, Th and Pb content with the electron microprobe. The microprobe method lacks the analytical precision that can be obtained through isotopic studies, but this technique allows analyses to be done *in-situ* at a very small scale (grains smaller than 20 µm) such that textural information is retained. The ability to perform analyses *in-situ* makes it ideally suited to studies of rocks with polygenetic histories where petrographic information is critical. Currently the microprobe remains the only instrument capable of dating grains or parts of grains less than 10 µm as well as the only one that is non-destructive.

Geochronologic studies that utilize the electron microprobe are also developing around the electron microprobe's ability to quickly and effectively collect compositional maps. Not only is it possible to obtain age information from single grains, but it is also becoming apparent that numerous age/compositional domains can be retained in single monazite crystals (William and others, 1999). Although analytical uncertainties for this method may be large compared with standard isotope dilution methods, much of the geologic uncertainty can be removed by knowing the textural relationships of the grains being dated. It has also been well documented that monazite grains in metamorphic rocks commonly retain compositional zoning and that this zoning can be the result of a series of overgrowths of progressively younger ages (Crowley and Ghent, 1999; Williams and others, 1999). Through careful compositional mapping the errors associated with analysis of mixtures can be avoided and can lead to better understanding of complicated age histories

Several studies (e.g. Montel and others 1996; Williams and others, 1999) have shown the electron microprobe method to be a valuable tool for quickly differentiating between tectonic events of significantly different age. These studies have also shown that this method is ideal for use as a reconnaissance tool for finding events/ages that have not previously been recognized. Although the application is best suited to older terrains (Precambrian) where analyses are simplified by higher concentrations of Pb in monazite, it has been used effectively in Paleozoic terrains (Montel and others, 2000).

This paper reports the results of monazite geochronology obtained through electron microprobe analysis on a series of polymetamorphic and polydeformed schists from the New England Appalachians. The New England Appalachians represent the culmination of four major collision events and one major rifting event that generally get younger from west to east: Grenville (~1100-1000 Ma), rifting of Laurentia (~800-575 Ma), Taconic (~480-440), Acadian (~415-380) and Alleghenian (~300-275) (Hatcher, 1989). This study focuses on an area in southeastern Vermont where the effects of Grenville, Taconic, and Acadian orogenies have all been recognized (Sutter and others 1985). The electron microprobe method of dating has an analytical uncertainty such that it could be used to differentiate between the major tectonic events seen in the New England Appalachians. The purpose of this study was to try to establish the age or ages of metamorphism and deformation that affected this area at the scale of these major tectonic events, Taconian vs. Acadian. Given that garnet porphyroblasts from the region commonly contain unconformities (Rosenfeld, 1968) or microstructural truncations, this study also sets out to test the application of the electron microprobe dating method on Paleozoic samples that preserve complex histories.

## GEOLOGIC SETTING AND PREVIOUS STUDIES

Middle Proterozoic basement gneisses of the Chester and Athens Domes are unconformably overlain by a series of lithotectonic blocks ranging from the Late Proterozoic to the Devonian (Stanley and Ratcliffe, 1985; Ratcliffe and others, 1992). Directly overlying Proterozoic gneisses are pelitic schists and marbles of the Late Proterozoic to early Cambrian Hoosac formation. These rocks were over-thrust by a sequence of Cambrian to Middle Ordovician calcareous, pelitic and semi-pelitic metasedimentary and, mainly mafic, metavolcanic and intrusive rocks of the Rowe-Moretown (or Rowe-Hawley) lithotectonic unit (Fig. 1). The youngest lithotectonic unit in southeast Vermont is the thick Siluro-Devonian sequence of the Connecticut Valley Trough, separated from the Cambro-Ordovician rocks to the west by an angular unconformity (Ratcliffe, 1993, 1995a,b; Ratcliffe and Armstrong, 1995).

In southeastern Vermont, three distinct periods of deformation and metamorphism have been recognised as the Proterozoic Grenville, Ordovician Taconic and Devonian Acadian orogenies (Stanley and Ratcliffe, 1985; Armstrong and others, 1992). The effects of the Grenville orogeny are limited to gneisses that form the cores of Chester and Athens Domes and the Green Mountain Massif. Taconian metamorphism dominates the area to the west of the Green Mountain Massif while the affects of the Acadian predominate to the east. The Taconian Orogeny resulted from a series of west directed thrusts and accretion of a Cambro-Ordovician sequence with closing of the Iapetus Ocean and docking of an Ordovician island arc system. The Acadian Orogeny involved the closure of the Siluro-Devonian basin comprising the Connecticut Valley Trough (Fig. 1 of preface). This orogeny caused extensive folding of the whole Proterozoic to Devonian sequence (Bradley, 1983; Hepburn and others. 1984; Armstrong and others, 1992; Ratcliffe and others, 1992; Ratcliffe, 1995a, b; Ratcliffe and Armstrong, 1995). Metamorphism was the result crustal thickening with little or no magmatic heating that has been interpreted to have peaked in the rocks surrounding the domes during the Acadian (Armstrong and others, 1992; Ratcliffe and others, 1992). Thermobarometry done in conjunction with this study shows that peak temperatures reached 680°C for the region around the Chester and Athens Domes and that peak pressures were are as high as 14kbar.

Schists from southeastern Vermont commonly contain porphyroblasts that have spectacular microstructures preserved as inclusion trails. This area in SE Vermont has been the subject of several classic studies in metamorphic petrology as well as microstructural geology (e.g. Thompson and others, 1977). Early studies on garnet porphyroblasts done by Rosenfeld (1968) from this area have spawned continuous debate on the origin and nature of curved inclusion trails trapped in porphyroblasts. Microstructures preserved in garnet reveal an extensive deformation and metamorphic history regardless of the interpretations of their origins. An extended deformation history has been preserved in inclusion trails in garnet porphyroblasts in Cambrian through Devonian age schists from southeastern Vermont. At least four distinct episodes of garnet growth have been identified using axes of curvature of inclusions trail in porphyroblasts or **f**oliation **i**ntersection **a**xes (FIAs; Bell and others, 1998). These microstructural studies were used to develop a model involving regionally consistent periods of mineral growth termed FIA sets 0 through 4. Although the relative timing of porphyroblast growth has been established, the absolute timing of these events remained unclear. The presence of a set of microstructurally distinct mineral growth episodes further indicates the need for continued geochronologic studies in the region.

## BACKGROUND

Monazite is nominally a light rare earth element phosphate [(LREE)$PO_4$] with Ce and La as the dominant REEs. Because it typically incorporates significant concentrations of Th and U but excludes Pb during crystallization, it has been recognised as an important mineral for geochronologic studies (Parrish, 1990). Monazite is a relatively common accessory mineral in peraluminous granitic rocks as well as quartzitic, semi-pelitic and pelitic metamorphic rocks of lower amphibolite through granulite facies and as such, it has been used extensively for determining crystallization ages in plutonic rocks as well as used to constrain ages of metamorphism (Parrish, 1990). It has also been recognised as an authigenic mineral (Evans and Zalasieewicz, 1996). Although numerous recent studies (e.g., Smith and Barreiro, 1990: Lanzirotti and Hanson, 1996: Crowley and Ghent, 1999, Williams and others, 1999: and Foster and others 2000) have focused on using monazite to constrain the ages of metamorphism, the metamorphic phase relations of monazite are still not well understood. Smith and Barreiro (1990) and Ferry (2000) argued that detrital monazite breaks down to form allanite at lower greenschist facies. They argue that with increasing metamorphism, allanite becomes unstable with respect to monazite at or near the conditions suitable to grow staurolite. In contrast, Suzuki and others (1994) show that detrital monazite can remain stable up through granulite facies metamorphism. Although the mechanisms for monazite growth during metamorphism remain unclear, dating of monazite is still of significant importance for determining ages of metamorphism where these monazite grains can be shown to have grown during metamorphism.

There are several assumptions implicit to age determination using the electron microprobe. Firstly, it is assumed that as monazite crystallizes it does not incorporate any Pb such that all of the Pb that is present in a crystal is the result of radiogenic decay of U and Th. This assumption cannot be easily tested using the microprobe and generally requires isotopic analysis. However, it has been shown through numerous studies that the common Pb content of monazite is usually negligible (Parish, 1990). Secondly, it is assumed that inter-crystalline diffusion for U, Th, and Pb is sufficiently low that these elements are effectively immobile at the scale of the area being analysed. Monazite has been shown to have a closure temperature as high as 750°C, which would make Pb loss during amphibolite facies metamorphism minimal. In polymetamorphic terrains, where diffusional Pb loss may be a concern, high-resolution compositional X-ray maps or age maps can be used to test this assumption. Inheritance of relic grains has been recognised in monazite but it is thought to be far less common than in zircon (Parish, 1990). Recent studies have shown that metamorphic monazite can preserve inherited cores (Williams and others, 1999). Problems with inheritance can also be addressed by collecting compositional maps. The analysis volume of the microprobe is sufficiently small that included earlier grains can easily be identified, which in part makes this method extremely powerful.

The electron microprobe method has proven to be a viable technique by dating monazite grains of known age (Williams and others, 1999; Montel and others, 1996). Perhaps more significant than the fact that it has been shown to be a reliable inexpensive exploration tool for geochronologic studies, it has been used to precisely date geologic events that were previously unrecognized using isotope dilution techniques (Cocherie and others, 1998). Comparisons of the ages obtained with other methods such as SHRIMP and TIMS have shown excellent agreement in rocks as young as 300 Ma. The analyses described herein were obtained from the laboratory of M.L. Williams at the University of Massachusetts. Williams and others (1999) provide a comparison of monazite grains dated by this and other techniques.

## METHODS

### *Petrography*

Perhaps the most important aspect of geochronologic studies of this type is a full understanding of the textural and spatial relationships of the monazite grains being dated. This study focuses primarily on monazite grains trapped as inclusions in garnet, although monazite grains located in the matrix of each sample were dated as well. Monazite inclusions in garnet were used so that ages could be linked directly with microstructures preserved in garnet porphyroblasts. Garnet porphyroblasts from this area commonly retain evidence of multiple stages of growth. This is often exhibited as a change in the mineralogy of inclusions, density of the number of inclusions trapped, or through changing orientation of fabrics developed as inclusion trails in porphyroblasts. The spatial relationship of monazite grains located within these inclusion trails is important because the microstructures have been used to establish a pattern of relative timing of mineral growth for this region (see Bell and Hickey, 1997; Bell and others, 1998).

Although monazite is considered to be a common accessory phase in pelitic rocks, its occurrence is not ubiquitous. In all of the examined samples, monazite was much more likely to be found as a matrix phase than as an inclusion in garnet. For this reason, at least two polished sections were prepared for selected samples to ensure that numerous garnet grains would be present. Although monazite can be identified optically, it is difficult to locate as an inclusion in garnet because grains are generally small and monazite and garnet have similar indices of refraction. Figure 2 shows an example of two relatively large monazite grains trapped as inclusions in a garnet porphyroblast. All of the garnet porphyroblasts present in a thin section were checked for monazite inclusions by backscattered-electron (BSE) imaging and then grains were spot checked by qualitative energy-dispersive spectrometer (EDS) scans. Approximately 30 samples were examined and, from these, five samples were chosen for analysis that contained abundant monazite inclusions in garnet. These samples were also chosen because they contained the microstructural elements used to define the four FIA sets of Bell and others (1998). Four of the samples are pelitic and quartz-rich schists from the Cram Hill Formation on the east limb of the Spring Hill synform: V634A, V436A, V436B and V653 (Fig. 1). The other sample, V240, is from a high-Al pelitic schist of the Hoosac formation taken from the west limb of the Athens Dome (Fig. 1).

*Sample* ***V634A*** contains garnet porphyroblasts up to 1 cm in a matrix of muscovite, quartz, staurolite, and minor biotite. The cores of garnet porphyroblasts contain abundant chloritoid laths that are oblique to inclusion trails (Fig. 3). Chloritoid is absent from garnet rims and matrix. Garnet rims are interpenetrated with staurolite grains at the garnet edges. The staurolite grains are always connected to the matrix such that they are not completely armoured by garnet. Staurolite also occurs as a porphyroblastic phase throughout the matrix, often growing along foliations. Garnet porphyroblasts contain well-defined inclusion trails that are dominated by quartz in the core and ilmenite in the rims (Fig. 3). Monazite grains are abundant both as inclusions and throughout the matrix with grain sizes typically less than 25 $\mu$m (Fig. 3). Elongate grains also tend to lie parallel to surrounding inclusion trails or matrix foliations.

*Sample* ***V436A*** is a quartz-rich schist with garnet porphyroblasts up to 3 mm across in a matrix of quartz and muscovite with minor biotite. Plagioclase is rare but does occur locally as porphyroblasts overgrowing the matrix. Inclusions within garnet porphyroblasts are dominated by quartz in the core and ilmenite in the rim (Figs. 4d and 4e). Garnet porphyroblasts show evidence of at least two stages of growth (Fig. 4d). Garnet cores are generally equant to rounded and are overgrown by elongate garnet stringers that follow along muscovite seams in the matrix (Fig. 4). Monazite grains are present in garnet cores, rims and throughout the matrix and range in size from less 20 $\mu$m to as large as 50 $\mu$m.

*Sample* ***V436B*** is a muscovite garnet schist with numerous garnet porphyroblasts up to 1 mm across in a matrix dominated by muscovite and also containing biotite, quartz and late chlorite. Garnet porphyroblasts are equant with inclusion trails in the cores dominated by quartz and inclusion trails in the rims dominated by graphite (Fig. 5a). Garnet rims may also contain numerous thin euhedral bands of graphite that are aligned parallel to crystal faces. Monazite is less abundant in this sample than those previously described and was found only as inclusions in garnet rims as well as throughout the matrix. No monazite grains were identified that could be unequivocally linked to garnet cores. Monazite grains are typically elongate with maximum length of 25 $\mu$m (Fig. 5c).

*Sample* ***V653*** is a quartz-rich schist with garnet porphyroblasts up to 2 mm across in quartz-rich matrix that also contains muscovite and minor biotite. In more qurtz-rich layers, staurolite, chloritoid and chlorite are present and are commonly inter-grown. Garnet porphyroblasts are rounded to subhedral with inclusion trails that consist of coarse-grained quartz (Fig. 6). Monazite is present as inclusions only in garnet rims and as grains in the matrix. Inclusions of monazite were typically less than 30 $\mu$m with larger grains up to 80 $\mu$m identified in the matrix (Figs. 6c and 6d).

*Sample* ***V240*** is a muscovite, garnet, staurolite schist with very large garnet porphyroblasts in a matrix dominated by muscovite. Matrix phases also include porphyroblastic staurolite, paragonite, biotite, chlorite, ilmenite and quartz. Garnet porphyroblasts are large, up to 3 cm across, and have inclusions of chloritoid, staurolite, margarite-paragonite intergrowths, rutile, ilmenite and rare kyanite. Chloritoid, margarite and kyanite have not been observed in the matrix. Quartz inclusions are much less common than the previously described samples except in areas of early strain shadows that have been overgrown by garnet (Figs. 7a and 7c). Garnet porphyroblasts have a complex growth history revealed through their internal microstructures with sigmoidal inclusion trails in the cores that are truncated by inclusion trails in the rims. Monazite inclusions are abundant in the garnet rims and throughout the matrix (Figs. 7b and 7e) but no monazite inclusions were found in the garnet cores. One grain, Mz3, lies within the quartz-rich strain shadow of a large porphyroblast core that has been overgrown by a second generation of garnet (Figs. 7c and 7d). Monazite grains in this sample are larger than monazite grains all of the other samples with grains up to 100 $\mu$m.

Monazite grains are typically anhedral and may be elongate in all of the examined samples. Although monazite grains tend to have irregular shapes, inclusions have smooth surfaces and are typically completely armoured by garnet and do not have any other phases trapped along with them (e.g. Fig. 2 and Fig. 7b). In some cases, cracks leading from the matrix to monazite inclusions are present (e.g. Fig. 5c). Although the timing of these cracks is uncertain, there is no petrographic evidence to suggest that monazite inclusions have been altered post-entrapment. Matrix monazite grains tend to be similar in shape and size to those found as inclusions for every sample except V240. For samples V436A, V436B, V634A and V653, matrix monazite grains have smooth surfaces regardless of the mineral phases that surround them. In sample V240, both matrix monazites and hose trapped as inclusions are of comparable size, but matrix grains are always rimmed by a symplectite of apatite and allanite and have irregular surfaces (Figs. 7f and 8b).

### *Monazite Compositional Mapping*

X-ray intensity maps, which illustrate relative changes in mineral composition, were collected for all of the monazite grains that were to be used for age determination. Compositional maps of monazite were collected to check for chemical heterogeneities. This is a vital step in preparing for point analysis so that chemical domains that might reflect multiple growth events can be identified. Compositional maps were collected using the JEOL 840A electron microprobe in the Advanced Analytical Center at James Cook University, the Cameca SX-50 at Dept of Geology at the University of Massachusetts, and with the JEOL JXA-8100 at the JEOL Application and Research Center in Tokyo. Most of the analyzed grains were mapped for Y, U, Th and Pb. X-ray compositional maps of Y, Th, and U commonly show zoning patterns, whereas Pb maps did not reveal zoning that could be detected above background. The JEOL 840A at James Cook University is limited in that it is only equipped with three wavelength-dispersive spectrometers so Pb maps were collected for a few grains from each sample but not all. Compositional maps were collected as beam scans with wavelength-dispersive spectrometers set for elements of interest. Beam scans were considered more suitable for mapping small areas as the smallest step size available for stage scans was 1 µm. Maps were collected using a sample current of 100 or 200 nA and an accelerating voltage of 15 or 20kV with count times of 100 milli-seconds. Maps were generally collected as 128x128 analyses/pixels for small grains (less than 25 µm) or 256x256 for larger grains (greater that 25 µm). Representative examples of monazite compositional maps for each of the dated sample are given in figures 9 through 12. One further set of maps was collected at the JEOL Research Center after analyses for age determination were completed. A monazite grain from sample V436A with complex zoning for Y, Th and U (Fig. 10) was mapped using multiple channels for Pb to improve counting statistics. Figure 14 shows the full set of maps for V436A-Mz12 at the JEOL research lab.

### *Major and Trace Element Analysis*

Analyses used for age determination were collected on the Cameca SX-50 microprobe at the University of Massachusetts following the methods described in Williams and others (1999). First, compositional maps are examined for chemical heterogeneities. If distinct chemical domains are present, these domains are treated as separate grains during analysis. Once chemical domains were identified, major element analyses were collected for several monazite grains per sample. The distinction between major and trace elements as discussed here is based on the analytical scheme that was used for analysis rather than on absolute concentrations. Some confusion arises as Th and Y are included in both sets of analyses and as such, discussions of major and trace element data refer to the different datasets rather than implying anything about concentrations of elements. Major element analyses were collected using a sample current of 15 nA with an accelerating voltage of 15 kV counting for 20 seconds per element. Table 1 contains representative major element analyses for each sample. Once major element compositions were known, U, Th, Pb and Y concentrations used for age determination were measured using the trace element analytical scheme. A representative major element composition was entered into the Cameca trace-element analysis routine for each sample before trace element analyses were collected. Trace element analyses were collected with a beam current of 200 nA and an accelerating potential of 15 kV and using long count times, 900 secs/analysis, in order to improve counting statistics for Pb. The general analytical set-up for both major and trace element point analyses is given in appendix 1. A representative set of trace element analyses that were used for age determination is given in table 2 and the full set trace element data is provided in appendix 2. Analytical errors derived from counting statistics are provided in both tables at the 1-sigma level of confidence. Several analyses were collected for each grain or each compositional domain within a monazite grain. Attempts were made to obtain at least three analyses (5 where possible) per domain or grain so that an average age for each grain or domain could be calculated. This was not always possible for small grains or those with complex zoning. Grain edges were avoided and every effort was made to analyse the centers of each domain so that averaging of compositions could be avoided during analysis. This can also be further complicated by the nature of monazite surfaces in standard polished thin-sections. Only areas with exceptionally flat surfaces can be used for quantitative analysis. For grains that are less than 15 µm, there is usually very little area with sufficient surface to analyse. After thhe grains were analysed, BSE images were collected to check the exact positions of the points analysed to ensure that analyses were not collected on uneven surfaces, cracks or grain edges.

### *SHRIMP Analysis*

Several studies (e.g., Montel and others 1996; Williams and other, 1999) have shown that the U-Th total Pb method for age determination yields results that are consistent with conventional geochronologic methods. There are, however, assumptions implicit to this method that need to be addressed such as incorporation of common Pb during monazite growth and the possibility that the U-Th-Pb systematics have been altered since monazite growth. SHRIMP analyses were obtained for several grains that were analysed with the electron microprobe to check for age consistency as well as to test these assumptions. The analyses were carried out at the SHRIMP facility at Curtin University in Western Australia. From the five samples that were analysed by electron microprobe, two were selected for SHRIMP analysis: Samples V240 and V634A. V240 was chosen because it contained monazite grains large enough that they could be analysed numerous times. V634A was chosen for SHRIMP analysis because it contained a broad range of ages as discussed below. A total of 14 analyses on 5 grains were obtained for V240 and one analysis per grain on 6 grains for V634A. Full results from the SHRIMP analyses are presented in table 3. The SHRIMP analyses were collected from the same thin-sections that were used for microprobe analysis. The monazite grains that were analysed in V240 were easily large enough to accommodate several analyses per grain (Figs. 8a and 8b). Monazite grains in sample V634A are small and unfortunately, the beam size was slightly larger than the grains that were being analysed (Fig. 8c). This resulted in partial contamination by garnet for all of the analyses from this sample.

## RESULTS and INTERPRETATIONS

### *Monazite Chemistry and Compositional Zoning*

Monazite compositions are dominated by LREE, particularly Ce, La and Nd, and to a lesser extent Sm and Pr. The LREE content is generally consistent across all of the analyzed samples: $Ce_2O_3$ content ranges from 28-33 wt.%, $La_2O_3$ from 10-16 wt.%, $Nd_2O_3$ from 11-15 wt.%, $Pr_2O_3$ from 2.8-3.6 wt.% and SmO from 1.5-3.0 wt.%. $Gd_2O_3$ content is more variable with content ranging from 1-8 wt.%. Monazite compositions are highly variable with respect to U, Th and Y, both within individual samples as well as between samples. Y concentrations varied from 0-13,000 ppm, U from 300-26,000 ppm and Th from 12,000-55,000 ppm across all of the samples analyzed. Variation in U, Th and Pb content is of particular interest because these elements used for age determination.

The distribution and zoning patterns are significant in that monazite is thought to control distribution of the LREE whereas garnet is thought to be dominant in controlling the HREE distribution (Zhu and O'Nions, 1999). Compositional maps for the LREEs were not been collected and as such, any complexity in the zoning patterns for these elements were not observed. Ultimately we are interested in using monazite ages to further constrain the growth of other minerals, particularly garnet. Within individual samples, Y and U content varies by orders of magnitude, e.g. V436A. Y content varies from 0-11,800 ppm and U content varies from 2600-26,000 ppm. Even within individual monazite grains the compositions can vary considerably. For monazite grain V634A-Mz4, the Y concentration varies from  10,000 ppm in monazite core to  4000 ppm in the monazite rim (see Fig. 9 and table 2). Large relative shifts in Y such as this are thought to be linked to the timing of monazite growth relative to garnet (Lanzirotti and Hanson, 1996). High Y domains may have grown prior to garnet and the monazite rim grew after garnet growth began. Because single grains can show high variability for these elements, it is essential to use compositional maps in conjunction with point analysis (Williams and others 1999).

Most of the compositional maps of monazite show zoning patterns in at least one element, with many showing intricate zoning patterns for all three elements (Y, Th, and U). It would be expected that if monazite growth occurs in response to the breakdown of allanite, as suggested by Ferry (2000), at a fixed position in P-T space, then monazite grains should not exhibit complex zoning patterns. The zoning patterns for some of the grains presented here (e.g. V634 Mz4 in Fig. 9) suggest that monazite growth may occur in stages in response to a series of reactions or as a discontinuous reaction within an evolving chemical system throughout the metamorphic evolution. V634A-Mz4 has a core that can be distinguished by relatively high Y and a rim with high Th and U. In this case, there is a distinct boundary between core and rim, which suggests that little post growth diffusion has taken place especially given the small size of this monazite grain (15 μm wide). Several other grains show the same type of pattern: V436-Mz10, V436A-Mz11 and V653-Mz3 (Figs. 10 and 11). For several of these grains there is an inverse correlation between Y and U (e.g. Fig. 9, 10 and 11) however, this is not always the case. The zoning patterns are further complicated such that the Th content does not show a systematic correlation to either of the other elements. These observations suggest that monazite growth does not occur as a single reaction but rather as a series of reactions. A monazite grain from the garnet rim of sample 436A (Fig. 10) shows more complicated zoning that is inconsistent with a simple overgrowth mechanism. These patterns are more easily explained by monazite grains being partially dissolved and recrystallised. In this grain, there is an inter-fingering pattern between high-U and high-Y monazites. It is argued that the high-Y portion of the grain is older and has been partially dissolved and then later infilled with the high-U monazite.

Pb concentrations are typically less than 1500 ppm for all of the analyses. Detection limits for Pb are approximately an order of magnitude less than that (~ 250 ppm). The Pb maps clearly show the Pb concentration above background for monazite grains but did not show any zoning patterns. This observation in itself is important in that it indicates that Pb diffusion toward the grain margins was not observed. A series of trace element maps collected at the JEOL research center were used to further examine the possibility of Pb diffusion. Figure 14 shows high-resolution maps for V436A-Mz12. This grain illustrates the complex zoning patterns for U, Th, and Y as discussed above.

The Y and U content are antithetic to one another as has been observed in numerous grains. The Th content is patchy with the exception of a small area of high Th labelled on the Th map in figure 14. Areas of high Pb correspond directly with the area of high U and Th, which suggests that Pb is derived locally and remains largely immobile.

It should also be noted that compositional maps and to a certain extent the point analyses are a reflection of the area that has been sectioned. This is perhaps accentuated by the relatively small size of the grains being mapped as it is less likely that a true center cut was obtained. This is not particularly important for mapping because the maps are largely used as a guide for point analyses. If the monazite cores tend to reflect older domains then off-center cuts may have the affect of artificially shifting the general age distribution towards younger ages.

### *Microprobe Age Determination and Uncertainties*

Electron microprobe ages were determined using the U-Th-total Pb techniques outlined in Montel (1996) and Williams and others (1999). Ages for individual analyses were determined using the age equation of Montel (1996). Absolute concentrations of U, Th and Pb in ppm are used and the equation is solved by iteration. Several analyses were made on each monazite grain or each compositional domain within a grain. For monazite grains containing distinct composition domains, such as those discussed above, each compositional domain was treated as separate grain in terms of age determination and error analysis. A mean age and standard error of the mean was calculated for each grain or compositional domain. The monazite ages for all of the analysed grains are given in table 4 with associated errors given at the 1-sigma confidence level.

It is important to note that the calculated precisions presented here are based solely on standard errors resulting from the mean ages of monazite populations and do not consider the errors associated with analytical uncertainty. The analytical error associated with each point analysis is largely a function of the counting statistics for Pb especially for Palaeozoic samples such as these. Estimates of analytical errors range from 5-10 my for Pb rich samples (>2000 ppm) to 10-30 my for monazite with lower Pb content (Williams and Jercinovic, 2002). It is expected that the true analytical errors on the analyses presented here will fall within the latter range. Long counting times (900 secs/analysis) were used to try to reduce these errors. In addition, as stated above, numerous analyses were collected for each monazite grain or compositional domain so that estimates of uncertainty could be evaluated for populations rather than single analyses.

A normal distribution probability curve was calculated for the mean age and standard deviation of the mean for each monazite grain. For each sample, a set of curves was plotted (Figs. 15a through 15e) with each of the small curves (non filled curves) representing a single monazite grain. A total probability curve was then calculated for each sample to see if clusters of ages could be seen within the accumulated data,. This plot is simply the sum of all of the smaller curves and does not include the greyed curves mentioned below. These curves are not particularly useful in terms of relating true probability although they do show clusters of age distribution that may be used as a first approximation to correlate ages between samples.

Monazite grains were separated according to microstructural position, that is, whether they lie in the core, median or rim of a garnet porphyroblast, or in the matrix. Ages determined for single monazite grains and the associated errors were then used to calculated weighted averages for each sample. These weighted average ages were calculated at the 2-sigma level of confidence for all the monazite grains separated according to their microstructural position. The weighted averages are interpreted to represent the best-fit ages to a population of monazites within a sample. Weighted averages are plotted on the graphs as the gray shaded curves in figures 15a through 15e. In the discussion below the distinction is made between individual monazite ages and weighted averages. Individual monazite ages are the mean ages calculated for a single monazite grain where the ages reported for samples are the weighted averages calculated from populations within those samples. A probability curve was then plotted for the entire dataset (Fig. 17), first from all of the single monazite data, and then from the weighted averages for comparison. This was done to see if different monazite populations, and thus different garnet growth events, could be correlated from sample to sample.

### *Microprobe and SHRIMP Monazite Ages*

Individual monazite microprobe ages from all five analyzed samples range from 309 Ma to 432 Ma (see Fig. 17 and table 4). All of the samples show a range of ages as indicated by the total probability curves for each sample (Figs. 15a through 15e). The total probability curves (dark curves in Fig.15) should represent the statistical estimate of the full range of ages preserved in each sample whereas peaks in these curves give an indication of clusters of data. In each case, the monazite populations were separated by microstructural position and then ages were calculated for monazite populations. All of the single monazite ages discussed below are at the 1-sigma level of confidence and the weighted averages are calculated at the 2-sigma level of confidence.

For **V634A,** four distinct ages were calculated using monazite inclusions from garnet cores, medians, rims and the matrix at 424 ± 2.4 Ma, 405 ± 6.0, 386 ± 6.0 and 366 ± 3.8 respectively. Two monazite grains from this sample, Mz37 and Mz38 (see Fig. 3a), are grouped as with inclusions from garnet cores. These two grains lie outside the garnet cores in a stain shadow that is interpreted to have formed at the same time as the garnet cores. These strain shadows also preserve an early crenulation cleavage that is orthogonal to the matrix foliation (Fig. 3a). As mentioned above, monazite grains were grouped according to microstructural position and these two grains, although outside the garnet cores, lie in the same foliation as the other grains in the garnet cores. The weighted averages given above (plotted as grey curves in Fig. 15a) are statistically distinct. As a first approximation, these data alone, taken along with total probability curve for this sample, suggest an episodic nature to the geologic event that is being dated. These ages are interpreted here to represent the ages of foliation development that predate the garnet that overgrowths them. The garnet cores are interpreted to have grown after 424 Ma and before 405 Ma, the garnet median between 405 Ma and 386 Ma, and so forth. Inclusion trails in garnet porphyroblasts from this sample are orthogonal at the core-rim interface (Fig. 3a), which suggests that there should be a gap in time between the growth of garnet cores, medians, and rims. This spacing in the age distributions is not surprising given the nature of the microstructural geometry for this sample. SHRIMP ages for this sample are problematic. All of the SHRIMP analyses for this sample are partly contaminated by surrounding garnet and as such, a large common Pb correction is required for all of the analyses. The data for monazite grain Mz30 has been discarded because of a very large common Pb correction. SHRIMP ages range from 357 ± 7 Ma to 387 ± 6 Ma. There is no correlation in the trend of ages between these two methods. V634A-Mz22 yielded a microprobe age of 431 Ma and a SHRIMP age of 362 Ma. A weighted average calculated from the population of SHRIMP ages for this sample yielded an age of 374 ± 15. The 207/206 ages for this sample have very large errors as well, so these ages should be viewed with caution.

Sample **V436A** yielded two distinctive ages at 391 ± 7.2 and 368 ± 6.1 for core and rim respectively. Again, the garnet porphyroblasts have distinct core and rim with orthogonal inclusion trails and these populations are interpreted to represent distinct events. It should also be noted that the total probability curve for this sample does not show any obvious peaks that could represent unique events across the spectrum of ages.

Samples **V436B** and **V653** did not contain any monazite inclusions that could be unequivocally linked to microstructures in garnet cores. Monazite inclusions in the garnet rims are common (Figs. 5 and 6). These samples yielded ages calculated for rim monazite populations at 352 ± 5.8 Ma and 350.1 ± 5.0 Ma respectively. These two populations should be considered equivalent in age. Both samples contained anomalously older grains in the garnet rims. V436B contained a grain in the garnet rims Mz2 dated at 416 ± 7 Ma that is considered to be distinct from the rest of the population. Similarly an age of 369 ± 4.0 Ma was calculated for a portion of the monazite grain Mz1 (Fig. 6) for V653 that is also considered to be distinct. This monazite is zoned with the older age coming from the high Y portion of the grain.

As in the two previously discussed samples, **V240** does not contain any grains that clearly lie in the garnet cores. Two grains from the garnet rim and one matrix grain yielded an average age of 377 ± 5.6. Monazite Mz3 (Figs. 7c and 7d), which lies in a strain shadow that is interpreted to have formed around the garnet core, yielded an older age than the rim grains at 423 ± 8.0 Ma. This grain is also chemically distinct with Y content nearly an order of magnitude higher than the other grains from this sample. Garnets are typically enriched in Y and HREE (Hickmott and others, 1987; Spear and Pyle, 2002), which should lead to a depletion of these elements in the matrix. It would be expected that monazite grains that grew prior to garnet would be relatively enriched in Y compared with those that grew at the same time or later (Zhu and O'nions, 1999; Foster and others, 2000). This sample contains a very high modal abundance of garnet with a complicated history (see Ch. 3 of this dissertation). Monazite Mz3 lies in a strain shadow of a garnet core, suggesting that it predates or grew simultaneously with the garnet core and has been shielded from later deformation and dissolution because of its microstructural position. SHRIMP analyses were collected for the same grains analyzed by electron microprobe for this sample. The data for this sample are tightly clustered around concordia (Fig. 16a) and appear to represent a single population including monazite Mz3 with an age of 381 ± 4 Ma. This age is in excellent agreement with electron microprobe age of 377 ± 5.6 Ma from above as well as with the age of 377.8 ± 3.4 Ma from Vance and Holland (1993) for garnet rims from the same lithology (Cambrian Gassetts Schist). The SHRIMP data also suggest that these monazite grains did not undergo any significant Pb loss and that common Pb was not a factor. This should suggest that these are ideally suited to age determination using the microprobe techniques. However, the SHRIMP data do throw into question the older microprobe age for monazite Mz3. The SHRIMP age reported here was calculated as a weighted average of all analyses for this sample as they were could not be statistically separated into distinct populations. The isotopic data for monazite Mz3 is the result of a single analysis on this grain. This grain contains chemical zoning occurring at a finer scale (Fig. 13) than the beam size used for the SHRIMP analysis which may further complicate age determination. These data confirm that garnet growth postdates or is coeval with monazite growth at 380 Ma for this sample but the microprobe ages further show that older events may have been preserved as well. Given the complex nature of the garnet zoning and microstructures for this sample it is also likely that metamorphism and possibly garnet growth extended back to 425 Ma.

### *Total Microprobe Dataset*

A plot of the full set of monazite ages with the total probability curve that was generated from that data is given figure 17. As stated above, the total probability curves alone can be misleading. Although there are obvious peaks in the total probability curve, these data could be viewed as representing a spread of ages spanning from 310 Ma to 430 Ma. A separate total probability curve was generated using only the weighted averages shown in figure 17b. The grayed curves represent the weighted averages for each of the samples with the sum of the curves drawn over the top. When the data are viewed in this way, clear peaks in the age distribution that are equivalent in both sets of curves are evident.  These peaks on both curves occur at approximately 426, 402, 387, 368 and 350 Ma, and are interpreted to represent the monazite populations with distinct ages. It is also important to consider that the populations coincide with garnet growth events differentiated by microstructural observation. When weighted averages are viewed individually they appear as a punctuated event, however, it should be considered that individual ages span the duration of the total curves. Statistically the single ages are less powerful but still need to be considered as potentially geologically valid.

## DISCUSSION and CONCLUSION

### *Monazite Growth History in Relation to Metamorphism*

Although it is widely recognised that monazite occurs as a metamorphic mineral, the mechanism by which monazite appears in metamorphic rocks is not fully understood. Knowledge of the monazite producing reactions is crucial to a full understanding of the temporal history that can be derived by dating monazite. The monazite producing reactions are generally considered to involve the breakdown of allanite and a phosphate, either apatite or xenotime, to produce monazite (Smith and Barreiro, 1990; Ferry 2000).

It has been proposed that this reaction coincides with the staurolite isograd at low pressure (Smith and Barreiro, 1990) or the kyanite isograd at high pressure (Ferry, 2000). A simple one-stage reaction cannot adequately explain the nature of monazite behaviour in the examples presented here. The age and spatial distribution of monazite in schists from southeastern Vermont suggests that monazite-producing reaction or reactions can occur over an extended time-frame and at a variety of P-T conditions. Many monazite grains retain distinct compositional domains and in some cases these domains yielded different ages. This observation suggests that monazite growth cannot have occurred as a single reaction at a single time. This is not to say that it cannot be the same reaction occurring over a period of time. The monazite producing reaction likely involves the breakdown of other accessory phases, e.g. allanite and xenotime, which may well be trapped as inclusions in other minerals. It seems likely that access to these reacting phases may depend on the breakdown of the occluding phases through time.

Monazite is preserved as inclusions in garnet cores, garnet rims and throughout the matrix and have yielded ages spanning > 100 m.y. This study focused specifically on samples with monazite grains trapped as inclusions with the intention that this would reveal the most extensive history. The data presented here may not adequately represent the general habit of monazite in pelites but they clearly show that monazite growth can occur early in the metamorphic reaction history. Sample V634A has monazite inclusions in the garnet cores that are interpreted to have formed in an early foliation along with chloritoid (Fig. 3b). This sample preserves grains that yielded ages ranging from □ 430 Ma to □ 360 Ma (see Fig. 15a). The mechanism by which monazite first grows in these samples remains unclear. Allanite was not recognised in any of the samples except for V240 where it appears to be the result of monazite breakdown (Fig. 8b). It is significant that the first appearance of monazite does not appear to be linked to a single reaction occurring as a more or less instantaneous event in all of the samples but rather as one that occurs over an extended period. These proposed reactions do not consider the possible effects of bulk composition on the position of those reactions in P-T space or the stability of minerals involved in those reactions.

X-ray compositional maps of monazite from these samples show zoning patterns that suggest multiple growth stages of growth preserved within single grains. Numerous monazite grains have chemically distinct cores and rim overgrowths that yielded different ages: V634A-Mz4 (Fig. 8), V436A-Mz10 and Mz11 (Fig. 10)**,** and V653-Mz3 (Fig. 11). V634-Mz4 has a high Y core that yielded an age of 418 Ma and a high U rim with an age 387 Ma. Once monazite became stable in these samples it continued to grow in an episodic manner. In some cases, the compositional zoning reflects a more complicated history than core and rim overgrowths. V436A-Mz12 (Fig. 14) is from the rim of the same garnet porphyroblast as V436A-Mz10. The zoning patterns for these two grains are distinct. Monazite grain Mz10 is interpreted to have a distinct core and rim, where Mz12 contains a small zone of high Th that is now rimmed by a grain with more complex zoning. The rim overgrowth is comprised of interpenetrating areas of high Y and high U. Although these are compositionally distinct, they are analytically indistinguishable in age. This texture is interpreted to represent a partial dissolution and then later regrowth and although they record the same age there may be a hiatus between these two events that is smaller that the analytical uncertainty.

The appearance of monazite early in these samples along with the nature of the zoning preserved is clear evidence that monazite did not grow from a single reaction. Several studies (e.g. Lanzirotti and Hanson, 1996) have suggested that there is a relationship between the relative Y content of monazite and the timing of growth relative to garnet. Monazite cores tended to be higher in Y and where distinct ages could be determined, they were older. However, sample V634A has a large number of monazite trapped in garnet cores and rims and no clear correlation between microstructural position and Y content could be established.

### *Age Distribution*

The age distribution presented in figures 15 and 17 suggests that metamorphism began prior to 425 Ma and may have continued to 320 Ma. Complexity in the full dataset further shows that a single age representing the peak of metamorphism inadequately describes the orogenic evolution of the region. This study attempted to constrain the timing of deformation and metamorphism within times scale of the orogen using the electron microprobe technique for dating monazite. Previous studies have reported that the peak of the Acadian Orogeny in Vermont occurred at approximately 380 Ma (Laird and others 1984; and Sutter and others, 1985). Individual monazite ages may well reflect the timing of growth of those grains. Given that individual grains may have large errors, greater than 10 m.y., these ages can be difficult to interpret on a grain-by-grain basis. The weighted averages, which are calculated from populations of grains in a petrographic context are much more meaningful. This is highlighted by the correspondence of peaks between the two graphs presented in figure 17. The peaks of these curves represent periods of metamorphic mineral growth at 426 Ma, 402 Ma, 387 Ma, 368 Ma and 350 Ma. These results are largely based on populations of monazite grains trapped as inclusions in garnet. Garnet growth must have commenced after 425 Ma and continued through to 350 Ma. A series of garnet growth episodes are interpreted to have occurred prior to 387 Ma, 368 and 350 Ma. These ages suggests that garnet growth occurred as punctuated events. The monazite ages alone do not provide sufficient data to conclude that metamorphic mineral growth and deformation must have episodic especially given the limited number of monazite inclusion that were analysed. However, the ages presented here are taken from samples that contain porphyroblasts with unconformities in the form of microstructural truncations (e.g. Figs. 4d and 5a). In addition, the microstructural truncations are often marked by changes in the mineralogy of included phases. As these unconformities in themselves mark a hiatus in metamorphic mineral growth then the monazite ages give an indication of the time-span of these breaks. Although this suggests punctuated mineral growth, there must also have been some continuity between these events as the monazite ages do show a spread across these peaks.

As was discussed above the SHRIMP ages for v634a are problematic because the analyses are all partly contaminated by garnet. The SHRIMP age for V240 is in excellent agreement with the microprobe ages for three of the grains dated with the microprobe: V240-Mz1, V240-Mz2, and V240-Mz7. The SHRIMP age determined for that sample was 381 Ma and the microprobe data yielded a weighted average of 377 Ma (Fig. 15e). An older age of 423 Ma was obtained for V240-Mz3 using the microprobe method. A single SHRIMP analysis was collected for this grain and was included in the SHRIMP age determination. Although this grain has a slightly older $^{206}Pb/^{238}U$ age (390 Ma) than the rest of the population, it is not considered statistically distinct and so included with the rest of the data used to calculate an age on concordia. The microprobe age should be considered valid given that he grain lies in a strain shadow inside the garnet rim (Fig. 7c) and has a Y content that is an order of magnitude higher that the rest of the monazite population for this sample. It should also be noted that the $^{208}Pb/^{232}Th$ are systematically younger than the U/Pb reported in table 3. This is interpreted as an analytical problem requiring further exploration.

### *Age of Orogenesis (Acadian vs. Taconian)*

Peak metamorphic conditions around the Chester and Athens domes have been considered Acadian by most researchers (e.g. Spear and Harrison 1989; Armstrong and others 1992; Vance and Holland, 1993; Bell and others, 1998). Vance and Holland dated the growth of garnet rims from the Gassetts Schist at approximately 380 Ma. This age is in close agreement with $^{39}Ar/^{40}Ar$ plateau ages from hornblende from the core of the Chester Dome presented by Spear and Harrison (1989). A spectrum of ages determined by electron microprobe dating of monazite inclusions in the samples presented here is shown in figure 17. The age data presented above are consistent with electron microprobe ages for monazite grains from garnet rims for V634A, V240 and core data from V436A. The data presented here support the interpretation that there was widespread mineral growth at this time (380 Ma) and this age may correspond to the thermal maximum for this region. Microprobe ages suggest that metamorphism began as early as 430 Ma. Numerous grains from garnet cores of V634A reveal ages of 424 and 405 Ma (see table 4). A monazite grain trapped in the strain shadow of the garnet core for V240 yielded an age of 423 Ma. Although the monazite ages cannot be used to directly determine the ages of garnet growth, they have been useful for bracketing the ages of mineral growth and deformation. These data would suggest that the growth of garnet cores occurred at 425 Ma or earlier.

Re-interpretations of the duration of the orogenic events affecting New England have recently emerged. Ratcliffe and others (1998) argued that the age for the end of the

Taconian might have been as late as 445 Ma. Spear and Harrison (1989) documented Ar/Ar ages as old as 440 to the east of the Green Mountain Massif and have interpreted these to be partially reset Taconian ages. Other workers in the similar lithotectonic blocks in Quebec have also argued that the Acadian Orogeny extended back to the Silurian (Cawood, 1994). The Acadian Orogeny is considered Devonian based on the recognition of Acadian structures and mineral assemblages in the Siluro-Devonian stratigraphy in southeastern Vermont (Fig. 1). Bell and others (1998) suggest that the bulk of deformation and mineral growth must have occurred during the Acadian as oldest microstructures they observed (FIA set 1) occurred in rocks that are assigned a Devonian age. Monazite ages from garnet cores of V634A that extend back to 432 Ma suggest that metamorphism may have begun as early as the earliest Silurian. These data show that further geochronologic studies are needed for the New England Appalachians to reconcile the timing of metamorphism across the full stratigraphic section currently exposed. It is expected that continued examination of monazite geochronology in this region will produce a further spread of ages associated with both the Taconian and Acadian orogenies. Further tectonic models should not consider these as separate events but rather a continuous orogenesis with punctuated periods of mineral growth during episodes of deformation.

The possibility that the older monazite grains are relics remains a possibility. However, given the current age assignments for the stratigraphic succession this is not likely. The stratigraphic age of the samples is considered to be Ordovician and the oldest ages that have been measured are from the earliest Silurian. However, there is the possibility that these ages may represent partial resetting, as there is no reliable isotopic data for the oldest monazites measured. However, point analyses and compositional maps of many monazite grains with distinct compositional domains reveal sharp zoning suggesting that intergranular diffusion was limited. Additionally, there appears to be a systemic clustering of ages between 425 to 415 Ma that is interpreted here to represent the onset of metamorphism following the Taconian. Ultimately the monazite ages reflect the time that monazite lock-in their concentration of U and Th and then these ages need to be interpreted in the context of the metamorphism or tectonism that coincides with this period. An understanding of complex age distributions can only be realized if the petrographic and zoning relationships of the monazite grains being examined are known. Garnet porphyroblasts from the area commonly contain inclusion trails with clear truncations at the core/rim interface that are interpreted to represent distinct periods of garnet growth. Monazite growth in these samples and corresponding metamorphism began prior to 424 Ma and last until at least 350 Ma. Peaks in the probability curves represent the pulses in metamorphism. Data taken from inclusion trails in garnet along with monazite age data suggest that garnet growth was episodic and further reflects the episodic nature deformation and mineral growth within a generally continuous orogenic event.

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