Prolonged Acadian Orogenesis: Revelations from Foliation Intersection Axis (FIA) Controlled Monazite Dating of Foliations in Porphyroblasts and Matrix

PETER W. WELCH
School of Earth Sciences
James Cook University
Townsville, Australia

ABSTRACT. Numerous phases of garnet growth are revealed by detailed studies of foliation inflection/intersection axes preserved in porphyroblasts (FIAs) in Acadian metamorphic rocks in the Chester Dome region of Vermont, U.S.A. A regionally consistent succession of four different FIA tends in garnet porphyroblasts has been dated by analyzing monazite inclusions with an electron microprobe. These monazite inclusions, which lie within the foliations that define the FIAs, provide absolute ages for multiple periods of deformation and punctuated periods of garnet growth. The monazite inclusions reveal a progression in foliation ages from 431±2 to 349±3 million years within porphyroblasts and from 366±3 to 327±5 million years in pervasive matrix foliations. Three samples of schist reveal a range of ages of 70 to 75 million years from the cores of porphyroblasts, through the medians to the rims and then into the matrix. Ages determined from monazite grains within garnet porphyroblasts link directly to periods of deformation and episodic garnet growth defined by the FIAs. The four FIA sets began forming prior to 424±3, 405±6, 386±6 and 366±4 million years ago, respectively. Thus, multiple stages of garnet growth occurred throughout Acadian deformation and metamorphism in Vermont, and orogenesis was far more prolonged than previously thought. Invariably, garnet growth occurred early in the accompanying deformation event.

Dating of monazite inclusions without careful separation of phases of garnet growth by microstructural studies will lead to a spread of ages that will confuse rather than elucidate the metamorphic and structural history. Analysis of monazite grains in the matrix alone will likely only present ages for the youngest events. These ages can be amalgamated from grain to grain to yield apparently precise ages, but such ages reveal nothing about the deformation and metamorphic processes operating during orogenesis, or the overall continuity of the deformation and metamorphism that accompanies plate motion. Microstructural studies of successions of inclusion trails allow numerous phases of garnet growth to be distinguished and then dated using monazite grains that have been preserved as the successive foliations developed. This in turn allows very long and involved metamorphic histories to be fully integrated with similarly complex structural histories.

INTRODUCTION

The rocks around the Chester and Athens Domes (Fig. 1) have been the basis for a significant amount of fundamental petrologic work from the fifties through to the nineties by Thompson (1957), Thompson and Thompson (1976), Thompson et al. (1977) and Vance and Holland (1993). They also provided the source for the garnets containing spiral inclusion trail studies by Rosenfeld (1968, 1970). They are a remarkable group of rocks because inclusion trails and compositional zoning in porphyroblasts are preserved in almost every sample, potentially allowing the metamorphic and structural history to be fully integrated. Microstructural work of Rosenfeld led to numerous further detailed studies of inclusion trail geometries from this region (e.g. Bell and Hayward 1991: Bell and others, 1998). Recent work done in conjunction with this study attempts to integrate those studies with similarly detailed metamorphic studies using the controls on timing and separation of periods of metamorphic growth provided by the microstructural work.

Recent structural (Hickey and Bell, 2001) and microstructural studies in Vermont (Bell and Hickey, 1997; Bell et al., 1998; Ham, 2001) using newly developed quantitative methods have revealed a more extensive history of deformation and metamorphism than previously recognized. These methods have resulted in the recognition of successions of multiple porphyroblast growth and foliation development and provided a powerful means for establishing relative timing. This in turn has supplied a way of dating multiple metamorphic events using monazite grains that grew, dissolved and re-crystallized as successive foliations developed. Monazite grains later overgrown by garnet porphyroblasts are preserved and shielded from subsequent dissolution and re-growth occurring within the matrix foliation that preserves only the very latest deformational history.

This paper reports the results of dating monazite grains preserved as inclusions in successive foliations moving outwards from the core to rim of garnet porphyroblasts. These foliations have been grouped into periods of foliation development and metamorphism by measurement of foliation inflection/intersection axes preserved as inclusion trails in porphyroblasts (FIAs). These FIAs have allowed the distinction of a succession of four periods of metamorphism and foliation development in the region around the Chester and Athens domes (Bell et al., 1998) over an area greater than 4000 square kilometers. The successful microprobe dating of monazite grains associated with multiple foliations outwards from the core for successive FIA sets has revealed a consistent and extensive deformation and metamorphic history for southeastern Vermont.

GEOLOGIC SETTING

Middle Proterozoic basement gneisses of the Chester and Athens Domes are unconformably overlain by the Late Proterozoic to Early Cambrian Hoosac Formation (Stanley and Ratcliffe, 1985; Ratcliffe and others, 1992). These rocks were overthrust by a eugeoclinal 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, which is separated from the Cambro-Ordovician rocks to the west by an angular unconformity (Ratcliffe, 1993, 1995a,b; Ratcliffe and Armstrong, 1995).

In southeastern Vermont, two distinct periods of deformation and metamorphism have been recognized as the Ordovician Taconic and Devonian Acadian orogenies (Stanley and Ratcliffe, 1985; Armstrong and others, 1992). Taconian metamorphism predominates to the west of the Green Mountain Massif while the affects of the Acadian orogeny predominate to the east. Spear and Harrison (1989) documented ^{40}Ar/^{39}Ar ages as old as 440 Ma to the east of the Green Mountain Massif and have interpreted these to be partially reset Taconian ages. The Acadian Orogeny involved the closure of the Siluro-Devonian basin comprising the Connecticut Valley Trough. This orogeny caused extensive folding of the entire 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). Acadian metamorphism in southeast Vermont peaked at about 680°C and 10.5 kb at 395-385 Ma, and, unlike parts of the orogen farther east, was a consequence solely of crustal thickening with little or no magmatic heating (Armstrong and others, 1992; Ratcliffe and others, 1992; Vance and Holland, 1993).

All microstructural work on FIAs done to date shows the same progression of garnet growth in the Siluro-Devonian sequence as in the older units, indicating that mineral growth occurred during the Acadian Orogeny (Bell et al., 1998; Ham, 2001). No folds or foliations that are unequivocally Taconic age have been identified in these studies although some are old enough to possibly lie in the transition from Taconic to Acadian. The FIAs and dates described herein come from the 35 x 125 km area extending from just north of the Massachusetts border in the south to some 50 km north of the Chester Dome (Fig. 1). 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 (or late Proterozoic?) to Silurian stratigraphic units, mainly the Moretown, Northfield, Cram Hill and Waits River Formations (Fig. 1). Samples selected for monazite dating were taken from pelitic to quartzose units of the Cram Hill formation. A sub-vertical N-S to SSW-NNE striking crenulation cleavage has formed as an axial plane structure to the domes termed cleavage S_5 after Hayward

(1991, 1992). S_5 overprints a microscopically and mesoscopically prominent crenulation cleavage, S_4, that transects the axial plane to the Spring Hill synform lying to the west of the waist-like shape between the domes (Fig. 2; 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). Therefore, it appears that folding during D_5 has rotated an originally sub-horizontal D_4. A sporadically developed sub-horizontal coarsely spaced crenulation, S_6, locally overprints S_5 (Hickey and Bell, 2001). No mesoscopic deformation fabrics earlier than S_3 were observed. Hayward (1992) argued that at least two additional foliations, which he called S_1 and S_2, are preserved in the porphyroblasts. Most large tight folds, like the Spring Hill Synform (Fig. 2), appear to be pre-D_5 (Hickey and Bell, 2001). Some are D_4 structures, but others may be D_3 or earlier. Hayward (1991) found that the asymmetry of S_4 on S_5 switched on either side of the Chester Dome, suggesting that the latter is a D_5 feature. However, recent work by Ham (2001) suggests the domes may be much older structures that were intensified during younger deformations.

SAMPLES DATED

The succession of FIA development in these rocks has been previously described by Bell and others (1998). In summary, across a 35 by 125 km area, the rocks preserve a consistent succession of four FIA sets within garnet porphyroblasts trending successively SW-NE, W-E, NNW-SSE and SSW-NNE (Fig. 3). The succession was determined using samples that preserve changes in FIA trend from core to rim or core to median to rim (Bell et al., 1998).

FIA set 1, as shown on the rose diagram in figure 4 of all FIAs measured from this region, lies on the edge of the distribution of FIA set 4. However, it is a distinct population (see small rose diagram inset on figure 4; a detailed statistical analysis is provided in Bell et al., 1998), as, with only one exception, it occurs only within the cores of porphyroblasts, with one of the other FIA sets preserved in the median or rim.

In the one example where this is not the case, the inclusion trails are truncated by the matrix foliation in every vertical thin-section cut around the compass used to measure the FIA (8 thin-sections 30° apart with 2 more 10° apart close to the FIA). Where the inclusion trails define FIA set 4, they are always continuous with the matrix foliation in all or most thin-sections cut around the compass (Bell et al., 1998).

Bell and others (1998) interpret this succession of FIAs to reflect progressive changes in the direction of bulk shortening during Acadian orogenesis associated with changes in the direction of relative plate motion. Deformation is always heterogeneously distributed in the earth’s crust and foliations can form from location to location at different times, and, in some locations, several foliations are preserved around individual FIAs. They argue that the consistent succession of FIAs from sample to sample reflects periods of time over which the direction of bulk shortening remained constant before shifting to another trend.

Approximately 30 samples were examined to find monazite grains that could be linked to the microstructures within the porphyroblasts. After inspection of the eight or more thin-sections cut for each sample to determine the FIAs, at least two spatially oriented polished thin-sections were prepared for each sample from the same blocks of rock used for the FIA determinations. Less than one third of these samples were found to contain monazite grains, with only half of those having sufficient monazite grains within porphyroblasts. Samples with core - rim FIA relationships were chosen to test whether the monazite ages are consistent with the FIA succession determined microstructurally by Bell et al. (1998). Only one sample containing microstructures related to the earliest FIA was found to have monazite present as inclusions; however, garnet growth in this sample occurred during development of the second FIA set. The succession and orientations of FIAs in the samples dated are shown in figures 3 and 4.

The four samples dated were taken from the Cram Hill formation on the east limb of the Spring Hill synform from pelitic and quartzitic schists. Sample **V634A** contains garnet, muscovite, quartz, minor biotite, staurolite porphyroblasts with chloritoid occurring only as inclusions within garnet porphyroblast cores. The inclusion trails within the cores of garnet porphyroblasts are dominated by quartz (Figs. 5 and 6) whereas the inclusion trails in the rims contain lesser amount of quartz with ilmenite and are inter-grown with staurolite. Abundant monazite is present as inclusions and matrix grains in the cores, medians, rims, strain shadows and matrix of this sample (Fig. 5B).

Sample **V436A** contains garnet, muscovite, minor biotite, quartz and locally porphyroblastic plagioclase. The inclusions within garnet porphyroblasts are dominated by quartz in the core and ilmenite in the rim (Figs. 7 and 8). Monazite inclusions are present in the core and rim (Fig. 7B) and monazite grains are present in the matrix of this sample. The cores and medians of garnet porphyroblasts are rounded to subhedral and are overgrown by stringers of garnet in the rims. Sample **V436B** contains garnet, muscovite, biotite, quartz and late chlorite. The inclusions within garnet porphyroblasts are dominated by quartz in the core and graphite in the rim (Figs. 9 and 10). Monazite grains are present only in the rim of garnet porphyroblasts (Fig. 9B). Sample **V653** contains garnet, muscovite, minor biotite, quartz and locally staurolite, chloritoid and chlorite that are commonly inter-grown. The inclusions within garnet porphyroblasts are dominated by quartz (Figs. 11 and 12). Monazite is present as inclusions only in the rims of garnet porphyroblasts and as grains in the matrix (Fig. 11B). All of the samples contain accessory tourmaline, ilmenite and apatite, and zircon is locally present as inclusions and in the matrix. All of the samples contain garnet porphyroblasts that preserve compositional zoning with several showing complex Ca zoning that is coincident with changes in the microstructure (Figs. 5C, 7C, 9C and 11C); all are distinctly texturally zoned (Figs. 5A, 7A, 9A and 11A). The metamorphic grade attributed to the rocks in this region peaked at about 680°C and 10.5kb at around 395-385 Ma (Armstrong and others, 1992; Ratcliffe and others, 1992). However, thermobarometric work done as part of this study suggests that the rocks described herein may have achieved higher pressures but lower temperatures than previously described. The results of this thermobarometric work are discussed in detail in the subsequent chapters of this dissertation.

AGES

Age Determination

Monazite ages were determined using the U-Th-total Pb technique outlined in Montel et al. (1996) and Williams et al. (1999). This technique is ideally suited to the analysis of monazite grains in-situ, which was critical to this study. It has been proven to be a viable technique by the dating of monazite grains of known age by these authors. The analyses described herein were obtained from the laboratory of M.L. Williams at the University of Massachusetts and Williams et al. (1999) contains a comparison of monazite grains dated by this and other techniques. Comparisons of the ages obtained with other methods such as SHRIMP and TIMS have shown excellent agreement in rocks as young as 300Ma.

Monazite inclusions in garnet are difficult to identify optically so grains were identified using back-scattered electron imaging and spot checked by qualitative EDS scans. Compositional maps of U, Th, Y and Pb were obtained for all monazite grains to be analyzed to check for multiple growth phases using the methods outlined in Williams et al. (1999). An example of a set of compositional maps for sample V436A is shown in figure 13. Spot analyses were collected for all compositional domains in a given grain. A number of analyses were collected for each grain, or compositional domain in each grain, so that an average age could be calculated (for example, Fig. 8B). The point analyses and compositional maps were collected on a Cameca SX-50 in the Department of Geological Sciences at the University of Massachusetts. Grains were analyzed with beam conditions of 15kv and 100nA and 900 second count times.

For each monazite grain dated, a mean age was calculated from several analyses (for example, all the analyses in table 1 for the monazite grain shown in Fig. 8B). Two ages were calculated for grains with complex zoning where such variation was apparent. A standard deviation and a standard error were calculated for those analyses. The age data and associated errors for each grain from each sample are reported in table 2 at the 1-sigma level of confidence. As noted in Chapter 1 of this dissertation, the errors are calculated solely from the deviation from the mean on a set of ages for each grain. The analytical errors for each element have not been propagated through the age equation. A normal distribution probability curve was calculated for the mean and standard deviation of each monazite grain. These data are plotted as the small non-grayed curves for each sample in figure 14. A total sum probability curve was then calculated for each sample from these curves. This curve is simply the sum of all of the smaller curves and does not include the grayed curves mentioned below. This was done to see if multiple ages could be seen for the different FIAs when the data were accumulated together rather than just examined in terms of their microstructural location relative to foliations in the core, median and rim.

Each graph in figure 14 also contains weighted average ages with error ranges. These weighted average ages were calculated at the 2-sigma level of confidence for all the monazite grains separated according to FIA and whether they lie in the core, median or rim of a given garnet porphyroblast, or the matrix. In other words, monazites were grouped according to microstructural positions and then weighted averages were calculated for these groups. The weighted averages are also plotted on the graphs in figures 14 and 15 as the gray shaded curves.

Foliations, FIA Sets and their Monazite Ages

Sample V634A shows evidence of the earliest FIA set as the axis of the crenulated cleavage lying between the differentiated crenulation cleavage seams preserved as the inclusion trails in the core (Fig. 5b). The sample contains FIA set 2 as the axis of curvature of the foliation in the core. It also contains FIA set 3 defined by the differentiated crenulation cleavage at stage 3 and stage 4 in the median inclusion trails and FIA set 4 in part of the rim. Monazite grains are present in every microstructural position within garnet porphyroblasts as well as within the matrix (Figs. 5B and 6). The probability distribution for all monazite grains dated in this sample is shown in figure 14A and indicates four peaks in the distribution. These coincide with the ages calculated from the weighted averages for monazite grains in the core median, rim and matrix at 424±2 Ma, 405±6 Ma, 386±6 Ma and 366±4 Ma and which are shown in figure 14 as gray shaded curves. The progressively younger age of the monazite grains from core to rim is readily apparent.

Sample V436A contains FIA set 3 in the core of garnet porphyroblasts and set 4 in the rims. Monazite grains are present in the cores and rims of these porphyroblasts as well as in the matrix (Figs. 7B and 8) and their ages range from above 390 Ma in porphyroblast cores down to around 321 Ma in the matrix. The probability distribution for all monazite grains dated in this sample is shown in figure 14B and indicates three peaks in the distribution. These coincide with the ages calculated from the weighted averages for monazite grains in the core, rim and matrix at 391±8 Ma, 368±6 Ma and 321±23 Ma respectively and which are shown in figure 14B as gray shaded curves. The progressively younger age of the monazite grains from core to rim to matrix is readily apparent.

Samples V436B and V653 contain FIA set 3 in the core of garnet porphyroblasts and FIA set 4 in the rims, but monazite grains are only present in the rims. Sample V436B yielded ages of 349±8 for monazite grains in the rim and matrix as well as an anomalously old age of 416±14 Ma (Figs. 9B, 10 and 14C). This ellipsoidal shaped monazite grain (grain Mz1 in Fig. 10) lies in the rim of the garnet porphyroblast at a high angle to the surrounding inclusion trails. It has the same orientation as the foliation defined by inclusion trails in the core (Fig. 10). Sample V653 yielded an age of 350±11 Ma for monazite in the rims (Figs. 11B and 12). Monazite grains are also present in the matrix; the youngest were 316±9 Ma.

The Combined Age Data Set

An analysis of all forty-seven ages of individual monazite grains obtained from these samples, shown in figure 15A via a probability density curve, produced a series of five peaks at 425 Ma, 400 Ma, 387 Ma, 365 Ma and 350 Ma. These can be compared with the 5 peaks determined from the weighted average ages based on FIA set and microstructural location (see below) combined for all samples, shown in figure 5B, at 425 Ma, 405 Ma, 387 Ma, 367 Ma and 352 Ma.

INTERPRETATION

Foliation Development and Preservation as Inclusion Trails

Quartz, graphite, muscovite and biotite are the minerals in pelitic rocks that commonly define the matrix foliation. Porphyroblasts generally overgrow and preserve quartz and graphite from the matrix as inclusion trails but not muscovite and biotite. The latter minerals are rarely preserved because they tend to be consumed during the reactions that produce the porphyroblastic phases. Every time a new foliation forms to stage 3 or more of differentiated crenulation cleavage development (Bell, 1986; Fig. 16A-E), the matrix reconstitutes as deformation and metamorphism take place. This may have the result of resetting any isotopic clocks present in minerals such as monazite and zircon if they are affected by progressive shearing (for example, Page and Bell, 1986). This reconstitution involves deformation, re-crystallization, dissolution and solution transfer and removal of non-platy minerals, such as quartz, from zones of progressive shearing (cleavage seams), during crenulation cleavage development (Fig. 16B,C, D; Bell & Cuff, 1989) or reactivation of bedding (Bell, 1986). It also involves re-crystallization of the phyllosilicates left behind in the cleavage seams (Bell and Cuff, 1989). Those minerals dissolved may nucleate and grow again in zones of progressive shortening, most obviously in strain shadows adjacent to porphyroblasts but also generally within the matrix (for example, Williams et al., 2001). During this process, some material may also be removed entirely from the local system (Bell and Cuff, 1989).

Monazite Behaviour during Foliation Development

The phase relations of monazite are not well understood but it is thought to occur as a metamorphic mineral in amphibolite facies rocks (Parrish, 1990; Smith and Barreiro, 1990; Lanzirotti and Hanson, 1996). The data presented here demonstrate that successively younger generations of foliations preserved from the cores to rims of porphyroblasts as inclusion trails contain progressively younger monazite grains, with even younger grains commonly present in the matrix foliation (Figs. 5 to 12). Two possible explanations for the behaviour of monazite that would explain this progressive reduction in ages each time a new foliation forms (see also Shaw et al., 2001; Williams and Jercinovic, 2002) are presented here. Each time a new foliation has formed the older monazite grains preserved in porphyroblast cores have been plastically deformed and re-crystallized, or they have been plastically deformed on their margins, dissolved, undergone solution transfer to a new site and nucleated and grown as new grains. The latter process would certainly reset the internal radiogenic clock that results from the decay of U and Th. The former process would probably reset the radiogenic clock as well, because the movement of high angle grain boundaries through the monazite grains as they re-crystallized should release any Pb that had built up from radiogenic decay. For the rocks described herein monazite is thought to have formed and re-crystallized numerous times during a P-T-t history involving a range in temperature from 500°C to well over 600°C and pressures ranging from 6 to well over 12 kbars. (See Ch. 3). This makes it an ideal mineral for dating foliations that accompany the growth of many of the most common porphyroblastic phases in pelites. The U, Th and Pb content of monazite grains that lie in foliations can be measured on a microprobe and the age of that grain/foliation can then be calculated (Montel et al., 2000; Williams and Jercinovic, 2002).

Monazite Microstructural Relationships

Observations of monazite microstructural relationships throw further light on the behaviour of this mineral during foliation development. Monazite can grow within a developing foliation over minerals such as ilmenite that define an earlier formed foliation and preserve them as inclusions as shown in figure 12d. Relatively early formed monazite grains can be preserved in the strain shadow of a porphyroblast and remain protected from the effects of subsequent deformation and younger foliation development (for example, grain Mz38 in Fig. 5b). Some monazite grains have been affected by the development of a younger foliation but have not fully re-crystallized and retain the age of an older foliation in their cores (for example, grains Mz10 and Mz12 in Fig. 8, and Mz4 in Sample V634A, table 2). Locally, monazite grains (for example, grains Mz27 in Fig. 5b, Mz11 in Fig. 8a,b and Mz1 in Fig. 10) preserve anomalously old ages in porphyroblasts or matrix where other monazite grains have much younger ages. In the case of Mz1 in sample V436B, the monazite grain is quite elongate and lies at a high angle to the surrounding foliation preserved as very fine inclusion trails in the surrounding porphyroblast or in the matrix. These elongate grains are similar in size and lie exactly parallel to those inclusions that define the foliation in the core of the porphyroblast. These are interpreted as relict grains that have survived the effects of subsequent foliation development because they crystallographically lay in an orientation where they remained strong relative to the deforming forces and did not plastically deform. This prevented re-crystallization and dissolution (Bell et al., 1986; Bell and Cuff, 1989). Mancktelow (1981) documented this phenomenon in quartz and showed that some grains have their C-axes in orientations whereby they are very strong relative to the superimposed forces and can survive the effects of intense deformation and maintain their original orientation. Without internal plastic deformation, re-crystallization or dissolution, solution transfer, nucleation, and growth are prevented and resetting of the age does not occur. The age determined from these grains provides an age for the core foliation. Monazite grain Mz36 in Fig. 6 is similar to the grain just described but is interpreted to have undergone some internal plastic deformation because it has been rotated relative the foliation in the core. Yet, it too has maintained a core age. Internal plastic deformation was insufficient to cause this grain to re-crystallize. As a result, the age in the monazite core as not reset. The latter four of the five monazite microstructural features described herein bring into focus the possibility of inheritance of older monazite ages (for example, Harrison et al., 1999) and lead loss (Smith and Giletti, 1997). The Cram Hill formation from which these samples were taken is considered Ordovician in age (stratigraphic age), whereas the oldest age obtained for a monazite inclusion is 430 Ma. This Silurian age is too young to be an inherited monazite unless some intra-crystalline diffusion has occurred. Preservation of compositional zoning in monazite from these samples is common (Fig. 13) suggesting that intra-crystalline diffusion did not occur or was very limited. This is further supported by the succession of ages from core to rim of the porphyroblasts and the consistency of these ages for successive FIA sets from sample to sample.

Interpretation of the Ages Obtained from Each Sample

Figure 14 shows for each sample the probability curve for the age of each monazite grain dated, as well as the total probability curve resulting from the sum of all of the individual monazite age curves. It also shows the weighted average age calculated for monazite grains according to the FIA and microstructural setting (porphyroblast core, median or rim and the matrix) and curves (shaded in gray) defining these weighted average ages. Figure 5 shows a garnet porphyroblast from sample V634A and contains a large range of monazite ages where the microstructural and FIA setting of the grains enable the interpretation and dating of a long history of FIA development. The ages of the monazite grains within the foliation crossing the core are 434, 431 and 430 Ma. This foliation is a differentiated crenulation cleavage at stage 4 of development (Fig. 16) with the remains of the crenulated cleavage from which it formed preserved in Q-domains. The axes of the crenulated cleavage belong to FIA set 1 and thus the monazite ages in the core are interpreted to reflect the age of the development of FIA set 1. The core of the porphyroblast formed during FIA set 2 (Fig. 17A). The 424 Ma ages at locations Mz37 and Mz38 (Fig. 5B) formed in the strain shadow of the core after it developed and provide an indication of the age of FIA set 2. The 400 Ma (432 Ma is relic of core) and 402 Ma ages in the median of the porphyroblast are preserved within a stage 3 differentiated crenulation cleavage (Fig. 16B,C) that was the first foliation that formed during FIA set 3 in this sample (Fig. 17B). This portion was subsequently overgrown by garnet (Fig. 17C). Shear during a younger event formed a truncational differentiated crenulation cleavage at stage 4 of development (Fig. 16D,G, J) against the median containing monazite grains dated at 379 Ma, 398 Ma (the 413 Ma for Mz27is a relic of core grain as described earlier; Fig. 17D). Similarly, overgrowth of a younger gently dipping differentiated crenulation cleavage by garnet occurred during further development of FIA set 3 (Fig. 17E). The matrix contains monazite grains dated at 366 Ma. The latest visible differentiated crenulation cleavage in the matrix was overgrown by staurolite porphyroblasts during a weakly developed crenulation event that causes shallow microscopically visible deflections through the staurolite grains and defines FIA set 4. This was the only younger event recorded in this rock and the matrix has not preserved the affects of any other events.

Figure 7 shows a garnet porphyroblast from sample V436A that preserves a microstructurally visible core, median and rim, based on inclusion trail density and composition, associated with FIA sets 3 (core) and 4 (median and rim). The porphyroblasts in this sample contain monazite age relationships relative to the microstructural setting that reveal significant characteristics of the behaviour of monazite during foliation development. Figures 7 and 8 show that the cores of these porphyroblasts contain monazite grains dated at 392 and 393 Ma. Garnet overgrew this quartz rich core during the development of FIA set 3 and these grains formed before or during this period; based on sample V634A described above, the foliation containing these grains is interpreted to have formed during FIA set 3. Figure 8D,F shows monazite grains M20 and M21 that formed during the development of the rim at 358 and 363 Ma (the younger ages from M20 are regarded as anomalous). Monazite grains M10 and M12 occur in the median and rim respectively, where the inclusion trails define foliations that formed during the development of FIA set 4, and both grains contain an older core at 390 and 402 Ma and a younger rim at 364 and 373 Ma respectively. The older core is interpreted to be remains of the foliation preserved in the porphyroblast cores. The younger rim is interpreted to be the age of development of the foliation in the median and the rim for Mz20 and Mz21 respectively, both of which developed during FIA set 4. The Mz11 grain has the same age and orientation as the monazite grains in the porphyroblast cores (Fig. 8A,B). This suggests that it was not significantly affected by plastic deformation during the development of foliation in the median. As reported above, it appears to have remained in a strong orientation relative to the stress field.

Figures 9 and 10 show garnet porphyroblasts from sample V436B that preserve a microstructurally visible core, median and rim, based on inclusion trail density and composition, which define FIA set 3 in the core and FIA set 4 in the median and rim. No monazite grains were found in the core. However, a few grains were found in the median with ages of 362, 357, 349 and 348 Ma (for example, Fig. 9). One monazite grain, Mz1 that lies in the median, is elongate at a high angle to the foliation surrounding it but parallel to that within the core (Fig. 9). This grain has an anomalously old age of 416 Ma interpreted as a relic of the latter foliation, as mentioned in the section above. Consequently, it could have formed before or during FIA set 3. A few grains in the matrix have younger ages of 338 and 337 Ma and are interpreted as providing an age for the matrix foliation.

Figures 11 and 12 show garnet porphyroblasts from sample V653 that preserve a microstructurally visible core and rim, based on inclusion trail density and composition, and defining FIA set 3 in the core and FIA set 4 in the rim. No monazite grains were found in the core. However, monazite grains were found in the rim. These monazite grains have ages of 359, 358, 358 and 354 Ma with two anomalously younger ages at 345 and 309 Ma. The few monazite grains observed in the matrix have younger ages ranging from 350 and 347 to 327 and 319 Ma. The potential significance of this spread of matrix ages is discussed below.

Significance of Monazite Ages and Episodic Porphyroblast Growth Reactions

Progressively younger ages of monazite grains preserved in the succession of foliations from the core to rims of porphyroblasts in figures 5 to 12 and 14 reveal 70 million years of episodic growth of garnet at intervals separated by as much as 20 million years. The progressively younger monazite grains outside of the porphyroblast cores occur in foliations that have formed against successively grown portions of the porphyroblast rims (for example, Fig. 16F-J). Inclusion trail geometries suggest that each phase of porphyroblast growth occurred early in a deformation event and that after growth ceased, the foliation in the matrix intensified against the porphyroblast rim (for example, Fig. 16F-J). These ages obtained in this study provide further evidence for the episodic nature of porphyroblast growth that has been recognized through microstructural work of Bell and co-workers (Bell and Johnson, 1989; Bell and

Hayward, 1991; Spiess and Bell, 1996). Some porphyroblast producing reactions were significantly interrupted and recommenced several times over a period of 70 million years without necessarily going to completion.

Foliation Ages vs. Porphyroblast Age

As described above, the ages of monazite grains within a foliation are interpreted to reveal the age of foliation development for that foliation**.** Therefore, monazite grains occurring in simple inclusion trail geometries cannot be used to determine the absolute age of the porphyroblast encompassing that foliation. They simply indicate that the porphyroblast grew after the formation of that monazite grain. However, once a porphyroblast has overgrown the foliation preserved in its core, new foliations commonly form against garnet rims during younger deformations (Fig. 16G, I, J). Incorporation of these younger foliations within the porphyroblast during later phases of growth is also common, and generates more complex trail geometries such as spiral and staircase shapes (Fig. 16F, H, J). This process of foliation development against a porphyroblast rim and subsequent incorporation by later porphyroblast can be repeated many times. Where this occurs it allows bracketing of the time of growth of portions of the porphyroblast if monazite grains are preserved as inclusions in each foliation. Numerous phases of growth are common (see examples, Bell and Johnson, 1989) for this part of Vermont. Sample V634A provides an excellent example of the process just described. Foliation in the core contains monazite grains dated at 424±2.4 Ma (Figs 5, 6 and 14). Therefore, the garnet overgrowing the core grew after that date (Fig. 17A). Differentiation associated with curvature on the edge of the core ranges in age from 405±6 to 386±6 Ma. Therefore, the garnet in the core grew between 424±2.4 and 405±6 Ma (Fig. 17B). Monazite inclusions in the stage 3 differentiated cleavage (Fig. 16) on the edge of the core are dated at 405±6 Ma and were overgrown by garnet before the truncational stage 4 crenulation cleavage (Fig. 16) formed that contains monazite inclusions dated at 386±6 Ma (Fig. 17C). Therefore, the garnet overgrowing the edge of the core formed after 405 Ma, but before 386 Ma (Fig. 17C). The matrix contains monazite grains dated at 366±4 Ma. Therefore, garnet in the rim (Fig. 17E) grew before 366 Ma and after 386 Ma. A gently dipping portion of the outermost rim contains garnet that grew during FIA set 4 around or after 386 Ma (Fig. 17F). Similar but younger histories are recorded by the other samples.

The Correlation of Ages with FIA Trends

The progression in monazite ages with the succession of FIA sets is consistent from sample to sample. It provides independent and quantitative confirmation of the potential to correlate FIA sets as described by Bell et al. (1998), which was based on consistent core to rim changes in FIA trends over a 4375 square kilometer region. It suggests that once a succession of FIA trends has been defined and dated, they can be used as a guide to the age of the deformation and metamorphism in other samples from that region. Thus, successive sets of FIAs may provide a new and powerful means of correlating and dating deformation and metamorphism across and along an orogen. Since the orientations of successive FIAs ought to directly reflect changes in the relative direction of plate motion (Bell et al., 1992; 1995; 1998) and if the FIAs are related directly to shifts in plate motion then this leads to the possibility of accessing and dating the history of plate motions that have formed orogens older than the 170 Ma age of the oldest oceans.

FIA vs. Matrix Ages

This data from 180 analyses of forty-seven monazite grains from four different samples suggests that switches in trend for the consistent FIA succession recorded by Bell et al. (1998) for Vermont from SW-NE to W-E, W-E to NNW-SSE and NNW-SSE to SSW-NNE occurred around 425 Ma, 400 Ma and 375 Ma respectively. However, deformation and metamorphism are interpreted to have occurred throughout this period of time. It is likely that the peaks in the total distribution of ages shown in Fig. 15 may broaden as more samples across the region containing monazite grains are discovered and dated. However, a peak in the distribution of ages within each FIA set may still be present with further dating. This would result from a lag in the pervasiveness of deformation that ought to occur after each change in the relative direction of plate motion indicated by a change in FIA trend (Bell et al., 1998). The matrix preserves ages ranging from 360 Ma to 320 Ma. All deformation that involves a component of bulk shortening is inherently partitioned across and through the crust into components of progressive shortening and shearing (Bell, 1981). Alleghanian deformation around 300 Ma has been documented in shear zones mantling the Pelham Dome only 60 km to the SSE of this region (for example, Moecher, 1999). The effects of this younger period of orogenesis have propagated a large distance from the boundary with Avalon to the SE and could have affected rocks this relatively short distance further north. The discrete nature of Taconian, Acadian and Alleghanian orogenesis as previously described may disappear as more age information of this type is derived. This interpretation suggests that deformation was essentially continuous but heterogeneously distributed throughout the orogen from 431 Ma to 349 Ma and possibly to 327 Ma. Significantly, this is effectively the age range between the Taconic and Alleghanian orogenies.

DISCUSSION

The Heterogeneity of Deformation and FIA Development

Deformation within the earth's crust is inherently heterogeneous due to competency contrasts from the grain scale upwards in rocks (Bell, 1981). This heterogeneity results in partitioning of the deformation into zones of progressive shortening, consisting of low coaxial strain, and zones of progressive shearing consisting of high non-coaxial strain. In contrast, the driving force for orogenesis, the collision between plates, is a very steady state process (Cox and Hart, 1986), with the exception of the effects associated with a change in the direction of relative plate motion. The dates reported herein suggest that deformation and metamorphism during the Acadian extended for at least 80 million years. The history of deformation and metamorphism recorded by the FIAs is far more extensive than that recorded by the matrix and Bell et al. (1998) have shown that some samples contain extensive histories of multiple foliation development around the one FIA trend. This is supported by the extended history of foliation development and monazite ages associated with the development of FIA set 3 in sample V634A that is shown in figure 17. Although attempts have routinely been made to try to correlate matrix foliations from outcrop to outcrop, it has been shown that this can be problematic (Hobbs et al., 1976). The integration of FIA data, detailed microstructural studies of porphyroblasts and geometrical studies of large-scale folds (Bell and Hickey, 1997; Hickey and Bell, 2001) has demonstrated that foliations cannot be correlated from sample to sample within porphyroblasts but FIAs can. However, each FIA develops over a period of time with some samples recording several foliations accompanying FIA development and others only one. Consequently, different foliations defining a particular FIA can have formed at any stage over the period of time that the relative plate motion that developed that FIA trend remained constant. There were nine changes in the relative direction of plate motion between Africa and Europe associated with the development of the European Alps from 115 million years ago to the present day ranging from 31 to 9 million years apart (Platt et al., 1989). Foliation ages associated with the development of a particular FIA could range over similarly varying lengths of time. This study reported detailed dating of monazite grains in four samples. The absolute age range of each of the FIA trends cannot be defined at this stage, but this should be possible when more of this type of work has been done within the Appalachians. This should be kept in mind when viewing the total distribution of monazite ages and associated FIA sets in figures 14 and 15. The peaks in this distribution belong to the FIA sets shown but the age boundaries of those FIA sets are not absolute. The best estimate for the age ranges for the FIA sets 1 through 4 are prior to 425 Ma, from 425 Ma to 400 Ma, from 400 Ma to 375 Ma, and from 375 Ma to 350 Ma. The matrix ranges from 360 Ma to 340 Ma with some evidence for local resetting down to 316 Ma.

Confirmation of the Episodic Nature of Metamorphism

It has been argued for over a decade that the microstructural record of foliation development preserved within porphyroblasts indicates that porphyroblast growth is episodic rather than discrete or continuous (for example, Bell and Johnson, 1989; Bell and Hayward, 1991; Jones, 1994; Williams, 1994; Spiess and Bell, 1996). The age data presented herein provides further evidence for the episodic nature of porphyroblast growth indicated by the microstructures. Garnet porphyroblasts are interpreted to have grown in these rocks by reactions that did not go to completion over several phases of porphyroblast growth rather than a discrete set of univariant reactions. That is, some periods of episodic growth of garnet, separated by millions of years, were not the result of change in the reaction that took place. This phenomenon can be explained through deformation controls on micro-metasomatic access of the material needed for porphyroblast growth (Bell and Hayward; 1991), along with the role of strain energy on the activities of the components involved in the reactions (Wintsch and Dunning, 1985).

Significance of Episodic Growth of Porphyroblasts

Episodic growth of a porphyroblastic phase without the necessity for a change in the reaction producing that phase has considerable significance for unraveling metamorphic histories. Reactions should continue to completion once the temperature and pressure required for that reaction to proceed has been reached or overstepped as long as sufficient heat is added to the reacting rock mass. Microstructural indications that this is not the case have been described and discussed for many years. Episodic reaction progress remains difficult to reconcile with simple petrologic models in which the primary controls of reactions are temperature and pressure (for example, Spear, 1993). Microstructural evidence that porphyroblast growth reactions only occur at the commencement of deformation can be thought of in terms of the equilibrium approach by suggesting that the reaction slows down by orders of magnitude once stage 3 of crenulation cleavage development (Fig. 16B, F, H) has been reached because of diminishing access of the components needed for the reaction to continue (Bell and Hayward, 1991). However, it has not been demonstrated that porphyroblast growth continues within a single deformation event once a differentiated crenulation cleavage has formed (Fig. 16A) during that event. This is strongly supported by the succession of ages of monazite grains from the core to rim of porphyroblasts in sample V634A (Figs 5 and 6; for example, Bell and Hickey, 1999; Hickey and Bell, 1999).

The Age of the Acadian

Figure 14 and table 2 show that the forty-seven individual monazite grains within the four samples dated range in age from 432 to 309 Ma. This study set out to date a previously determined set of garnet growth events (Bell et al., 1998) using monazite grains preserved within the foliations that define those events. If these rocks had been dated without this microstructural work, this range probably could have been interpreted as reflecting one period of Acadian metamorphism around 370 Ma in spite of the precision of the ages of individual monazite grains toward either end of the age range. However, the consistent FIA succession and matching progression of dates reveal that this spread of ages is due to episodic but, overall, essentially continuous deformation and metamorphism from at least the 425 to 340 Ma suggested by the peaks on the probability distribution for all samples (Fig. 15). The progression of FIAs is directly reflected by a succession in ages.

Acadian vs. Taconic Orogenesis

The oldest age around 425 Ma obtained in this study (Fig. 14A) was derived from an early foliation in the cores of garnet porphyroblasts preserving the oldest FIA (sample V634A). Approximately 60 kms to the NNE of the Chester Dome, along the same regional anticlinorium axis, lies the Pomfret Dome. The rocks surrounding this dome contain the same succession of FIA trends as those in the region around the Chester and Athens domes, except for an earlier formed NW-SE trending FIA set (Bell et al., 1998; Ham, 2001). If the FIA trends can be correlated regionally then this would suggest that deformation and metamorphism may have begun in the rocks around the Pomfret dome prior to 425 Ma but did not affect the region around the Chester and Athens domes. Alternatively, no porphyroblasts grew at that time in the latter region to preserve the older ages. Recent interpretation on the age range for the Taconic orogeny has been extended towards the latest Ordovician (Ratcliffe et al., 1998). It may eventuate that the break between Taconian and the Acadian, as suggested by previous workers, did not occur within the core of the orogen and that orogenesis was essentially continuous from the Taconic through the Acadian to less than 350 Ma.

Continuity of Plate Motion with Few Matrix Deformations

The small number of deformation events preserved within the matrix of rocks that have undergone orogenesis versus the continuous nature of relative plate motion, led to the suggestion that individual deformation events result from successive collision of continents or island arcs carried by the plate undergoing subduction (for example, Kent and Keppie, 1988). However, the data presented herein, and FIA data in general, suggests deformation is episodic but overall continuous throughout the whole period that plates are colliding, independent of whether an island arc or continent, carried in on the plate being subducted, collides with the subduction zone. The successions of orthogonal (sub-vertical and sub-horizontal foliations) that are trapped in porphyroblasts, and that cause the different trending successions of FIAs to form, are most easily explained in this way. The limited number of deformations preserved in the matrix of orogenic belts results from reactivation of earlier formed foliations and decrenulation of newly forming crenulation cleavages (Bell, 1986).

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