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Preservation of Acadian deformation and metamorphism through intense Alleghanian shearing

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Abstract

The Northfield syncline in Massachusetts, USA, preserves the same Acadian succession of FIA trends (foliation intersection axes preserved in porphyroblasts) as that in Southeast Vermont, in spite of the overprinting effects of intense Alleghanian deformation and metamorphism resulting from this syncline being thrust southwards over the Pelham gneiss dome. Therefore, both regions were multiply tectonized about the same succession of directions of shortening prior to the Alleghanian, but all relics of Acadian metamorphism were obliterated in the matrix of the Northfield syncline rocks during southwards thrusting. Within the most intensely foliated rocks at the contact between the Northfield syncline and the Pelham gneiss dome, the compositional zoning within the garnet porphyroblasts was homogenized. The 55 °C increase in the rims of these garnet porphyroblasts against the matrix appears to be a product of shear heating that occurred when these rocks were thrust over the Avalonian rocks of the Pelham dome. The lack of equivalent intense Alleghanian shearing in Vermont suggests north central Massachusetts marks the upper contact of the northwest extremity of Avalon. This extremity was less than 10 km thick if it reached SE Vermont suggesting that these rocks were tectonically wedged into North America rather than simply underthrust, and that some delamination of the upper part of this portion of Avalon occurred in Alleghanian times.

Keywords: Shear heating; Homogenization of compositional zoning; Effect of homogenization on inclusion trail geometry; Porphyroblasts; FIAs; Correlation of metamorphism

1. Introduction

It has long been apparent that porphyroblasts preserve evidence for foliations and other microstructures destroyed in the matrix, and, potentially provide windows into the geologic history. It has recently been suggested that the extent to which this occurs in polydeformed and polymetamorphosed rocks is far greater than previously conceptualized (Bell et al., 2003). Protracted histories of deformation and metamorphism, for which all evidence has been destroyed in the matrix, have been revealed by the measurement of foliation intersection/inflection axes preserved within porphyroblasts (FIAs) and the dating of monazite inclusions that help define them (e.g. Bell and Welch, 2002). The amount of metamorphic information available from porphyroblasts is limited by the modification or homogenization of compositional zoning patterns, such as those in garnet porphyroblasts. Such modifications occur with time at metamorphic temperatures around 700 °C (Tracy, 1982). However, this should not affect the structural information preserved by inclusion trails, where there has been no internal deformation of the porphyroblast and homogenization of compositional zoning occurs by internal diffusion. Consequently, the history of phases of porphyroblast growth may be preserved by successions of FIAs in rocks where there has been very intense overprinting by deformation and metamorphism associated with subsequent periods of orogenesis, especially where it can be correlated with rocks that have been left unaffected. Where the temperatures have not reached 700 °C, the history of metamorphism may also be preserved within the compositional zoning and be able to be correlated sample to sample through the FIAs.

Porphyroblasts preserve long histories probably because they appear to grow during successive deformation and metamorphic events that are partitioned through their immediate vicinity (Bell and Hayward, 1991; Spiess and

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Bell, 1996). This commonly allows the inclusion trails to track the local deformation and metamorphic history that predates the development of the matrix foliations (other than bedding) that are finally preserved in the rock (Adshead-Bell and Bell, 1999; Bell and Hickey, 1999; Kim, 2000; Stallard and Hickey, 2001a,b). One way in which this history can be accessed is by the quantitative measurement of FIAs (Bell et al., 1998). Potentially, the relative timing resulting from the observed FIA successions can be used to reconstruct the metamorphic history utilizing the composition of inclusions and zoning patterns. Certainly, monazite grains lying within the foliations that define successive FIA sets, where several sets are preserved within a sample, can then be used to examine the ages of successive periods of deformation and metamorphism by direct dating with a microprobe (Williams et al., 1999; Bell and Welch, 2002).

The margin of the Pelham Gneiss dome of north central Massachusetts with the overlying rocks was so extensively deformed and metamorphosed in the Alleghanian (Robinson et al., 1992), that garnet porphyroblasts had their compositional zoning profiles completely homogenized (Moecher, 1999). This Alleghanian tectonism totally reconstituted the matrix foliation from Acadian conditions, which according to Moecher (1999), were around 800–825 °C and 6 ± 1 kbar to those of the Alleghanian around 600–650 °C and 6 ± 1 kbar. However, one would not expect Acadian compositional zoning to be preserved in garnet porphyroblasts that had reached temperatures around 800 °C (Tracy, 1982). Do the inclusion trails within these porphyroblasts, and those in adjacent rocks such as the Northfield syncline, preserve an earlier Acadian deformation and metamorphic history that has been overprinted by a younger similar Alleghanian history, or did the bulk of the porphyroblasts grow only during the Alleghanian? This paper attempts to answer these questions by comparing the history preserved within the porphyroblasts of southeast Vermont, where the effects of Acadian polymetamorphism have been documented and dated (Bell and Welch, 2002), with that preserved in porphyroblasts from the Northfield syncline adjacent to the Pelham Dome, where the effects of the Alleghanian overprint are thought to dominate (Robinson et al., 1992; Moecher, 1999). We show that the history preserved in these two groups of rocks, which lie only 60 km apart (Fig. 1), is strikingly similar suggesting that the Acadian history has been preserved through the effects of the overprinting by intense shearing and metamorphism during the Alleghanian, in spite of significant local modification of the internal zoning profiles of many garnet porphyroblasts. Our results have implications for the large-scale tectonic setting and history of these rocks and we consider them as well.

2. Geological setting

The regions discussed herein lie to either side of the Connecticut Valley Border Fault in north central Massachusetts and southeast Vermont (Fig. 1). Both regions contain PreCambrian rocks (although of different age) within the core of a gneiss dome plus a cover sequence of metamorphosed Ordovician, Silurian and Devonian sedimentary and volcanic rocks (Zen et al., 1983; Tucker and Robinson, 1990; Ratcliffe et al., 1997). The porphyroblastic samples described herein come from the cover sequences. The samples from Massachusetts come from units considered to be Devonian (Fig. 2). The samples from Vermont were taken from units ranging in age from the Ordovician to the Devonian (Fig. 3; Ratcliffe et al., 1997).

Deformation and metamorphism of the Appalachian orogen within north central Massachusetts was regarded as occurring during the Acadian (Tracy et al., 1976). However, Alleghanian 290–300 Ma (late Pennsylvanian) plus Acadian 330–370 Ma (late Devonian) ages were discovered in these rocks using U–Pb monazite, zircon and titanite and ^{40}Ar–^{39}Ar hornblende ages (Harrison et al., 1989; Spear and Harrison, 1989; Tucker and Robinson, 1990; Robinson et al., 1992). Robinson et al. (1992) concluded that the kyanite zone of the Northfield syncline (Fig. 2a) was re-metamorphosed during the Alleghanian orogeny (we collected samples around this syncline from both the staurolite and kyanite zones). They based this on U–Pb monazite/titanite ages of 290–295 Ma from a variety of formations including the Mt. Mineral and Littleton Formations (Fig. 2a; Tucker and Robinson, 1990; Robinson et al., 1992). Deformation and metamorphism in southeast Vermont is regarded as occurring during the Ordovician Taconic and the Devonian Acadian orogenic events (Stanley and Ratcliffe, 1985; Armstrong et al., 1992; Thompson et al., 1993). As mentioned above, Acadian metamorphism in the vicinity of the Northfield syncline peaked at about 800–825 °C and 6 ± 1 kbar, according to Moecher (1999). However, it is likely that this occurred at a much lower temperature because compositional zoning is well preserved in garnet porphyroblasts formed at this time (e.g. Tracy, 1982), or was the result of structural juxtaposition of rocks of different temperature. Conditions shifted to around 600–650 °C and 6 ± 1 kbar in the Alleghanian (Moecher, 1999). Acadian metamorphism in the Chester–Athens dome region of southeast Vermont peaked at less than 610 °C and around 13.5 kb (Welch, 2003).

3. Structural relationships

The contact of the Pelham dome with the Northfield syncline differs from the contact of the Chester and Athens domes with their surrounding rocks in that it contains pervasively sheared rocks with a mylonitic character against the gneiss dome. These rocks contain a strong mineral elongation lineation aligned N–S as shown in Fig. 2b, and have a younger age than measured elsewhere in the region (Tucker and Robinson, 1990; Robinson et al., 1992). Away from the gneiss dome the lineations are more variable in orientation, as shown in Fig. 2b, but not within the rocks of the Northfield syncline where they remain N–S-trending.

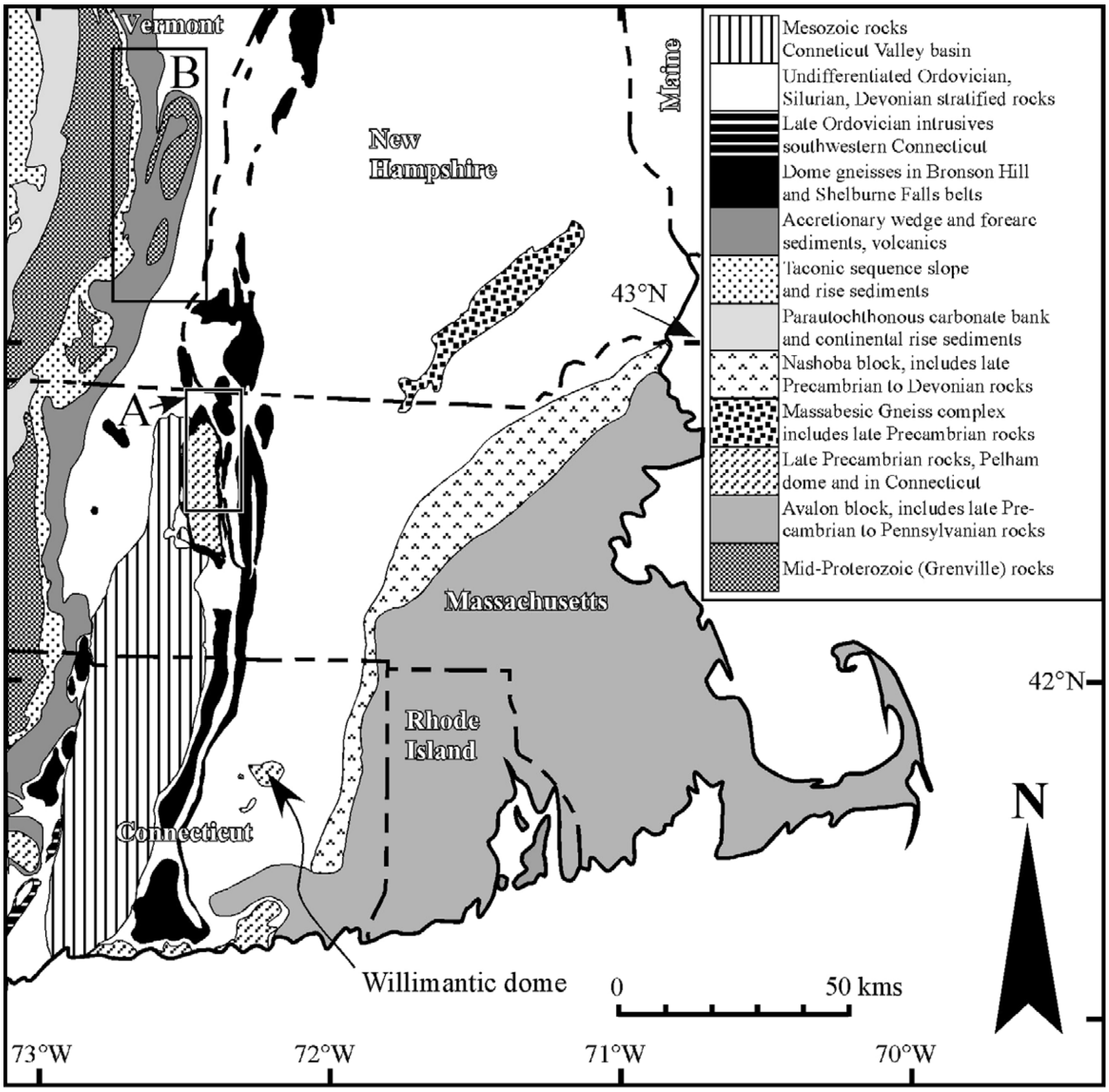

Fig. 1. Generalized geological map of New England showing location of the areas described and shown in Figs. 2 (box A) and 3 (box B).

S–C fabrics, asymmetric winged porphyroclasts, asymmetric strain shadows and asymmetrically boudinaged pegmatites in sections cut parallel to the lineation and perpendicular to the foliation containing this lineation, reveal a consistent top to the south shear sense (Peterson and Robinson, 1993; Reed, 1993). Dating suggests that this foliation has a younger Alleghanian age of 295–290 Ma rather than the Acadian ages determined from the surrounding rocks (Robinson et al., 1992). This foliation, which also pervades the matrix of schists in the Northfield syncline, is folded about the Pelham dome.

4. Inclusion trails and FIA measurement

Inclusion trails observed within garnet porphyroblasts in north central Massachusetts range from straight or sigmoidal to spiral or staircase shaped geometries. Porphyroblast inclusion trails in all the samples studied are truncated by the matrix foliation in 3-D (Fig. 4a; Kim, 2000). Inclusion trails within garnet porphyroblasts in southeast Vermont also range from straight or sigmoidal to spiral or staircase shaped geometries (Bell and Hickey, 1997; Bell et al., 1998). Porphyroblast inclusion trails in more than half of the samples studied are truncated by the matrix foliation (Fig. 4b; Bell et al., 1998). However, the youngest porphyroblasts have inclusion trails that are continuous with the matrix foliation (see below).

4.1. FIA measurement

FIA measurements are made relative to both geographic coordinates and a line perpendicular to the earth's surface. The measurement is thus independent of assumptions, inferences, or interpretations about the timing of the inclusion trails relative to any other structures present in the rock and whether or not the porphyroblast has rotated. Detailed descriptions of how this is done are provided in

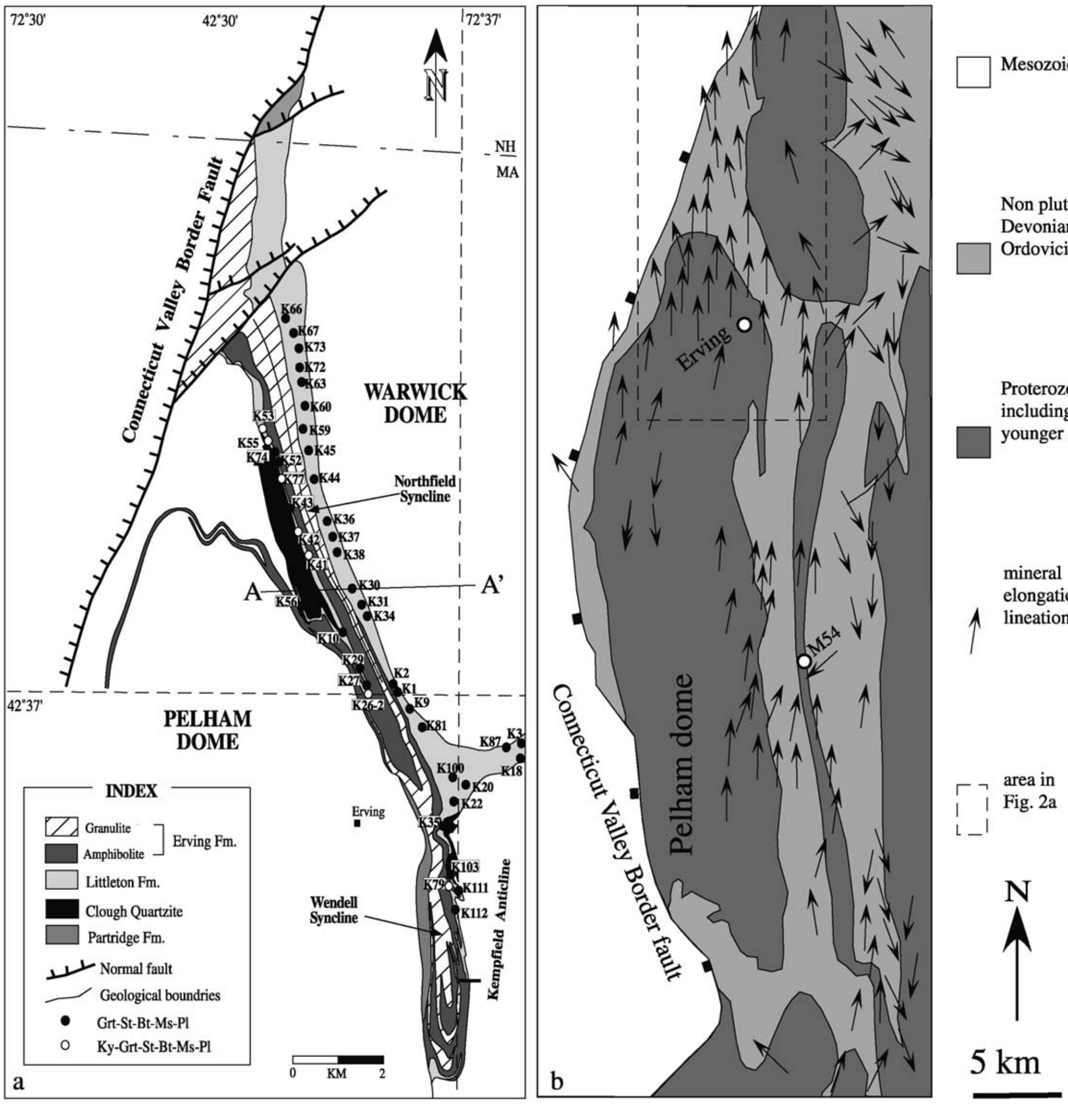

Fig. 2. (a) Geological map showing sample location and metamorphic mineral assemblages (Grt–St and Ky–Grt–St grade rocks) around the Pelham and Warwick Domes in north central Massachusetts (after Zen et al., 1983). Most samples were collected from the Devonian Littleton and Erving Formations. (b) Map showing the orientation of mineral elongation lineations in the region. Modified from a compilation by Reed (1993). Dashes show location of (a).

Hayward (1990) and Bell et al. (1995, 1997, 1998). A FIA is recorded for a sample, rather than for an individual porphyroblast, by locating the asymmetry switch of inclusion trails using vertical thin sections with different strikes from each sample, as shown in Fig. 5. A minimum of eight vertical thin sections are required to measure a FIA trend within a 10° range, with one cut every 30° around the compass and two cuts 10° apart between the sections where the asymmetry of the inclusion trails switches. Because the blocks for thin sectioning are cut from a horizontal slab 2.5 cm thick, the thin sections are always vertical with the strike parallel to the long edge and the way up marked with a single barb, as shown in Fig. 5. There is a very significant microstructural advantage in cutting sections this way because the inclusion trails contained in many porphyroblasts can be observed from a large range of orientations, providing a much better record of the complete inclusion trail geometry than is available from cutting just one or two thin sections. Furthermore, the orientation and asymmetry of matrix structures can be plotted directly onto cross-sections or determined in 3-D and plotted onto maps, and the asymmetries of inclusion trails can be recorded from sections lying at a high angle to the FIA.

We have observed up to four changes in FIA trend within porphyroblasts from the core to the rim (e.g. Bell and Hickey, 1997; Bell et al., 1998). Different porphyroblastic phases can preserve different portions of the deformation and metamorphic history allowing the succession of FIAs to be extended in the one sample. For example, the foliations defined by inclusion trails in the garnet porphyroblasts from the Bolton Syncline (Bell et al., 1997) are always truncated by the matrix foliation, whereas those in the staurolite porphyroblasts tend to be more continuous with the matrix foliation. This potentially allows a succession of three FIA sets within garnet and two younger ones within staurolite to be distinguished in one sample. The data from all the samples is then combined and if a consistent relative succession results, the relative timing for the full succession can be derived. This provides the possibility of absolutely dating the FIA succession using monazite grains preserved within the foliations that define each of the FIAs (e.g. Bell and Welch, 2002).

4.2. FIA data

Kim (2000, 2001) measured a total of 65 FIA trends in garnet porphyroblasts in samples from north central Massachusetts and determined their relative timing (Table 1). He used oriented samples of graphitic mica schist taken around the Northfield syncline on the NE flank of the Pelham Dome (Fig. 2a). These samples were mainly taken from the Littleton Formation, with some from the Erving Formation. Using changes in FIA trend from the core to median to rims of porphyroblasts he demonstrated a consistent succession of FIA trends. The first formed FIA set, FIA set 0, developed with a NW–SE trend. It was followed by FIA sets 1–4, which have NE–SW, E–W, NNW–SSE NNE–SSW trends, respectively (Fig. 6; Kim, 2000). The inclusion trails defining all FIA sets are truncated by the matrix foliation.

Bell et al. (1998) measured a total of 130 FIA trends in garnet porphyroblasts in samples from southeast Vermont and determined their relative timing. They used oriented samples of metasedimentary, garnet bearing, non-carbonaceous quartz–mica schists and carbonaceous pelitic and semi-pelitic phyllites and schists taken from a range of Cambrian (Proterozoic?) to Silurian stratigraphic units. These units were mainly the Moretown, Northfield and Waits River Formations (Fig. 3) around the Athens and Chester Domes and the Spring Hill Synform. Using changes in FIA trend from the core to median to rims of porphyroblasts they demonstrated a consistent succession of FIA trends. FIA set 1, developed with a NE–SW trend. It was followed by FIA sets 2–4 with E–W, NNW–SSE and NNE–SSW trends, respectively (Fig. 7; Bell et al., 1998). One example has been found of a FIA that trends NW–SE, predates FIA sets 1–4, and which is called FIA set 0 (Fig.7d). Bell and Welch (2002) have dated FIA sets 2–4 of this succession in southeast Vermont as ranging from 425 through 404 Ma, 404 through 385 Ma, 385 through 360 Ma and down below 350 Ma in the matrix. The inclusion trails defining all FIA sets except the youngest, FIA set 4, are truncated by the matrix foliation.

Rose diagrams for the total garnet FIA are shown for both the north central Massachusetts (Fig. 8a) and Vermont areas (Fig. 8b). These figures also show the data for single and multi FIAs for each region. Fig. 8c shows a cross-section through the Northfield syncline along the line A–A′ in Fig. 2. The FIA data in Figs. 6 and 8 are unaffected by proximity to the Pelham gneiss dome. The trends of the FIA

Table 1
Garnet FIAs for the area in north central Massachusetts

Sample	Set 1	Set 2	Set 3	Set 4	Set 5
KI			105		
K3			95		
K20	140				
K22					10
K29		65			15
K34		65			
K36	125				
K38	140	60			
K41		55			
K42			110		
K44		60			
K45	125	65			
K52	125			160	
K63		40			
K72		50			
K73			105		
K77	125	45			
K81			110		
K146					
K26-2		50			
K30	140	35			
K79	135	55			
K2		50			
K9		55			
K18		65			
K27		35	90		
K31			105		
K35			100		
K37	140	50			
K43	145	60			
K53	140	70			5
K55				165	
K56	130	40			
K59	135				15
K60	140	50			
K66	130	70			
K74					10, 5
K87		40			
K100		40	80		
K103	120	70			
K111	130				
K112		30, 70		165	
M54			110, 80		

peaks are very similar from north central Massachusetts to SE Vermont (compare Fig. 8a and b) with the exception of FIA peaks 1 and 2, which have shifted anticlockwise by 10 and 15°, respectively. The asymmetry of the inclusion trails associated with each FIA set and separated for both limbs of the Northfield syncline is shown in Fig. 8d.

5. Compositional map and thermobarometric data

X-ray maps of garnet porphyroblasts from the Northfield syncline (Fig. 9) and SE Vermont (Fig. 10) show that these porphyroblasts are compositionally zoned in

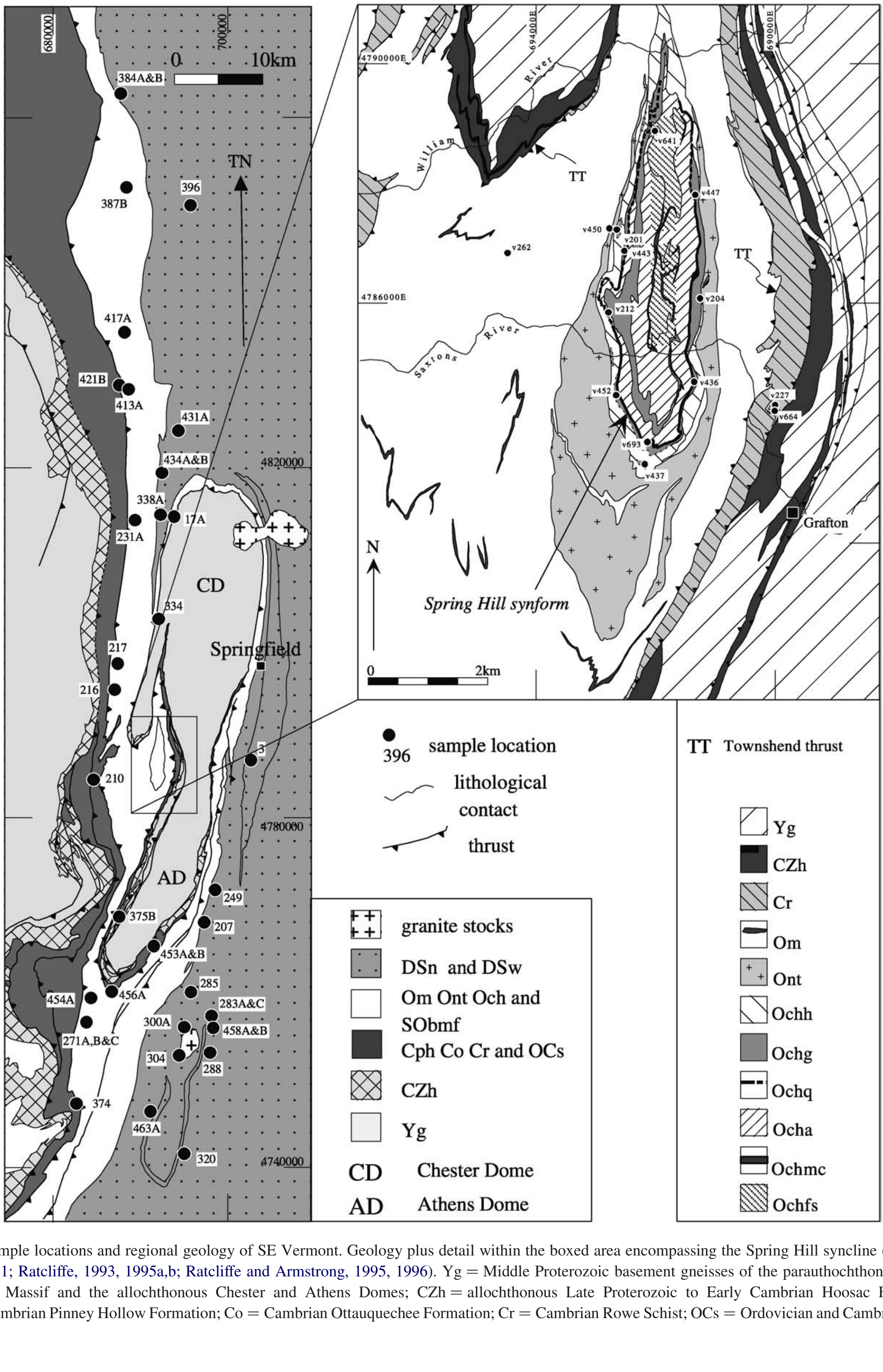

Fig. 3. Sample locations and regional geology of SE Vermont. Geology plus detail within the boxed area encompassing the Spring Hill syncline (after Doll et al., 1961; Ratcliffe, 1993, 1995a,b; Ratcliffe and Armstrong, 1995, 1996). Yg = Middle Proterozoic basement gneisses of the parauthochthonous Green Mountain Massif and the allochthonous Chester and Athens Domes; CZh = allochthonous Late Proterozoic to Early Cambrian Hoosac Formation; Cph = Cambrian Pinney Hollow Formation; Co = Cambrian Ottauquechee Formation; Cr = Cambrian Rowe Schist; OCs = Ordovician and Cambrian Stowe

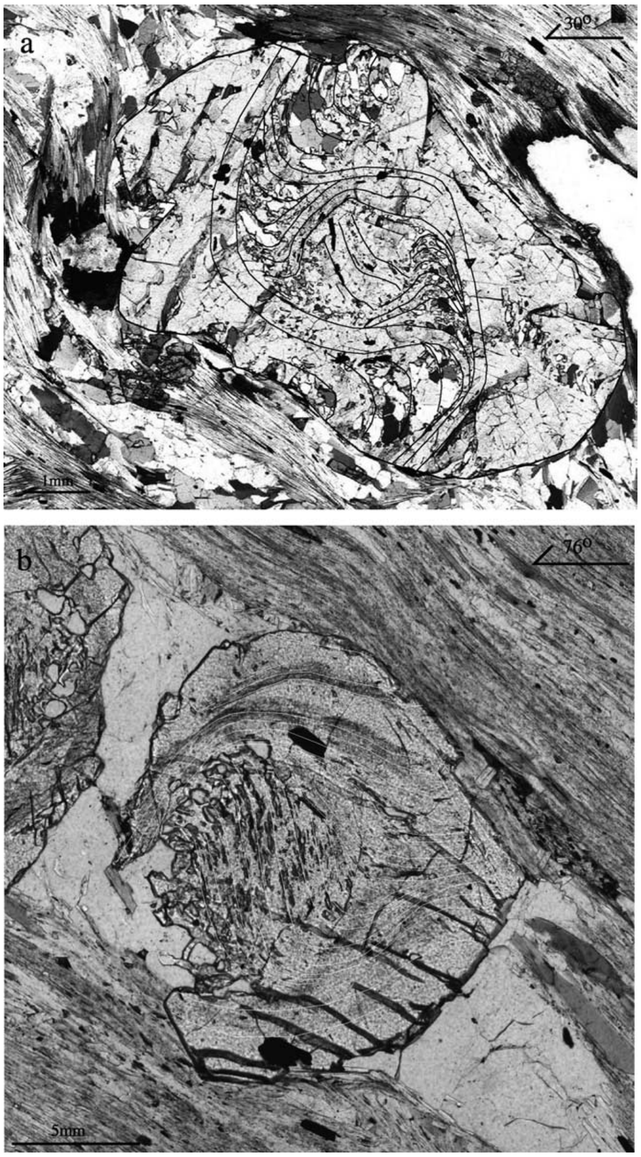

Fig. 4. (a) Shows inclusion trails defining several foliations in a garnet porphyroblast that are truncated by the matrix foliation in north central Massachusetts. Strike and way up shown by single barbed arrow. Sample K53. (b) Shows inclusion trails defining several foliations in a garnet porphyroblast that are truncated by the matrix foliation in SE Vermont. Vertical thin section. Strike and way up shown by single barbed arrow. Sample V436B.

Ca, Mg, and Mn and have similar zoning patterns. Sample K53 from north central Massachusetts contains 10 mm diameter garnet and staurolite porphyroblasts, and the matrix consists of kyanite, biotite, muscovite, plagioclase, chlorite and ilmenite. The garnet porphyroblast shown in Fig. 9a contains a microstructurally well defined core, median and rim that are readily visible in the compositional zoning maps particularly for Ca, but also for Mg and Mn (Fig. 9a). Note how growth during development of the median defines the crenulation hinge at that time and this is also revealed by zoning in Ca. Just outside of the core, Ca (Fig. 9a—Ca) increases in a patchy manner and then decreases. Across the median-rim boundary, the Ca content increases abruptly. Mn decreases and Mg increases from the core to the rim. Note how the Mg content is higher around the quartz rich inclusion trails that reach the porphyroblast rim, with a concomitant decrease in Mg. The Mn and Mg zoning patterns are not as consistent with microstructural growth boundaries as Ca, and show a pattern that suggests some later modification by diffusion. Thermobarometric data for three differently oriented vertical thin sections striking at 30, 90 and 140° from this sample are shown in Table 2. The thermobarometric calculations were carried out using Thermocalc V3.21 and the Holland and Powell (1998) dataset with subsequent upgrades. Average P–T calculations were done for the full sets of independent reactions for each of the samples where a sufficient number of end members were available. Temperature and pressure conditions along with associated errors for each sample are summarized in Table 2. Estimates for the final P–T conditions recorded for each sample were calculated using garnet rim compositions and compositions for matrix minerals (Bt, Ms, Pl and St). Biotite and muscovite compositions were used where they touch garnet. In the case of staurolite and plagioclase, we used rim compositions because these are not in contact with garnet. Kyanite occurs in the matrix with staurolite and texturally formed late in the metamorphism. It was used to calculate peak metamorphic conditions.

Sample K77 from north central Massachusetts contains 6 mm diameter garnet and kyanite porphyroblasts and the matrix consists of kyanite, staurolite, quartz, biotite and plagioclase. The garnet porphyroblast shown in Fig. 9b contains a microstructurally well-defined core and rim that is also visible in the compositional zoning maps, particularly that for Ca (Fig. 9b—Ca). Note how growth during development of the early stages of the median tends to follow the crenulation hinge as revealed by the higher concentrations of Ca. High Mn concentrations around 25 mol.% in the core decrease to low concentrations of 4 mol.% in the rim (Fig. 9b—Mn) and Mg increases in the opposite direction (Fig. 9b—Mg). Note how the Mg content is higher around the quartz rich inclusion trails that reach the porphyroblast rim. Indeed, this phenomenon has been so extensive that the upper right portion of the porphyroblast is an island of lower Mg surrounded by a moat of higher Mg content,

Formation; Om = Ordovician Moretown Formation; Ont = Ordovician North River Igneous Suite; Och = Ordovician Cram Hill Formation; Sobmf = Ordovician to Silurian Barnard Gneiss; DSn = Devonian and Silurian Northfield Formation; DSw = Devonian and Silurian Waits River Formation. (b) Sample locations and geology of the Spring Hill Synform. Adapted from Ratcliffe and Armstrong (1995).

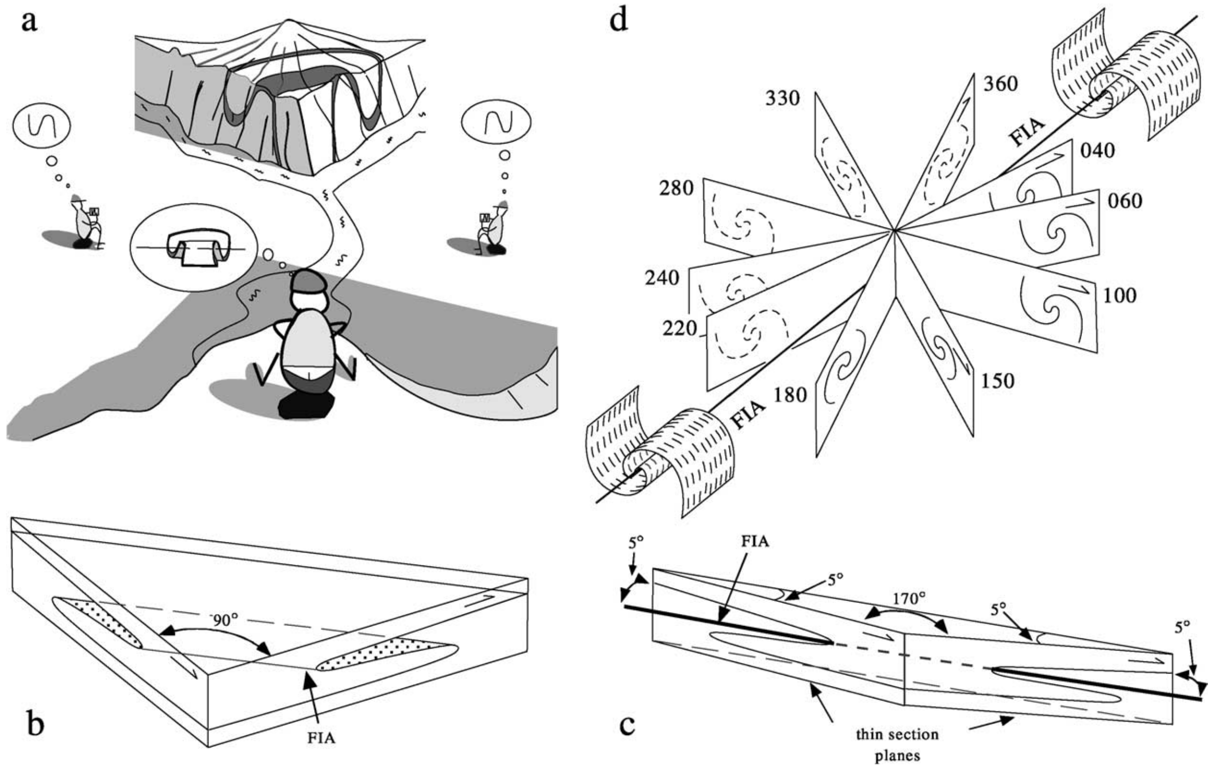

Fig. 5. (a) Sketch illustrating the principle behind measurement of FIAs. The geologists to either side see the opposite asymmetry for same fold in a cliff face. They have no idea of its trend in 3-D. The geologist in the center sees the fold on both cliff faces and knows it must trend from one to the other (modified from Lee (2000)). (b) Shows asymmetry of a sigmoid axis in two sections cut 90° apart. (c) Shows the sigmoid axis of (b) in two sections cut 10° apart lying on either side of the axis. The switch in asymmetry between them defines the location of the axis within a 10° range. (d) Shows a spiral and its asymmetry on a series of differently striking vertical sections. The asymmetry flips across the spiral axis when viewed in the same direction.

Table 2
Average P–T conditions for samples from the Littleton Formation in the Northfield syncline and the Mount Mineral Formation calculated from Thermocalc in average P–T mode (Powell and Holland, 1990) to obtain the pressure and temperature at which the garnet rim equilibrated

Samples	Grt		St	Bt	Ms	Pl	Average P–T ± sd (2s)		Cor.[a]	Sigfit.[b]
	F/(F + M)[c]	X_{Ca}[d]	F/(F + M)	F/(F + M)	N/(N + K)[e]	X_{An}[f]				
K53 (30)[1, 3, 5, 7, 12]	0.813	0.058	0.795	0.449	0.224	0.288	667 ± 24	7.9 ± 1.1	0.058	0.85 (1.61)
K53 (90)[1, 3, 8, 9, 13, 14]	0.861	0.060	0.790	0.439	0.261	0.262	652 ± 23	6.3 ± 1.2	0.054	1.08 (1.54)
K53 (140)[1, 3, 8, 9, 13, 14]	0.862	0.061	0.747	0.428	0.220	0.288	643 ± 21	7.0 ± 1.0	0.015	0.78 (1.54)
K77 (130)[1, 3, 5, 7, 10, 11, 12]	0.836	0.095	0.739	0.428	0.270	0.243	621 ± 23	8.8 ± 1.0	0.001	1.09 (1.49)
K77 (130)[1, 10, 12, 5, 15]	0.841	0.088	0.743	0.421	0.280	0.260	637 ± 21	8.7 ± 1.4	0.015	1.50 (1.54)
K77 (H)[1, 3, 5, 7, 12, 13]	0.859	0.090	0.735	0.446	0.205	0.281	627 ± 21	8.2 ± 1.0	0.001	0.93 (1.54)
K77 (H)[1, 2, 3, 5, 6, 7, 13]	0.849	0.085	0.756	0.461	0.197	0.297	624 ± 14	7.9 ± 0.9	0.584	0.70 (1.49)
K79 (0)[1, 3, 5, 7, 10, 11]	0.797	0.065	0.788	0.422	0.264	0.229	645 ± 45	7.7 ± 1.4	0.767	0.29 (1.73)
K79 (0)[1, 3, 5, 7, 10, 11]	0.791	0.061	0.806	0.419	0.240	0.247	624 ± 23	8.0 ± 0.9	0.070	1.13 (1.49)
M54 (83)[1, 2, 3, 9, 13, 14]	0.852	0.022	0.765	0.525	0.220	0.129	703 ± 20	6.1 ± 1.1	0.737	0.87 (1.54)
M54 (123)[1, 3, 5, 9]	0.866	0.022	0.804	0.548	0.199	0.090	694 ± 50	7.0 ± 1.9	−0.033	0.77 (1.73)

All independent sets of reactions for P–T calculations. The numbers on each sample represent used independent equilibria. 1. gr + 2ky + q = 3an; 2. pa + 3an = gr + ab + 3ky + H_2O; 3. 3east + 6q = py + 2mu + phl; 4. 3east + 2ky + 7q = 2py + 3mu; 5. ann + 2ky + q = alm + mu; 6. 8py + 31 gr + 24mu + 6mst = 24east + 93an + 12H_2O; 7. 23ann + 6fst + 48q = 31alm + 23mu + 12H_2O; 8. 6mst + 75an = 8py + 25gr + 96ky + 12H_2O; 9. 6fst + 75an = 25gr + 8alm + 96ky + 12H_2O; 10. mu + 2phl + 6q = py + 3cel; 11. py + 3mu + 4q = 3cel + 4ky; 12. 25mu + 14mst = 2py + 25 east + 124ky + 28H_2O; 13. phl + 2ky + q = py + mu; 14. py + ann = alm + phl; 15. 4phl + 3fst + 12an = 4gr + 4alm + 4mu + 3mst.

[a] Correlation coefficient between P and T.

[b] Sigfit values of average P–T conditions (sigfit values for 95% confidence).

[c] F/(F + M) = Fe/(Fe + Mg).

[d] X_{Ca} = Ca/(Fe + Mg + Mn + Ca).

[e] N/(N + K) = Na/(Na + K).

[f] X_{An} = Ca/(Ca + Na + K).

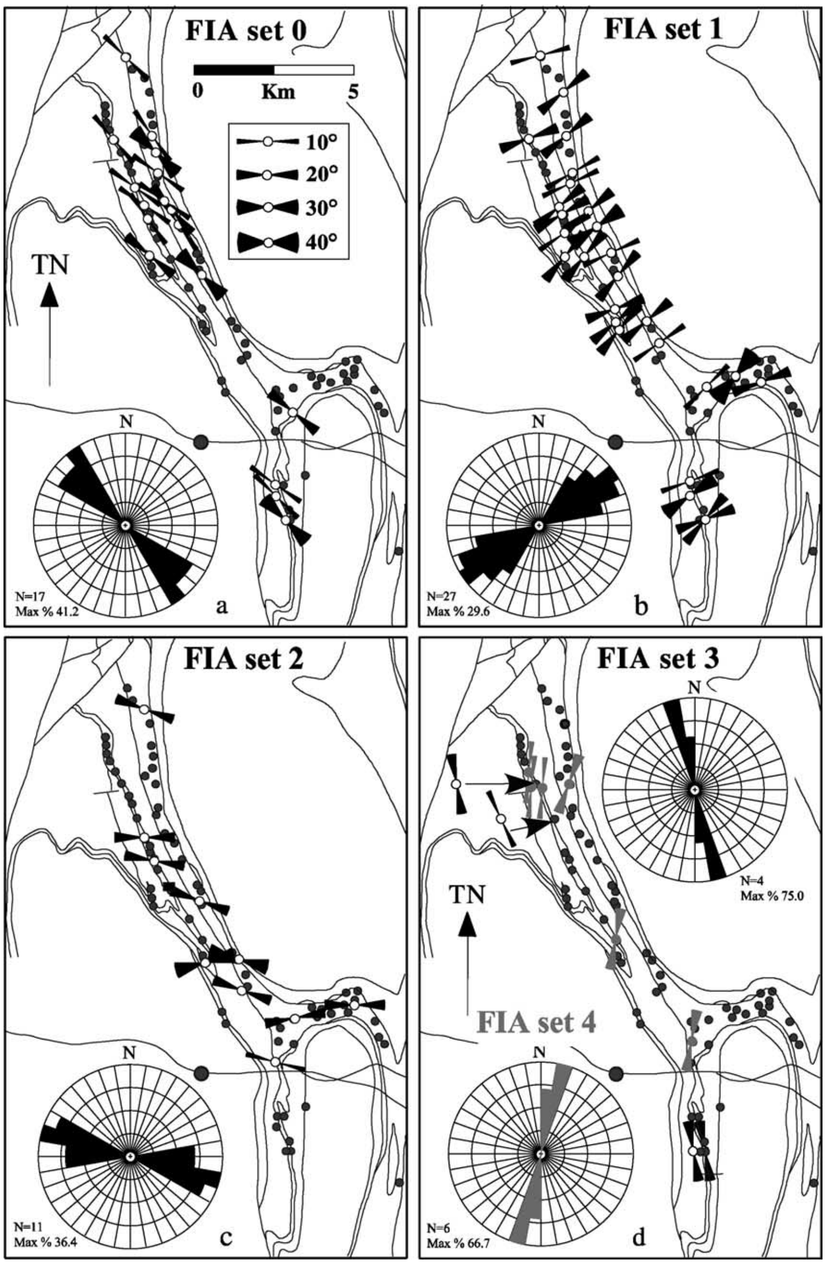

Fig. 6. Shows the trends of garnet FIAs within FIA sets 0–4 on equal area rose diagrams around the Northfield and Wendell Synclines between the Pelham and Warwick Domes. FIA sets 3 and 4 are both shown in (d) with the latter in gray tones.

suggesting some later modification by diffusion. Thermobarometric data for three different thin sections from this sample, two of them vertical and striking at 130° and the third cut parallel to the horizontal, are shown in Table 2. These were calculated using matrix mineral compositions (Bt, Ms, St, Pl) and the rim compositions of garnet porphyroblasts.

Sample V436B from southeast Vermont contains garnet porphyroblasts and the matrix consists of muscovite, biotite and quartz with minor ilmenite and apatite. The garnet porphyroblast shown in Fig. 10 contains a microstructurally well-defined core, median and rim that are readily visible in the compositional zoning maps particularly for Ca, but also for Mg and Mn (Fig. 10). Mn decreases and Mg increases from the core to the rim. Note how the Mg content is higher around the quartz rich inclusion trails that reach the porphyroblast rim, with a concomitant decrease in Mg. The Mn and Mg zoning patterns are not as consistent with microstructural growth boundaries as Ca, and show a pattern that suggests some later modification by diffusion.

The 4 mm diameter garnet porphyroblasts from the Mount Mineral Formation in north central Massachusetts from the eastern edge of the Pelham dome (location M54 in Fig. 2a) contain microstructurally distinct cores containing trails and inclusion free rims, as shown in Fig. 11. They

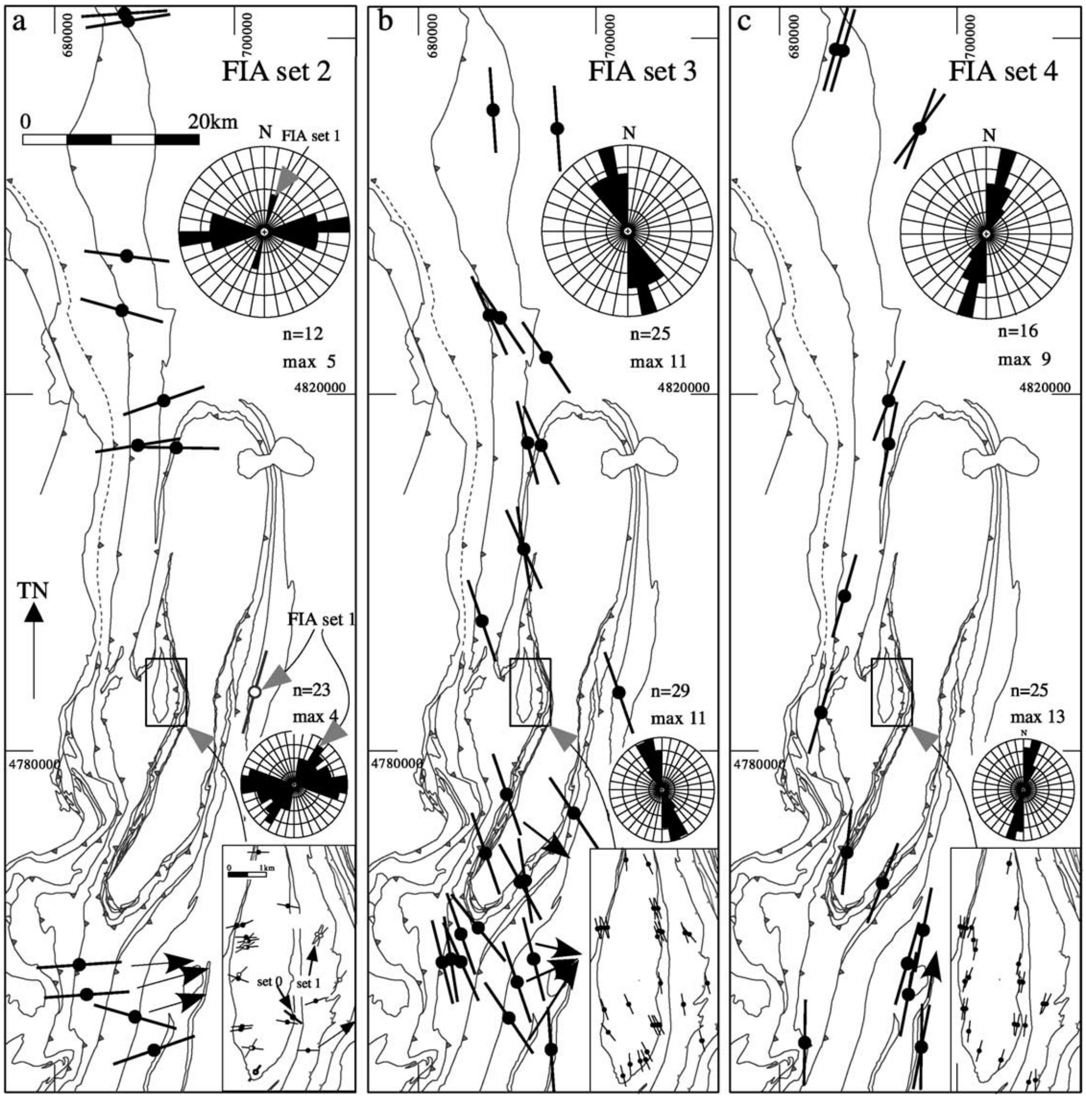

Fig. 7. Shows the trends of garnet FIAs within FIA sets 0–4 on equal area rose diagrams and around the Chester and Athens domes ((a)–(c)) and the Springhill syncline ((d)–(f)).

were regarded as unzoned because of the homogenization effects of localized intense Alleghanian deformation and metamorphic overprinting (e.g. Moecher, 1999). As reported by Moecher (1999) the compositions are close to fully homogenized for Mn and Mg (Fig. 11; our compositional map of one of Moecher's, samples). However, we found that this was not the case for Ca (Fig. 11) where the zoning matches the microstructural boundary separating the two growth zones (as is the case for our own sample (M54) from this region). A 2 mm diameter garnet porphyroblast from the Littleton Formation in the Wendell syncline also shows homogenized compositional zoning in Mg and Mn (Fig. 12a). We measured the FIAs in these samples (M54 and K79, Table 1) and found they were consistent with the rest of our samples (Table 1). The thermobarometric data in Table 2 were calculated using matrix mineral compositions (Bt, Ms, St, Pl) and the rim compositions of garnet porphyroblasts.

6. Interpretation

6.1. Structural relationships of the matrix foliation around the Pelham dome

The pervasive matrix foliation within the Northfield syncline and around the Pelham dome truncates all inclusion trails in porphyroblasts and, therefore, postdates them. This foliation is locally mylonitic, especially close to the gneisses of the Pelham dome. It contains a N–S-trending mineral elongation lineation that has an associated top-to-the-south shear sense (Peterson and Robinson, 1993; Reed, 1993). These relationships, combined with its 290–295 Ma age, suggest that this foliation developed during Alleghanian thrusting to the south of the overlying rocks. The dramatic effects of southwards thrusting on the Northfield syncline are best seen in a near W–E-trending cross-section (Fig. 8c). This cross-section shows a syncline that has been rotated to

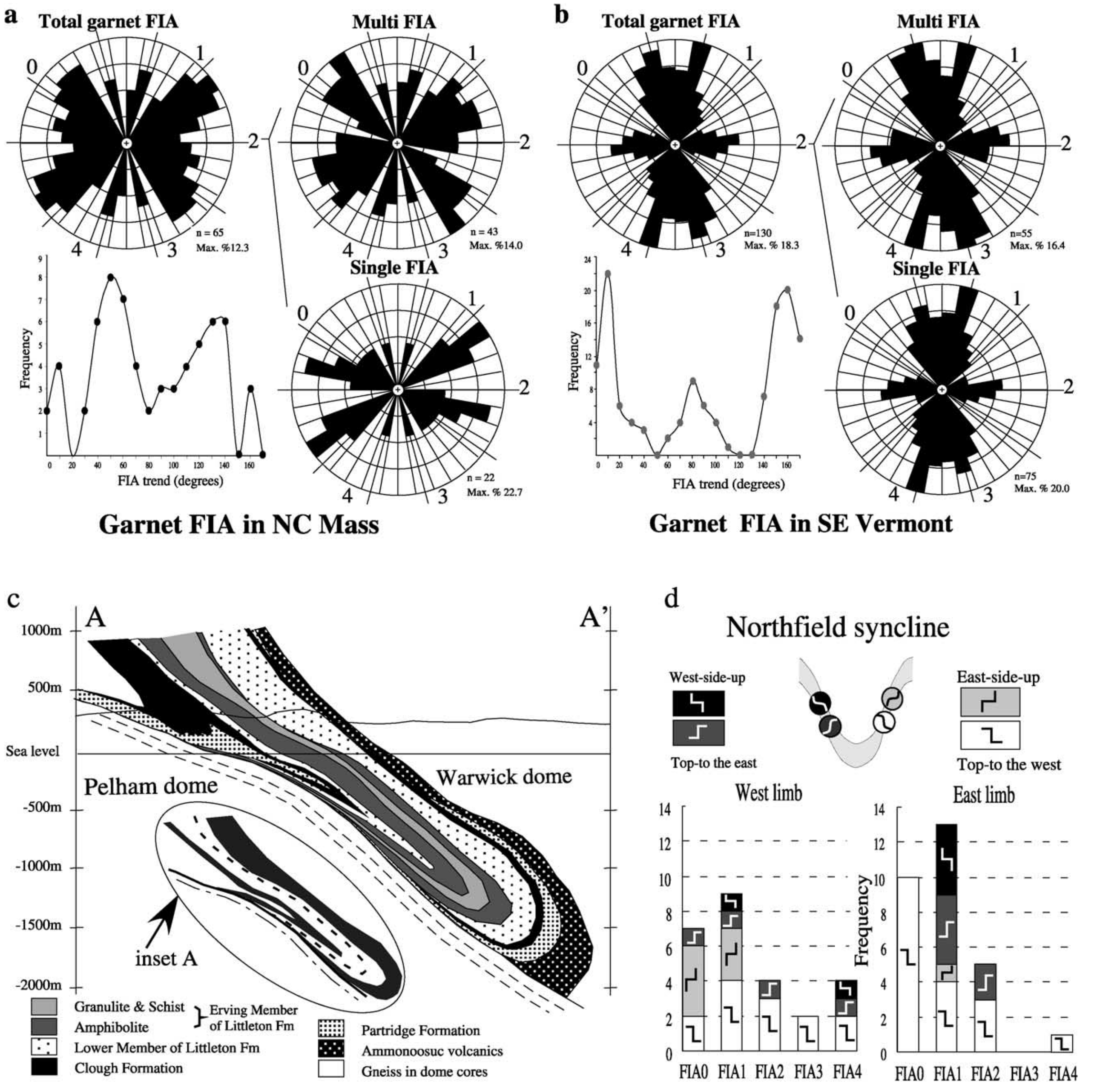

Fig. 8. Comparison of FIA trend distribution between north central Massachusetts (a) and SE Vermont (b). Shows single FIAs, multi FIAs and total FIAs for garnet. (c) Cross-section along line A–A′ in Fig. 2 across the Northfield syncline. Dashed lines show mylonitic foliation trend in the gneiss dome. For ease of viewing, the inset shows the outline of the syncline (axial plane dashed) in black. The syncline is rotated isoclinally and its hinge is destroyed as it gets sheared against the Pelham Dome. (d) Histogram showing the asymmetry of the porphyroblast inclusion trails associated with each FIA set in each sample and recorded as a switch from steep to gentle or gentle to steep so that they can be compared with the fold limbs. The asymmetries were recorded in thin sections cut at a high angle to the FIA measured for that sample.

an east dip from an upright orientation, tightened into an isoclinal fold, and then had its hinge rotated under and up to the west into an antiformal syncline as it got sheared out against the gneisses of the Pelham dome. The syncline is so tight that it is difficult to pick in the cross-section (it is cored by granulite and schist of the Erving member of the Littleton Formation) and it can be best seen in the simplified inset to Fig. 8c. Apparently, motion on the dominant matrix foliation (orientation shown by the dashed lines in the cross-section), with its N–S stretching lineation and shear sense indicating top-to-the-south was the cause of this spectacular geometry. If this was the case, then a large amount of N–S displacement is required to produce this geometric relationship on a near W–E-trending cross-section, and this is supported by the degree of disruption of the hinge of the syncline against the Pelham gneiss dome. This means that the Pelham dome rocks did not lie below the Northfield syncline prior to thrusting taking place in the Alleghanian.

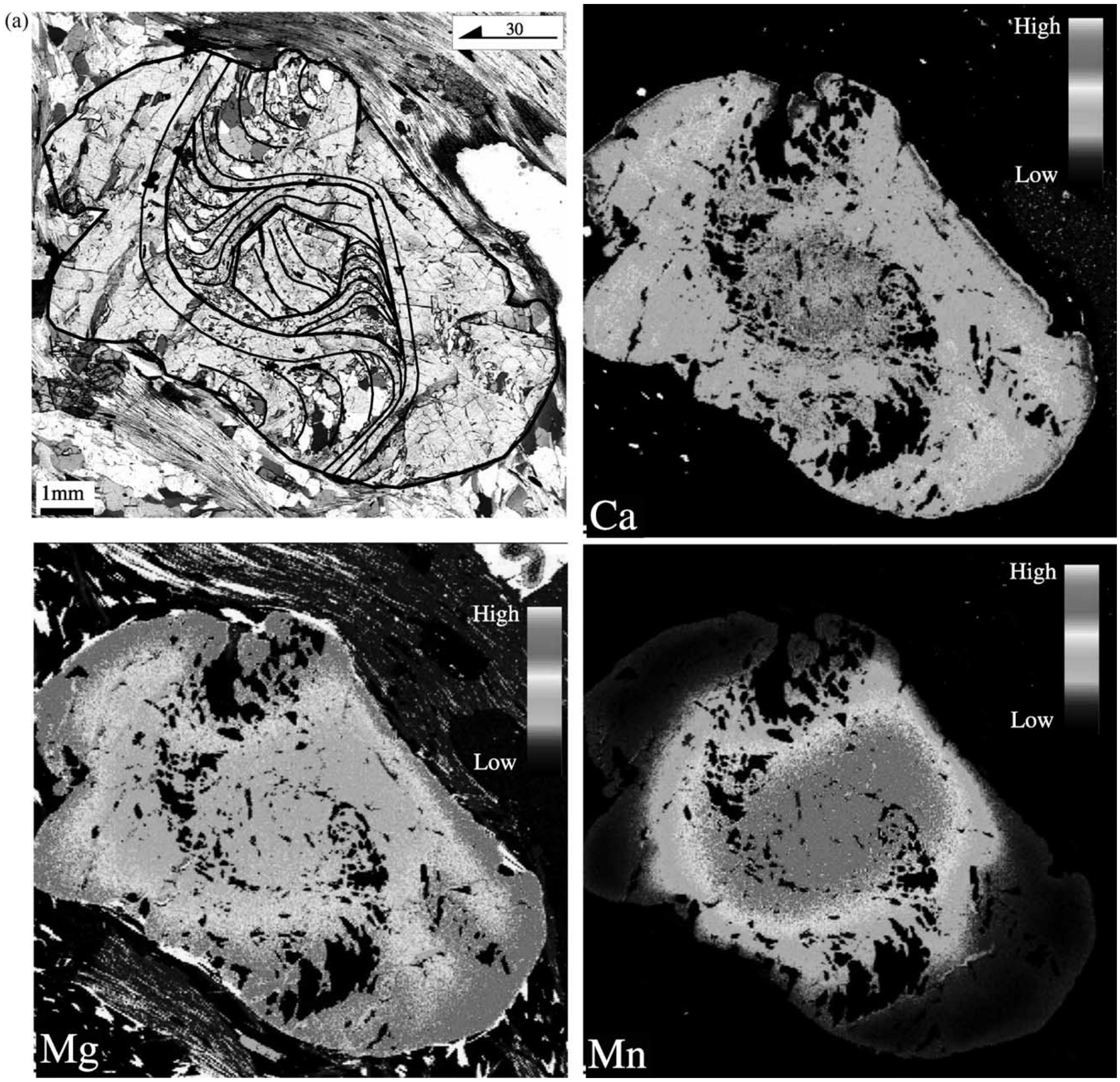

Fig. 9. (a) Compositional X-ray maps of calcium (Ca), manganese (Mn) and magnesium (Mg) in a garnet porphyroblast plus a photo of the porphyroblast at the same scale with highlighted inclusion trails in north central Massachusetts. Sample K53. Vertical thin section with strike and way up shown by single barbed arrow.

6.2. FIA sets

The succession of FIA trends from the Northfield syncline in north central Massachusetts is identical to that in SE Vermont (Fig. 8) except that FIA set 0, which was the first to form in the former area, developed rarely in the latter region. However, FIA set 0 is well developed in the Pomfret dome area further to the NE in Vermont (Bell et al., 2003). The FIA sets in SE Vermont range progressively from pre-425 Ma through 405, 385 and 360 Ma, respectively, to 350 Ma in the matrix as revealed by the dating of monazite grains defining foliations that form each FIA set (Bell and Welch, 2002). We interpret that the succession of FIA sets observed in the Northfield syncline have similar Acadian ages. The truncation of all the inclusion trails in garnet porphyroblasts in the north central Massachusetts rocks by the matrix foliation accords well with the development of this locally mylonitic foliation during the Alleghanian (Robinson et al., 1992) with its strong N–S aligned mineral elongation lineation. Therefore, we conclude that all growth of garnet porphyroblasts containing inclusion trails within the Northfield syncline occurred during the Acadian orogeny.

6.3. FIA asymmetry and fold timing

The asymmetry of the inclusion trails associated with the

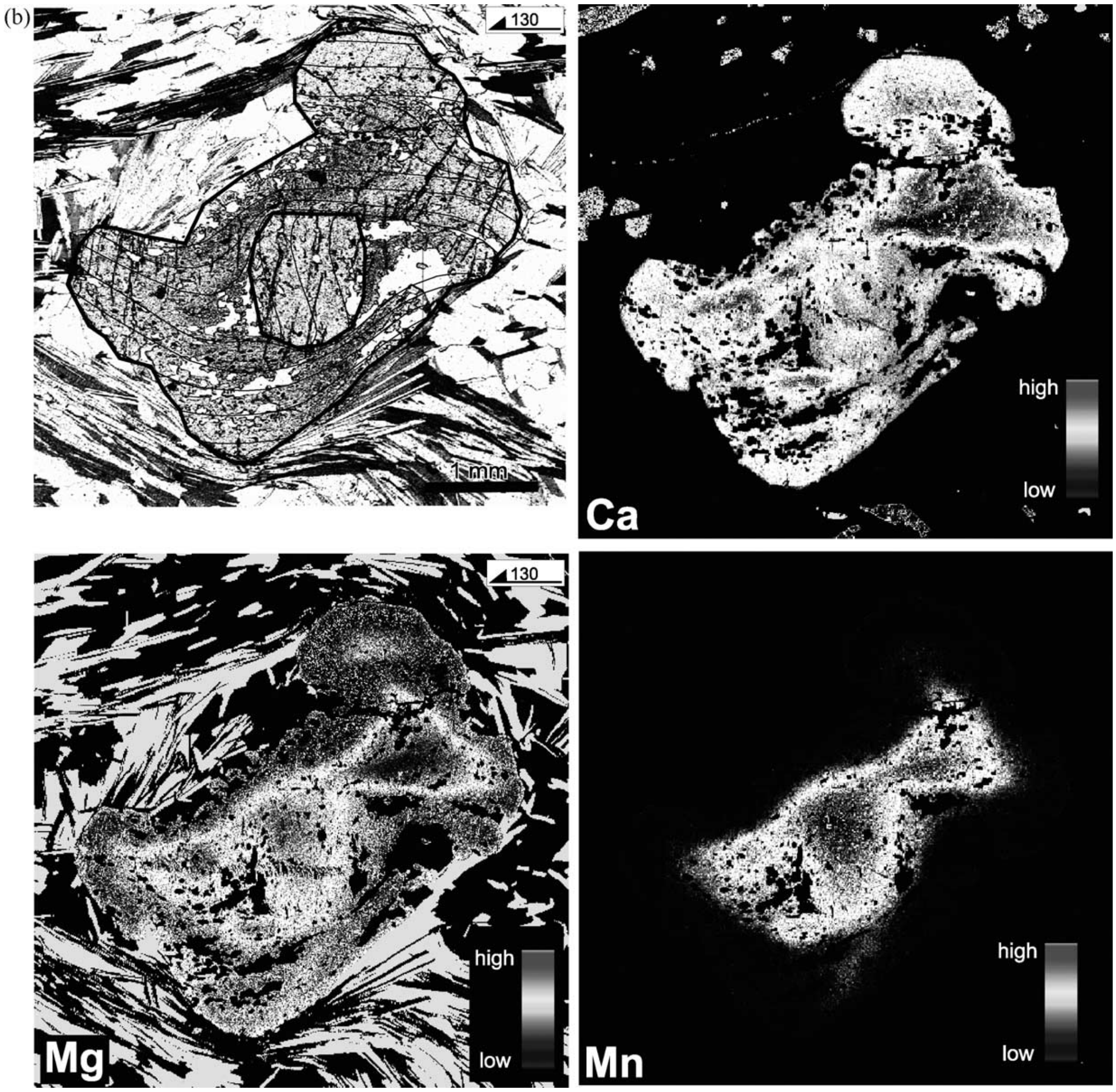

Fig. 9 (b) Compositional X-ray maps of calcium (Ca), manganese (Mn) and magnesium (Mg) in a garnet porphyroblast plus a photo of the porphyroblast at the same scale with highlighted inclusion trails in north central Massachusetts. Sample K77. Vertical thin section with strike and way up shown by single barbed arrow.

succession of five FIA trends recorded for the Northfield syncline is shown in Fig. 8d (that for SE Vermont is reported in fig. 10c and d in Bell et al. (2003)). Any garnet porphyroblasts that grew synchronous with fold development should show a dominance of west side up asymmetries on the west side and east side up asymmetries on the east side, as shown in the upper boxes to either side of the fold sketch. However, no FIA set contains porphyroblast inclusion trail asymmetries that switch across the fold hinge in this manner, suggesting that the fold formed very early during the history of deformation and metamorphism in a similar manner to that described and discussed by Bell et al. (2003) for several regional folds, including one in SE Vermont. Indeed, as observed by those authors, the opposite asymmetry to that expected tends to dominate one limb of the fold. They attributed this phenomenon to the fact that the fold was present prior to porphyroblast growth. This generally enabled reactivation of the bedding to occur on one limb from the commencement of each deformation event, decreasing the number of suitable sites for porphyroblast nucleation and growth on that limb. Consequently, we argue that the Northfield syncline formed early during the deformation history, as did the folds in SE Vermont.

6.4. Compositional maps

Compositional zoning in garnet porphyroblasts in samples from the Northfield syncline (Fig. 9) is similar to that in garnet porphyroblasts in SE Vermont (Fig. 10). This suggests that the porphyroblasts, which grew in the Acadian

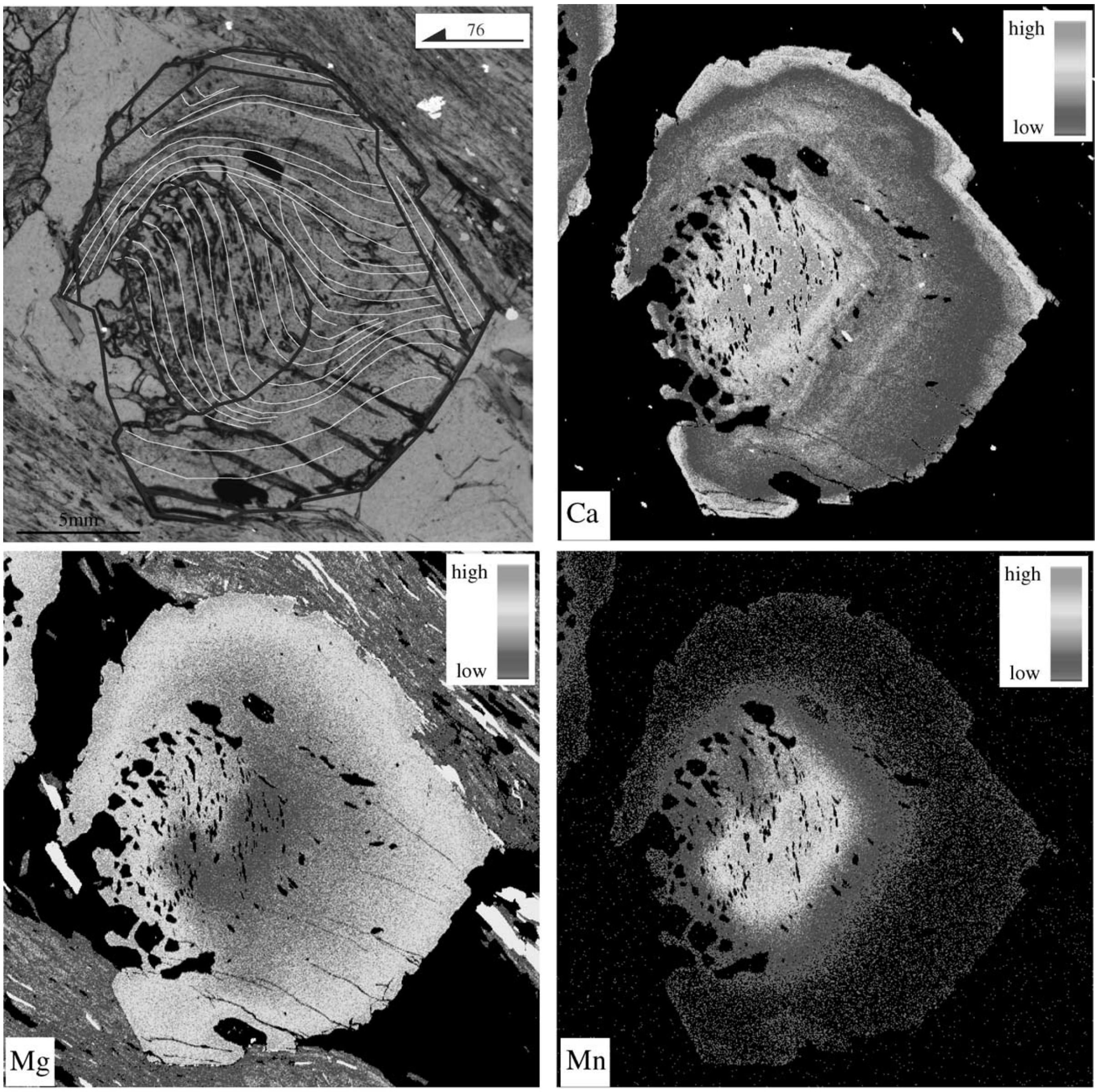

Fig. 10. Compositional X-ray maps of calcium (Ca), manganese (Mn) and magnesium (Mg) in a garnet porphyroblast plus a photo of the porphyroblast at the same scale with highlighted inclusion trails in southeast Vermont from sample V436B. Vertical thin section with strike and way up shown by single barbed arrow.

in the Northfield syncline, were only slightly or not affected by homogenization during overprinting by Alleghanian deformation and metamorphism of the matrix, even though the resulting foliation truncates the inclusion trails inside every porphyroblast. This is not surprising as similar truncation of the inclusion trails by the matrix foliation occurs for all garnet porphyroblasts in SE Vermont, except those that grew during the youngest FIA event. In both SE Vermont and north central Massachusetts, the Mg content is higher around quartz inclusion trails that reach the porphyroblast rim. This pattern suggests that the grain boundaries of quartz inclusions were important in post-garnet growth diffusion of Mg into the garnet porphyroblast, and concomitant removal of Mn. This has produced locally significant effects in the porphyroblast rims, but appears to have had little effect in the cores. The presence of this phenomenon in both regions suggests it was not the result of the Alleghanian overprint. The tendency for Ca zoning (and in some cases Mg and Mn zoning) to follow inclusion trails defining the crenulation hinge around the core in Fig. 9a and b is interpreted to result from the role of microfracture along phyllosilicates in porphyroblast nucleation and growth, as described in Bell et al. (1986).

The relationships described above for the Northfield syncline, however, are very different from those observed in the intensely deformed rocks of the Mount Mineral formation (e.g. sample M54), which lie in contact with gneisses on the eastern side of the Pelham Dome (Robinson

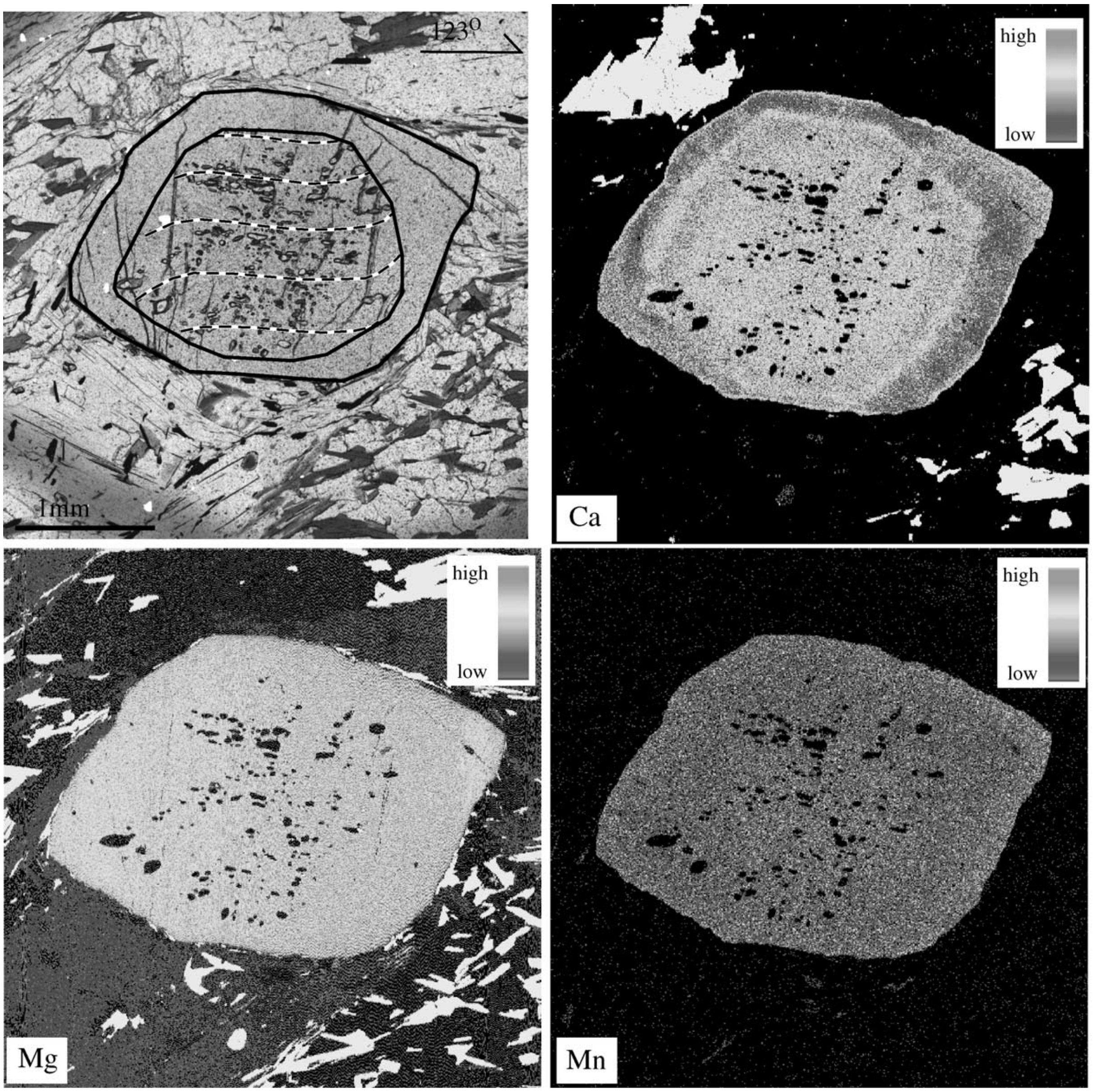

Fig. 11. Compositional X-ray maps of calcium (Ca), manganese (Mn) and magnesium (Mg) in a garnet porphyroblast plus a photo of the porphyroblast at the same scale with highlighted inclusion trails in north central Massachusetts. Sample M54 from the Mount Mineral Formation. Vertical thin section with strike and way up shown by single barbed arrow.

et al., 1992; Moecher, 1999), as well as a sample from the eastern limb of the Wendell syncline to the east of the Pelham dome, which contains small 2 mm diameter garnet porphyroblasts (sample K79; location shown in Fig. 2a). These samples show homogenization of compositional zoning in garnet porphyroblasts, which in elements such as Mg and Mn (Figs. 11—Mn and 11—Mg and 12) with small atomic sizes, is complete. However, elements such as Ca (Fig. 11–Ca), which have much larger atomic sizes, are much less affected and preserve evidence for similar compositional zoning patterns to those observed in a range of elements for samples collected around the Northfield syncline (Fig. 9) and in SE Vermont (Fig. 10). It is important to note that the 2 mm diameter of the porphyroblasts in sample K79, compared with samples K54 (10 mm) and K77 (6 mm), may have promoted homogenization of the compositional zoning in this rock relative to the latter ones. Diffusion of Mg and Mn but not Ca through the garnet crystal lattice to a uniform distribution, indicates that homogenization was not all pervasive and we expect the inclusion trail geometries were not affected. This could be why the FIAs in M54 accord with the FIAs in the samples from around the Northfield syncline and K79. Insufficient FIAs have been measured within the Mount Mineral formation to know whether the rocks from this unit show the same succession as those within the Northfield syncline.

We interpret that homogenization of the garnet

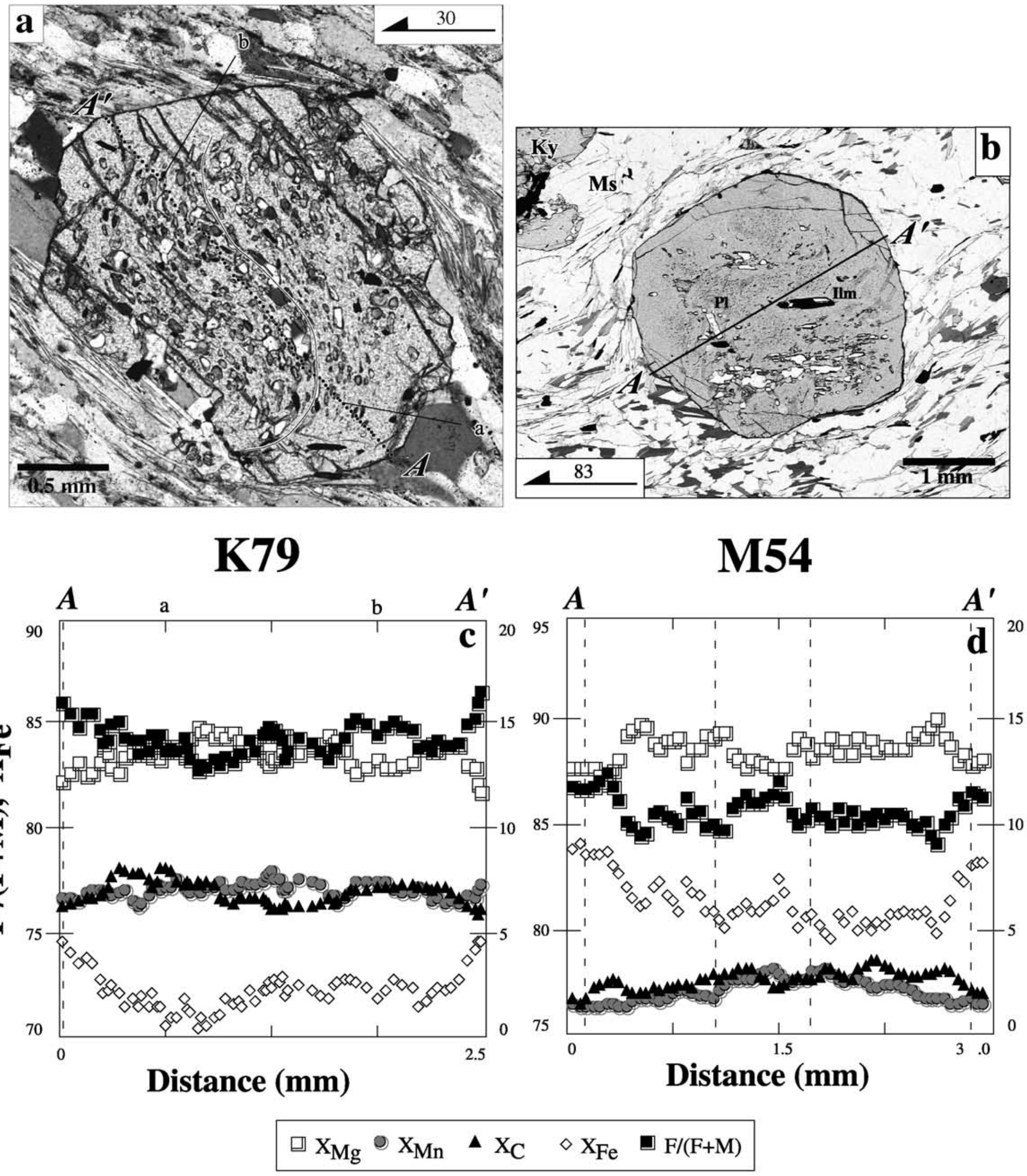

Fig. 12. (a) Photo of garnet porphyroblast showing a sigmoidal-shaped inclusion trail. Lowercase and uppercase letters indicate locations analyzed. Vertical thin section (striking 30°) of sample K79. Partially crossed polars. (b) Photo of garnet porphyroblast from sample M54 (vertical thin section with strike of 83° and way up shown by single barbed arrow) from the Mount Mineral Formation. Sample location is the same as stop 7 of Robinson et al. (1992). (c) and (d) Profile diagrams of compositional zoning of the garnet porphyroblasts in samples K79 and M54.

porphyroblasts in sample M54 resulted from shear heating associated with the very intense, locally mylonitic deformation that took place along the boundary of the overlying rocks with the gneisses of the Pelham dome, which has been dated as having occurred at 290–295 Ma. Another possible interpretation is that hotter Alleghanian rocks from the south were over-ridden. However, we prefer the shear heating alternative as a result of interpreting the thermobarometric data below.

6.5. Thermobarometric data

The rims of older garnet porphyroblasts should tend to re-equilibrate towards younger matrix conditions due to diffusional exchange between the rim and the developing matrix foliation. Hence the garnet rim temperature and pressure results shown in Table 2 should tend to reflect Alleghanian matrix conditions. Samples K53 and K77 lie 1.5 km along strike from one another along the same limb of

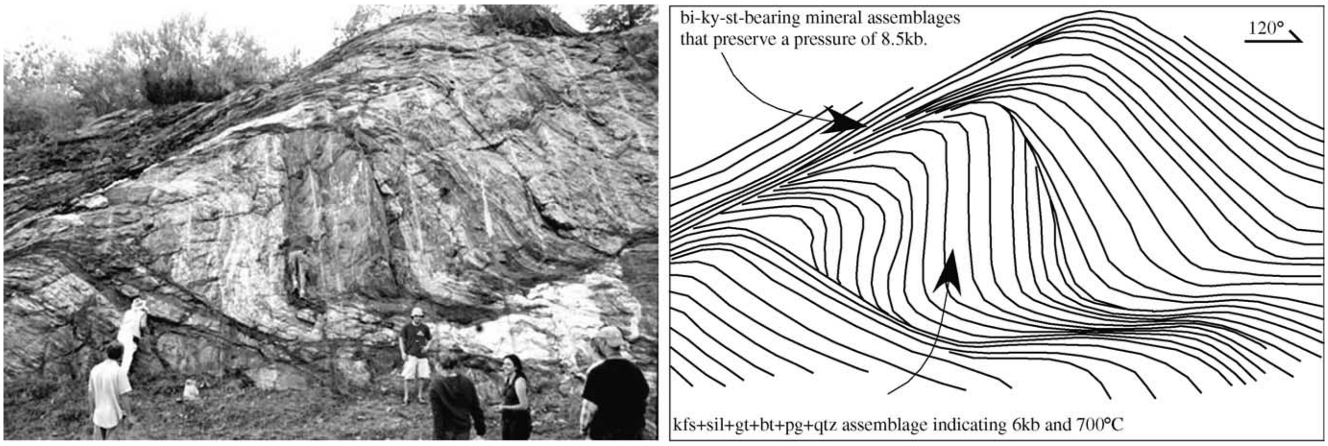

Fig. 13. (a) Outcrop of the top of the Willimantic Dome showing the partitioning of deformation on the scale of the roadcut into zones of progressive shearing that bound zones of progressive shortening. (b) Detailed line diagram of foliation within outcrop shown in (a) revealing that earlier partitioning of strain has occurred between two of the blocks within the zone of progressive shortening prior to development of the shallowly dipping younger zones of progressive shearing. The location of two different mineral assemblages is shown. Single barbed arrow shows strike of outcrop.

the Northfield syncline, and 2 km or more across strike from the margin of the Pelham dome. Their calculated temperatures and pressures are within error of one another and average around 638 °C and 7.8 kb compared with sample K79 at 634 °C and 7.85 kb, which lies in a similar location but on the east limb of the Wendell syncline. Because the compositional zoning in K79 has been homogenized we interpret that these conditions reflect those of the Alleghanian matrix at the time of pervasive shearing, but away from the zone of more mylonitic deformation on the margin of the gneiss dome. We attribute the near homogenization of the Acadian compositional zoning of the garnet in K79 to the small size of these porphyroblasts and potentially closer proximity to the margin of the dome during the earlier stages of development of the shear zone.

Sample M54 lies within the zone of most intense deformation along the contact with the gneiss below. The 699 °C temperature recorded by the rim of sample M54, compared with the 636°C average for the rims of samples K53, K77 and K79 and the much lower core temperature of M54, was due to:

1. Deformation, metamorphism and shear heating that took place during the Alleghanian, or
2. The emplacement of the Northfield syncline over much hotter rock causing the temperature to rise in the most sheared rocks, but not in rocks from within the Northfield syncline, or
3. Errors in the P–T calculations.

Potentially, this rim temperature of 699 °C developed at the same time as the internal homogenization of the compositional zoning in garnet porphyroblasts (e.g. Tracy, 1982) that appears to be characteristic of this horizon (e.g. Moecher, 1999; Fig. 11). We believe the first of these interpretations is the most likely. The matrix conditions suggested above for samples K53, K77 and K79 are 63 °C lower, requiring a much too high a thermal gradient for the Alleghanian. Table 2 shows that the errors in the P–T calculations range from 14 to 50 °C, but with most around 22 °C. The bulk of the data for samples K53, K77 and K79 does not overlap with that for M54, strongly suggesting that the temperature increase of 63 °C is significant. We believe that it is unlikely that the rocks below were dramatically hotter than the rocks above during emplacement as we interpret the rocks within the gneiss dome to have been the leading northern edge of a tectonic wedge of Avalon crust. We, therefore, expect it to be heating up with progressive orogenesis rather than cooling down.

6.6. Structural relationships

A similar contact in terms of its large-scale geological relationships (e.g. Wintsch and Sutter, 1986; Moecher and Wintsch, 1994; Moecher, 1999) is present in Eastern Connecticut between the gneissic rocks of the Willimantic dome and the rocks above. However, this contact differs from that around the Pelham dome in that several locally intensely developed foliations rather than one main pervasive foliation are present and the youngest of these involved top-to-the-north rather than top-to-the-south shear as shown in Fig. 13. This gently-dipping, non-pervasive foliation has been dated at 275–280 Ma (Moecher and Wintsch, 1994) and therefore is 10–20 million years younger than the one seen above the Pelham dome. Earlier formed, gently-dipping foliations trapped within the strain shadows of the large scale pods shown in Fig. 13 preserve evidence for the development of top-to-the-south shear prior to the younger top-to-the-north shear (Ben Rich, pers. comm. of unpublished data, 2003). We infer that the contact of Avalon to the east with the Putnam–Nashoba terrane to the west connected with the shear zone on the boundary above the Willamitic dome (after Moecher and Wintsch,

1994) and with the shear zone above the Pelham dome at around 295 Ma and was formed by thrusting of the rocks lying to the north over those to the south. Certainly, the displacement required in a N–S direction to produce the distortion of the Northfield syncline seen in the near W–E cross-section in Fig. 8c is extraordinary and strongly supports this interpretation. This zone was subsequently folded by younger horizontal shortening developing locally sub-vertical foliations (Ben Rich, pers. comm. of unpublished data, 2003) and then portions of it were reused in the vicinity of the Willimantic and Putnam–Nashoba boundaries by younger events with the opposite shear sense.

7. Discussion

7.1. Lack of rotation of porphyroblasts

The distribution and succession of FIA trends from both north central Massachusetts and SE Vermont could not be explained if the porphyroblasts had rotated during deformation or as they grew. If the porphyroblasts rotated as they grew, FIA set 0 in north central Massachusetts would have been rotated by a range of angles up to 180° around FIA set 1 (Fig. 14a) as the inclusion trails defining this FIA set curve up to at least this amount (e.g. Figs. 4a and 9). FIA set 1, plus the rotated spread of FIA set 0, would have been rotated by a range of angles up to 180° around FIA set 2 (Fig. 14b) as the inclusion trails defining this FIA set curve up to at least this amount. FIA set 2, and the rotated spreads of FIA sets 0 and 1, would have been rotated by a range of angles up to 180° around FIA set 3 (Fig. 14c) as the inclusion trails defining this FIA set curve by angles up to at least this amount. Finally, FIA set 3, and the rotated spreads of FIA sets 0–2, would have been rotated by a range of angles up to 180° around FIA set 4 as the inclusion trails defining this set curve by angles up to at least this amount. We did not bother showing this in Fig. 14 as the FIA covered the whole stereo after the development of FIA set 3 (Fig. 14c). Similarly, FIA set 1 in SE Vermont would have been rotated by a range of angles up to 360° around FIA set 2 (Fig. 14d) as the inclusion trails defining this FIA set curve up to at least this amount (Bell et al., 1998). FIA set 2, and the rotated spreads of FIA set 1, would have been rotated by a range of angles up to 360° around FIA set 3 as the inclusion trails defining this FIA set curve by angles up to at least this amount (Fig. 14e). Finally, FIA set 3 and the rotated spreads of FIA sets 1 and 2, would have been rotated by a range of angles up to 360° around FIA set 4 as the inclusion trails defining this set curve by angles up to at least this amount. We did not bother showing this in Fig. 14 as the FIA covered the whole stereo after the development of FIA set 3 (Fig. 14e). Clearly, the result in both regions would have been an incredibly complex distribution (Fig. 14) rather than the simple one that we observe. Significantly, there would have been none of the consistency that is observed in the trend of successive FIAs determined from core, median and rim changes (e.g. Bell et al., 1998) or in the succession of ages (Bell and Welch, 2002). Apart from this, FIA plunges have been measured in the Spring Hill portion of SE Vermont and they are all very gently plunging (Bell and Hickey, 1997). As shown in Fig. 14d and e, this would be impossible if the porphyroblasts had rotated. Consequently, we can be confident that the porphyroblasts did not rotate when they formed or during subsequent deformations.

7.2. High shear strains during north to south thrusting and their implications

Emplacement of the Northfield syncline over the Pelham dome gneisses during the Alleghanian developed an intense schistosity that is locally mylonitic in character and which truncates the inclusion trails preserved in all porphyroblasts. Based on the cross-section relationships shown in Fig. 8c and the pervasive N–S stretching lineation, we interpret that very large top-to-the-south displacements accompanied the development of this locally mylonitic schistosity. The Northfield syncline had an axial plane striking at a low angle to this N–S motion. Consequently, large displacements were required to generate sufficient shearing and shortening to rotate this syncline into the antiformal syncline against the Pelham gneiss dome shown in Fig. 8c. Indeed, the intensity of shearing was so great that much of the hinge of this syncline was obliterated against the gneiss dome. Significantly, the porphyroblasts were not rotated by the highly non-coaxial nature or intensity of the shearing (Figs. 6 and 8), confirming similar observations from shear zones elsewhere (e.g. Jung et al., 1999).

7.3. Shear heating versus Alleghanian metamorphism

The role of shear heating versus the emplacement of hotter rock is difficult to assess in most geologic environments (e.g. Camacho et al. (2001) versus Bjørnerud and Austrheim (2002)). For the situation described herein, we can be fairly confident that the temperature for Alleghanian metamorphism of the matrix in the rocks of the Northfield syncline has been determined and that the gradient in temperature into the contact zone with the Pelham gneiss dome is significant (Table 2) as it is too great for a normal geothermal gradient. Shear heating, or the emplacement of hotter rock below, appear to be the only viable alternatives. For the increase in temperature to result from the emplacement of hotter rock below, then these rocks would have come from the hot core of the Alleghanian orogen. The Pelham dome is interpreted as being continuous with Avalon to the southeast (e.g. Moecher, 1999; Dorais et al., 2001). If this is correct, then the rocks within the Pelham dome form the northwards leading edge of Avalon, and the hot orogen core lay well to the south or SSE. The deformation that occurred along the boundary of the Pelham gneiss dome within the Mount Mineral formation was

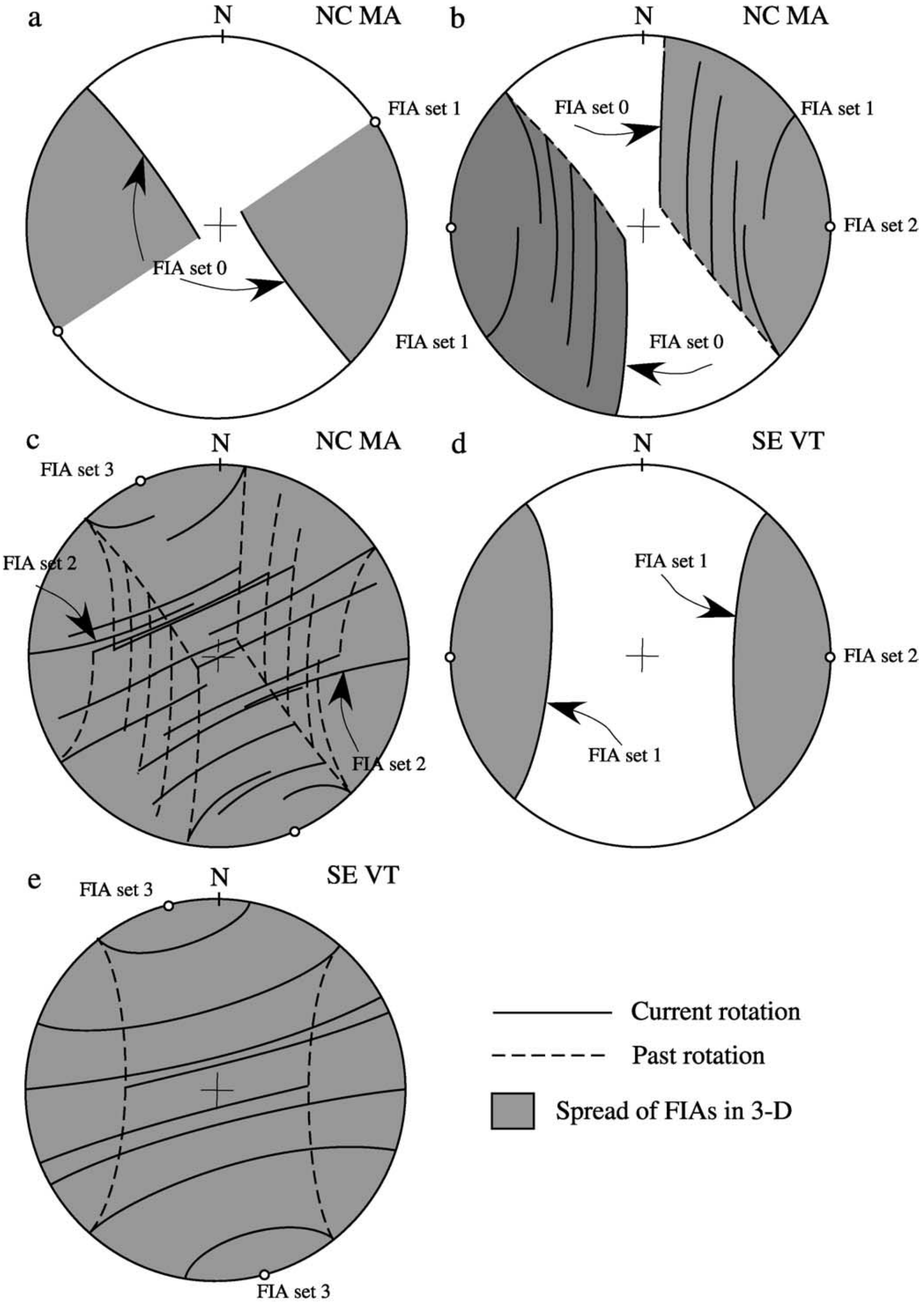

Fig. 14. Stereographic projections of the trend of successive FIA sets rotated about subsequently formed ones to examine the effects of any porphyroblast rotation accompanying spiral inclusion trail development. The maximum possible rotation for north central Massachusetts is greater than 180° as the largest curvatures of inclusion trails accompanying each FIA set exceed this—all inclusion trails are truncated by the matrix foliation. The maximum is more than 360° for SE Vermont. (a) For north central Massachusetts, FIA set 0 formed at about 90° to FIA set 1. If the curved inclusion trails formed by rotation of the garnet porphyroblasts FIA set 0 should be variably rotated on a small circle by 90° to either side about FIA set 1 (totaling 180°) as shown. (b) FIA set 2, lies about 45° from FIA set 1. Up to 180° of further rotation of FIA set 0 are shown, plus the effects of this rotation on FIA set 1, producing a large variation of FIA trends. (c) Further rotation about FIA set 3 cause earlier-formed FIAs to cover the projection. (d) For SE Vermont, FIA set 2 formed at about 50° to FIA set 1. If the curved inclusion trails formed by rotation of the garnet porphyroblasts FIA set 1 should be variably rotated on a small circle by 180° to either side about FIA set 2 (totaling 360°) as shown. (e) Further rotation about FIA set 3 produces an enormous variation of FIA orientations that covers the projection. Consequently, the effects of FIA set 4 for both areas were not incorporated. Note that there is a consistency in FIA orientations from limb to limb across the large-scale folds in both regions (see also Figs. 6 and 7).

mylonitic in character and intensity penetrating well into the overlying Northfield syncline rocks. As mentioned above, our interpretation of the structural relationships requires large-scale southwards shearing of the latter rocks over the Pelham dome, which equates well with them being thrust over Avalon. Consequently, we suggest that shear heating best explains our observations. Indeed, the one deep geological environment where work hardening, and thus shear heating, can potentially occur, is in a mylonite zone where strain rates are so high that plastic deformation dominates over diffusional mass transfer (Hickey and Bell, 1996). Wintsch and Dunning (1985) showed that dislocations potentially only play a significant role in metamorphic processes that accompany ductile deformation at extremely high dislocation densities such as those that can develop during mylonitization.

7.4. Tectonic development

Moecher and Wintsch (1994) and Moecher (1999) suggested that the mylonitic deformation occurring on the contact of the Pelham dome with the overlying rocks of the Northfield syncline correlates with the mylonitic deformation that occurred on the top of the Willamitic dome and that the underlying rocks could be a part of the composite terrane that comprises Avalon (see also Dorais et al., 2001). The correlation of these domal cores with Avalon was based on a common lithologic assemblage including meta-igneous rocks with Late Proterozoic ages as defined by U–Pb zircon crystallization ages. This age is recorded in southeast Avalon and the Willimantic dome at about 620 Ma (Wintsch and Aleinikoff, 1987) and in the Pelham dome at 615 Ma (Tucker and Robinson, 1990). A problem with this correlation has been the top-to-the-north shear sense apparent in Fig. 13 and the 10–20 million year younger age obtained from the mylonitic foliation above the Willamitic dome. However, recent detailed work on spatially oriented samples obtained from the outcrops shown in Fig. 13 has shown that an earlier history of top-to-the-south shearing predates the top-to-the-north shear visible in the outcrop and the bulk of the matrix (Ben Rich, pers. comm. of unpublished data, 2003). Consequently, we interpret that the gneisses underlying both domes are part of Avalon and were emplaced into their current location beneath North America around 290 Ma. We also interpret that Avalon had a wedge shape that thinned to nothing just to the north as there is no indication of these rocks in SE Vermont, which lay some 10–15 km below the crustal level exposed in north central Massachusetts at the time that thrusting took place. Any wedge of Avalon had to be much less than 10 km thick if it did reach SE Vermont, or some significant effects of Alleghanian orogenesis would have been apparent in the latter rocks.

7.5. Correlation across the Connecticut Valley Border Fault

The Proterozoic through Devonian rocks of north central Massachusetts and SE Vermont have been strongly affected by multiple folding events and intense metamorphism during the Acadian orogeny (Robinson et al., 1990, 1992; Bell and Welch, 2002). Correlation of structural and metamorphic events across the Connecticut Valley Border Fault has always been a problem, partially because the rocks in SE Vermont reached pressures around 5 kb higher than those to the east (including the rocks in the Northfield syncline), and partially because of the parallelism of younger matrix foliations. The identical FIA succession from FIA sets 0–4 from north central Massachusetts to SE Vermont provides a way of correlating in detail periods of deformation and metamorphism preserved on both sides of this fault, as well as allowing the ages determined for the SE Vermont rocks (Bell and Welch, 2002) to be suggested for the north central Massachusetts rocks and tested in the future by dating any monazite preserved as inclusion trails. FIAs provide an approach that will eventually allow a detailed and sophisticated comparison of the progressive history of metamorphism on both sides of this major boundary. We argue that the rocks to either side of the Connecticut Valley Border Fault have undergone the same periods of Acadian deformation/metamorphism and have not been brought together from a large distance apart by strike-slip faults or major thrusts late in the tectonic history. The rocks from the west side of the Connecticut Valley Border Fault were simply uplifted late in the deformation history.

7.6. A first pass comparison of T–t across the Connecticut Valley Border Fault

Chemical zoning within garnet porphyroblasts in north central Massachusetts can be divided into two types; (1) strong zoning patterns (Fig. 9; e.g. samples K53 and K77); and (2) homogenized zoning patterns (Fig. 11; e.g. samples K79 and M54). Such patterns require either that the temperatures reached in samples K79 and M54 were greater and/or attained for longer times than those in samples with strongly zoned profiles, or that the intense deformation that took place adjacent to the Pelham dome was a significant factor through the input of strain energy (e.g. Wintsch and Dunning, 1985). Fig. 15 combines data from a range of currently published sources in a simple, first pass fashion to show possible Acadian to Triassic, Temperature–time (T–t) paths for the area of the Pelham Dome and the Bronson Hill Zone based on monazite, titanite, hornblende, muscovite, biotite, and K–feldspar U–Pb, Ar–Ar and K–Ar ages (Tucker et al., 1988; Harrison et al., 1989; Spear and Harrison, 1989; Tucker and Robinson, 1990; Wintsch et al., 1992; Kim, 2001). The T–t paths for staurolite- and kyanite-grade rocks in SE Vermont are based on data from Armstrong and Tracy (2000). The peak temperature for SE Vermont was about 600 °C around 384 Ma (Armstrong and Tracy, 2000). The peak temperature for the Mount Mineral formation in north central Massachusetts was about

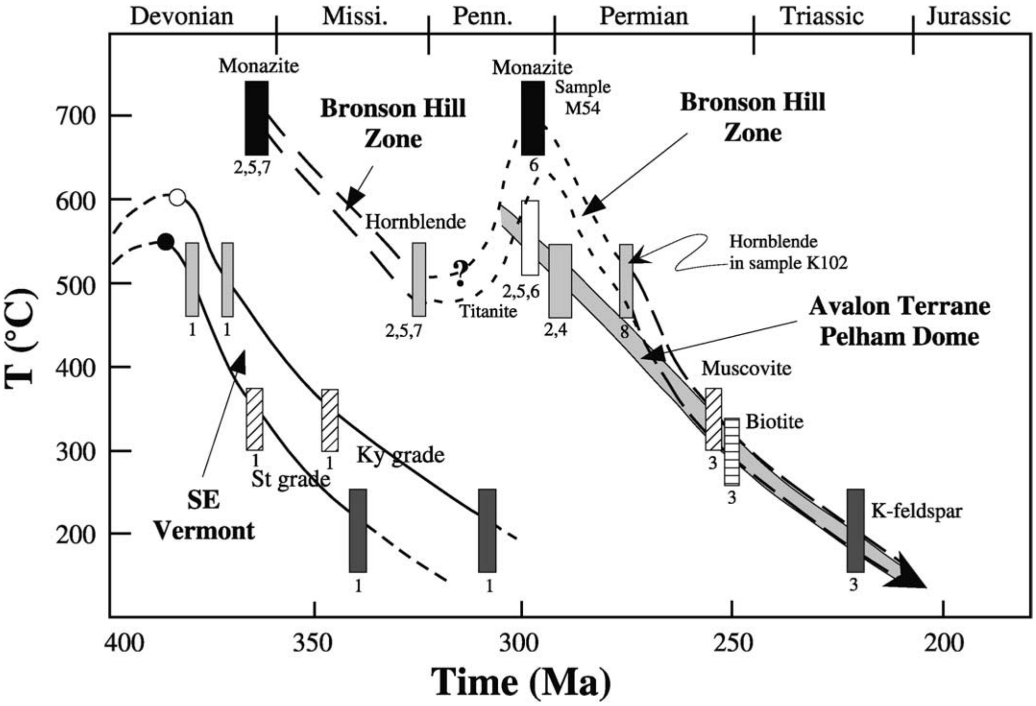

Fig. 15. Possible Late Paleozoic Temperature–time (T–t) paths for SE Vermont and the Pelham Dome and Bronson Hill Zone in north central Massachusetts using currently published data from the range of sources mentioned below. Geochronologic data for staurolite-grade rocks (filled circles) and kyanite-grade rocks (open circles) in SE Vermont are from Armstrong and Tracy (2000)[1]. Geochronologic data for the Pelham Dome and Bronson Hill Zone are from Tucker et al. (1988)[2], Harrison et al. (1989)[3], Spear and Harrison (1989)[4], Tucker and Robinson (1990)[5], Robinson et al. (1992)[6], Wintsch et al. (1992)[7] and Kim (2001)[8]. Superscripts show data source for each portion of the figure.

700 °C in the Pennsylvanian around 290 Ma (Robinson et al., 1992). This temperature could homogenize the chemical zoning of garnet (Tracy, 1982) although the effects of the very intense deformation in the Mount Mineral formation, or some combination of these two phenomena, cannot be excluded.

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