Journal of Structural Geology 26 (2004) 825–845

JOURNAL OF STRUCTURAL GEOLOGY

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Partitioning of deformation along an orogen and its effects on porphyroblast growth during orogenesis

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Received 15 April 2003; received in revised form 4 November 2003; accepted 11 November 2003

Abstract

An identical succession of foliation inflection/intersection axis trends in porphyroblasts (FIAs) is present in three separate areas affected by Acadian deformation and metamorphism along 130 km of the Appalachians from East Central Vermont to North Central Massachusetts. The FIAs trend successively NW–SE, SW–NE, W–E, NNW–SSE and SSW–NNE and appear to have formed during the same succession of deformations, which have been dated in SE Vermont as follows; not yet dated, pre-425, 425–404, 404–385 and 385–360 Ma, respectively. The two areas that are furthest apart, in east central Vermont and north central Massachusetts, have strikingly similar total distributions of FIAs in garnet porphyroblasts that show a somewhat inverse relationship to those observed in the Chester–Athens dome area of SE Vermont that separates them. That is, the number of samples containing the first formed FIA set is greatest for the two regions lying furthest apart and decreases in younger sets, whereas the number of samples containing the first FIA set is the least in the central region and increases for more recently developed sets. Partitioning of deformation into zones of progressive shearing and shortening has been demonstrated to control the sites of development of differentiated crenulation cleavage versus porphyroblast growth and sites of porphyroblast growth on one limb of a regional fold versus the other. We argue that partitioning of the deformation around competent feldspathic gneiss bodies at an orogen scale produced the variation in the number of samples containing the various FIA sets between the central and outer areas described above.

Porphyroblasts most commonly grew during SW–NE directed shortening to the north and south of the Chester–Athens dome region of the Appalachians, but only rarely grew in the latter region. This suggests that deformation at this time partitioned around an outlier of competent basement feldspathic gneiss that underlies the Chester–Athens dome region, and this protected the rocks above and in the strain shadow to the NW and SE from the effects of the great bulk of the deformation that occurred over the period of time during which NW–SE-trending FIAs formed. We attribute the increase in the number of samples containing progressively younger FIAs in the Chester–Athens dome area during subsequent periods of NW–SE-, N–S-, WSW–ENE-, and WNW–ESE-directed shortening to the rise in temperature and pressure recorded in the rocks above the Chester–Athens dome with peak conditions occurring during the development of the NNW–SSE oriented FIA set between 404 and 385 Ma. As the temperature and pressure increased, the gneiss below would have become less competent, allowing the deformation associated with the succession of FIA sets to partition more pervasively through the dome core. This provided more sites for porphyroblast nucleation and growth and hence the number of samples recording these FIA sets increased. The concomitant decrease in the number of samples in which porphyroblasts grew in the rock within the areas to the north and south with successive FIAs possibly resulted from a progressive increase in competency of these rocks as the number of porphyroblasts increased.

Keywords: Deformation partitioning; Porphyroblast growth sites; FIAs; Regional structural correlation

1. Introduction

It was recognized in the 1980s that the partitioning of deformation into zones of progressive shearing (shearing generally with a component of shortening) and shortening (coaxial shortening plus or minus no strain), controls the sites of development of differentiated crenulation cleavage versus porphyroblast nucleation and growth, respectively (Fig. 1; Bell, 1981; Bell et al., 1986). This and subsequent work has shown that porphyroblasts preferentially nucleate and grow in discrete zones of progressive shortening such as crenulation hinges (Hayward, 1992; Davis, 1993, 1995; Williams, 1994; Stallard, 1998), whereas non-platy and non-fibrous minerals tend to be dissolved in zones of progressive shearing (Bell and Cuff, 1989). Growth of

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doi:10.1016/j.jsg.2003.11.021

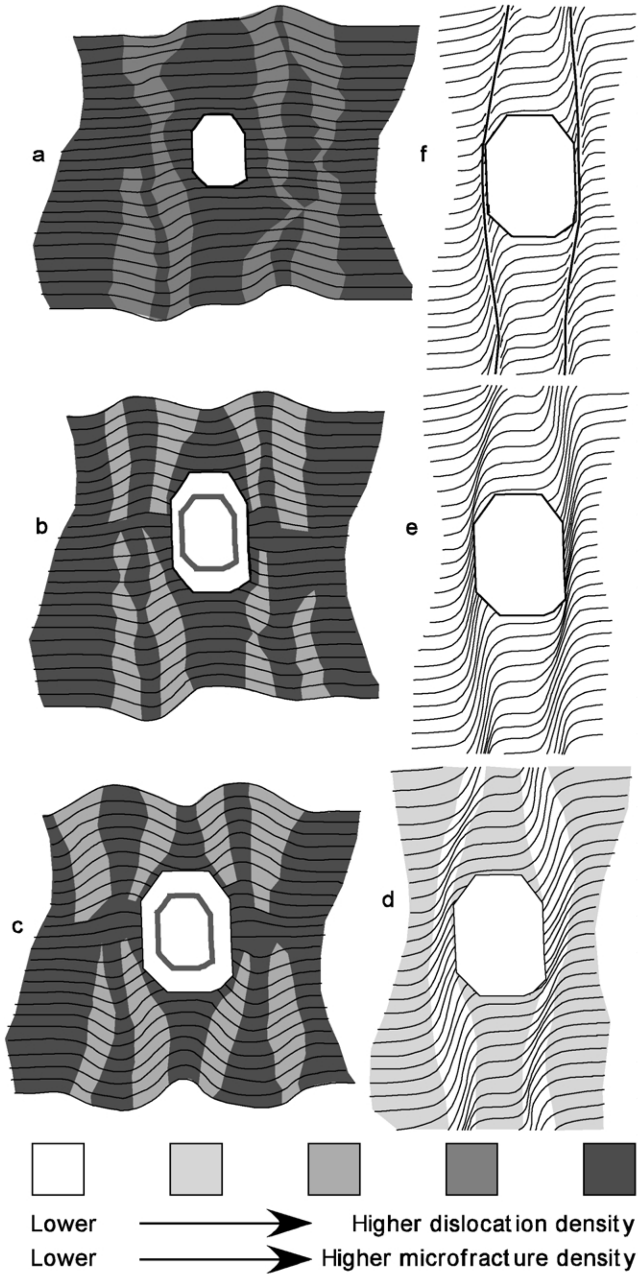


Fig. 1. Conceptual sketches showing in 2D the progressive development of deformation partitioning during the one event through a patch of rock, based on Bell et al. (1986) and Bell and Hayward (1991). The shapes of the deformed foliation may apply at virtually any scale. The higher fracture densities may apply at the scale of 100's of metres down to microscopic. Higher dislocation densities may apply at the scale of a porphyroblast (white euhedral shapes in the centre of each sketch). High dislocation densities and microfracture development occur soon after the commencement of deformation while the strain is relatively coaxial as shown in (a). As the deformation becomes more non-coaxial in portions of the rocks, the dislocation density and microfracture density in those portions decreases as shown in (b) and (c). Once a consistent pattern of deformation partitioning is achieved and the deformation becomes non-coaxial across the block as shown in (d), porphyroblast growth has ceased and the dislocation density decreases significantly. The differentiated crenulation cleavage shown in (d)–(f) intensifies with increasing strain from the crenulated foliation connecting across the zone of progressive shearing in (d) and (e) to it being truncated (f) by micas recrystallizing along this zone.

porphyroblasts in zones of progressive shortening would be aided by any concurrent microfracture, as this would allow access of the materials needed for the reactions to take place. If such microfracture occurred, it would develop most readily during the relatively coaxial stages of deformation (Bell and Hayward, 1991), prior to the establishment of a pervasive pattern of deformation partitioning as shown in Fig. 1. A build up of strain energy in crenulation hinges, in the form of dislocation density, would further aid the formation of porphyroblasts that have a high activation energy barrier to overcome before they will nucleate (Wintsch, 1985; Wintsch and Dunning, 1985; Bell et al., 1986). Detailed work with porphyroblasts containing complex inclusion trail geometries has been accomplished over a large range of metamorphic grades (e.g. Bell and Cuff, 1989). Such work has revealed that each phase of porphyroblast growth that traps a portion of the inclusion trail geometry occurred early during the deformation in which it occurred, at which stage the deformation is relatively coaxial, as shown for growth during a single event in Fig. 1 (e.g. Hayward, 1992; Jones, 1994; Adshead-Bell and Bell, 1999).

The role of the partitioning of deformation in mineral growth was particularly highlighted by the work of Moecher and Wintsch (1994). They described Middle Devonian migmatitic kfs + sil + gt + bt + pg + qtz gneisses preserving metamorphic conditions of 6 kb and 700 °C that were overprinted by a higher-pressure event during the late Paleozoic Alleghanian orogeny in the Willimantic dome, Connecticut (Figs. 2 and 3). This latter event had no discernible impact on the mineralogy or the texture except where the progressive shearing component of deformation was partitioned into metre-scale zones around pods of earlier deformed gneiss (Fig. 3). Within the zones dominated by progressive shearing, the new schistosity is defined by biotite–kyanite–staurolite-bearing mineral assemblages that preserve a pressure of 8.5 kb. Subsequent tectonic unloading recrystallized these schists, again only in local shear zones, where kyanite was replaced by sillimanite and locally by andalusite, indicating a decompressing P–T path from 600 °C and 6 kb to 550 °C and 3 kb.

An additional role for deformation partitioning in sites for porphyroblast growth at outcrop and larger scales became apparent with the development of a technique for measuring foliation inflection/intersection axes preserved in porphyroblasts (FIAs) (Hayward, 1990; Bell et al., 1995). The trend of a FIA, which includes the axes of sigmoidal, staircase- or spiral-shaped, inclusion trails, can be measured for all the porphyroblasts in a sample as a whole (Fig. 4a and b) within a range of 10°. Many samples contain differently-trending FIAs in the core versus the median versus the rim of porphyroblasts. Consistent relative timing of successions of FIA trends obtained from such samples enables a relative chronology for the total FIA succession to be determined (e.g. Bell and Hickey, 1997). Quantitative data obtained using this method revealed that three different FIAs can be

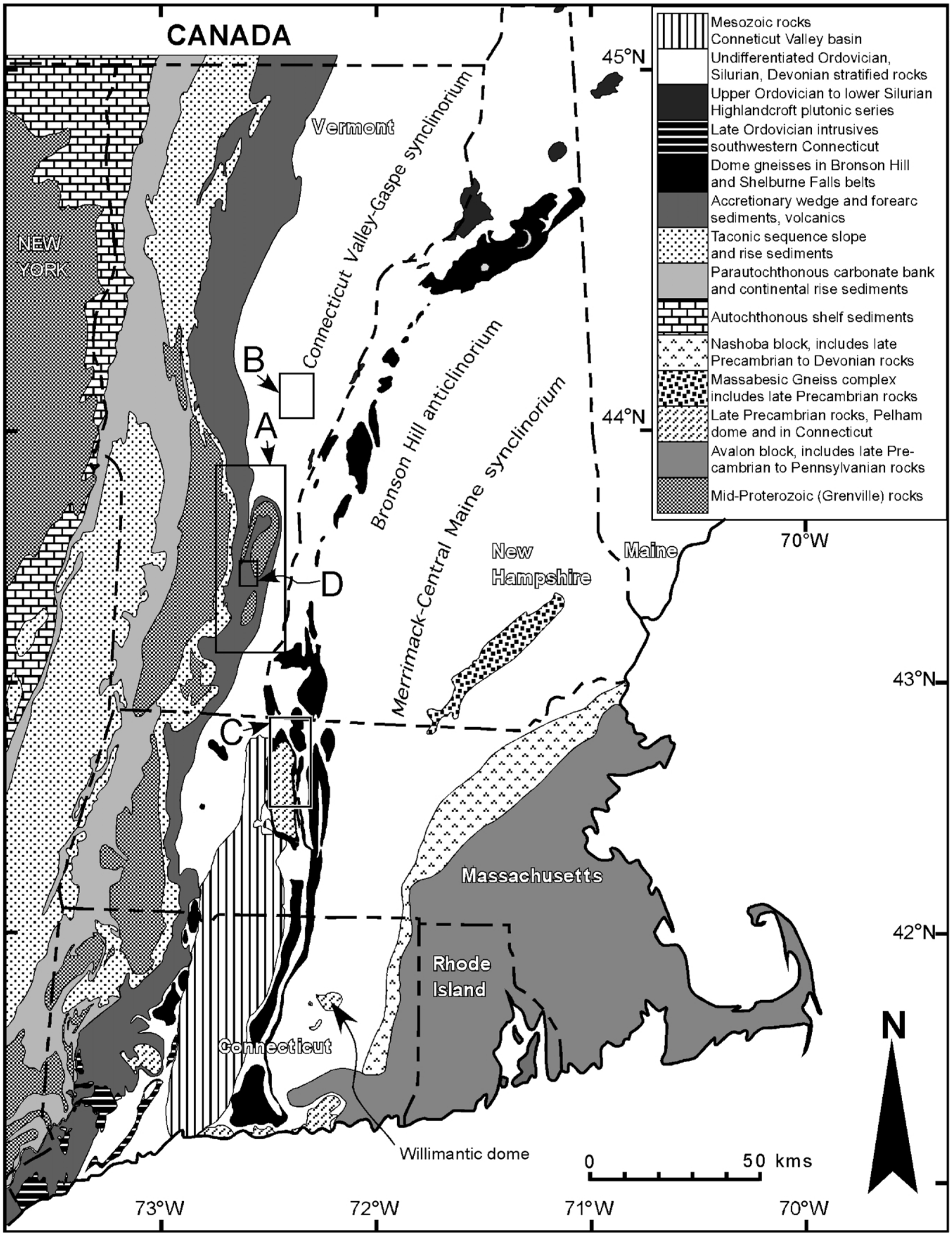


Fig. 2. Simplified geological map of Vermont, New Hampshire, Massachusetts, Connecticut and Rhode Island showing the location of the areas described herein plus the Willimantic dome in Connecticut. The boxes A–D show the locations of the Chester–Athens dome, Pomfret dome, Northfield syncline and the Spring Hill synform.

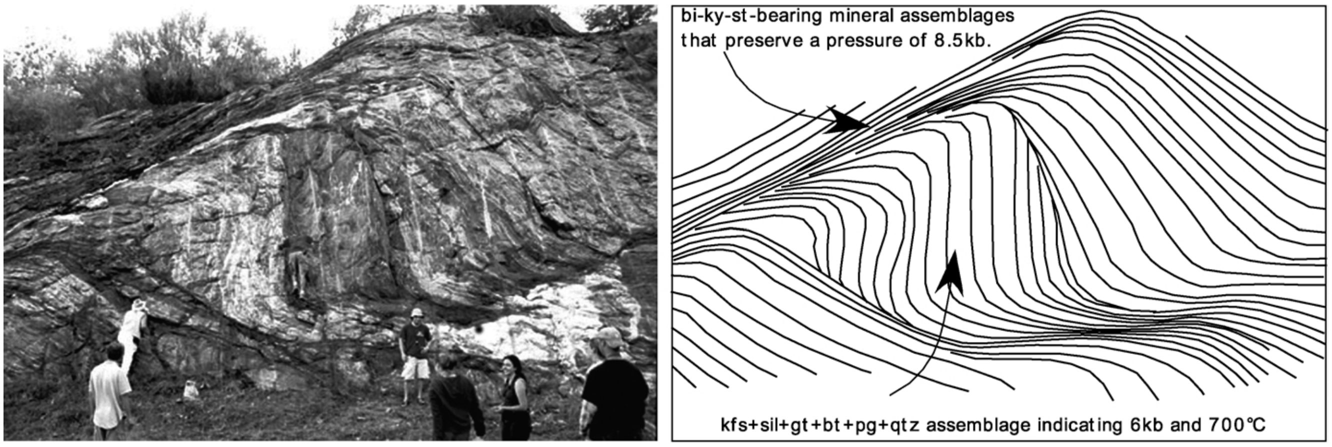


Fig. 3. (a) Outcrop of the top of the Willimantic dome in Connecticut showing the partitioning of deformation on the scale of the road cut into zones of progressive shearing that bound zones of progressive shortening. (b) Detailed line diagram of foliation within outcrop shown in (a) revealing that earlier 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 of the different assemblages referred to in the text is shown. Single barbed arrow shows strike of outcrop.

preserved in a 20 × 10 m outcrop, with all three, two, or just one of the FIAs present in three different samples taken across it (Bell et al., 1998). Where such an outcrop consists of one rock type and there are no faults or younger shear zones nearby, the rocks present therein must have gone through a similar P–T history. Therefore, variation in the growth history of porphyroblasts must in part result from the effects of deformation partitioning at the scale of a porphyroblast. We are certain of this because in the sample where only one of the three FIAs observed in such an outcrop is present, there are no foliations produced by the deformations that developed the extra FIAs in the other samples. In the sample where two of the three FIAs are present, there are no foliations produced by the deformations that developed the extra FIA in the third sample. This paper examines the distribution of FIAs on a regional

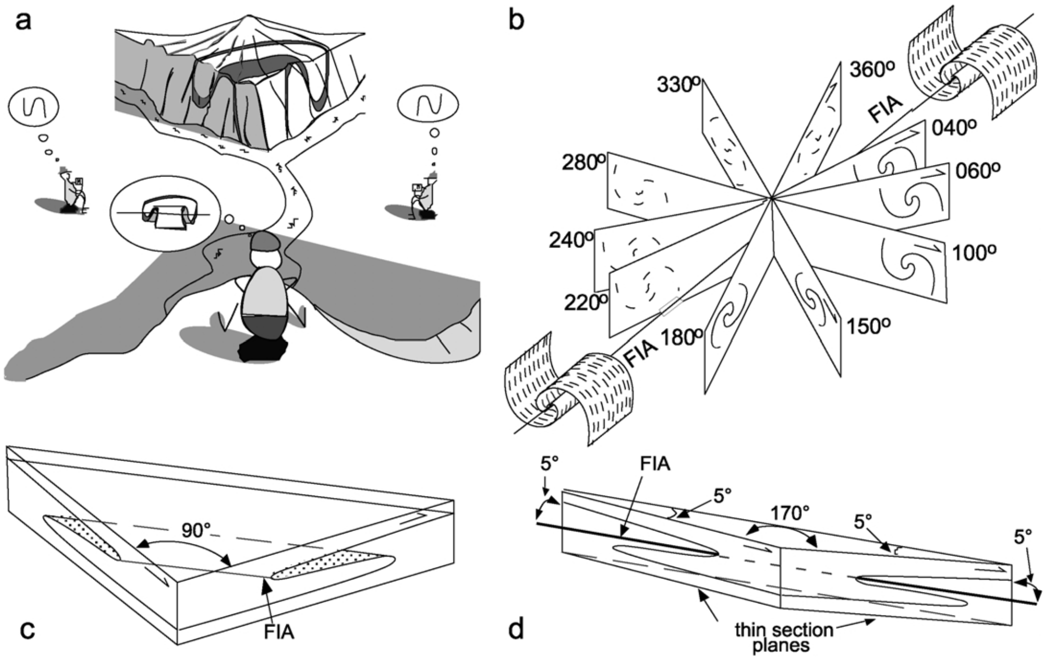


Fig. 4. (a) Sketch illustrating the principle behind measurement of FIAs. The geologists to either side see the opposite asymmetry for same fold in a cliff face. They have no idea of its trend in 3-D. The geologist in the centre sees the fold on both cliff faces and knows it must trend from one to the other (modified from Lee, 2000). (b) 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. (c) Shows asymmetry of a sigmoid axis in two sections cut 90° apart. (d) Shows the sigmoid axis of (c) 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.

scale, in three separate areas (Fig. 2) where a large amount of quantitative data has been gathered, in order to determine how FIAs vary along this part of the Appalachian orogen.

2. Geological setting

The region shown in Fig. 2 extends from Vermont south to Connecticut and Rhode Island and contains a series of domal structures ranging from the Pomfret dome in the north to the Pelham dome in the south. This portion of the Appalachian Orogen contains Precambrian basement gneisses showing both unconformable and tectonic contacts with younger rocks. These younger rocks range in age from the Late Proterozoic to the Devonian. However, the basement gneisses below the Pelham dome in North Central Massachusetts are younger (Robinson et al., 1992) than the Middle Proterozoic gneisses below the Chester–Athens dome (Ratcliffe et al., 1992) and were overthrust by Acadian metamorphosed rocks (Wintsch et al., 1992) from the north during the Alleghanian at around 290 Ma (Peterson and Robinson, 1993). Lack of exposure of basement gneisses to the north and east (during Acadian times) of the Chester–Athens dome may have resulted from thinning of the crust during the period of extension that formed the Connecticut Valley trough (Hatch, 1987, 1988).

Deformation and metamorphism in the region may first have occurred during the Ordovician Taconic orogeny (Stanley and Ratcliffe, 1985; Armstrong et al., 1992). It was actively underway throughout the Siluro-Devonian Acadian orogeny (Bell and Welch, 2002). In the south, the rocks are locally, strongly overprinted by the effects of the Alleghanian orogeny (Robinson et al., 1992). In the rocks overlying the basement gneisses in south-east Vermont, Acadian metamorphism peaked around 404–385 Ma (Bell and Welch, 2002) at 650 °C and 13.5 kbars (Welch and Bell, 2003), 450 °C and 6–8 kbars in the vicinity of the Pomfret Dome (Menard and Spear, 1994) and 650 °C and 8 kbars to the NE of the Pelham dome (Kim, 2001).

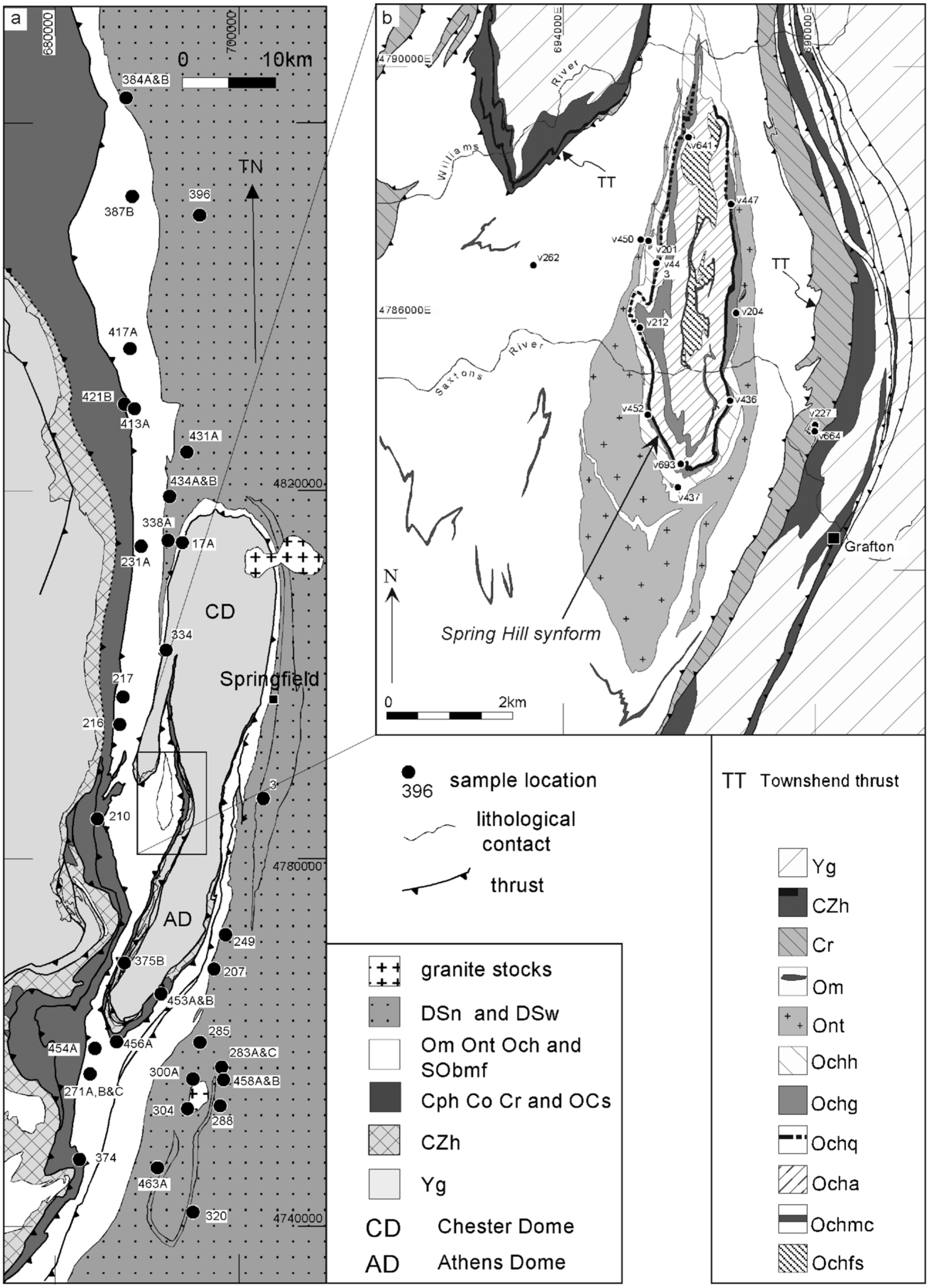
3. Deformation history recorded by the matrix

Structural maps of the rocks around the Chester–Athens dome, Pomfret dome, and Northfield syncline are shown in Figs. 5 and 6. The rocks from the Chester–Athens and Pomfret domes preserve the same structural history in the matrix. Three cleavages are typically preserved over much of the region (e.g. Fig. 7). An early penetrative fabric commonly lies parallel or at a small angle to bedding (S_0) and is locally axial planar to mesoscopic, tight to isoclinal folds of S_0. This cleavage appears to have formed with an upright orientation (preserved in porphyroblast strain shadows) and was overprinted by a well-developed crenulation cleavage, which formed with a gently NW-dipping to sub-horizontal attitude as it is more gently dipping than either limb (e.g. Hickey and Bell, 2001). This crenulation cleavage was in turn overprinted by a steeply dipping, NNE-striking, crenulation cleavage. These foliations are called S_3, S_4, and S_5, respectively (Fig. 7), based on correlation with the structures around the Chester Dome (Hayward, 1992) and the Spring Hill synform (Bell and Hickey, 1997). Earlier formed foliations preserved in porphyroblasts have been rotated into parallelism with S_0 in the matrix due to reactivation of the bedding (Hayward, 1992; Hickey and Bell, 2001). A late crenulation with a subhorizontal axial plane, called S_6, is developed locally. Matrix foliations in the vicinity of the Spring Hill synform (Fig. 5b) using monazite ages range in age from 360 Ma to possibly as young as 320 Ma (Bell and Welch, 2002). However, older foliations ranging in age from 431 to 360 Ma are preserved in porphyroblasts, and this requires that the matrix foliation parallel to S_0 has been reactivated during the younger deformations, destroying remains of earlier developed foliations for which evidence is now only preserved within the porphyroblasts (Bell and Welch, 2002).

Four matrix foliations have also been observed in the Northfield syncline area adjacent to the Pelham dome (Fig. 6b). They consist of a pervasive matrix foliation S_c that is parallel to compositional layering and which truncates the inclusion trails preserved in porphyroblasts of Fig. 8. Within this foliation relics of two earlier foliations are preserved, S_a and S_b are preserved as shown in Fig. 8a and b. Overprinting S_c is a crenulation event S_d as shown in Fig. 8a–d. The rocks of the Northfield syncline are strongly overprinted by the effects of Alleghanian mylonitization (Peterson and Robinson, 1993), especially close to the margin with the gneisses of the Pelham dome. Consequently, no attempt at correlating matrix foliations with those to the north has been made.

4. FIA measurements

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 (Hayward, 1990; Bell et al., 1995, 1997, 1998; Bell and Chen, 2002). 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. 4. 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 cut 10° apart between the sections where the asymmetry of the inclusion trails flip. 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. 4. A very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387B
396
417A
421B
413A
431A
434A&B
4820000
338A
17A
231A
CD
334
Springfield
217
216
210
4780000
AD
249
375B
207
453A&B
285
456A
454A
283A&C
300A
458A&B
271A,B&C
304
288
374
463A
320
4740000
b
694000E
4790000E
River
Williams
TT
v641
v447
v450
v201
v44
3
v262
TT
4786000E
v212
v204
Saxtons
River
v436
v452
v227
v664
v693
v437
Grafton
N
Spring Hill synform
0
2km
396 sample location
lithological contact
thrust
granite stocks
DSn and DSw
Om Ont Och and SObmf
Cph Co Cr and OCs
CZh
Yg
CD Chester Dome
AD Athens Dome
TT Townshend thrust
Yg
CZh
Cr
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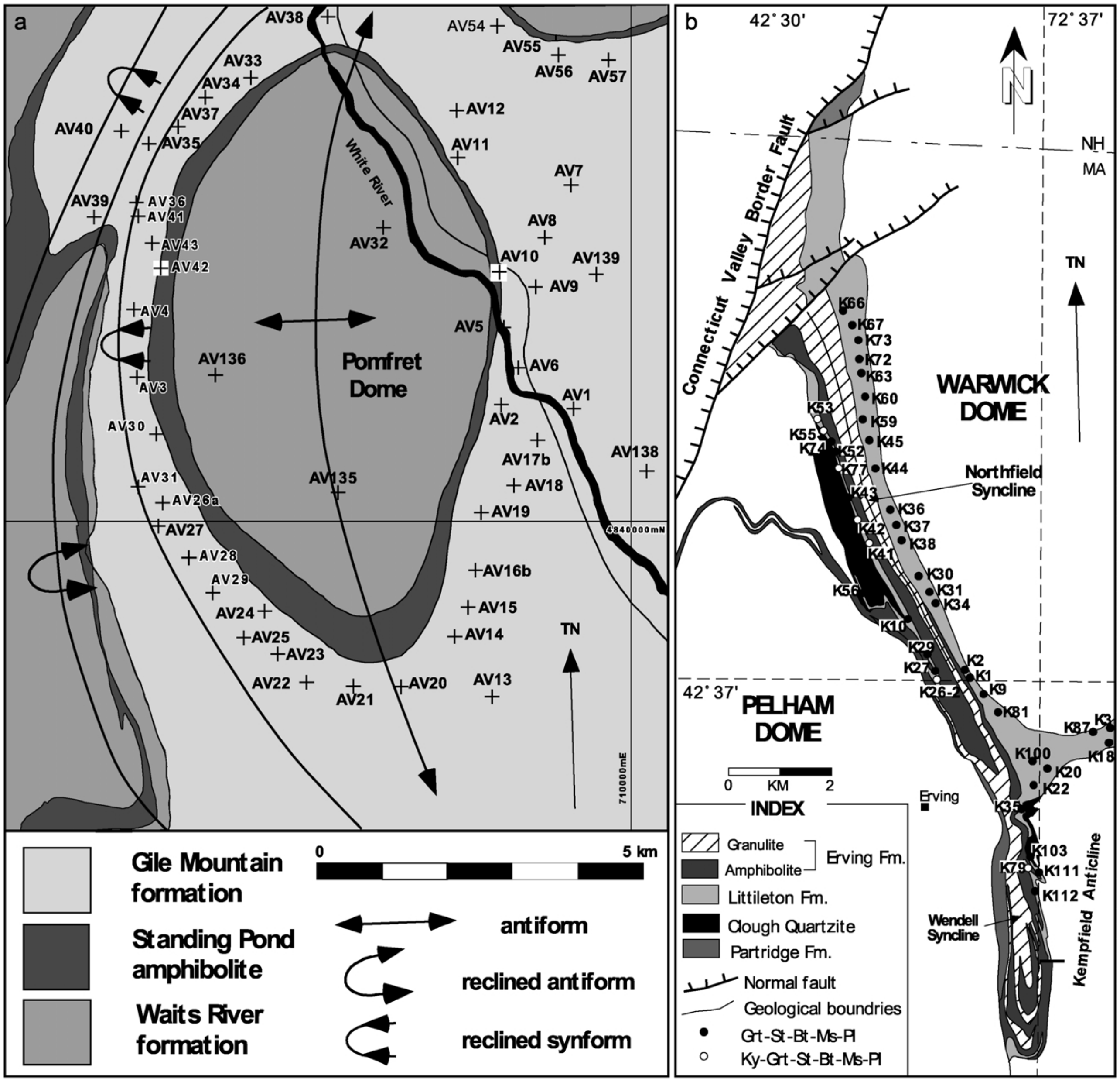

Fig. 6. (a) Sample locations and simplified geologic map of the Pomfret Dome (box B in Fig. 2; after Lyons, 1955). (b) Sample locations and simplified geologic map of the Northfield syncline (box C in Fig. 2; after Robinson, 1967).

significant microstructural advantage results from 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 available from cutting just one or two thin sections. The orientation and asymmetry of matrix structures can be plotted directly onto cross-sections or determined in 3-D and plotted onto maps. Of particular significance, the asymmetries of inclusion trails can be recorded from sections lying at a high angle to the FIA.

Fig. 5. (a) Sample locations and regional geology of southeast Vermont (box A in Fig. 2). Geology after Doll et al. (1961), Ern (1963), Hepburn et al. (1984), Stanley and Ratcliffe (1985), Thompson et al. (1990), Ratcliffe et al. (1992), Ratcliffe (1993, 1995a,b) and 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 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 (box D in Fig. 2). Adapted from Ratcliffe and Armstrong (1995) and Hayward (1991). Symbols as for Fig. 1a. TT = Townshend Thrust.

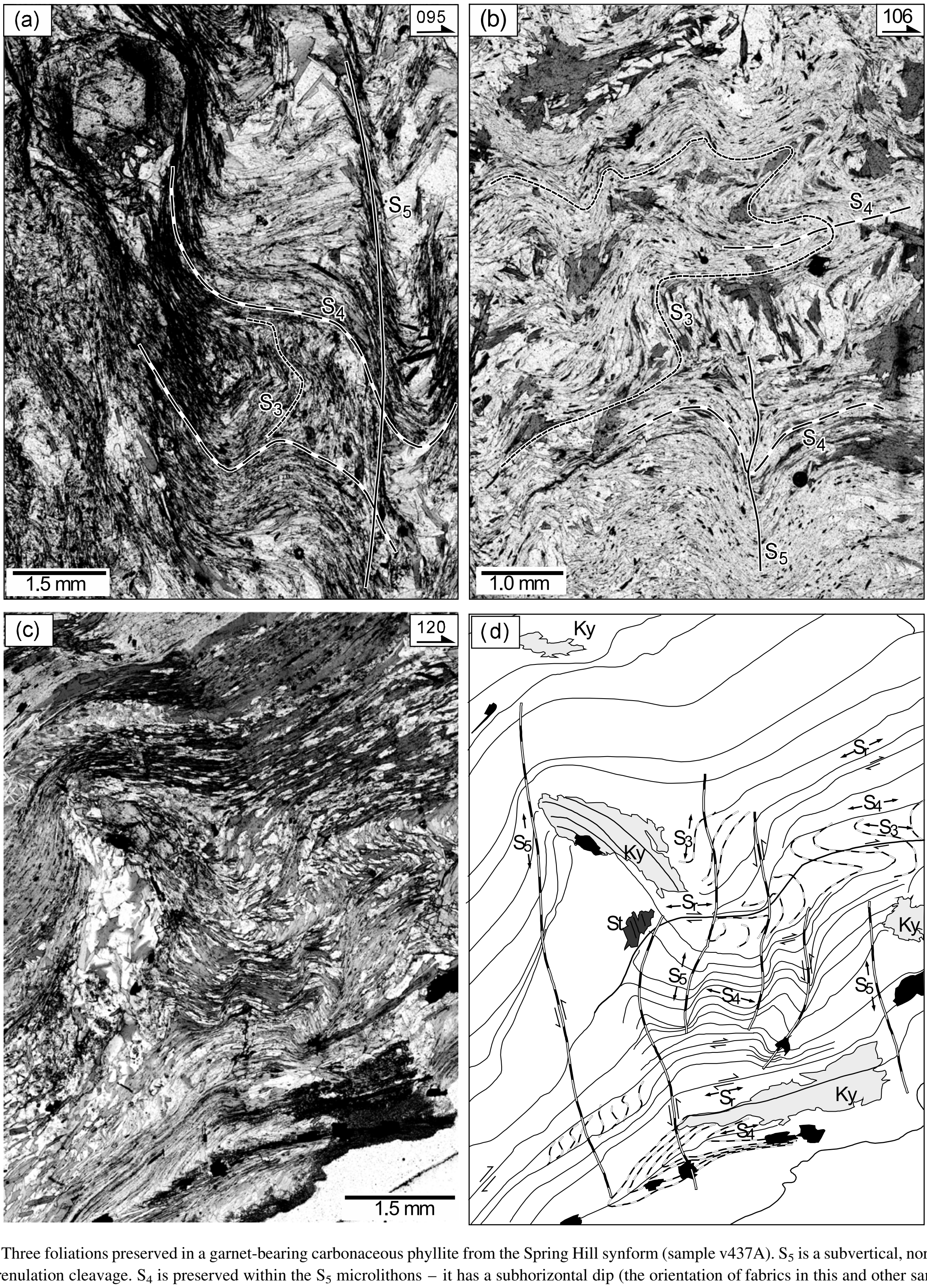

Fig. 7. (a) Three foliations preserved in a garnet-bearing carbonaceous phyllite from the Spring Hill synform (sample v437A). S_5 is a subvertical, north–south-striking crenulation cleavage. S_4 is preserved within the S_5 microlithons – it has a subhorizontal dip (the orientation of fabrics in this and other samples was determined from the variation in foliation pitch and asymmetry of curvature in as many as eight differently oriented thin sections). S_4 crenulates an earlier foliation, S_3, which in S_5 microlithons has a subvertical enveloping dip between spaced S_4 folia. Vertical sections with single barbed arrows showing strike and way up, are oriented subperpendicular to the intersection of S_3, S_4 and S_5. Plane polarized light. (b) Garnet–mica schist from the hinge of D_5 fold on the west limb of the Spring Hill synform (sample v45OA). A weak subvertical S_5, symmetrically overprints subhorizontal S_4. S_4 crenulates subvertical S_3. Vertical section showing strike and way up oriented sub-perpendicular to the intersection of S_3, S_4, and S_5. Plane polarized light. (c) Schist (sample AV30) with line diagram (d) from the western limb of the Pomycret dome. Weakly developed sub-vertical foliation S_5 crenulates sub-horizontal S_4. S_4 crenulates S_3, which has

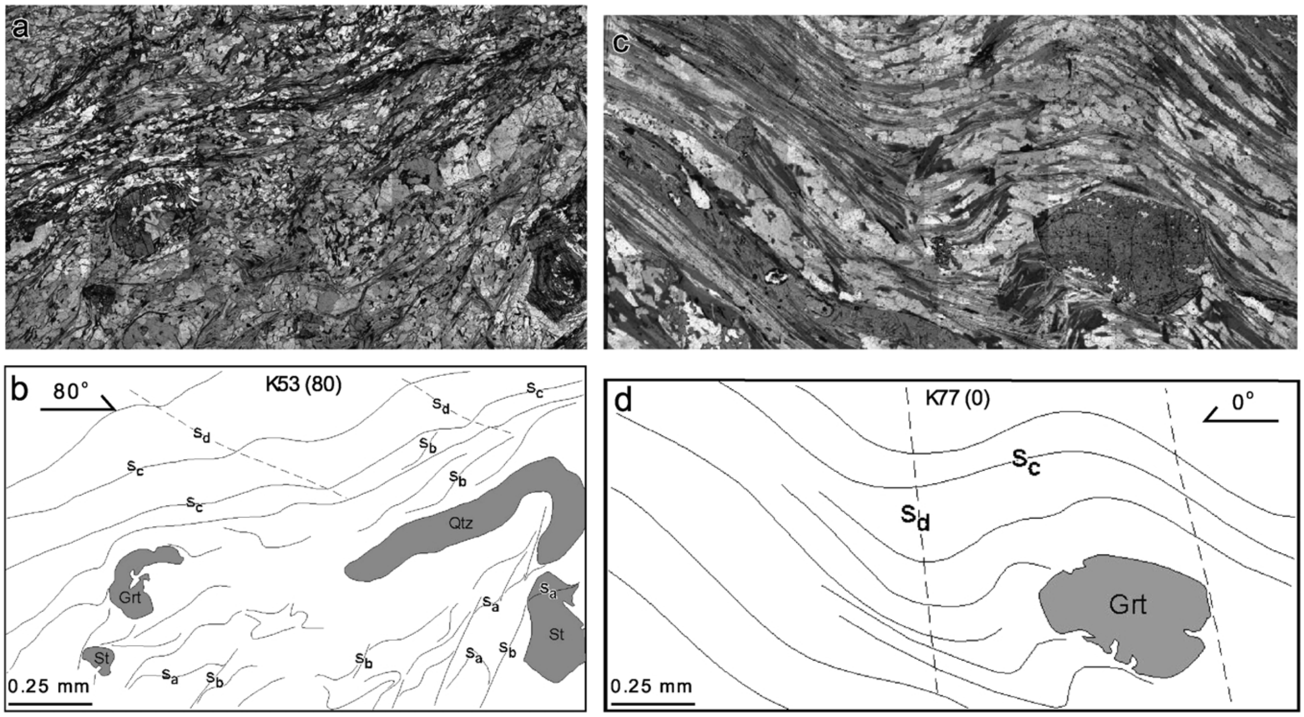

Fig. 8. Photo (a) and line diagram (b) showing matrix foliations in sample K53 from the Northfield syncline. The main matrix foliation S_c contains local relics of earlier formed foliations S_a and S_b preserved in the strain shadows of coarse-grained vein quartz and porphyroblasts. A weak crenulation S_d overprints S_c. Plane polarized light. Vertical thin section with single barbed arrow showing 80° strike and way up. Photo (c) and line diagram (d) showing matrix foliations in sample K77 from the Northfield syncline. The main matrix foliation S_c is overprinted by a weak crenulation S_d. Plane polarized light. Vertical thin section with single barbed arrow showing 0° strike and way up.

Changes in FIA trend within porphyroblasts can occur from the core to the rim, from the core through the median to the rim (e.g. Bell and Hickey, 1997; Bell et al., 1998; Bell and Chen, 2002), or more rarely from the core through two medians to the rim (Bell, unpublished data). 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 the 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).

5. FIA data from garnet porphyroblasts and its analysis

Bell et al. (1998) measured 130 FIAs (Table 1) from garnet porphyroblasts in oriented samples of metasedimentary, non-carbonaceous quartz–mica schists and carbonaceous pelitic and semi-pelitic phyllites and schists. These samples were taken from a range of Ordovician to Silurian stratigraphic units, mainly the Moretown, Northfield and Waits River Formations (Fig. 5) around the Athens and Chester Domes and Spring Hill Synform. They showed that the first formed FIA set in the Chester and Athens Dome area developed with a NE–SW trend. It was followed by FIAs with E–W, NNW–SSE and finally NNE–SSW trends (Fig. 9). These FIA sets (1–4) have been dated as forming prior to 425 Ma, ranging from 425 through 404 Ma, 404 through 385 Ma, and 385 through 360 Ma (Bell and Welch, 2002). The inclusion trails defining all FIA sets except the youngest, FIA set 4, are truncated by the matrix foliation. One example of an earlier-formed FIA set has recently been found in this region trending NW–SE. This set is herein called FIA set 0.

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a sub-vertical pitch adjacent to kyanite (Ky) or staurolite porphyroblasts (St). Away from the porphyroblasts, S_4 is reactivated during D5, which decrenulates and unfolds D5 crenulations plus crenulated S_3. Reactivated foliations are labelled Sr and the sense of shear on the reactivated layer is antithetic to shear on S_5. Vertical section showing strike and way up. Plane polarized light.

Table 1
FIA trends determined for each sample and the set to which they belong for the Chester and Athens Dome area and Spring Hill synform

Sample	Set 0	Set 1	Set 2	Set 3	Set 4
Spring Hill synform					
v200A				161	11
v200B					6
v201					21
v202				151	
v203				168	1
					11
v204					11
v205				161	
v208A					11
v208B				156	
v209		31	96		13
v212E		51			21
v213			108		14
v214			91	176	
v226				166	
v257		36		166	
v258			91		
v259A					16
v260A					1
v261A		26		161	
v261B		16			
v261C		41		141	
v360			71	171	16
					26
v435A					6
v436A	136			156	1
					11
v436B				156	
v436D			101	151	
v437A				166	
v437B		36			
v438				166	12
v439				156	
v440B				176	
v441			66		
v443A			81		
v443B		46			
v443C			91		1
v444B		61	86		11
v445B				156	
v447A			101		11
v447B				156	
				164	
				176	
v449A				156	
v449B				156	
v450A				165	9
v450B				176	
					1
					11
v450C			76		
v450D				161	
v450E				171	
v452A				141	6
v452E			81		
v452G			86		

Sample	Set 1	Set 2	Set 3	Set 4
Chester and Athens dome area				
v3	16		161	
v17A		91	159	
v207			161	
v210				16
v216			161	
v217				16
v231A		81		
v249			146	
v271A			156	
v271B			168	
v271C			166	
v283A			166	1
v283C				11
v285				11
v288		106		
v300A		86		16
v304				11
v320			176	
v334			156	
			171	
v338A			166	11
v374				1
v375B			161	6
v384A		86		16
v384B		81		16
v387B			176	
v396			176	21
				36
v413A			146	
			156	
v417A		96	167	
v421B		106		
v431A			146	
v434A				21
v434B		71		
v453A			151	21
v453B			171	
v454A			161	
v456A			141	
v458A		86	146	
v458B			161	
v463A		71		

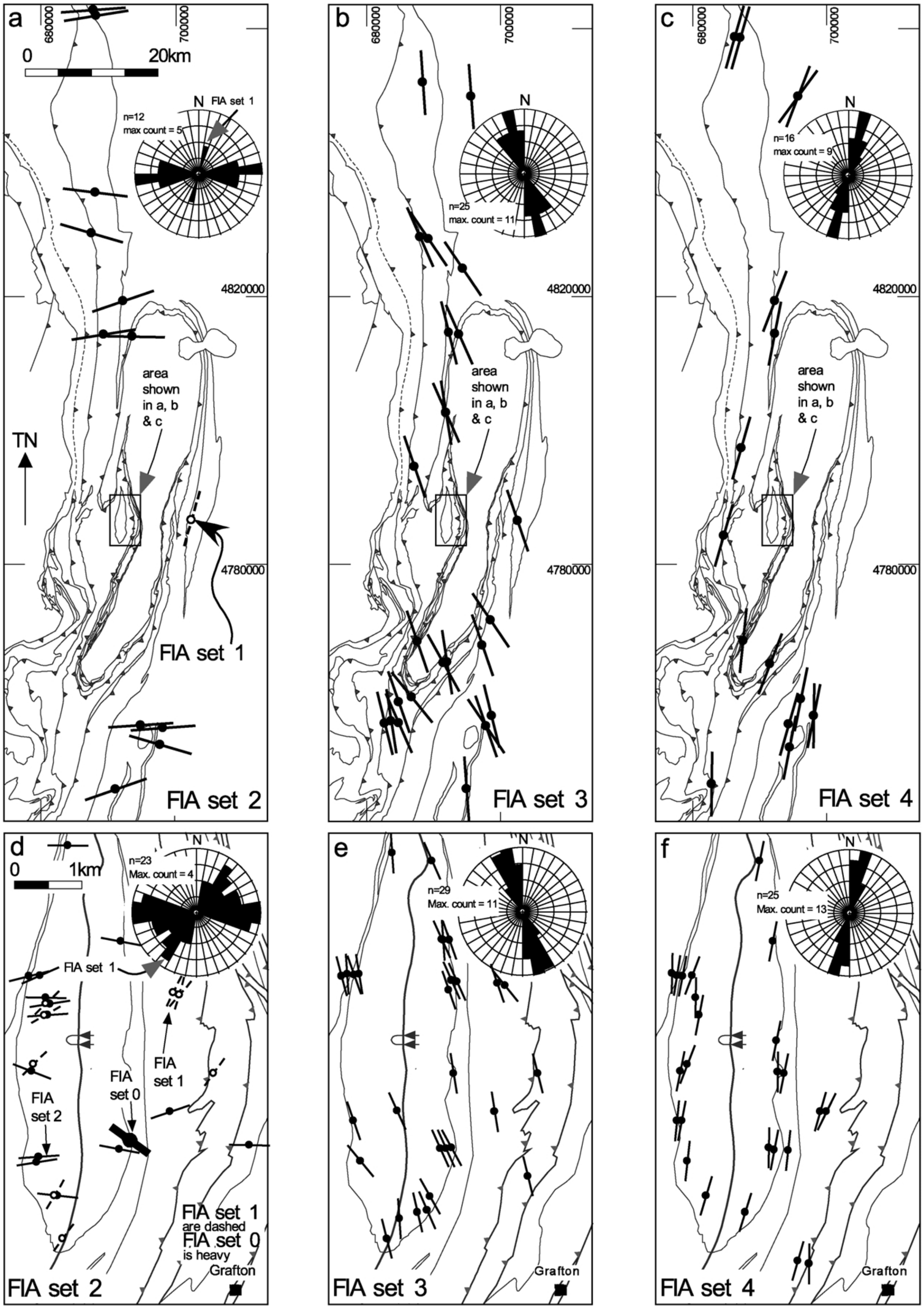
a
680000
700000
0
20km
n=12
max count = 5
FIA set 1
N
4820000
area
shown
in a, b
& c
TN
4780000
FIA set 1
FIA set 2
b
680000
700000
N
n=25
max. count = 11
4820000
area
shown
in a, b
& c
4780000
FIA set 3
c
680000
700000
N
n=16
max count = 9
4820000
area
shown
in a, b
& c
4780000
FIA set 4
d
0
1km
n=23
Max. count = 4
N
FIA set 1
FIA
set 1
FIA
set 0
FIA
set 2
FIA set 1
are dashed
FIA set 0
is heavy
Grafton
FIA set 2
e
N
n=29
Max. count = 11
Grafton
FIA set 3
f
N
n=25
Max. count = 13
Grafton
FIA set 4

Table 2
FIA trends in garnet determined for each sample and the set to which they belong for the Pomfret Dome area

Sample	Set 0	Set 1	Set 2	Set 3	Set 4
East Limb—Pomfret dome					
AV2	120		85		
AV5a	135	55		175	
AV5b	135	45		175	
AV7		50			
AV8		60			
AV11			100		25
AV12	140	30			
AV13		50 + 55			
AV14		45			
AV15	125	45	85		
AV16b	120			165	
AV17b	130	60 + 55			
AV18	135		95		
AV19		55	90		
AV20		60		150	
AV32b					25
AV138					10
AV139	125				
West Limb—Pomfret dome					
AV3			110		
AV4			100		15
AV21		35			
AV22		50		160 + 165	
AV23		45		160	
AV24	135				
AV25	135				
AV26a			85		
AV27					15
AV29		40*			
AV30	135			155	
AV31		45	95		
AV33			85	155	
AV34	130				
AV35	135				
AV36c	120				15
AV36v	125		75		
AV36z	125		80		
AV38	130				
AV39	135				
AV40	125				
AV41					20
AV43		40			

Table 3
FIA trends determined for each sample and the set to which they belong for the Northfield syncline area

Northfield syncline Sample	Set 0	Set 1	Set 2	Set 3	Set 4
Garnet FIA sets					
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		

Table 2 shows 67 FIAs measured from garnet porphyroblasts in oriented samples of metasedimentary schists from the Waits River and Gile Mountain formations located around the Pomfret Dome (Fig. 10). Table 3 shows 65 FIAs measured from garnet porphyroblasts in samples obtained mainly from the Littleton formation, but with a few from the Erving formation, and located around the Northfield syncline (Fig. 11). The relative timing of the FIAs comprising the Pomfret dome and Northfield syncline sets of data was determined using the method described in Bell et al. (1998) involving porphyroblasts containing two or more FIA trends from the core to the rim. Since the core of a porphyroblast has to form before the rim, the FIA trend in the core must predate that in the rim. The succession of

Fig. 9. FIA trends for successive FIA sets in the Chester and Athens Dome area (box A in Fig. 2). (a) Map and rose diagram of FIA set 1 (dashed lines) and set 2 (solid lines). (b) Map and rose diagram of FIA set 3 trends. (c) Map and rose diagram of FIA set 4 trends. (d) Map and rose diagram of FIA trends for the samples collected around the Spring Hill Synform (small box within box A in Fig. 2) for FIA set 0 (heavy line), set 1 (dashed lines) and set 2 (solid lines). (e) Map and rose diagram of FIA set 3 trends. (f) Map and rose diagram of FIA set 4 trends.

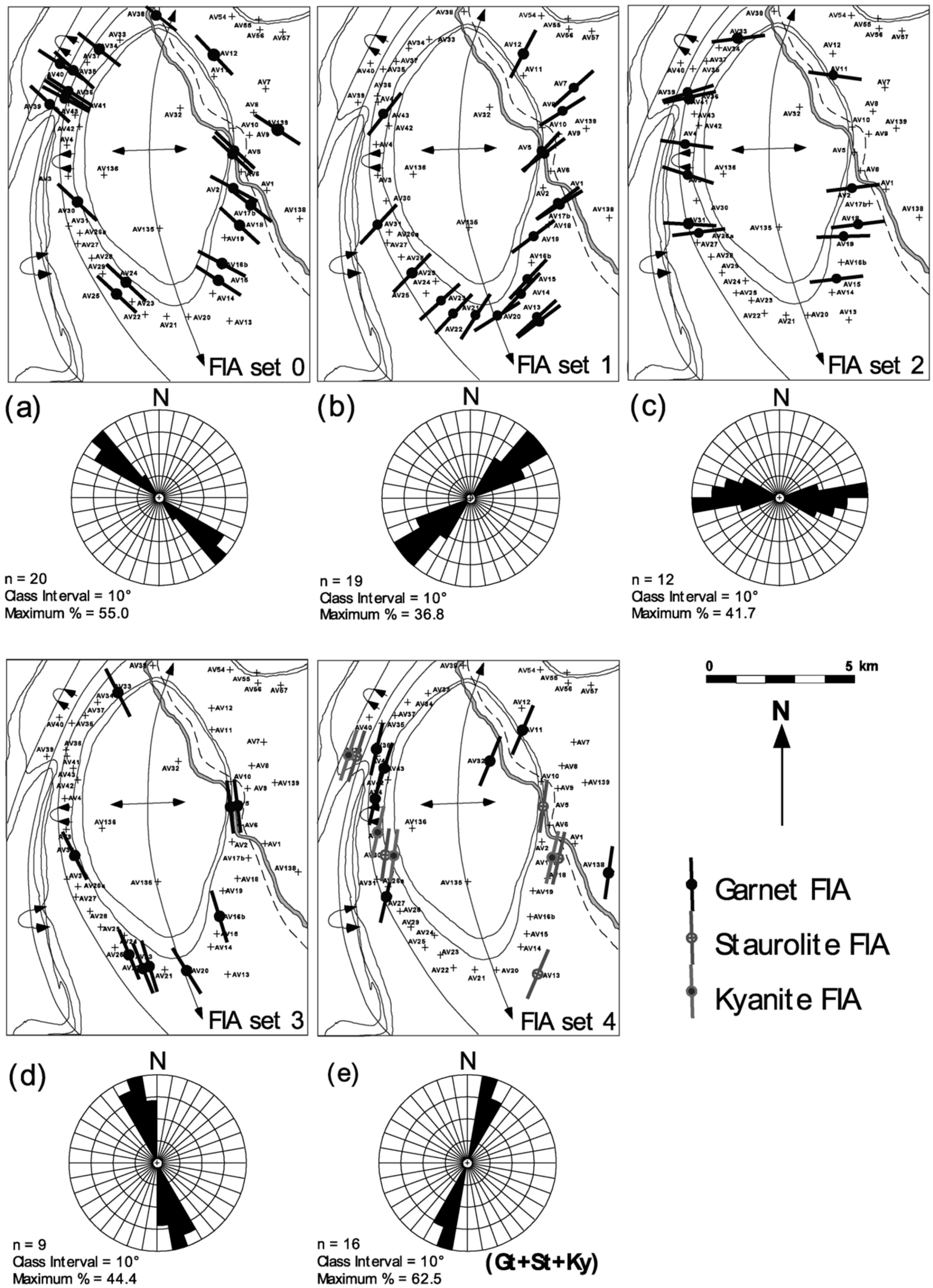

Fig. 10. FIA trends for successive FIA sets in the Pomfret Dome area (box B in Fig. 2). (a) Map and rose diagram of FIA set 0 trends. (b) Map and rose diagram of FIA set 1 trends. (c) Map and rose diagram of FIA set 2 trends. (d) Map and rose diagram of FIA set 3 trends. (e) Map and rose diagram of FIA set 4 trends.

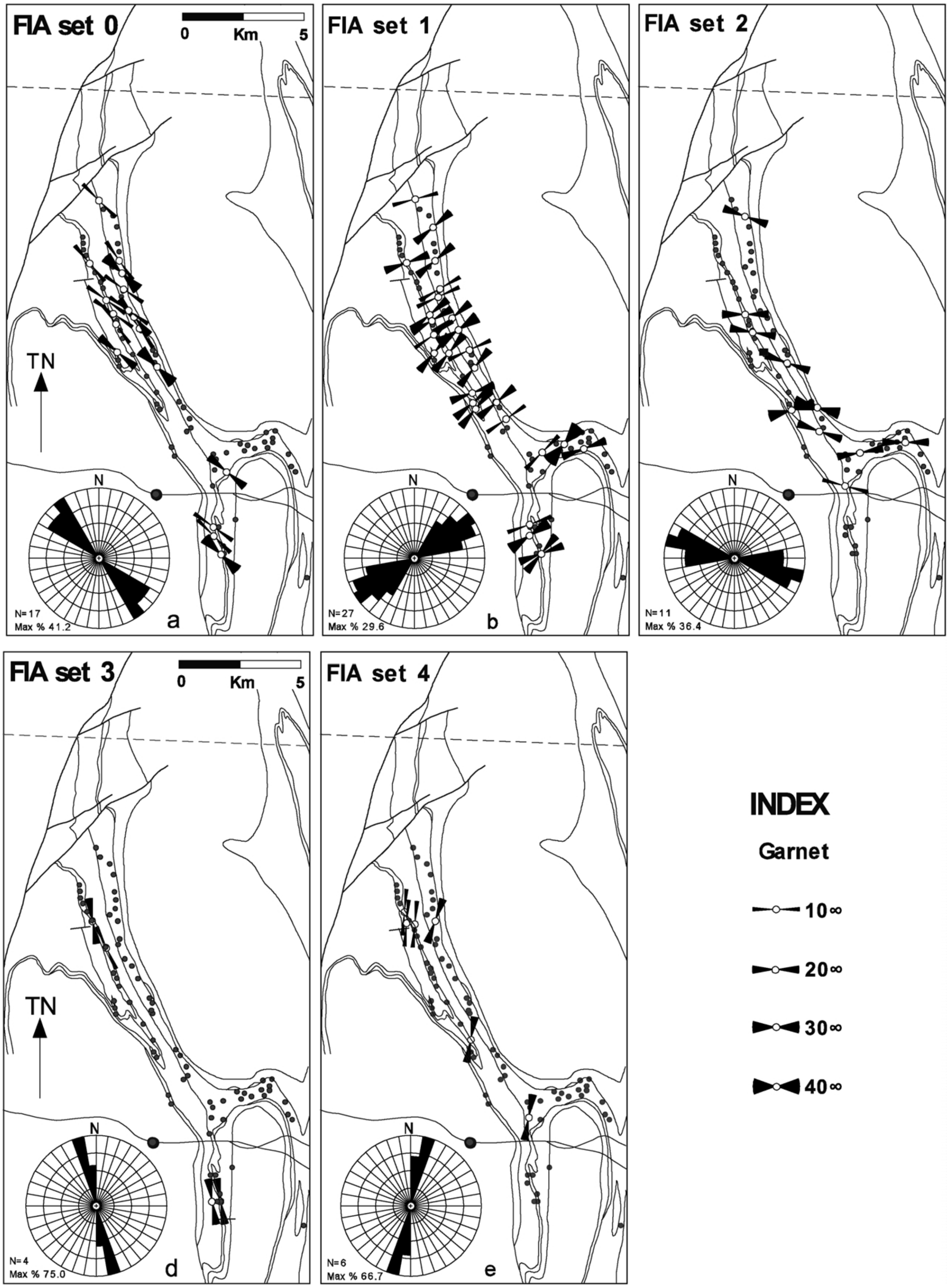

Fig. 11. FIA trends for successive garnet FIA sets in the Northfield syncline area (box C in Fig. 2). (a) Map and rose diagram of FIA set 0 trends. (b) Map and rose diagram of FIA set 1 trends. (c) Map and rose diagram of FIA set 2 trends. (d) Map and rose diagram of FIA set 3 trends. (e) Map and rose diagram of FIA set 4 trends.

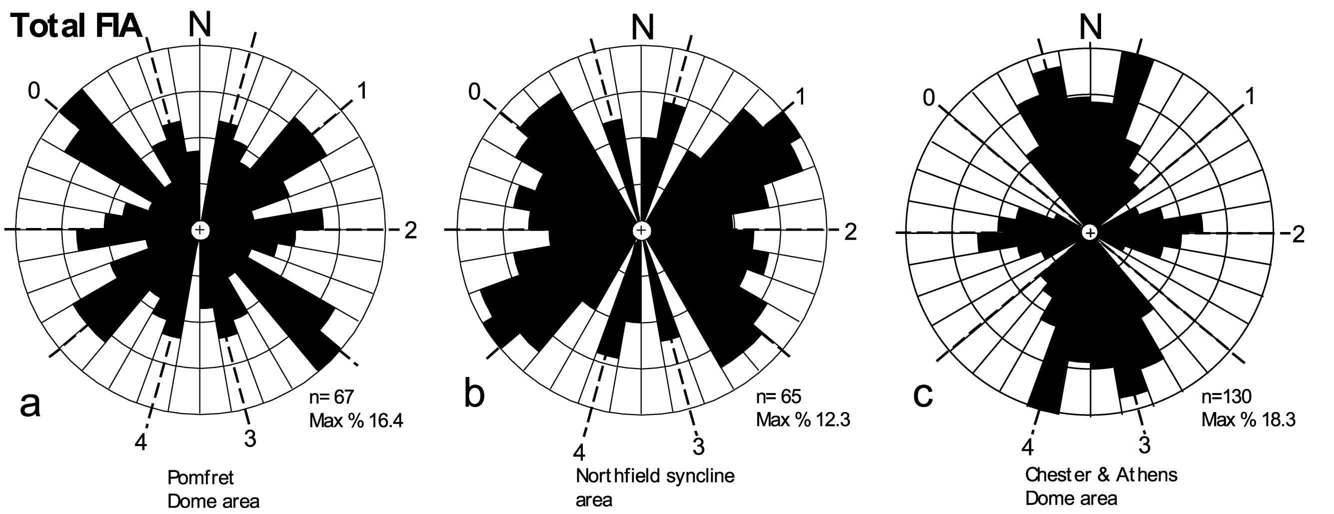

Fig. 12. Equal area rose diagrams of the total FIAs in porphyroblasts determined for: (a) the Pomfret Dome area, (b) the Northfield syncline area, and (c) the Chester and Athens Dome area. The trends of the FIA sets 0–4 are marked. For the Chester and Athens dome area, only one sample contains FIA set 0 and FIA set 1 lies on the edge of the large FIA set 4 distribution and is difficult to distinguish in the total FIA plot.

trends derived in this manner is consistent in each region and is shown in Fig. 12. The first-formed FIA set in both regions developed with a NW–SE trend. It was followed by FIAs with NE–SW, E–W, NNW–SSE, and finally NNE–SSW trends (Fig. 12). The inclusion trails in the porphyroblasts belonging to FIA set 4 are continuous with the matrix foliation in the rocks surrounding the Pomfret dome, whereas those belonging to FIA sets 0–3 are truncated by the matrix foliation. However, the inclusion trails in all porphyroblasts in the rocks folded around the Northfield syncline are truncated by the pervasive matrix foliation.

6. Interpretation and discussion

6.1. Development of the matrix foliation in the Northfield syncline versus elsewhere

In the Northfield syncline area, Alleghanian 290–300 Ma (late Pennsylvanian) plus Acadian 330–370 Ma (late Devonian) ages were discovered using U–Pb monazite, zircon, and titanite ages 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. 6b), and the shear zone on the contact of these rocks with the gneisses in the Pelham dome, were re-metamorphosed during the Alleghanian orogeny, basing this on U–Pb monazite/titanite ages of 290–295 Ma from the Dry Hill gneiss, Poplar Mountain, Mount Mineral, and Littleton Formations (Tucker and Robinson, 1990; Robinson et al., 1992). The schistosity within this shear zone is locally mylonitic and contains a pervasive, N–S-trending, mineral elongation lineation with an associated shear sense of top-to-the-south (Peterson and Robinson, 1993). This lineation is also present in the schistose rocks of the Northfield syncline, but not as pervasively as around the margins of the Pelham dome. The ages determined from monazite in the Mount Mineral formation on contact with the Pelham gneiss dome indicate that this shear zone foliation formed during the Alleghanian at 290–295 Ma (Robinson et al., 1992). We interpret the mix of Acadian and Alleghanian ages recorded in Northfield syncline to have resulted from shearing of the matrix foliation during the Alleghanian when the rocks of the Northfield syncline were thrust southwards over the gneisses of the Pelham dome. This shearing of the matrix foliation truncated all the inclusion trails preserved within the garnet porphyroblasts because, as we show below, they grew in the Acadian, although they were modified during the Alleghanian (Kim and Bell, unpublished data).

6.2. Correlation of FIA trends in the Northfield syncline and Pomfret dome

The succession of differently trending FIAs in porphyroblasts around the Pomfret dome and the Northfield syncline is identical (compare Tables 2 and 3 and Figs. 10 and 11). In particular, the actual distribution of FIAs within each FIA set in the total rose diagram shown in Fig. 12 are remarkably similar from the Pomfret dome to the Northfield syncline. Thus the rocks in each of these areas, which are around 110 km apart, have recorded a nearly indistinguishable succession of FIA orientations plus a very similar proportion of samples bearing each FIA set. We find these data very compelling and interpret that the succession of FIAs in each area must have formed at the same time by the same sequence of changes in direction of bulk shortening during orogenesis. We suggest that the similar proportion of FIAs from set to set requires that the rocks in both regions were deformed in a very similar manner over the whole period of time that porphyroblasts were growing (greater than 75 m.y., see below) and during which there were five significant shifts in the direction of bulk principal shortening. Bell and Hayward (1991) have shown that the partitioning of deformation in the immediate vicinity of, and at the scale of, a porphyroblast appears to be required for it to grow. If their arguments are correct then the similarity in the proportion of the total number of samples containing each FIA set between these two areas requires that the scale of partitioning of deformation in each region was very similar for each period of porphyroblast growth for each FIA set. For example, if during the development of one of the FIA sets, one of the deformations had been very widely partitioned in one of the areas, such as shown in Fig. 3, then only a small portion of the rock in that area would develop the foliations that developed that FIA. Consequently, the volume of rock within in which porphyroblasts could grow and trap the foliations defining that FIA would be much less than in an area where it was partitioned more pervasively. This would result in fewer samples containing that FIA and this should be reflected in the rose diagrams.

6.3. Correlation of FIA trends across the region

The succession of differently trending FIAs around the Pomfret dome and Northfield syncline is the same as that seen around the Chester–Athens dome (Tables 1–3). However, the density of the distribution of FIAs on rose diagrams is remarkably different with those around the Chester–Athens dome showing a proportion of the total number of samples in each FIA set that is approximately the inverse of those around the Pomfret dome and Northfield syncline (Fig. 12). That is, around the Chester–Athens dome most samples contain FIAs belonging to the youngest developed FIA set and least samples contain FIAs belonging to the oldest set. Around the Pomfret dome and Northfield syncline most samples contain FIAs belonging to the oldest set and least samples contain FIAs belonging to the youngest set (Fig. 12). We interpret that the succession of FIAs in all three areas formed as a result of the same sequence of changes in the direction of bulk shortening during orogenesis and argue below that the variation in density results from a significant variation in the distribution of deformation partitioning across the region. Consequently, we correlate the ages of the five FIA sets measured in the Pomfret and Northfield regions with those determined adjacent to the Chester–Athens dome by Bell and Welch (2002). Within the Chester–Athens dome region we have not yet dated when the NW–SE-trending FIA set 0 formed. However, we know that the SW–NE-trending FIA set 1 developed prior to 425 Ma. The W–E-trending FIA set 2 formed between 425 and 404 Ma. The NNW–SSE-trending FIA set 3 formed between 404 and 385 Ma and the SSW–NNE-trending FIA set 4 formed from 385 down to 360 Ma (Bell and Welch, 2002). We interpret that the direction of bulk shortening accompanying each FIA set lay perpendicular to the relevant FIA trend (e.g. Bell et al., 1995; Bell and Wang, 1999).

6.4. Continuity of inclusion trails versus truncation and lack of porphyroblast rotation

The inclusion trails for FIA set 4 are continuous with the matrix foliation in the Pomfret and Chester–Athens dome regions but are truncated in the Northfield syncline region because of the truncational effects of the intense Alleghanian shear that accompanied the thrusting of these rocks from the north and over the gneisses within the Pelham dome (Peterson and Robinson, 1993; Robinson et al., 1992; Wintsch et al., 1992). This Alleghanian shear produced a foliation on the contact with the gneiss dome that is locally mylonitic in intensity, and sheared and reset the age of the great bulk of the matrix foliation in the Northfield syncline, truncating all inclusion trails, and yet the porphyroblasts were not rotated. Indeed the FIA distribution and density within that distribution are nearly identical from the Pomfret dome to the Northfield syncline. This data strongly supports the lack of rotation of porphyroblasts relative to geographic coordinates and the vertical within ductile shear zones or during ductile deformation in general (e.g. Bell and Hickey, 1997; Jung et al., 1999; Hickey and Bell, 2001; Stallard and Hickey, 2001; Bell and Chen, 2002).

6.5. Variation in FIA distribution between the Chester–Athens dome region and those to the north and south

The similarity between the density distributions of the total FIA rose diagrams for the Pomfret dome and Northfield syncline areas, and their near inverse relationship in terms of density versus FIA succession to the rose diagram for the Chester–Athens dome region, requires explanation. As mentioned above, the similarity appears to have resulted from the comparable scale of partitioning of the deformation through both groups of rocks while porphyroblasts were growing during the numerous events that affected this region over a period of more than 75 million years (Bell and Welch, 2002) and while the directions of bulk shortening changed five times. However, why should deformation, which is so heterogeneous, have similar patterns of partitioning in two regions 110 km apart, yet be dissimilar in the intervening Chester–Athens dome region?

6.5.1. Distribution of the gneissic basement

A solution may lie in the distribution of the Precambrian feldspar-rich, gneissic basement across this region during the Acadian orogeny and the decreasing competency of these rocks with increasing temperature. The gneissic basement that now lies below the Pelham dome was not present during the Acadian, as it was underthrust from the south during the Alleghanian, as revealed by pervasive and intensely developed lineation within the mylonitized contact, the shear sense and the age data (Peterson and

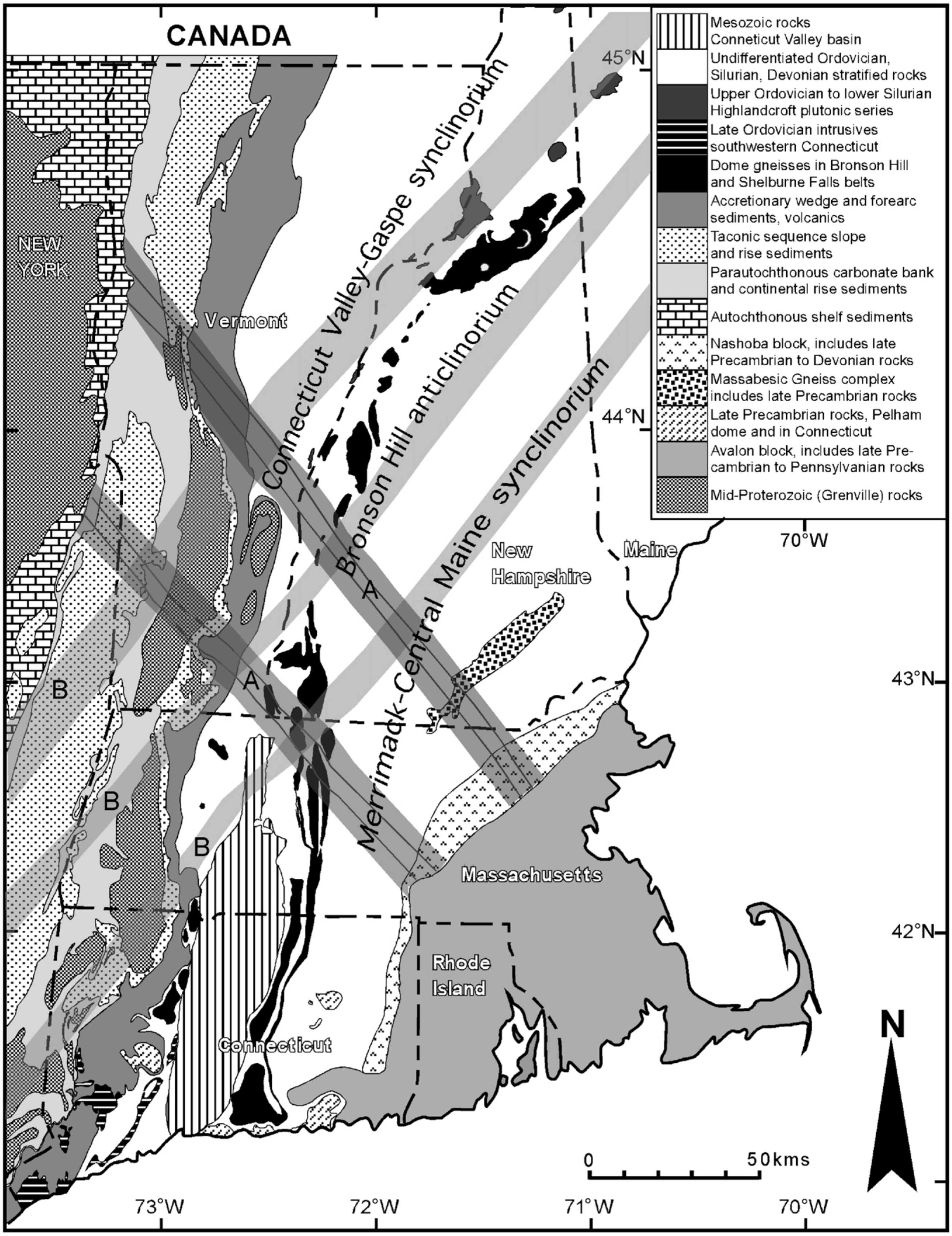

Fig. 13. Map showing how the distribution of feldspathic gneiss units across New England may have controlled the localization of deformation described herein during the development of FIA sets 0 and 1. The bands labelled A reflect the zones of more intensely developed FIA set 0 to the north and south of the Chester–Athens dome area. The bands labelled B reflect the more intense development of FIA set 1. The feldspathic gneiss in the core of the Pelham dome has been left off this map because it was overthrust by North America after the periods of deformation under consideration.

Robinson, 1993). Consequently, a large mass of competent feldspathic gneiss lay directly below metasediments that overly the Chester–Athens dome during the Acadian but we know of none that lay directly below the rocks in the Pomfret dome or Northfield syncline areas. This shallow distribution of gneiss relative to the thickness of the sedimentary pile appears to be an eastwards protrusion of the Green Mountain massif, which thins to the north and south as shown in Fig. 13. We suggest that when the extension occurred it resulted in the deposition of the large mass of sediments that comprise the Ordovician–Silurian–Devonian portion of the Connecticut Valley trough, the portion of gneiss below the Chester–Athens dome was left as a high standing eastward horst of the Precambrian gneiss massif to the west. The width of the Siluro-Devonian succession increases to both the north and south of this central region as the exposed width of gneiss decreases (Fig. 13). Fig. 13 shows the distribution of geologic units as they occur today, apart from the Pelham gneiss dome. There will have been some translation and displacement of units during the Acadian, although what were regarded as large scale nappes in SE Vermont have been discounted by Ratcliffe et al. (1992) and Hickey and Bell (2001). However, since this map provides the only guide to the distribution of units during the Acadian that is currently available, we use it in our interpretations below.

6.5.2. Partitioning during development of FIA set 0

The first phase of horizontal shortening recorded by the Acadian FIA succession was directed SW–NE as the FIA trends NW–SE (FIA set 0 in Fig. 12), and bulk shortening would tend to lie perpendicular to this direction. This deformation would have tended to partition around the thick mass of gneiss underlying the Chester–Athens dome and cut across the Green Mountains to the west through the potentially thinner portions of gneiss shown by the shaded zones marked with an ‘A’ in Fig. 13. This would cause the rocks in the zones marked ‘A’ to be more deformed, and those protected by the gneiss in the Chester–Athens dome area to be less deformed. We have found rare examples of FIA set 0 within the Chester–Athens dome area and so very locally the effects of this deformation were able to partition through this mass of gneiss. However, the bulk of the gneiss remained undeformed at this time, as we have no record of the foliations developing during this direction of bulk shortening in any other rocks from the Chester–Athens dome region, and we know from pseudosections constructed using THERMOCALC on the samples from this region that the bulk composition of many samples were suitable for porphyroblast growth at this time (Welch, 2003). Such a pattern of deformation partitioning, where large pods of rock are left undeformed and the deformation is confined to zones that wrap around them, is very typical of how bodies of granitic gneiss deform (e.g. Page and Bell, 1986). Consequently, we argue that no or very little porphyroblast growth occurred in the Chester Athens dome region over the period of time that FIA set 0 took to develop, because we interpret that unless deformation partitions on the scale of a porphyroblast, there can be no access of the components needed for porphyroblast growth to a nucleation site from the surrounding rock (e.g. Bell et al., 1986, 1998, 2003; Bell and Hayward, 1991). Significantly, the lack of partitioning of deformation into the Chester–Athens dome area over this period of time would result in more pervasive deformation of the regions to either side where the rocks of the Pelham dome and Northfield syncline are located. This would explain the similar proportion of the total FIAs that formed in each of these regions over the period of time that FIA set 1 developed.

6.5.3. Partitioning during development of FIA set 1

During development of the SW–NE-trending FIA set 1 (Fig. 12), the direction of horizontal bulk shortening would have been NW–SE and deformation would have tended to partition around the mass of feldspathic gneiss that underlies the Chester–Athens dome region as shown by the shaded zones labelled B in Fig. 13. This potentially affected the Pomfret dome and Northfield syncline regions in a similar manner to that that just described for FIA set 0. It must also have had some affect on the Chester–Athens dome region to produce the uncommon growth of porphyroblasts that took place in these rocks and indicates that more deformation was partitioned through this region than previously as more examples of foliations that formed at this time are trapped within porphyroblasts. However, it was not partitioned at all pervasively through the great bulk of the area, as most of the samples contain no evidence of any of the foliations that formed at this time.

6.5.4. The effects of a progressive temperature increase

During the development of FIA set 2, oriented W–E, the direction of bulk shortening was N–S and deformation may have tended to partition a little more through the competent gneiss because of its shape relative to this direction of shortening. However, probably the most significant factor in the progressive increase in the pervasiveness of deformation partitioning through the rocks around the Chester–Athens dome, as recorded by the porphyroblasts, was a progressive increase in temperature through FIA sets 0–4, and a progressive increase in pressure through FIA sets 0–3 (Welch, 2003). This would have greatly aided the partitioning of deformation through the gneiss. Indeed, the proportion of porphyroblast growth during the development of FIA sets 3 and 4, versus the total of the FIAs that we have recorded for the region, was very high (Fig. 12). Each sample with porphyroblasts containing these FIAs preserves the foliations within the porphyroblast rims that define these two FIA sets. Therefore, because of the high proportion of samples preserving these foliations, the partitioning of the deformation through these rocks during the development of FIA sets 3 and 4 must have been quite pervasive.

6.5.5. The decrease in the proportion of samples containing FIA sets 3 and 4 in the Pomfret dome and Northfield syncline areas

Three possibilities can be considered for the decrease in the number of samples containing FIA sets 3 and 4 in the Pomfret dome and Northfield syncline regions relative to the Chester–Athens dome region.

1. There may have been a competency increase in these rocks due to the number of porphyroblasts that had grown within them previously, reducing the pervasiveness of deformation partitioning through the rock mass.
2. The partitioning of deformation throughout the whole mass of rock may have evened out by this time, providing relatively fewer sites in these two regions.
3. The effective bulk composition for porphyroblast growth may have shifted through fractionation of some components into previously grown porphyroblasts and reduced the opportunity for further porphyroblast growth.

We are conducting detailed metamorphic investigations using pseudosections to see if we can resolve which of these possibilities, if any, provides a solution.

6.6. Implications for the ages of formations in the Pomfret and Northfield regions

Correlation of the FIA successions from Chester–Athens Dome area with the Pomfret Dome and Northfield syncline areas requires re-examination of the age of the rocks collected from the latter regions because of the ages obtained for FIA sets 1–4 by Bell and Welch (2002). FIA set 1 began forming prior to 425 Ma from their data, which means that FIA set 0 began to form even earlier. This requires that these rocks, which include the lower half of the Gile Mountain formation and Waits River formation in the Pomfret dome region and the Littleton formation in the Northfield syncline area, were deposited prior to the mid-Silurian, possibly back as far as the early Silurian or upper Ordovician. This possibility is supported by the fact that the age of the rocks in the Pomfret dome region is problematic with possible ages ranging from Ordovician to Devonian (Spear and Harrison, 1989; Hueber et al., 1990). The age of the Littleton formation is well known from fossils to be mid-Devonian. Our correlation of the FIAs in the rocks from the Northfield syncline with those around the Chester–Athens dome requires that what is called the Littleton formation in North Central Massachusetts must be at least as old as the Lower Silurian.

Acknowledgements

We gratefully acknowledge the early work of Nick Hayward, the considerable input and help of Ken Hickey, discussion with Peter Welch, comments on a first draught of the manuscript by Dave Moecher, and a review by Nick Ratcliffe. The Australian Research Council is acknowledged for providing the funding for this research. The School of Earth Sciences at JCU and staff therein are thanked for providing the superb facilities for microstructural and metamorphic research available at James Cook University. The Departamento de Geodinamica at the Universidad de Granada provided facilities that allowed the final major revision of this manuscript to be made. We also thank the three Journal of Structural Geology reviewers whose incisive comments made us dramatically change the emphasis of this paper.

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