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Permian bulk shortening in the Narragansett Basin of southeastern New England, USA

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Abstract

Pennsylvanian age sediments within the Narragansett Basin allow the effects of Alleghanian deformation to be distinguished from the Taconic and Acadian orogenies that affected the rocks to the west. Three-dimensional microstructural analyses of both matrix foliations and structures preserved in porphyroblasts define two extended periods of deformation and metamorphism about two differently-trending foliation intersection/inflection axes in porphyroblasts (FIAs). SSW–NNE-trending FIAs (set 1) formed first followed by WSW–ENE-trending FIAs (set 2). The SSW–NNE FIA trends from the south-central zone lie parallel to regional folds in the entire southern graben. The changes in FIA trends reveal that the direction of maximum bulk shortening changed from WNW–ESE to NNW–SSE during amphibolite facies metamorphism within the Central Zone of the basin. They reveal a more varied history than the simple kinematic framework of solely W–E directed bulk shortening that was previously suggested.

Keywords: Bulk shortening; Inclusion trail axes of curvature; Porphyroblast timing

1. Introduction

Much of the complexity within the structural and metamorphic history of the New England Appalachians resulted from three overprinting Palaeozoic orogenic pulses, the Taconic (455–442 Ma), the Acadian (423–385 Ma) and the Alleghanian (300–260 Ma). Each orogenic pulse has been associated with a major collisional orogenic event. In particular, the youngest of these, the Alleghanian, is regarded as coinciding with development of Pangaea as Africa collided with North America around 300 Ma ago (Mosher, 1983). Regional Alleghanian metamorphism occurs within the Avalogn Composite Terrane (Wintsch and Sutter, 1986; Zartman et al., 1988; Dallmeyer and Takasu, 1992) but the extent to which the associated deformation penetrates away from Avalon is debated (Fig. 1). Significantly, recent studies suggest an important role for Alleghanian tectonism throughout New England (Getty and Gromet, 1992; Wintsch et al., 1992; Moecher, 1999).

Sediments within the Narragansett Basin of Rhode Island and Massachusetts contain Pennsylvanian (post-Acadian; 325–295 Ma) plant fossils (Lyons, 1984). The basin provides a unique opportunity for examining the effects of Alleghanian deformation that cannot be attributed to the preceding Taconic or Acadian orogenies. The structural history of the Narragansett basin is complex as early collisional deformation was overprinted by periods of wrench style tectonics. This study is focused on constraining the relative timing of deformation and metamorphism associated with Alleghanian tectonism within the Narragansett Basin.

Kinematic indicators such as stretching and mineral aggregate elongation lineations have been used to interpret bulk movement directions during deformation (Wintsch, 1979; Reed and Williams, 1989; Robinson and Peterson, 2002). However, these lineations can be reoriented through reuse of the foliation plane on which they lie during later events (Bell, 1986; Bell and Johnson, 1992; Bell et al., 2003). As a result, matrix lineations may not be a reliable marker of movement direction during orogenesis. However, foliation inflection/intersection axes preserved within porphyroblasts (FIAs) potentially provide a movement direction indicator that is unaffected by subsequent ductile deformation (e.g. Bell et al., 1998a; Bell and Mares, 1999).

Porphyroblast growth occurring early during crenulation development commonly preserves foliations as inclusion trails (Bell et al., 1986). The curvature of an included foliation, S_i, generally results from an overprinting deformation, with the

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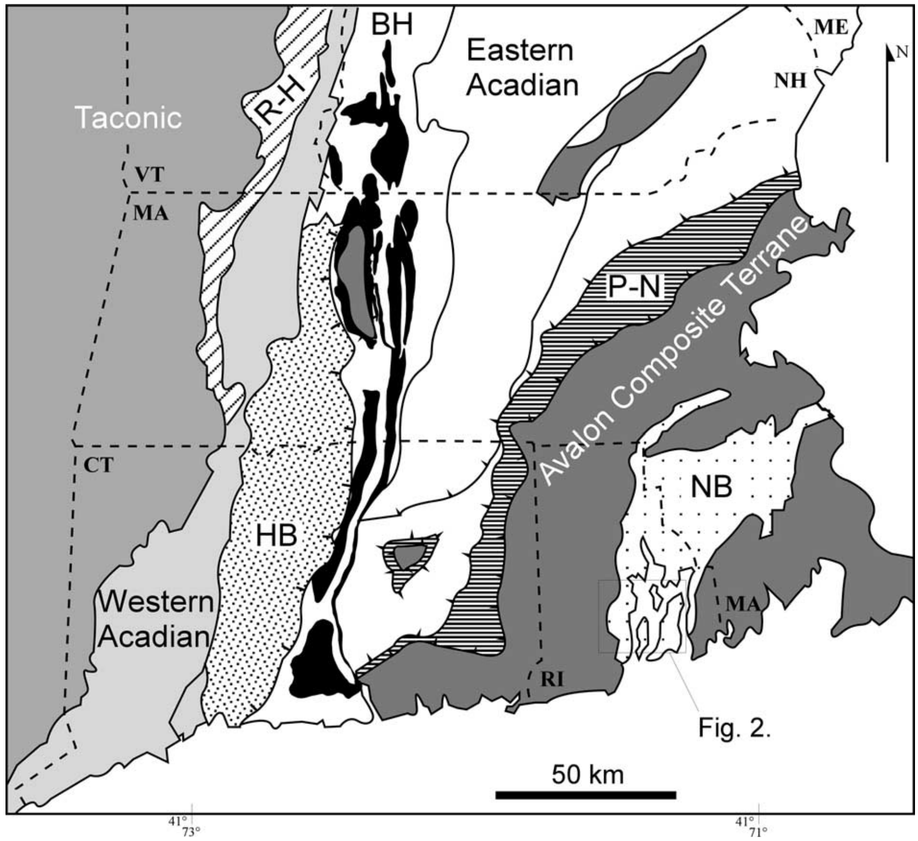

Fig. 1. The location of the area shown in Fig. 3 within a regional geological map of southern New England showing the major metamorphic realms as presented by Armstrong et al. (1992). Also shown are the major sedimentary basins: HB—Hartford Basin (Mesozoic) and the NB—Narragansett Basin (Pennsylvanian), the Middle Proterozoic Rowe Hawley terrane (R-H), the Late Proterozoic to Early Palaeozoic Putnam Nashoba terrane (P-N) and the Late Ordovician Bronson Hill magmatic arc. Regional Alleghanian metamorphism has been documented broadly within the Avalon Composite Terrane (Wintsch and Sutter, 1986).

asymmetry of curvature resulting from the inflexion of an earlier foliation affected by a younger event (Bell and Rubenach, 1983). The truncation of one included foliation by another results from intensification of that deformation in the matrix after porphyroblast growth ceased, or the effects of a younger deformation (Bell and Hayward, 1991). Preservation of FIAs within porphyroblasts prevents them being destroyed by reactivation or shear on the compositional layering during subsequent deformations. Consequently, they provide a reliable kinematic indicator (Bell and Johnson, 1992; Bell and Hickey, 1999; Ham and Bell, 2004). The trends of FIAs can be determined by observing the switch in asymmetry of inclusion trails in differently oriented vertical thin sections (Bell et al., 2004).

The FIA is the product of overprinting successive foliations, which, when a porphyroblast core is present, form subvertically and subhorizontally against the margins, independent of the orientation of the matrix (Bell et al., 1995, 1998b; Hickey and Bell, 1999). The trend of a FIA is the product of the strike of the subvertical foliation, as the FIA generally represents the intersection of the subvertical foliation with a previously or subsequently formed subhorizontal foliation (Bell and Wang, 1999). Thus the axis of the S_i curvature/intersection provides a linear indicator that formed perpendicular to the direction of bulk horizontal shortening during deformation that is synchronous with metamorphism (Bell et al., 2004). In contrast, the direction of motion along thrusts and shallowly dipping foliations can be controlled by the topographic high of the orogen (Bell and Wang, 1999). This study of matrix foliations and porphyroblast inclusion trail relationships has revealed a sequence of differently oriented FIAs that provide a relative time frame for the collisional deformation and associated metamorphism within the Narragansett Basin.

2. Geologic setting

The Rhode Island Formation is the dominant rock type within the basin and when porphyroblastic was preferentially sampled. Previous workers have suggested these interbedded sandstones, carbonaceous shales and coarse conglomerates were deposited within an evolving composite graben system as meandering to braided stream deposits (Mosher, 1983). The oldest reported plant fossils in the southern portion of the basin are Westphalian (Skehan et al., 1979; Skehan and Murray, 1980). The basin has an unconformable or fault contact with the late Proterozoic meta-igneous rocks and Cambrian metasedimentary units of the Avalon basement. The general consensus of opinion on the tectonic history of this basin, summarised by Cogswell and Mosher (1994), suggests there were several generations of E–W directed compressional

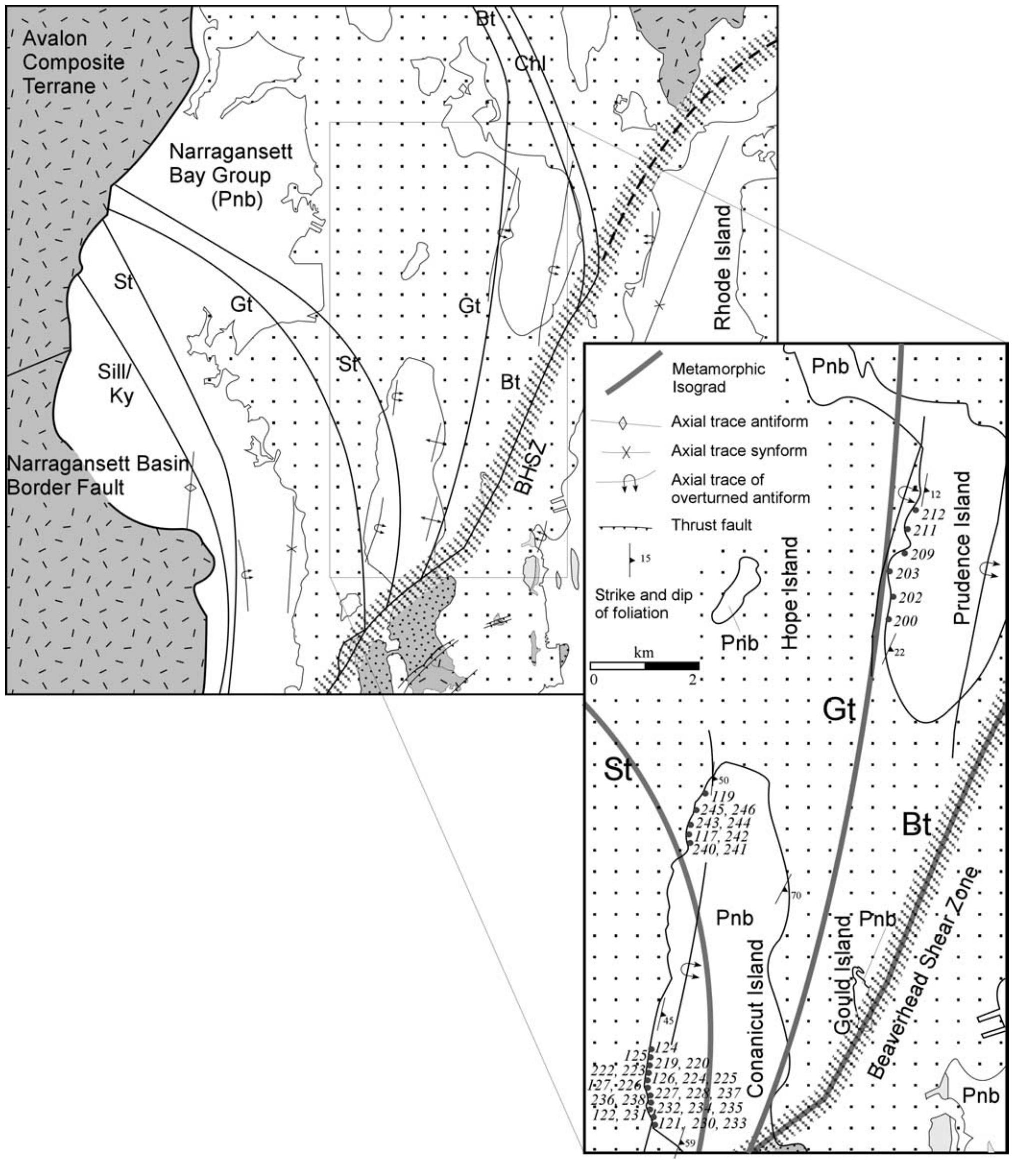

Fig. 2. Map of a portion of Rhode Island showing the fault controlled boundaries between the Avalon Composite Terrane and the Rhode Island Formation metasediments (Pnb) of the Narragansett Basin. Isograds highlight the marked increase in metamorphic grade towards the southwest corner of the basin (modified after Hermes et al., 1994). The inset shows the approximate localities for oriented rock samples used in this study.

nappe-like folding events, followed by two independent periods of wrenching. Greenschist facies metamorphism affected the bulk of the basin although the grade increases southwest to the upper amphibolite facies (Fig. 2).

The earliest recorded compressional deformation event, D_1, is present throughout the basin. F_1 fold axes trend sub-parallel to the long graben margins. In the northern graben this is regarded as the only deformation event present (Mosher, 1983). F_1 folds in the southern graben have been split into two generations of isoclinal folds that formed during a period of progressive deformation. F_{1a} folds are isoclinal folds of bedding with fold axes trending N–NNE. Associated with F_{1a} is a strong, generally axial planar foliation, S_{1a}. F_{1b} folds are also isoclinal with a similar fold axis trend but fold bedding plus S_{1a} and they verge distinctly westward (Reck and Mosher, 1988). Associated with F_{1b} is a less well developed axial planar cleavage, S_{1b}. Westward directed thrusting accompanied F_1 folding in the southern graben (Mosher, 1983). A second deformation event, D_2, affected the eastern portion of the southern graben, folding S_1 into tight to open NNW–NNE-trending structures with an eastward vergence. S_1 is locally crenulated to form a pervasive S_2 cleavage. The main stage of prograde metamorphism, M_1, began synchronous with D_1 in the western portion of the southern graben and migrated north and east (Mosher, 1983). Peak metamorphism is thought to predate a third deformation event, D_3, being syn-D_1 in the west of the southern graben and synchronous with D_2 in the north and east of the Narragansett Basin. S_3 occurs as E–W-trending cross-cutting crenulations (Reck and Mosher, 1988), E- and NE-trending, open, chevron and box folds (Mosher and Berryhill, 1991) or as a pervasive foliation with a NW–SE to W–E trend (Cogswell and Mosher, 1994). Late stage retrograde metamorphism, M_2, has been associated with a fourth deformation event, D_4, which involved right lateral wrenching of the entire basin complex. D_4 is represented by a range of structures including NE-trending dextral strike slip faults and en échelon folds with NNE axes (Mosher, 1983).

The area examined contains the Conanicut and Prudence Islands within the central zone of the southern graben (Fig. 2). This region is removed from the basin margin and any influence that that margin might have had on the distribution and/or geometry of deformation. It is also removed from any contact metamorphic affects associated with the intrusion of the Narragansett Pier granite. Cogswell and Mosher (1994) suggested that the south-central basin contains all the major early syn-metamorphic deformation events.

3. Description of samples

Samples were taken from the western coastal outcrops of Conanicut and Prudence Islands, which contain staurolite and garnet grade rocks, respectively. Sixty-three spatially oriented samples were taken. Thirty-nine contain porphyroblasts with well preserved inclusion trails and were selected for further analysis. Up to 18 vertical thin sections with different strikes were cut from each sample and provided the basis for the microstructural analysis.

Rocks sampled from Conanicut Island include highly carbonaceous pelitic schists, quartz-rich pelitic schists and massive hornblende–garnet amphibolite pods. Porphyroblast species present within the carbonaceous schist include garnet, staurolite, biotite, plagioclase and chlorite. The matrix consists of a well developed foliation (S_m) defined by preferential alignment of muscovite and quartz plus graphite. Additional matrix forming minerals locally include ilmenite, plagioclase and chlorite plus minor tourmaline and pyrite. Biotite is generally present as porphyroblasts with quartz strain shadows. Chlorite alteration of matrix forming muscovite occurs along bedding and crenulation hinges. Chlorite alteration of biotite and muscovite is visible adjacent to thin, matrix cross-cutting folded quartz veins. The penetrative matrix fabric lies at a low angle to relict bedding. Crenulations are defined by reoriented muscovite and quartz. The quartz rich schist contains garnet porphyroblasts and a matrix of quartz, muscovite, biotite and feldspar. A weaker but still pervasive cleavage is defined by elongated quartz grains, aligned muscovite and biotite. Amphibolite pods contain hornblende and garnet porphyroblasts with a matrix of plagioclase, quartz, carbonate and chlorite.

Garnet grade rocks were noted only on the northwestern tip of Prudence Island. The samples from Prudence Island are metamorphosed carbonaceous sandstones. The matrix mineralogy includes quartz, muscovite, graphite and carbonate plus locally plagioclase, ilmenite and chloritoid. The dominant foliation is defined by aligned muscovite and elongate quartz grains. Younger crenulation cleavages are defined by aligned muscovite. Plagioclase and chloritoid occur locally as porphyroblasts.

4. Morphology of inclusion trails

All samples selected for analysis from Conanicut Island contain garnet porphyroblasts that typically range in size from 0.5 to 5 mm, the larger ones usually occurring in highly graphitic layers. Inclusion trails consist of quartz, graphite and ilmenite. Some garnet porphyroblasts have texturally distinct cores with a zonation in the abundance and/or mineralogy of inclusions suggesting more than one stage of growth. Porphyroblasts can have inclusion rich cores and inclusion free rims or vice versa. In quartz-dominated sedimentary layers, garnet is generally xenoblastic and the inclusions are dominated by quartz. In graphite-rich compositional layers garnet has well-defined crystal faces, can exhibit sector zoning and commonly contains both quartz and graphite inclusions. Inclusion trails within garnet are generally sigmoidal shaped and are truncated locally by an external matrix foliation (Fig. 3). Sigmoidal inclusion trail geometries are either smoothly curving across the porphyroblast or straight with curvature restricted to the porphyroblast rim (Figs. 3 and 4). Garnet porphyroblast rims are locally altered to muscovite ± chlorite ± quartz.

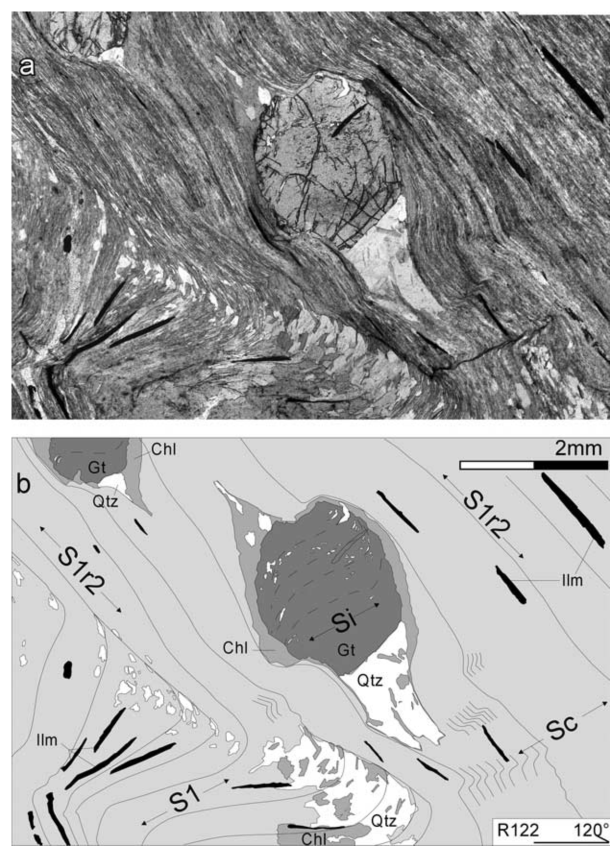

Fig. 3. (a) Photomicrograph and (b) line diagram of simple sigmoidal (>90° curvature) shaped inclusion trails within a garnet porphyroblast. The internal foliation (S_i) is truncated by the external foliation. The matrix has a well developed foliation (S_{1r2}) defined by preferential alignment of muscovite and quartz + graphite. Crenulations are defined by reoriented muscovite and quartz. Photomicrograph of a vertical thin section of sample R122 (single barbed arrow indicates way up and strike at 120°). Plane polarised light.

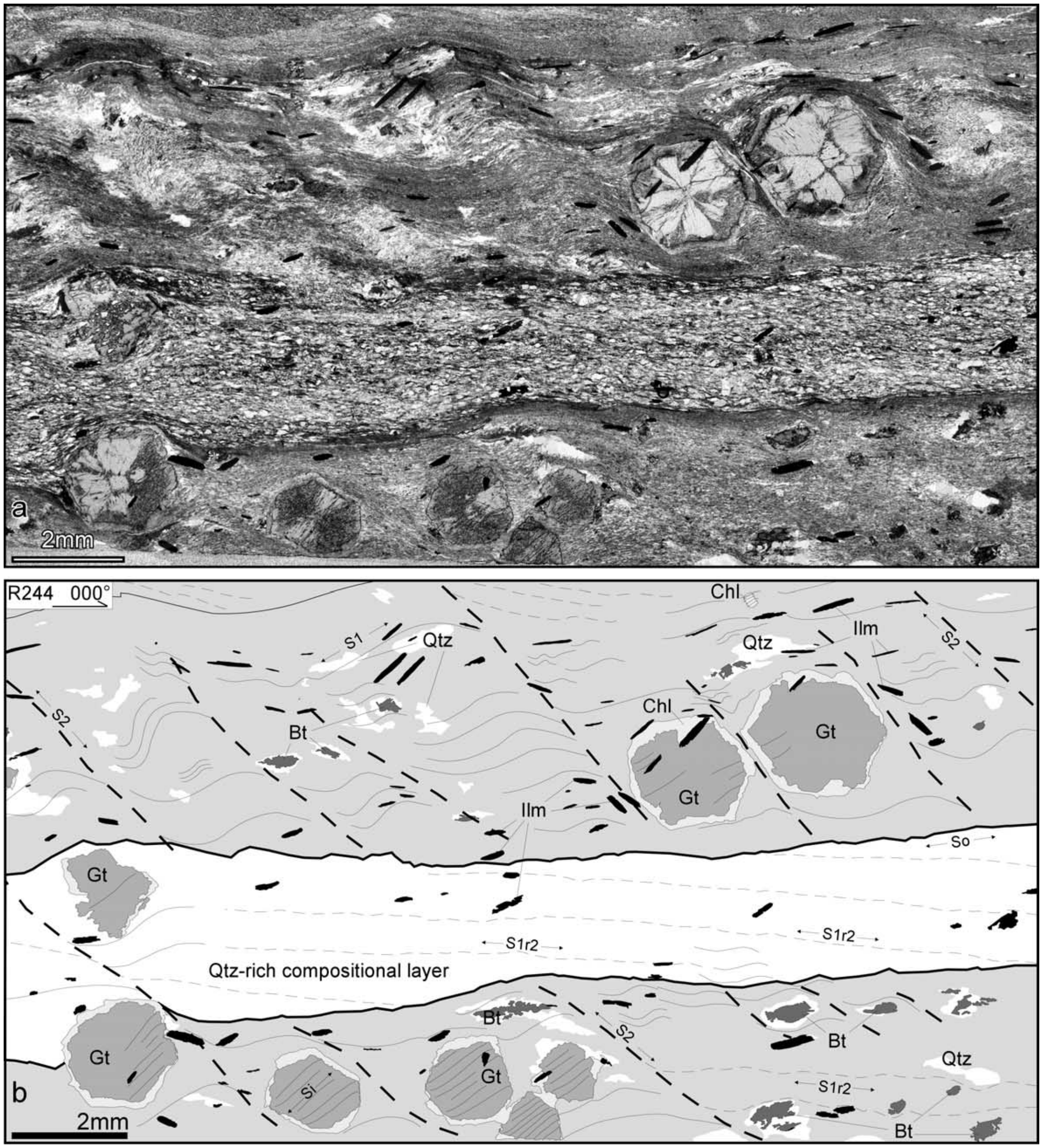

Fig. 4. (a) Photomicrograph of sample R244 from the western shore of Conanicut Island and accompanying line diagram (b) showing a heterogeneous sub-vertical foliation S_2 overprinting a sub-horizontal foliation S_1. Away from the porphyroblasts, S_1 is reactivated during D_2, which decrenulates S_2. The included foliation trace S_i, is continuous with the matrix. The penetrative matrix fabric (S_{1r2}) lies at a low angle to relict bedding (S_0) defined by a compositional change from muscovite-rich to quartz-rich. Photomicrograph of vertical thin section (single barbed arrow indicates way up and strike at 000°). Plane polarised light.

Large staurolite porphyroblasts up to 30 mm in length are abundant in the carbonaceous schist. Graphite and quartz form common inclusions within staurolite. Garnet and biotite porphyroblasts and their strain shadows can also be included within large staurolite porphyroblasts. The inclusion trails commonly have sigmoidal shapes and are continuous into the matrix (Fig. 5). Staurolite has locally overgrown and preserved differentiated crenulation cleavages as inclusion trails. Some porphyroblasts are partially replaced by chlorite, commonly with a muscovite reaction rim.

Plagioclase porphyroblasts with sigmoidal inclusion patterns have been analysed from both Conanicut and Prudence Islands. Plagioclase is generally inclusion rich with quartz, muscovite, graphite and/or carbonate trails that are generally continuous with the matrix foliation (Fig. 6). The density of porphyroblasts within a sample can range from 5% to approximately 80% with average long axes lengths of 2 mm.

Biotite porphyroblasts within the schist typically preserve sigmoidal graphitic inclusion trails that are predominantly straight with curvature restricted to the rim. However, some biotite porphyroblasts have been internally deformed and have undulose extinction. Others may have been deformed parallel to (001) and not show such extinction variation. Consequently, their inclusion trail geometry was not analysed. Chlorite

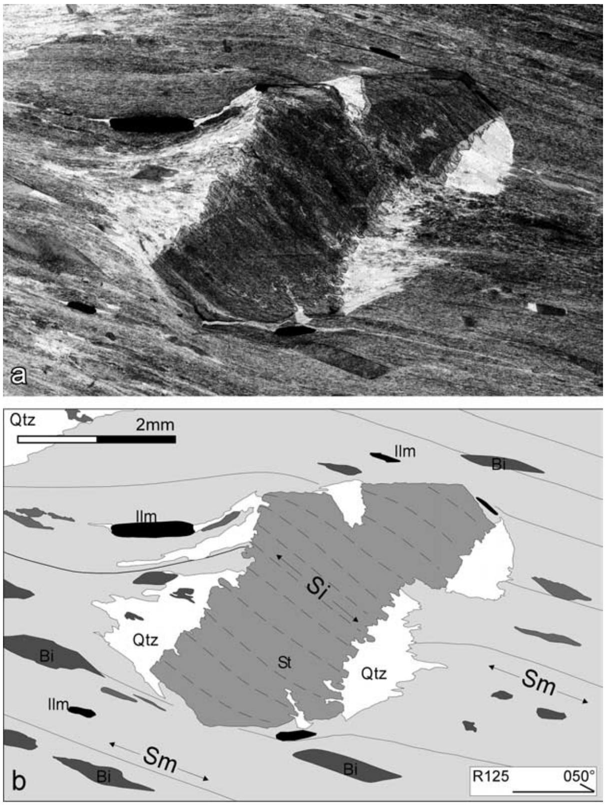

Fig. 5. (a) Photomicrograph and (b) line diagram of staurolite porphyroblast with inclusion trails that are continuous with the matrix foliation labelled S_m. The matrix consists of preferentially aligned of muscovite (S_m) and graphite. Photomicrograph of a vertical thin section of sample R125 (single barbed arrow indicates way up and strike at 050°). Plane polarised light.

growth appears to be very late relative to the matrix foliation. Chlorite porphyroblasts exhibit a variety of included microfold geometries that appear to be directly associated with overgrowth of variably deformed matrix and/or previously existing porphyroblastic phases. Therefore, chlorite asymmetries were not recorded either. Chloritoid in samples from Prudence Island grew late relative to the matrix foliation with long axes appearing to be randomly oriented relative to the matrix foliation.

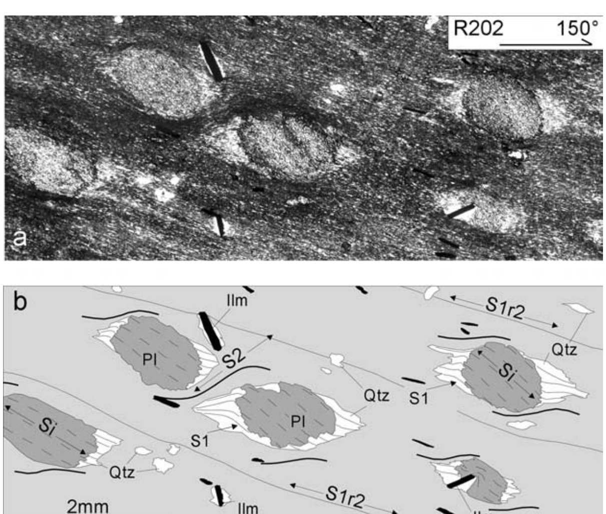

Fig. 6. (a) Photomicrograph and (b) line diagram of plagioclase porphyroblasts preserving a relict foliation (S_1) as inclusion trails (S_i). The dominant foliation is defined by aligned muscovite and elongate quartz grains plus graphite. Photomicrograph of vertical thin section of sample R202 (single barbed arrow indicates way up and strike at 150°).

5. Methods

5.1. FIA determinations

Three-dimensional microstructural analyses of both matrix foliations and structures preserved in porphyroblasts are presented to constrain the synmetamorphic structural history of the area. This has allowed the relative timing and kinematics of early basin compressional deformation to be determined. A method for analysing the spatial relationships of inclusion trail geometries within porphyroblasts was defined by Hayward (1990) and Bell et al. (1995). This technique allows the mean trend of a FIA to be determined for a given sample. A multiple thin section approach is applied to determine the location of the asymmetry switch for curving inclusion trails within the porphyroblasts. For each vertical section the asymmetry of curvature of single or overprinting inclusion trails is noted. A FIA is determined by recording the switch in S_i asymmetry (clockwise or anticlockwise) between successive vertically oriented thin sections observed from the same direction. The FIA trend for a single sample is the mean for the total population of porphyroblasts present in thin sections analysed.

5.2. Relative timing criteria and FIA successions

In some samples, multiple FIA trends are present in distinct microstructural domains. Differing FIA trends may be preserved by porphyroblasts through separate periods of mineral growth, for example, core versus rim (Fig. 7), or as different minerals that grew during progressive metamorphism such as garnet and then staurolite. By utilising established concepts of overprinting criteria, analysis of multi-FIA samples can determine the relative timing between successive consistent FIA trends. Sequentially grown porphyroblasts showing clear growth-timing relationships relative to surrounding foliations and partial replacement microstructures provide timing relationships relative to the surrounding foliations.

6. Results

6.1. Sample classification

A total of 57 FIAs were measured from porphyroblasts within 39 spatially oriented samples from the Rhode Island formation in the central zone of the Narragansett Basin. Thirty-five FIAs were measured using garnet porphyroblasts in 29 samples from Conanicut Island. Twenty-three samples preserve a single FIA and six contain a different FIA in the core versus the rim (samples R125, R126, R226, R234, R235 and R238; Fig. 7, Table 1). The rim FIAs were obtained from

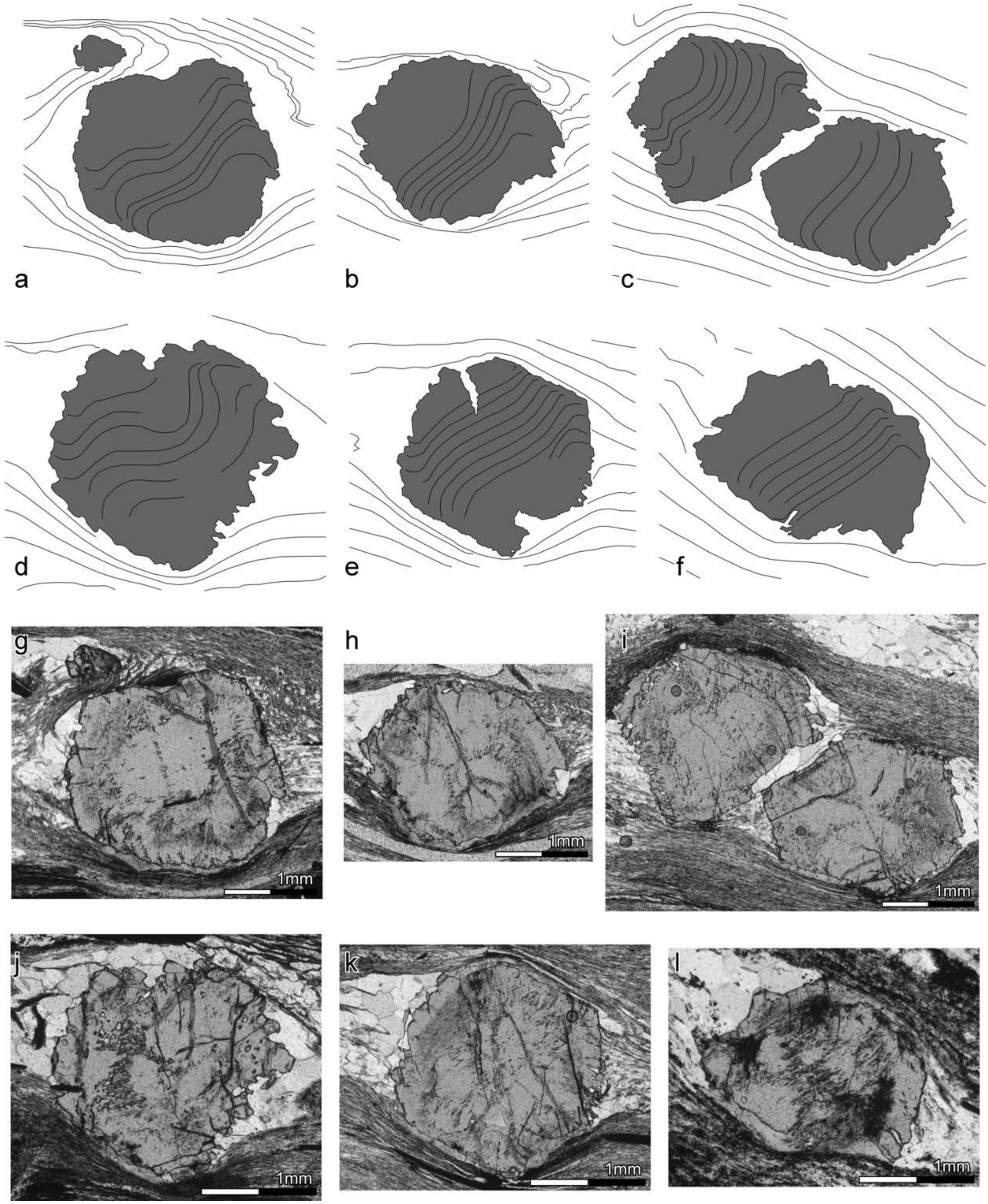

Fig. 7. Line diagrams ((a)–(f)) and photomicrographs ((g)–(l)) of garnet porphyroblasts from a vertical thin section striking at 40° (to the right of the page) from sample R234. The line diagrams highlight anticlockwise inclusion trail asymmetry preserved within the cores of the garnet porphyroblasts. A flip to clockwise asymmetry, in the rim of the porphyroblasts, is shown at varying degrees of preservation. Photomicrographs taken in plane polarised light.

inclusions in the rim that changed in asymmetry relative to the core and/or locally truncated those in the core. Ten FIAs were measured using samples containing staurolite porphyroblasts. Four samples preserve a staurolite FIA plus a core and rim garnet FIA (samples R125, R126, R226 and R238), four preserve a staurolite FIA plus a single garnet FIA and two preserve a single staurolite FIA (Table 1). Twelve FIAs were measured using samples containing plagioclase porphyroblasts. Four samples preserve a plagioclase FIA and a single garnet FIA (samples R240, R241, R243 and R244) and eight preserve single plagioclase FIAs (Table 1).

Fig. 8a shows a bi-directional rose plot (at 10° intervals) of all FIA trends measured. Two clusters of FIA trends are visible oriented NNE–SSW and WSW– ENE. In Fig. 8b–d,

Table 1
Structural data for samples from Conanicut and Prudence Islands. All samples are taken from the Rhode Island Formation. FIA data separated as staurolite, plagioclase and garnet core and rim. All orientations are relative to true north. The presence of biotite porphyroblasts are noted with an X

Sample	Sm		Garnet		St	Plag	Bt
	Dip	Dip dir.	Core	Rim			
Conanicut							
R117	39	95	75				
R119	45	103	65				
R121	28	103	15				
R122	53	85	25				
R124	19	115			40		X
R125	22	105	20	55	30		X
R126	31	111	15	80	20		X
R127	31	110		65	50		
R219	31	105	73				X
R220	26	103	18		18		X
R222	29	82	68				
R223	26	96	23		33		X
R224	22	96	63				
R225	33	89	18		18		X
R226	39	108	13	78	28		X
R227	24	103	73				X
R228	35	97			13		X
R230	40	84	13				
R231	59	93	78				
R232	59	112	18				
R233	47	103	13				
R234	28	100	8	83			
R235	44	87	13	78			
R236	48	83	18				
R237	55	83	18				
R238	23	99	18	88	18		X
R240	29	86	63			73	
R241	23	81	68			68	
R242	34	79	73				
R243	34	71		78		78	
R244	26	74	63			73	
R245	39	70				63	
R246	29	83				68	
Prudence							
R200	18	90				83	
R202	18	78				93	
R203	12	55				58	
R209	17	60				63	
R211	11	58				63	
R212	10	33				58	

respectively, garnet, staurolite and plagioclase FIAs are plotted in separate rose diagrams.

6.2. Relative timing from multi-FIA samples

A FIA trend from the core of a porphyroblast must be older than a FIA from the rim. Therefore, samples containing more than one FIA enable the relative timing of successive FIAs to be determined. A consistent succession of trends allows a paragenesis of FIAs to be established (Bell et al., 1998b). Garnet cores with SSW–NNE-trending FIAs are succeeded by rim FIAs with WSW–ENE trends. The remaining samples contain garnet porphyroblasts with just one FIA. These single FIAs have either SSW–NNE or WSW–ENE trends. Inclusion trails (S_i) in garnet porphyroblasts with a SSW–NNE FIA trend are truncated by the external matrix foliation. Samples with WSW–ENE-trending FIAs contain inclusion trails with varying degrees of continuity with the matrix. Staurolite inclusion trails defining a SSW–NNE FIA trend are commonly continuous with the external matrix foliation. Four samples contain SSW–NNE FIAs in staurolite plus garnet with the SSW–NNE cores and WSW–ENE FIA in the rims. Plagioclase inclusion trails contain WSW–ENE FIAs and are continuous with an external matrix foliation. Four samples contain this WSW–ENE plagioclase FIA trend plus WSW–ENE garnet FIAs.

6.3. FIA sets

Collectively the FIA trends show distinct modal peaks at 20° and 70°. SSW–NNE-trending FIAs occur in garnet porphyroblasts with a single FIA, staurolite porphyroblasts and in the cores of multi-FIA garnet porphyroblasts. Within this SSW–NNE trend garnet FIAs define the first measurable set at (average) 017° (± 4). The average FIA trend for staurolite porphyroblasts is 026° (± 10), which is within error of the garnet core FIA trend. Interestingly whenever garnet and staurolite FIA trends are measured from the same sample, the staurolite FIA is equal to or greater (more NE) than the garnet core. WSW–ENE-trending FIAs occur in garnet porphyroblasts with a single FIA, plagioclase porphyroblasts and in the rims of multi-FIA garnet porphyroblasts. Within this WSW–ENE trend, garnet FIAs define a measurable set at an average of 075° (±9). The average FIA trend for plagioclase porphyroblasts is 70° (±10), which is certainly within error of the garnet rim FIA trend. In the four samples where measured, plagioclase is equal to or more easterly-trending than the garnet rim. The suggested order for porphyroblast growth is therefore garnet core, staurolite, garnet rim and then plagioclase with a clockwise rotation of FIA trends of 017°, 026°, 075° and 070°, respectively (Fig. 9).

7. Interpretation

7.1. Significance of FIA data

These FIA trends provide a vital link to defining the succession of bulk movement directions during orogenesis in this portion of the Narragansett Basin. Microstructural and petrographic examination of schists from the central zone of the basin described herein indicates a two stage history of bulk movement. The interpretation of collisional deformation across the south central portion of the basin has been limited to overprinting N–S-trending F_1 and F_2 folding events (Mosher, 1983; Cogswell and Mosher, 1994). Conceptually, FIA trends form perpendicular to the direction of bulk horizontal shortening during deformation, which is synchronous with metamorphism (Bell et al., 2004). Therefore, microstructural geometries preserved within porphyroblasts suggest that they did not form within a simple kinematic framework of solely W–E directed bulk shortening. FIA set 1 comprises a SSW–

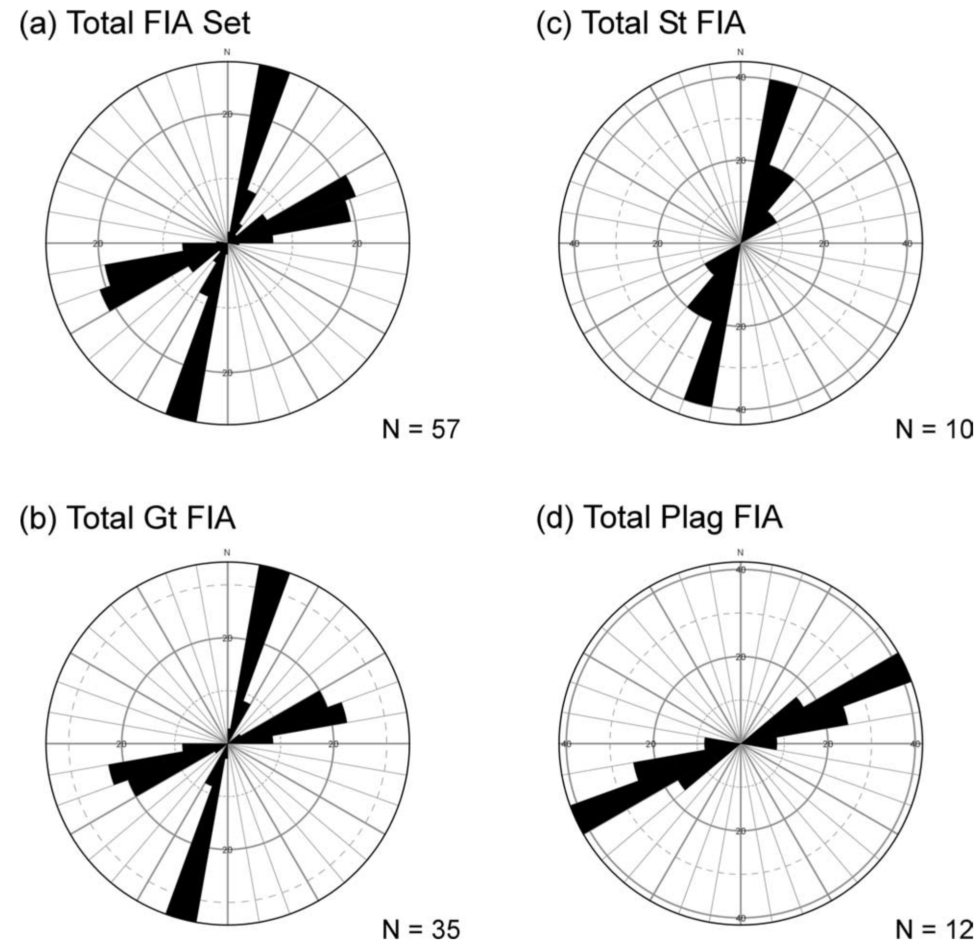

Fig. 8. (a) True area rose plot of the total FIAs for the central zone of the Narragansett Basin. For comparison, true area rose plots of FIA data for different porphyroblastic minerals (b) garnet, (c) staurolite and (d) plagioclase from the same area as (a).

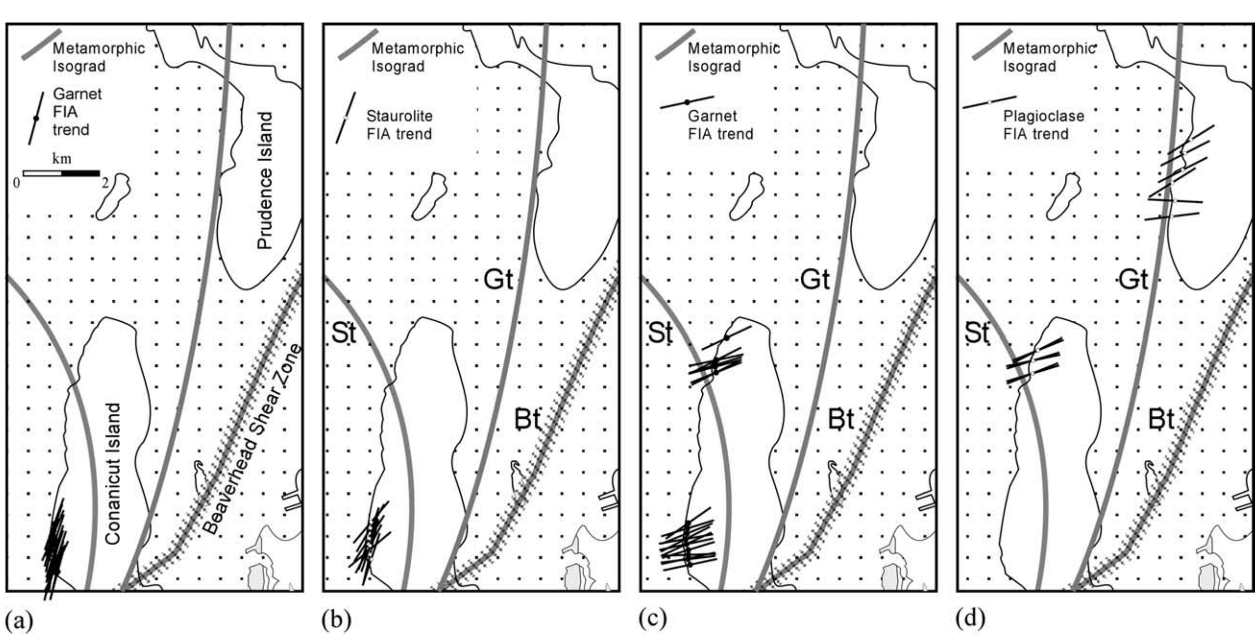

Fig. 9. FIA trends for successive FIA sets in the Narragansett Basin area. (a) Map of FIA set 1 garnet trends. (b) Map of FIA set 1 staurolite trends. (c) Map of FIA set 2 garnet trends. (d) Map of FIA set 2 plagioclase trends.

NNE trend (Fig. 9a and b), suggesting WNW–ESE bulk shortening. FIA set 2 records an ENE–WSW trend (Fig. 9c and d), suggesting NNW–SSE bulk shortening. Thus FIA set 2 records significant NNW–SSE bulk shortening that accompanied a major phase of prograde metamorphism within the Narragansett Basin, which is absent or misinterpreted in previously determined data sets.

8. Discussion

8.1. Peak metamorphism and the dominant matrix foliation

In light of the microstructural and petrographic evidence presented herein, it is necessary to reconsider the existing interpretation of the early deformation history of the Narragansett Basin that was summarised by Cogswell and Mosher (1994). Fig. 4 demonstrates that the dominant matrix foliation, S_{1r2}, postdates the peak of metamorphism. The foliation relationships suggest that S_{1r2} is a composite foliation consisting of reactivated and decrenulated pre-existing foliations. This matrix foliation, S_{1r2}, is the penetrative foliation (S_2) of Burks and Mosher (1996) and as such the peak of metamorphism predates all foliations as currently mapped within the Narragansett Basin. This highlights the inherent complexity associated with correlating foliations throughout the basin, as attempted in previous studies (Mosher, 1983; Cogswell and Mosher, 1994; Burks and Mosher, 1996), in that reactivation will commonly reorientate foliations into parallelism with bedding and thus obscure cross-cutting relationships.

8.2. Major fold axis orientations and FIA trends

Major fold axis orientations for the entire basin and FIA trends from the south-central zone are compared in Fig. 10 and

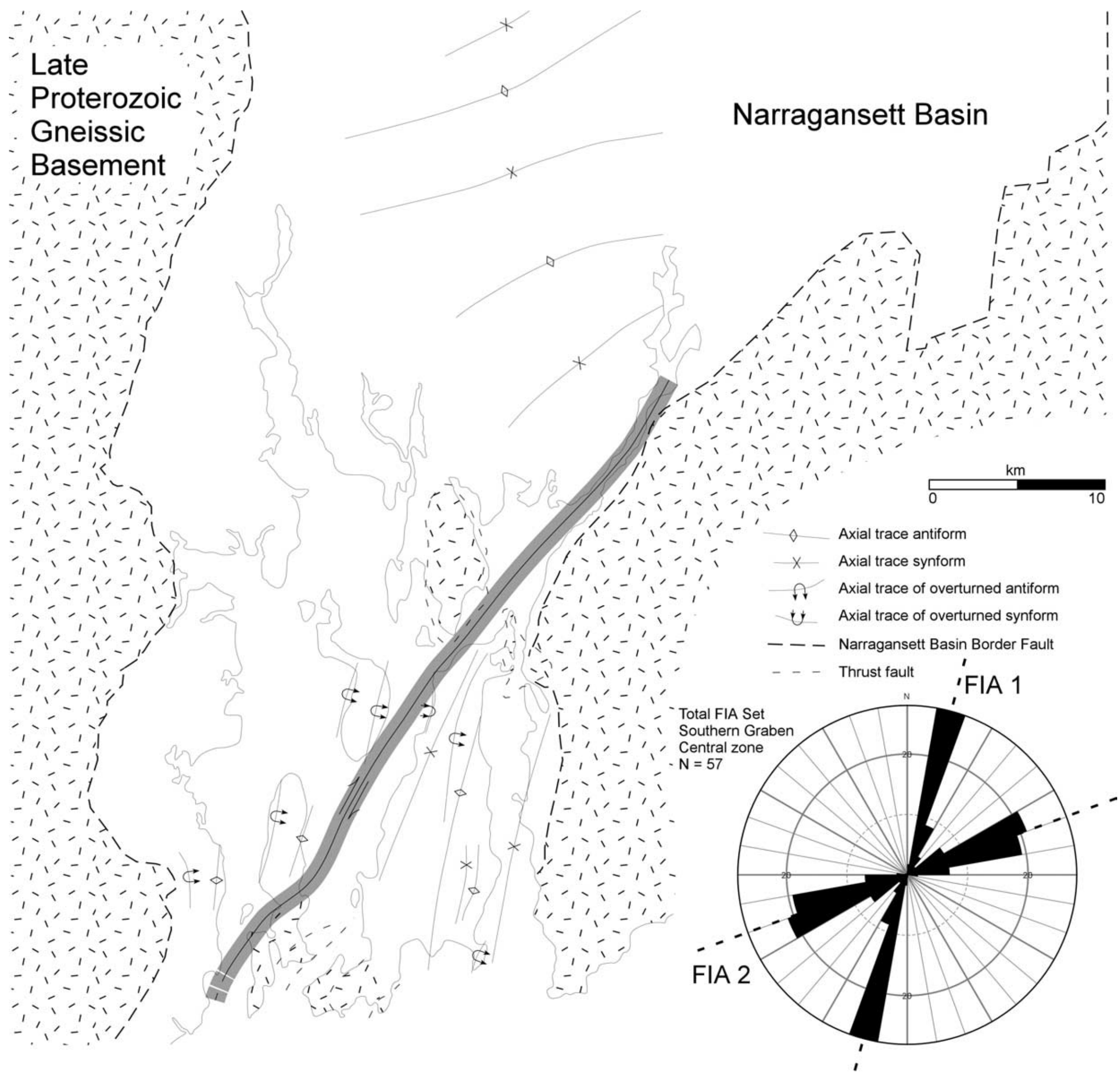

Fig. 10. Simplified geologic map of central southern Rhode Island (after Hermes et al., 1994) and true area rose plot of the total FIAs for the central zone of the southern Narragansett Basin.

are remarkably similar. FIA set 1 has the same trend (SSW–NNE) as major folds in the southern half of the basin. FIA set 2 has a similar trend (ENE–WSW) as major folds in the northern half of the basin. The similarity in orientation of the FIA set 1 trend and SSW–NNE-trending folds in the southern half of the basin suggests a direct relationship between the two data sets, i.e. that FIA set 1 recorded WNW–ESE compression associated with the formation of the early NNE-trending folds. A mechanism suggested for the formation of the ENE–NE-trending folds was that they developed during rotation and closure of the northern graben in response to W–E bulk shortening (Mosher, 1983). The similarity in orientation of the FIA set 2 trend and the ENE–NE-trending folds in the northern half of the basin allows two alternative mechanisms to be suggested: (1) FIA set 2 could be recording the NNW–SSE compression associated with the formation of early NNE-trending folds, or (2) folds formed during FIA set 1 associated WNW–ESE compression were subsequently rotated during the development of FIA set 2 and associated NNW–SSE deformation. In the northern area FIA set 2 deformation could have reoriented these folds, whereas in the south this deformation may have been weaker so that the original N–S trend of folds was preserved. This second scenario is supported by the gradually changing trends of folds in the northern part of the Narragansett Basin. Going from south to north, one sees that fold trends progressively curve from SW–NE to WSW–ENE (Fig. 10).

8.3. NNW–SSE directed compression

The evidence for NNW–SSE directed bulk shortening is significant as it is not accommodated by the current model for the collisional deformation in the Narragansett basin (McMaster et al., 1980; Mosher, 1983). In Rhode Island, pull-apart graben style basins were thought to have formed as a response to sinistral strike slip motion along a broad mobile zone adjacent to the Avalon–North American boundary (Fig. 11a). Collisional deformation within the basin is envisaged to have been driven by a change to dextral motion along the mobile zone resulting in W–E compression (Mosher and Berryhill, 1991). Reactivation of basement faults driving subsequent periods of sinistral and dextral strike slip motion on NNE-, NE- and ENE-trending shear zones has been well documented by Mosher and Berryhill (1991), Burks and Mosher (1994) and Cogswell and Mosher (1996). Progressive movement on the shear zones produced overprinting mesoscale non-coaxial folds and crenulation cleavages at chlorite grade metamorphism. It is likely that a change in plate motion early in the basin's history initiated significant NNW–SSE directed bulk shortening and accompanied prograde metamorphism

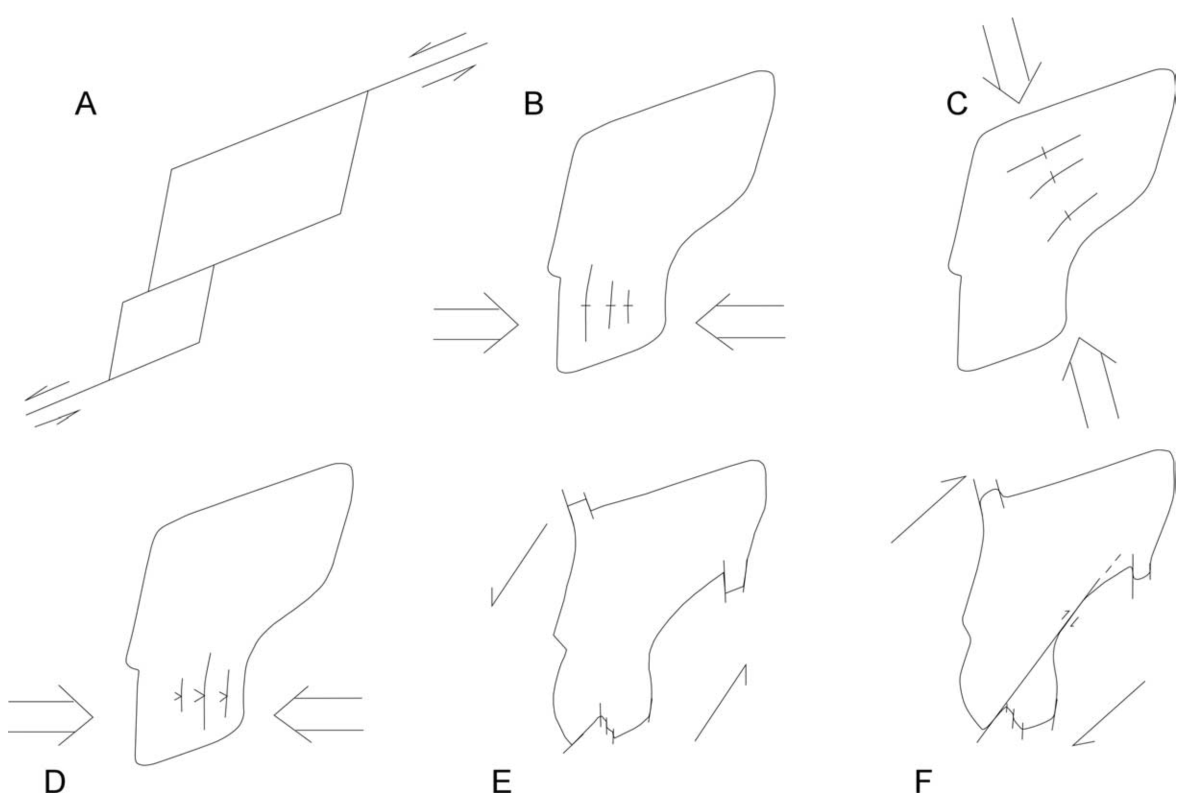

Fig. 11. Model for Narragansett Basin formation and deformation as a response to changes in motion along and within a mega shear zone between an Avalon microcontinent, the European–North American plate and the African plate. Figures modified from Mosher (1983). (A) Late Palaeozoic sinistral movement resulted in the formation of pull apart basins; (B) E–W compression [F_{1a}, FIA set 1] related to dextral motion forcing closure of the basin; (C) N–S directed compression [F_1 folds northern graben, FIA set 2]; (D) E–W compression [F_2]; (E) late-stage Alleghanian sinistral shearing; (F) subsequent dextral motion.

without the reactivation of basement faults initiating wrench style deformation (Fig. 11b).

8.4. A clockwise rotation of bulk shortening direction

Similarities are noted between the change in bulk shortening direction suggested by FIA trends in the Narragansett Basin (WSW–ENE to NNW–SSE) and a clockwise rotation of thrusting direction as suggested by petrological and structural data from the Honey Hill fault system (Wintsch and Sutter, 1986) in eastern Connecticut. Previous comparisons of this data correlated the change to a N–S shortening direction in eastern Connecticut with the change in deformation style from E–W compressional to shearing within the Narragansett basin (Reck and Mosher, 1988). This argument was dismissed by Reck and Mosher (Dallmeyer, 1982) because of apparent kinematic discrepancies stemming from dominantly dextral motion along the Beaverhead Shear Zone being instead compatible with N–S extension. The FIA trends from metasediments of the Narragansett Basin, however, record a change in bulk shortening direction from WSW–ENE to NNW–SSE, which was synchronous with peak metamorphism. Samples taken from garnet grade rocks on Conanicut Island yielded 245 Ma $^{40}Ar/^{39}Ar$ postmetamorphic biotite cooling ages (Wintsch and Lefort, 1984), which suggest peak metamorphism occurred during the middle Permian. The clockwise rotation in bulk shortening directions from WSW–ENE to NNW–SSE preserved by FIA trends in the metasediments of the Narragansett Basin, therefore, occurred during the same period as a clockwise rotation of thrusting directions in eastern Connecticut from ESE at 290 Ma to due south at 250 Ma, as proposed by Wintsch and Lefort (1984).

9. Conclusions

Three-dimensional microstructural analyses of both matrix foliations and structures preserved in porphyroblasts define two periods of deformation and metamorphism in metasediments of the Rhode Island Formation from the central zone of the Narragansett Basin. Two axes of inclusion trail curvature trends have been distinguished, a SSW–NNE FIA trend (FIA 1) and a WSW–ENE trend (FIA 2), that formed approximately orthogonal to the maximum bulk shortening directions during accompanying high grade metamorphism. Major fold axis orientations for the entire basin and FIA trends from the south-central zone are remarkably similar. The clockwise rotation in bulk shortening directions from WSW–ENE to NNW–SSE in the Narragansett basin and a clockwise rotation of thrusting directions in eastern Connecticut from ESE to due S both occurred during the middle Permian.

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References

Armstrong, T.R., Tracy, R.J., Hames, W.E. 1992. Contrasting styles of Taconian, Eastern Acadian and western Acadian metamorphism, central and western New England. Journal of Metamorphic Geology 10, 415–426.

Bell, T.H., 1986. Foliation development and reactivation in metamorphic rocks: the reactivation of earlier foliations and decrenulation due to shifting patterns of deformation partitioning. Journal of Metamorphic Geology 4, 421–444.

Bell, T.H., Hayward, N., 1991. Episodic metamorphic reactions during orogenesis; the control of deformation partitioning on reaction sites and reaction duration. Journal of Metamorphic Geology 9, 619–640.

Bell, T.H., Hickey, K.A., 1999. Complex microstructures preserved in rocks with a simple matrix; significance for deformation and metamorphic processes. Journal of Metamorphic Geology 17 (5), 521–535.

Bell, T.H., Johnson, S.E., 1992. Shear sense: a new approach that resolves conflicts between criteria in metamorphic rocks. Journal of Metamorphic Geology 10, 99–124.

Bell, T.H., Mares, V., 1999. Correlating deformation and metamorphism around orogenic arcs. American Mineralogist 84, 1727–1740.

Bell, T.H., Rubenach, M.J., 1983. Sequential porphyroblast growth and crenulation cleavage development during progressive deformation. Tectonophysics 92, 171–194.

Bell, T.H., Wang, J., 1999. Linear indicators of movement direction versus foliation intersection axes in porphyroblasts (FIAs) and their relationship to directions of relative plate motion. Earth Science Frontiers 6, 31–46.

Bell, T.H., Rubenach, M.J., Fleming, P.D., 1986. Porphyroblast nucleation, growth and dissolution in regional metamorphic rocks as a function of deformation partitioning during foliation development. Journal of Metamorphic Geology 4, 37–67.

Bell, T.H., Forde, A., Wang, J., 1995. A new indicator of movement direction during orogenesis: measurement technique and application to the Alps. Terra Nova 7, 500–508.

Bell, T.H., Hickey, K.A., Upton, G.J.G., 1998a. Distinguishing and correlating multiple phases of metamorphism across a multiply deformed region using the axes of spiral, staircase and sigmoidal inclusion trails in garnet. In: Anonymous (Ed.), American Geophysical Union 1998 Spring Meeting 79. American Geophysical Union, pp. 365–366.

Bell, T.H., Hickey, K.A., Upton, G.J.G., 1998b. Distinguishing and correlating multiple phases of metamorphism across a multiply deformed region using the axes of spiral, staircase and sigmoidal inclusion trails in garnet. Journal of Metamorphic Geology 16, 767–794.

Bell, T.H., Ham, A.P., Hickey, K.A., 2003. Early formed regional antiforms and synforms that fold younger matrix schistosities: their effect on sites of mineral growth. Tectonophysics 367, 253–278.

Bell, T.H., Ham, A.P., Kim, H.S., 2004. Partitioning of deformation along an orogen and its effects on pophyroblast growth during orogenesis. Journal of Structural Geology 26, 825–845.

Burks, R., Mosher, S., 1996. Multiple crenulation cleavages as kinematic and incremental strain indicators. Journal of Structural Geology 18, 625–642.

Cogswell, M.J.P., Mosher, S., 1994. Late-stage Alleghanian wrenching of the southwestern Narragansett Basin, Rhode Island. American Journal of Science 294, 861–901.

Dallmeyer, R.D., 1982. $^{40}Ar/^{39}Ar$ ages from the Narragansett Basin and southern Rhode Island basement terrane: their bearing on the extent and timing of Alleghanian tectonothermal events in New England. Geological Society of America Bulletin 93, 1118–1130.

Dallmeyer, R.D., Takasu, A., 1992. $^{40}Ar/^{39}Ar$ ages of detrital muscovite and whole-rock slate/phylite, Narragansett Basin, RI-MA, USA: implications for rejuvenation during very low-grade metamorphism. Contributions to Mineralogy and Petrology 110, 515–527.

Getty, S.R., Gromet, L.P., 1992. Evidence for extension at the Willimantic Dome, Connecticut; implications for the late Paleozoic tectonic evolution of the New England Appalachians. American Journal of Science 292, 398–420.

Hermes, O.D., Gromet, L.P., Murrary, D.P. 1994. Bedrock geologic map of Rhode Island. In: Rhode Island Map Series No. 1. Office of the Rhode Island State Geologist.

Ham, A.P., Bell, T.H., 2004. Recycling of foliations during folding. Journal of Structural Geology 26, 1989–2009.

Hayward, N., 1990. Determination of early fold axis orientations in multiply deformed rocks using porphyroblast inclusion trails. Tectonophysics 179, 353–369.

Hickey, K.A., Bell, T.H., 1999. Behaviour of rigid objects during deformation and metamorphism; a test using schists from the Bolton Syncline, Connecticut, USA. Journal of Metamorphic Geology 17 (2), 211–228.

Lyons, P.C., 1984. Carboniferous megafloral zonation of New England. In: Sutherland, P.K., Manger, W.L. (Eds.), Neuvieme Congres International de Stratigraphie et de Carbonfere Compte Rendu 2. Southern Illinois University Press, Illinois, pp. 503–514.

McMaster, R.L., de Boer, J., Collins, B.P., 1980. Tectonic development of southern Narragansett Bay and offshore Rhode Island. Geology 8, 496–500.

Moecher, D.P., 1999. The distribution, style, and intensity of Alleghanian metamorphism in south-central New England: petrologic evidence from Pelham and Willimantic Domes. Journal of Geology 107, 449–471.

Mosher, S., 1983. Kinematic history of the Narragansett Basin, Massachusetts and Rhode Island: constraints on Late Paleozoic plate reconstructions. Tectonics 2, 327–344.

Mosher, S., Berryhill, A.W., 1991. Structural analysis of progressive deformation within complex transcurrent shear zone systems: southern Narragansett Basin, Rhode Island. Journal of Structural Geology 13, 557–578.

Reck, B.H., Mosher, S., 1988. Timing of the Narragansett Pier granite relative to deformation in the southwestern Narragansett Basin, Rhode Island. Journal of Geology 96, 677–692.

Reed, R.M., Williams, M.L., 1989. Petrofabric kinematic indicators in the northern portion of the Pelham Dome, western Bronson Hill Anticlinorium, central Massachusetts. Geological Society of America, Northeastern Section, 24th Annual Meeting. Abstracts with Programs—Geological Society of America 21, 60.

Robinson, P., Peterson, V.L., 2002. Lineation patterns and associated kinematics in central New England; under-reported resource for interpretation of orogenic evolution. Geological Society of America, Northeastern Section, 37th Annual Meeting. Abstracts with Programs—Geological Society of America 34, 29.

Skehan, S.J., Murray, D.P., 1980. Geologic profile across southeastern New England. Tectonophysics 69, 285–319.

Skehan, S.J., Murray, D.P., Hepburn, J.C., Billings, M.P., Lyons, P.C., Doyle, R.G., 1979. The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Massachusetts, Rhode Island, and Maine. United States Geological Survey Professional Paper 1110A, 30pp.

Wintsch, R.P., 1979. The Willimantic Fault: a ductile fault in Eastern Connecticut. American Journal of Science 279, 367–393.

Wintsch, R.P., Lefort, J.-P., 1984. A clockwise rotation of Variscan strain orientations in SE New England and regional implications. In: Hutton, D.H.W., Sanderson, D.J. (Eds.), Variscan Tectonics of the North Atlantic Region. Blackwell Scientific Publications, Oxford, pp. 245–251.

Wintsch, R.P., Sutter, J.F., 1986. A tectonic model for the Late Paleozoic of southeastern New England. Journal of Geology 94, 459–472.

Wintsch, R.P., Sutter, J.F., Kunk, M.J., Aleinikoff, J.N., Dorais, M.J., 1992. Contrasting P–T–t paths: thermochronologic evidence for a late Paleozoic final assembly of the Avalon Composite Terrane in the New England Appalachians. Tectonics 11, 672–689.

Zartman, R.E., Hermes, O.D., Pease Jr., M.H., 1988. Zircon crystallization ages, and subsequent isotopic disturbance events, in gneissic rocks of eastern Connecticut and western Rhode Island. American Journal of Science 288, 376–402.