Chapter 1. Permian bulk shortening in the Narragansett Basin of southeastern New England, USA.

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.

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 Avalon 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. Significantly, recent studies suggest an important role for Alleghanian tectonism throughout New England (Getty and Gromet, 1992a; Wintsch et al., 1992; Moecher, 1999).

Sediments within the Narragansett Basin of Rhode Island and Massachusetts contain Pennsylvanian (post-Acadian; 325-295Ma) 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 deformation associated with right lateral wrenching of the entire basin complex. 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) poterntially 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, Si, generally results from an overprinting deformation, with the 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; Bell et al., 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)(Fig. 2).

Initially these inclusion trail geometries were interpreted as recording the rotation of a rigid object during non-coaxial strain (Rosenfeld, 1970). Recent work, however, suggests that porphyroblasts nucleate and grow in zones of progressive shortening (Bell et al., 1986) and may only rotate relative to geographic coordinates in relatively uncommon geological environments where there was no component of bulk shortening (Bell et al., 1989). This general lack of rotation of porphyroblasts has been confirmed by extensive data from multiply deformed and metamorphosed regions on foliation/ inflection axes preserved in porphyroblasts (Bell et al., 1998b; Hickey and Bell, 1999; Bell et al., 2003; Aerden, 2004; Cihan and Parsons, 2005; Sayab, 2005). 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 unit within the basin and was preferentially sampled when porphyroblastic. 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 east-west directed compressional 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. 3).

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- to 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 to 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 EW 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 echelon 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 north western 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 0.5mm to 5mm, 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. 4). Sigmoidal inclusion trail geometries are either smoothly curving across the porphyroblast or straight with curvature restricted to the porphyroblast rim (Fig 4 and 5). Garnet porphyroblast rims are locally altered to muscovite±chlorite±quartz.

Large staurolite porphyroblasts up to 30mm 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. 6). 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. 7). The density of porphyroblasts within a sample can range from 5 percent to approximately 80 percent with average long axes lengths of 2mm.

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 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.

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 (Fig. 8). 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. 9), 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 fifty seven FIAs were measured from porphyroblasts within thirty nine 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 twenty-nine 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, R238; Fig.9, Table 1). The rim FIAs were obtained from 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, 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, R244), and eight preserve single plagioclase FIAs (Table 1).

Figure 10a shows a bi-directional rose plot (at 10º intervals) of all FIA trends measured. Two clusters of FIA trends are visible oriented NNE-SSW and WSW- ENE. In Figure 10b, c and d 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 20º and 70º. 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 when ever 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 017°, 026°, 075° and 070° respectively (Fig.11).

7. Interpretation 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 north-south 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 that 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-NNE (Fig. 11a and 11b) trend that suggests WNW-ESE bulk shortening. FIA set 2 records an ENE-WSW trend (Fig. 11c and 11d) 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 in or misinterpreted in previously determined data sets.

Additionally, there appears to be a south to north metamorphic evolution of the FIA trends. FIA set 1 is defined in garnets in the south. Staurolites in the south already show some CW rotation. FIA set 2 is present in garnets from the south and the north, but not in any staurolites. Being it reasonable that foliations are regional, it is also reasonable to arguer that garnets in the northern part of Conanicut Island had not crystallized until FIA set 2 had been established. The same is true of the plagioclases. Thus the south to north evolution of metamorphic porphyroblasts follows the CW rotation of bulk shortening direction.

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). Figure 5 demonstrates that the dominant matrix foliation, S_m, postdates the peak of metamorphism. The foliation relationships suggest that S_m is a composite foliation consisting of reactivated and decrenulated pre-existing foliations. This matrix foliation, S_m, 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 dangers associated with correlating foliations throughout the basin, as attempted in previous studies (Mosher, 1983; Cogswell and Mosher, 1994; Burks and Mosher, 1996). All of the younger foliations mapped in the basin are correlated back to 'S_l'which locally can be a composite of any combination of foliations that predate and include S_m.

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 Figure 12 and 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 ENE 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. 12).

8.3 NNW-SSE directed compression

The evidence for NNW-SSE directed bulk shortening is significant as it is not accommodated by published models (McMaster et al., 1980; Mosher, 1983) for the collisional deformation in the Narragansett basin. 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. 13a).

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 (1996), Burks and Mosher (1994) and Cogswell and Mosher (1994). 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 without the reactivation of basement faults initiating wrench style deformation (Fig. 13b).

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 (1988). This argument was dismissed in 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 .

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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Chapter 2. On shear sense using cleavages that develop via crenulations.

Abstract

Foliation intersection/inflection axes preserved in porphyroblasts (FIAs), from the Rhode Island Formation in the central zone of the Narragansett Basin, have two distinct trends oriented NNE and ENE. Both trends occur in some samples and reveal a consistent succession from NNE to ENE. Each FIA trend is defined by asymmetric curved inclusion trails that in every case have an anticlockwise asymmetry looking NE. The two distinct trends and their consistent relative timing cannot be explained if the porphyroblasts had rotated. Therefore, a deformation history of progressive bulk inhomogeneous shortening with a consistent non-coaxial component of shear of top to the WNW followed by top to the NNW is required. This correlates with the macroscopic regional relationships suggested by the folds which verge WNW and provides a convincing demonstration that shear on cleavage corresponds with the differentiation asymmetry (curvature of a crenulated cleavage into differentiated crenulation cleavage).

1. Introduction

Since the start of the 20th century geologists have argued about the possibility of whether or not shear occurs on cleavage. The argument centres around whether cleavage-parallel offset of features across cleavage domains result from volume loss through pressure solution (Durney, 1972; Groshong, 1975; Cosgrove, 1976; Gray, 1979; Wright and Henderson, 1992) or volume loss coupled with or driven by cleavage-parallel shear movement between microlithons (Means and Williams, 1972; Williams, 1972, 1976; Bell, 1981, 1985; Murphy, 1990).

Arguments for and against shear on crenulation cleavage, in particular, are essentially based on the interpreted mechanism of folding. Fold mechanisms involving buckling, bending and passive flow infer that crenulation cleavage geometries suggesting that slip has occurred along cleavage seams result from pressure solution (Durney, 1972; Groshong, 1975; Cosgrove, 1976; Gray, 1979) with the associated volume loss generating apparent shear. They argue this is confirmed by the orientation of the cleavage and foliation planes forming parallel to the XY plane of the strain ellipsoid, which in bulk shortening should form perpendicular to σ_1.

However, displacement across crenulation cleavage seams has been observed in rocks at higher metamorphic grades than those at which pressure solution is thought to operate (Bell and Cuff, 1989). Williams (1976) and Gray and Durney (1979) revisited the shear parallel to cleavage conundrum and found that cleavage may not always form parallel to the XY plane and a shear component may occur parallel to cleavage if the strain is not coaxial.

A solution to the problem of the XY plane of the strain ellipsoid and shear was provided by a strain field model that drew inspiration from metamorphic differentiation associated with crenulation cleavage development around porphyroblasts. This model, presented in Bell (1981), is called progressive bulk inhomogeneous shortening (PBIS). It resolves the homogeneity of strain along the axial plane of the folds required by the strain field models of Ramsay (1963) and allows the space problems of bulk shortening to be reduced to those of heterogeneous simple shear. During PBIS, rock deformation is partitioned into components of progressive shortening and progressive shearing (Fig.1). Zones of progressive shortening contain portions that have undergone no strain or progressive shortening strain and form the low strain zones that are represented by the microlithons in a differentiated crenulation cleavage. Zones of progressive shearing include zones that underwent progressive shortening plus shearing strain and progressive shearing only strain that develop into anastomosing cleavage seams. This model produces cleavage parallel offset between microlithons across the cleavage seam due to shear in complete contrast to the buckling/pressure solution models.

The shear sense can be determined by examining transitions from zones of low to high strain. The shear sense is established by determining the deflection of any foliation preserved within a zone of low strain as it bends into an adjacent zone of increased shearing strain (Bell and Johnson, 1992). Any competent heterogeneity in a rock can provide an opportunity for shear sense resolution because the progressive shearing component of deformation tends to partition around it. Such heterogeneities include porphyroblasts, which commonly preserve asymmetric curving foliations as inclusion trails or in their strain shadows. Initially these geometries were interpreted as recording the rotation of a rigid object during non-coaxial strain (Rosenfeld, 1970). Recent work, however, suggests that porphyroblasts nucleate and grow in zones of progressive shortening (Bell et al., 1986) and may only rotate relative to geographic coordinates in relatively uncommon geological environments where there was no component of bulk shortening (Bell et al., 1989). This general lack of rotation of porphyroblasts has been confirmed by extensive data from multiply deformed and metamorphosed regions on foliation/ inflection axes preserved in porphyroblasts (Bell et al., 1998b; Hickey and Bell, 1999; Bell et al., 2003; Aerden, 2004; Cihan and Parsons, 2005; Sayab, 2005). In regions where it can be demonstrated using FIA data that the porphyroblasts have not rotated the sense of rotation of foliations as they pass from a more competent porphyroblast to the less competent matrix can be reliably interpreted to identify the shear sense across that boundary (e.g. Bell et al., 2003; Bell et al., 2004; Bell and Newman, 2005). This study presents and discusses the relevant porphyroblast inclusion trail asymmetry data collected during a microstructural analysis of metasediments of the Rhode Island Formation from the Narragansett Basin, Rhode Island in rocks where the direction of bulk shear is know from macroscopic relationships.

2. Permian orogenesis in southeastern New England

The Narragansett Basin sediments are unique within the New England Appalachians because they were deposited after the Acadian orogenic period had peaked and before the Alleghanian orogenic period had commenced. As a result these Pennsylvanian sedimentary rocks only record the effects of the Permian metamorphism and deformation (Dallmeyer and Takasu, 1992) that accompanied the Alleghanian orogeny. The basin mainly contains non-marine clastic sedimentary rocks, which, based on plant fossils, range in age from Westphalian B through Stephanian B (Lyons, 1984). These sediments belong to the Rhode Island Formation and lie in unconformable contact with the Proterozoic Avalonian basement (Thompson and Hermes, 2003). A detailed petrologic description of the Narragansett Basin sediments is presented in Towe (1959) and further regional geology in Quinn and Moore (1968) and Skehan and Murray (1980). Deformation throughout the north of the basin is limited to open, gently plunging folds and the sediments are regionally metamorphosed to chlorite grade (Dallmeyer, 1982). The southwest of the basin has a polyphase deformation history and records the effects of regional metamorphism up to sillimanite grade (Fig.2). Mapping by Mosher (1983) and Reck and Mosher (1988) of regional scale folds in the southwest of the basin has defined two major trends of deformation that are considered to have formed pre or syn-peak metamorphism. D_{1a} and D_{1b} form folds with NNE trending axes and verge northwest. D_2 formed indistinct NNW to NNE trending crenulations

(Cogswell and Mosher, 1994). Third generation structures, D_3, are thought to have formed at chlorite grade within discrete north trending shear zones and are represented by a variety of macroscale structures that suggest sinistral transcurrent motion (Mosher and Berryhill, 1991). Detailed discussion of the polyphase deformation history in the southwest of the basin, as deduced from regional mapping, is presented in Mosher (1983) and Cogswell and Mosher (1994).

A three-dimensional microstructural analysis of both matrix foliations and structures preserved in porphyroblasts from the south central zone of the Narragansett Basin defined two extended periods of deformation and metamorphism about two differently trending FIAs in porphyroblasts (Rich, 2005). SSW-NNE trending FIAs (Set 1) formed first and were followed by WSW-ENE trending FIAs (Set 2, Fig.3). The SSW-NNE FIAs from the south-central zone lie parallel to the major fold axes in the southern graben. The change in FIA trends indicates 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. A retrograde metamorphic event postdates compressional deformation within the basin and is attributed by Cogswell and Mosher (1994) to late fluid infiltration associated with late wrenching of the basin however ambient metamorphic fluid could also explain this retrograde event.

3. Multiple deformations and the distribution of FIA

This FIA data is impossible to rationalize using a rotation model for curved inclusion trail development in porphyroblasts because such models must explain the 2 distinct FIA trends (Figure 4a) with a consistent relative timing when both are present in a single sample. If the porphyroblasts rotated about different axes during the development of each FIA trend, the distribution of FIAs in the first trend should be spread over a large range. Figure 4b demonstrates this using the 90° of clockwise rotation required to produce the inclusion trail geometries in porphyroblasts defining FIA trend 2. This creates a 67° scatter in the trend for FIA set 1. If porphyroblasts from both FIA trends were rotated during the subsequent matrix deforming events, an increased spread in the data would be expected.

4. Inclusion trail asymmetries

Inclusion trail curvature is generally evident towards the rim of a porphyroblast, where the porphyroblast has overgrown differentiated matrix during a subsequent foliation forming event. The inclusion trail curvature asymmetry is most evident and best recorded perpendicular to the axis of curvature (the FIA). Table 1 presents asymmetry data for inclusion trails preserved in garnet, staurolite and plagioclase porphyroblasts. All of the FIA set 1 inclusion trail asymmetries are anticlockwise when recorded on a W-E thin section looking N (Fig. 5) and all of the FIA set 2 inclusion trail asymmetries are clockwise when recorded on a N-S thin section looking W (Fig.6).

5. Bulk structural relationships

The large-scale fold F_1 trends in the SW of the basin have NNE striking axial planes (Fig.2). These F_1 folds tend to verge westward and this has been interpreted to suggest a dominance of west-directed tectonic transport (Reck and Mosher, 1988; Cogswell and Mosher, 1994; Hermes et al., 1994). The sample locations on the westward shores of Prudence and Conanicut islands are on the overturned limbs of NNE trending F_1 folds with good evidence for younging provided by graded bedding, cross bedding and erosional surfaces.

6. Interpretation

The deformation partitioning approach to shear sense determination described by Bell and Johnson (1992) suggests that the direction of rotation of a crenulated foliation into a differentiated crenulation cleavage indicates the direction of shear. Bell et al. (2003) call this the differentiation asymmetry and showed that porphyroblasts that are synchronous with the matrix foliation preserve the same asymmetry in the curvature of inclusion trails. The inclusion trail asymmetries defining FIA sets 1 and 2 in the south central zone of the Narragansett Basin in every case have an anticlockwise asymmetry looking NE (Fig. 7). This suggests, according to Bell and Johnson (1992) and Bell et al. (2003), that the sense of shear along matrix foliations when they grew was top to the WNW and NNW respectively (Fig. 8). Furthermore, crenulation cleavage in the matrix preserves the same asymmetry into differentiated crenulation cleavage seams as inclusion trails that are continuous with the external foliation (Fig. 9). This strongly supports the interpretation that shear during early phases of foliation development, was east side up or top to the WNW or NNW.

FIA sets 1 and 2 are interpreted to have formed perpendicular to the directions of maximum bulk shortening associated with compressional deformation and peak metamorphism within the Narragansett Basin (e.g. Bell et al., 1998b). The FIA trends and their coupled shear sense directions interpreted from inclusion trail asymmetries suggest that the sense of bulk displacement during compressional deformation in the Narragansett Basin was always top to the NW. Consistent anticlockwise crenulation cleavage asymmetries for the overturned limb are predicted by the successive development of a steep and gently dipping foliation and their effects on early developed folds (Fig. 10). W-E directed compression would initially have resulted in the formation of macroscopic folds with an associated anticlockwise shear sense along crenulation cleavages (Fig. 11) on the west limb during the first stage of folding and a clockwise shear on the east limb (Bell et al., 2003; Bell et al., 2004; Bell and Newman, 2005). Any later phase of deformation producing a gently dipping foliation during NW directed shear would overprint and rotate the axial plane of these folds and preserve an anticlockwise inclusion trail asymmetry. The trend of FIA set 1 is parallel to the axial plane of F_1 folds in the south of the basin suggesting that these folds accompanied the development of this FIA set. W-E trending syn-peak metamorphic folds have not been mapped in the vicinity of the sample locations but the trend of FIA set 2 and the inclusion trail asymmetry data for this set indicates that compressional deformation continued directed NW, and the shear sense remained top towards the North American craton.

7. Discussion

Porphyroblasts are common in regionally metamorphosed rocks. Application of the asymmetry (Bell et al., 1995) or the FitPitch (Aerden, 2003) methods for measuring FIAs can be applied to any oriented porphyroblastic samples with well preserved inclusion trails. Identification of a consistent succession of FIA trends allows correlation of these FIA successions across a region and can be used to demonstrate that the curved inclusion trails can not have formed by rotation of the porphyroblast (Bell and Chen, 2002; Bell et al., 2003; Ham and Bell, 2004; Cihan and Parsons, 2005;

Sayab, 2005). Once it has been demonstrated that asymmetric inclusion trails have not formed by rotation of the porphyroblasts in which they lie, their asymmetry can be confidently used for shear sense determinations.

The inclusion trail asymmetry preserved in porphyroblasts always matches the differentiation asymmetry for a crenulation cleavage that accompanied porphyroblast development in this region and indicates top to the NW shear. This shear sense is confirmed macroscopically by the rotation of originally upright folds so that they verge NW. Therefore, the curvature of a crenulated cleavage into a differentiated crenulation cleavage provides an excellent shear sense criterion in this region. Crenulations are more common than porphyroblasts in regionally metamorphosed rocks. Since the differentiation asymmetry associated with a crenulation cleavage always coincides with the porphyroblast inclusion trail asymmetry it can be used to determine the shear sense along the foliation (Bell and Johnson, 1992). Crenulation cleavages, therefore, provide a most useful criterion for shear sense determination in metamorphic rocks.

The value of crenulation cleavage as an indicator of shear sense in metamorphic rocks has been noted before. The curvature of the s-surfaces into the c-surfaces of Berthe et al. (1979), were discussed in Simpson and Schmid (1983) as they evaluated criteria to deduce the sense of movement in sheared rocks. They observed the angular relationships between the two surfaces define the sense of shear in the rock. Additionally, they note that C-surface refers to “cisaillement’, which translates as shear, and that late discrete shearing would occur along the c-surface. Shear movement between microlithons has only rarely been suggested as cleavage is traditionally considered a plane of no finite shear strain along which slip is impossible. The data presented in this study however, suggests that the importance of shear on cleavage as part of any general model for ductile deformation has been undervalued. Only the progressive bulk inhomogeneous shortening fold model can account for the lack of rotation of the early formed FIA trend and for the direction of shear sense consistently preserved by inclusion trail asymmetries in the south central zone of the Narragansett Basin. Importantly, this deformation model involves significant axial plane shear on cleavage.

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Chapter 3. Progressive changes in bulk movement direction and shear sense during the transition from Acadian to Alleghanian orogenesis.

Abstract

High grade Pennsylvanian metamorphism appears pervasive throughout the Scotland Schist of the Merrimack Terrane in SE New England. This contrasts with previous work that suggested post-Acadian metamorphism within the cover sequence was limited to narrow fault controlled zones. A three dimensional microstructural analysis of both matrix foliations and structures preserved in porphyroblasts defined four periods of deformation and metamorphism about differently trending foliation/ inflection axes in porphyroblasts (FIAs). FIA sets 1 to 4 are oriented WNW-ESE, SW-NE, NNW-SSE and WNW-ESE, respectively. The SSW-NNE, NW-SE, WSW-ENE and SSW-NNE directions of bulk shortening that accompanied the development of this succession of FIA sets produced dominantly non-coaxial deformation in the rocks. NNE directed bulk orogenic flow accompanied high grade metamorphism during the earliest determined period of porphyroblast growth whereas WSW to NNE directed bulk orogenic flow accompanied high grade Pennsylvanian (310 Ma) metamorphism. Consistent NNE to WSW directed bulk orogenic flow in eastern Connecticut and southwest Rhode Island is not compatible with current models for loading of the Bronson Hill -Central Maine -Merrimack terranes by stacking thrust nappes towards the S and E.

1. Introduction

The New England Appalachians have been interpreted as a composite of sutured Proterozoic basement terranes overlain by Palaeozoic metasediments (Hatcher, 1989). The identification of domal basement inliers in the Acadian metamorphic belt of New England has resulted in the measurement and interpretation of tectonic indicators around their contact with the rocks above (Wintsch, 1979; Getty and Gromet, 1992a; Robinson et al., 1992) and to the east (Goldstein, 1982; Wintsch and Fout, 1982; Goldstein, 1989). Thermochronological studies have demonstrated reactivation of the basement-cover boundary fault zone (Getty and Gromet, 1992b; Wintsch et al., 1992; Moecher and Wintsch, 1994) but little correlation between these studies has been possible with no concurrence on the timing or direction of movement. Accumulated data from the southeastern New England fault system strongly suggests that multiple episodes of movement have occurred. However, tectonic movement indicators along the basement-cover boundary fault zone have shed little light on how most rocks within the Merrimack Terrane to the west have been deformed. Clearly, an investigation that could determine the directions of bulk shortening that accompanyied high grade metamorphism within the cover rocks, plus the extent to which pervasive Alleghanian metamorphism was present away from the reactivated fault zones, is vital to understanding this complex terrain.

During the past decade, a technique for determining the dominant directions of bulk shortening that accompanied high grade metamorphism within pelitic metasediments has emerged. This involves the measurement of Foliation Intersection/Inflexion Axes preserved in porphyroblasts (FIAs, Bell et al., 1995). The direction of bulk shortening theoretically lies orthogonal to a FIA with its orientation controlled by a vertical foliation (Bell and Wang, 1999). The measurement of a FIA is independent of whether or not porphyroblasts have rotated. FIA data can be readily used to determine whether or not rotation occurred before the data is used to interpret movement directions (Bell and Johnson, 1990; Bell et al., 1992; Hayward, 1992; Aerden, 1995; Bell and Forde, 1995; Hickey and Bell, 1996, 1999; Stallard and Hickey, 2001; Stallard et al., 2002; Stallard et al., 2003; Timms, 2003; Ham and Bell, 2004).

This microstructural study was conducted on rocks sampled from a multiply deformed cover sequence lying well away from the contact with exposed Avalon to the east (Rodgers, 1981). A companion geochronolgical investigation was undertaken to determine the ages of the foliations preserved within the porphyroblasts. Together these studies provide insight into the timing and extent of compressional deformation within the cover sequence away from regional zones of very coarsely partitioned deformation. They also provide a basis for further regional comparisons with existing data sets.

2. Geological Setting

The Silurian-Devonian metasediments of the Central Maine Terrane-Merrimack Terrane extend from Maine south through New Hampshire across Massachusetts and into eastern Connecticut (Fig. 1). Within Connecticut the Merrimack is bound to the west by the Bronson Hill anticlinorium and to the south and east by the Honey Hill and Clinton-Newbury thrust faults (Fig. 2). In Connecticut the rocks of the Merrimack Terrane are dominated by the generally calcareous Hebron Gneiss and have been metamorphosed to amphibolite grade or higher (Zartman and Naylor, 1984). Felsic gneissic rocks, pelitic schists and a mafic unit plus less common quartzites and marbles are present. No fossils have been found for direct dating of the rocks (Rodgers, 1981). Relative ages are generally inferred on the basis of correlations and structural interpretations (Dixon and Lundgren, 1968; Wintsch, 1979). On the eastern edge of the synclinorium the section from the Quinebaug Formation through the Scotland Schist has been suggested to represent as a normal stratigraphic sequence (Dixon and Lundgren, 1968) although the Clinton Newbury Fault as now mapped breaks this sequence (Rodgers, 1985). Rocks analysed for this work were sampled solely from the Scotland Schist (Fig. 3), which as a unit has consistently been interpreted as not bounded by any of the regional fault zones. Other metasedimentery formations within the Merrimack Terrane are metamorphosed to higher grades and have locally undergone intense cataclasis (Wintsch, 1979).

3. The Scotland Schist

The Scotland Schist dominantly consists of a muscovite schist with a well-developed pervasive foliation. Muscovite occurs as coarse grained plates that define the matrix foliation. This foliation is commonly crenulated. Other important rock forming minerals, which fluctuate in abundance with compositional layering, include quartz, staurolite, garnet, biotite, feldspar and kyanite (Table 1). Accessory minerals are chlorite, tourmaline, apatite, zircon, fibrolite and opaque minerals. A basal horizon incorporates approximately 2m of compositionally banded, fine grained, quartz-muscovite-biotite schist and pervasively foliated quartz-muscovite-biotite-plagioclase schist (Dixon and Shaw, 1965). This basal unit has a matrix foliation defined by biotite, muscovite and elongate quartz grains. Intermittent thin bands of calc-silicate rocks have been described within the basal zone (Dixon and Shaw, 1965).

Compositional layering controls the concentration and morphology of metamorphic minerals. Garnet porphyroblast density and diameter generally increase into more pelitic layers. Within quartz-rich layers, staurolite is commonly present as pseudomorphs (Fig. 4a) or isolated xenoblastic porphyroblasts. The abundance and apparent stability of this phase increase within pelitic zones. Kyanite and fibrolitic sillimanite are more common within quartz rich samples. Both can be observed with their long axes oriented parallel to the foliation (Fig. 4b) or in apparent random orientations as large porphyroblasts or coalesced mats (Fig. 4c). Chlorite overgrows the crenulated muscovite foliation (Fig. 4d) and occurs locally as a retrograde phase at staurolite boundaries.

A lengthy microstructural history is suggested by overprinting microfolding and crenulation events persisting within the matrix foliation. These structures are well developed in pelitic compositions where phylosilicates are more abundant. Quartz pods are generally folded at thin section (Fig. 4d) to outcrop scales.

4. Morphology of Inclusion Trails

All samples selected for analysis from the Scotland Schist contain garnet porphyroblasts that range in size from 1 to 6mm. Quartz, graphite and ilmenite and less commonly staurolite, muscovite, tourmaline and feldspar are visibly present as inclusions within garnet. The mineral phases included do not always appear to correlate with the matrix or the surrounding compositional layer. Garnet porphyroblasts residing in quartz rich layers typically have mostly quartz inclusions but can contain predominantly muscovite or ilmenite. Continuous inclusions trails within garnet porphyroblasts in pelitic layers are ilmenite dominated. Porphyroblasts inclusion trails defined by minerals that vary from the rim to the matrix are generally truncated.

The inclusion trails within both garnet and staurolite porphyroblasts range from straight with only slight curvature towards the porphyroblast rim to classic sigmoids. More complex trails have staircase or spiral shapes. Within single samples, a given population of porphyroblasts can preserve just one particular geometry in all porphyroblasts or contain a combination of geometries. Phases of garnet growth are distinguishable using inclusion trail morphology, distinct core crystal shapes and graphite/ ilmenite accumulations on rims. Inclusion trail morphology ranges from changes in inclusion density, mineral species or geometry from one part of the porphyroblast to another, one example being an inclusion rich core versus an inclusion poor rim.

5. Methods

Locating the asymmetry switch of asymmetric inclusion trails using vertical thin sections with different strikes, allows a FIA trend to be recorded for a sample (Bell et al., 1995; Bell and Hickey, 1996; Timms, 2003). A flip in asymmetry occurs across the axis. This microstructural analysis consists of measurements made from a minimum of eight vertical thin sections per sample. A section is cut every 30º around the compass with an additional two cut 10º apart where the inclusion trail asymmetry flips. The blocks for thin sectioning are cut from a horizontal oriented slab and the resulting vertical thin sections have their strike parallel to their long edge.

Different porphyroblastic phases within a sample can preserve different portions of the deformation history (Bell and Hickey, 1999). For example, in the Rhode Island Formation (Rich, 2005), foliations defined by inclusion trails in garnet porphyroblasts containing FIA 1 are always truncated by the matrix foliation whereas those in plagioclase porphyroblasts (FIA 2) are continuous with the matrix foliation. Changes in FIA trends within porphyroblasts can also occur (Fig 5, Fig 6). Differing FIA trends may be preserved by porphyroblasts from the core to the rim or from the core through the median to the rim (e.g., Bell et al., 1998b). By utilising established concepts of overprinting criteria, analysis of a multi-FIA sample can allow a succession of FIAs to be determined in the one sample. Data from all samples can then be combined and if a consistent relative succession results, the relative timing of each FIA can be derived (Bell et al., 2003).

In order for multiple distinct FIA trends to exist in a single sample porphyroblasts must not have rotated. This general lack of rotation of porphyroblasts has been confirmed by extensive data from multiply deformed and metamorphosed regions on foliation/ inflection axes preserved in porphyroblasts (Bell et al., 1998b; Hickey and Bell, 1999; Bell et al., 2003; Aerden, 2004; Cihan and Parsons, 2005; Sayab, 2005).

6. FIA analysis

6.1. FIA analysis of garnet porphyroblasts within the Scotland Schist

A total of sixty four FIAs were measured for the garnet porphyroblasts within thirty nine spatially oriented samples from the Scotland Schist in eastern Connecticut (Fig. 7b). Eighteen samples preserve a single FIA, fifteen contain a different FIA in the core versus the rim and five contain a different FIA in the core versus the median versus the rim. Where a median is recorded, the inclusion trails are distinguished from core trails by a change in the inclusion asymmetry, and locally by a visible truncation. These are overprinted by trails defining a separate rim FIA.

Figure 7b is a bi-directional equal area rose plot of the total garnet FIA trends measured for all samples. Three clusters of FIA trends are visible oriented WNW-ESE, NNW-SSE and SW-NE. In Fig. 8, single FIA samples are separated from multiple FIA samples. One principal trend oriented WNW-ESE is visible in the single FIA plot. The multiple FIA data shows three clusters of trends, oriented WNW-ESE, NNW-SSE and SW-NE.

In Fig. 9, FIA trends from porphyroblasts where the inclusion trails are continuous with the matrix (Fig. 9a) are separated from those where the trails are truncated by the matrix or precede an additional FIA in the median or rim of the porphyroblast (Fig. 9b). Figure 9a shows dominant WNW-ESE and NNW-SSE trends. Figure 9b displays a dominant trend oriented at WNW-ESE and small clusters oriented NNW-SSE and SW-NE.

FIAs measured from the core of garnets are separated from median and rim FIAs in Fig. 10. The rose plot of core FIAs shows a singe dominant trend oriented WNW-ESE. The rose plot for median FIAs shows three peaks oriented SW-NE, NNW-SSE and WNW-ESE. The rose plot for rim FIAs shows two dominant peaks oriented NNW-SSE and WNW-ESE.

6.2. U^2 Statistical Analysis

A notable characteristic of FIA data is the non-random multimodal nature of FIA trends when presented as rose diagrams. The U^2 statistical test of Watson (1961), modified for grouped data by Freedman (1981), and amended for the axial nature of the data by Upton and Fingleton (1989), has been applied to establish whether the multimodal nature suggested by the rose diagrams is significant. Table 2 shows the results of this test for the total FIA population measured from garnet and staurolite porphyroblasts. The resulting U^2 value (1.797) greatly exceeds the upper 0.1% critical value (U=0.268; Table 2), suggesting rejection of the null hypothesis, that the data are samples of FIA populations with random trends. Thus, the multimodal nature of the FIA population, shown in Fig. 7, is statistically different from a randomly distributed population.

6.3. Relative timing from multi-FIA samples

The relative timing of successive FIAs can be determined through analysis of the multi-FIA samples. A FIA trend determined from the rim of the porphyroblast must be younger than one in the core for the same sample. A paragenesis of FIA trends for samples containing multiple FIAs can be determined if regular successions of trends are present. Samples R36, R43, R44, R49, R50, R54, R76, R77, R83, R84, R86, R93, R96 and R98 preserve two FIAs within garnet. Samples R66, R75, R79, R94, R95 and R103 preserve core, median and rim FIAs within garnet. Samples R10, R36, R40, R49, R76, R84, R86, R93, R95, R108 and R109 contain a staurolite FIA plus one or more FIAs preserved in garnet.

Of the twenty multi-FIA samples, nineteen have a WNW-ESE core FIA trend. The remaining sample (R50) has a NNW-SSE core FIA trend. Seven samples (R54, R66, R75, R76, R94, R96 and R103) have WNW-ESE core FIA trends and NNW-SSE rim FIA trends. Three samples (R66, R75 and R94) have WNW-ESE core FIAs, SW-NE median FIA trend and NNW-SSE trending rim FIAs. The one sample (R50) with a NNW-SSE core FIA trend has a WNW-ESE trending rim FIA defined by trails that are continuous with the matrix foliation. Nine samples (R44, R46, R49, R50, R79, R83, R86, R93 and R95) have WNW-ESE trending FIAs defined by inclusions that are continuous with the matrix foliation.

6.4. Single FIA data

The rose plot for the eighteen single FIA garnet samples displays one modal peak with a WNW-ESE FIA trend. One of these samples (R46) has inclusion trails that are continuous with the matrix while the other seventeen have trails truncated by the matrix. The inclusion trails from the twelve staurolite FIA trends are all truncated by the matrix and orientated WNW-ESE.

6.5. FIA Sets

This paragenesis results in a core to rim succession that is summarised below.

1. The WNW-ESE core FIA trends are followed by SW-NE, NNW-SSE and continuous WNW-ESE trending FIAs.

2. SW-NE trending FIAs are followed by NNW-SSE FIA trends.
3. A NNW-SSE FIA trend is followed by a continuous WNW-ESE trending FIA.
4. Samples with WNW-ESE trending FIAs within staurolite contain inclusion trails that are truncated by the matrix foliation.

This succession allows the FIA groups to be divided into sets. The early WNW-ESE FIA group is called Set 1, followed by the early SW-NE FIA group called Set 2. Following Set 2 FIAs are the NNW-SSE trending FIAs called Set 3 and finally the youngest generation of FIA groups, the repeated WNW-ESE FIA trend group, is called Set 4 (Fig. 11).

7. Foliation asymmetry

7.1. Matrix foliation differentiation asymmetry

The dominant differentiation asymmetry in the matrix, that is, the curvature of crenulated cleavage into differentiated crenulation cleavage seams(Bell et al., 2003), was determined by examining NW-SE striking vertical thin sections from each sample. The majority of samples record an anticlockwise differentiation asymmetry looking NE for curvature of a sub-vertical crenulated cleavage into a sub-horizontal differentiated crenulation cleavage seam. The distribution of ACW versus CW asymmetries is presented on a map of the sample area in Fig.12, with black arrows representing ACW asymmetries and open ones indicating CW asymmetries.

7.2. Foliation asymmetry preserved within porphyroblasts

The asymmetry of overprinted foliations preserved within porphyroblasts record the differentiation asymmetry for each overprinting event (Bell et al., 2003). The asymmetries defining WNW-ESE trending FIAs, sets 1 and 4, were determined from vertical thin sections near orthogonal to this trend looking WNW. Those for sets 2 and 3 were determined looking NE and NNW, respectively. Fig. 13 shows a histogram in which the asymmetry of each individual FIA trend(s) appears as either a CW or ACW measurement, separated according to FIA set.

8. Interpretation

8.1. Directions of bulk shortening accompanying high grade metamorphism

Four periods of bulk shortening accompanied by high grade metamorphism have been preserved by porphyroblasts within the Scotland Schist. The sequence of changes in bulk shortening directions is interpreted to lie orthogonal to the succession of FIA trends (e.g. Bell and Welch, 2002) and thus changes in orientation from NNE-SSW, NW-SE, WSW-ENE to NNW-SSE. Fifty eight out of a total of seventy six measured FIAs trend WNW-ESE and, thus, NNE-SSW is the dominant bulk shortening direction preserved by porphyroblasts in the Scotland Schist.

8.2. Timing directions of bulk shortening

U-Th-Pb chemical dating of the foliations preserved within the porphyroblasts was undertaken via analysis with an electron microprobe of monazite grains (Rich, Chapter 4). Theoretically, monazite grains can be shielded from dissolution within porphyroblasts with quantitative, compositional insitu analysis revealing a U-Th-Pb ratio, and thus, a crystallisation date (Montel et al., 2000). Twenty-four individual monazite grains from the matrix and within porphyroblasts were analysed from seven samples. Monazite was found aligned and included with the foliations that define FIA sets 2, 3 and 4. No monazite was found included within the core of a garnet porphyroblast preventing the dating of FIA set 1. The U-Pb dates obtained for monazite grains aligned with the foliations that defined FIA set 2, 3 and 4 were found to be within analytical error of each other. The mean age for these analyses combined is 311 ± 5 Ma. The mean U-Pb age determined for monazite from the matrix of these samples is effectively the same at 314 ± 8 Ma. Thus, FIA trends set 2, 3 and 4 appear to have formed in quick succession during the Pennsylvanian.

8.3. Direction of bulk orogenic flow

8.3.1. Porphyroblasts

The deformation partitioning approach to shear sense determination described by Bell and Johnson (1992), uses the direction of rotation of a crenulated foliation into differentiated crenulation cleavage to determine the shear sense operating during foliation development. Bell et al. (2003) called this the differentiation asymmetry and showed that is also preserved by the asymmetric curvature of inclusion trails in porphyroblasts. FIA trends can be coupled with shear senses interpreted from inclusion trail asymmetries to determine the direction and sense of bulk displacement during orogenesis. Figure 13 shows the differentiation asymmetries preserved within porphyroblasts separated according to FIA trend. FIA set 1 is dominated by anticlockwise asymmetries that suggest a prevailing top to the NNE sense of shear. FIA set 2 contains both asymmetries within a small data set and is suggestive of coaxial deformation. FIA set 3 is again dominated by anticlockwise asymmetries suggesting top to the WSW displacement. FIA set 4 is dominated by anticlockwise asymmetries and suggests top to the NNE shear.

8.3.2. Matrix shear sense

Almost three quarters of the differentiation asymmetries recorded from the matrix are anticlockwise when viewed looking NE on NW-SE striking vertical thin sections (Fig. 12). This anticlockwise predominance also suggests top to the NW shear along sub-horizontal differentiated crenulation cleavage seams in the matrix, which formed late in the deformation history as they post date porphyroblast growth. The mineralogy of the fabric forming crenulation cleavage typically includes both muscovite and biotite.

8.3.3. Combined

The FIA data for all 4 sets suggests that the direction of bulk orogenic flow within the Scotland Schist has remained between WSW and NNE directed during the Pennsylvanian. Three of the four FIA sets are characterised by a marked dominance of an anticlockwise asymmetry looking NE (Sets 1, 3 and 4). The data therefore suggests a strong non-coaxial component to the deformation in Connecticut during the Pennsylvanian of top to the NW. Non-coaxial bulk shortening is common within the margins of orogenic zones as the amount of gravitational collapse driven displacement accumulates outward from the orogen core (Bell and Johnson, 1989; Bell and Newman, 2005).

8.4. Correlation of Scotland Schist FIA trends with south central Connecticut, north central Massachusetts, east central Vermont and southeast Vermont FIA trends

The FIA data for north central Massachusetts, southeast Vermont, east central Vermont and south central Connecticut (Bell and Newman, 2005) is remarkably consistent. These four areas lie in the Connecticut Valley Synclinorium or the Bronson Hill Anticlinorium (Fig.1) of the Acadian metamorphic belt. Each area preserves a succession of five FIA Sets labelled 0 to 4. Figure 14c, d, e and f shows the orientation of their FIA trends as well as those from the Bolton Syncline (Hickey and Bell, 1999), Rhode Island (Rich, 2005) and the region described herein.

The three Scotland Schist FIA trend orientations, WNW-ESE (W-E), SW-NE and NNW-SSE are present within the Bell and Newman (2005) data set. However, the succession of FIA trends from this new data set does not correlate with the FIA succession presented in Bell and Newman (2005). The south central Connecticut, north central Massachusetts, east central Vermont and southeast Vermont FIA trends all preserve a five stage apparent clockwise rotation of the bulk shortening direction. The Scotland Schist FIA trends preserve a three stage apparent anticlockwise rotation of the bulk shortening direction followed by a clockwise rotation. Additionally the WNW-ESE FIA trend is not repeated in the Bell and Newman (2005) data set.

This suggests that the eastern Connecticut set of FIAs is recording a different part of the tectonic history to that presented in Bell and Newman (2005). Furthermore, analysis with an electron microprobe of monazite inclusions within garnet porphyroblasts from the Scotland Schist has revealed that FIA trend sets 2, 3 and 4 formed during the Pennsylvanian (330-300 Ma, Rich, Chapter 4) or later. Thus, FIA trend set 1 (WNW-ESE) is the only FIA orientation set from the Scotland Schist that could possibly correlate with a FIA trend from the Bell and Newman (2005) data set (Bell et al., 2004). However, no monazite was found preserved within garnet or staurolite porphyroblasts grouped within the FIA set 1 trend from the Scotland Schist to refute or verify this prospect.

8.5. Correlation of Scotland Schist FIA trends with southwest Rhode Island FIA trends

East of the Scotland Schist within the Avalon Composite Terrane, lies the Narragansett Basin. Here, Pennsylvanian age sediments of the Rhode Island Formation, were regionally metamorphosed during the Permian Alleghanian orogeny (Dallmeyer, 1982). Grade increases toward the southwest of the basin from greenschist to upper amphibolite facies. The succession for the Rhode Island Formation (Fig. 14b, Rich, 2005) defines two extended periods of deformation and metamorphism about differently trending FIAs. Figure 14b shows fifty seven FIAs defining a SSW-NNE FIA 1 trend and a WSW-ENE FIA 2 trend. This data does not correlate with the Scotland schist data either. The Scotland Schist data set has no FIAs with the SSW-NNE FIA trend that dominates the Rhode Island data set.

8.6. Correlation of Scotland Schist FIA trends with north central Connecticut FIA trends

West of the Scotland Schist within the Bronson Hill Anticlinorium lies the Bolton syncline. The Devonian Littleton Formation that forms the Bolton syncline is thought to be of comparable age to the Scotland schist (Rodgers, 1985) and consist of carbonaceous quartz-mica pelitic and psammitic schists. A FIA data set for garnet and staurolite porphyroblasts from schists sampled within the Bolton syncline was published in Hickey and Bell (1999). Figure 14a shows the orientation of 37 FIA trends measured from 24 oriented Bolton syncline samples. Three modal peaks are apparent in the data; a dominant NNW-SSE FIA trend (175°), a variable SW-NE FIA trend (35° to 65°) and a single WNW-ESE FIA trend (110°). The timing of garnet versus staurolite porphyroblast growth was determined according to inclusion trail – matrix relationships. Within individual samples garnet porphyroblast inclusion trails are consistently truncated by the matrix while staurolite inclusion trails remain continuous. 21 garnet FIA trends form the 175° modal peak. 3 additional core FIAs trend at 40° and 100°. A timing relationship between these earlier core FIA trends was not demonstrated. 13 staurolite FIA trends are separated into a modal peak of 11 FIA trends at 35° plus 2 rim trends at 65°.

The distribution of the Bolton syncline FIA trends correlates reasonably well with the Scotland Schist FIA trend orientations. NNW-SSE, SW-NE and WNW-ESE modal peaks in FIA trend populations are present in both data sets. However, the proportion of FIAs distributed within FIA sets is dissimilar and a late WNW-ESE FIA trend was not recorded within garnet or staurolite from samples within the Bolton group. The ambiguous timing and limited number of FIA trends from early garnet cores from rocks of the Bolton Syncline limits the value of correlation these have with other data sets. Regardless, a rotation from early W-E and SW-NE FIA trends in garnet cores to a later NNW-SSE FIA trend in garnet rims occurs in both data sets.

8.7. Age control on FIA data sets

Monazite dating of foliations that define FIA trends in porphyroblasts by Bell and Welch (2002) provides absolute ages for FIA set 1 to 4 of Bell and Newman (2005). The monazite inclusions reveal Acadian ages which span a period from 430 to 350 Ma. Isotopic ages that can constrain the period of peak metamorphism and thus the development of FIA trends in the Narragansett Basin are presented by Dallmeyer (1982). $^{40}Ar/^{39}Ar$ release spectra ages of biotite (245 Ma) are interpreted to date a period of postmetamorphic cooling, which, when combined with palaeontologic control on the deposition of the sediments at the Westphalian-Stephanian boundary, ca. 300 Ma (Bouroz, 1978), and post-compressional deformation emplacement of the Narragansett Pier Granite at 273 Ma (Zartman and Hermes, 1987; Reck and Mosher, 1988), defines a narrow time bracket, 295 to 275 Ma, for attainment of peak metamorphic conditions (Dallmeyer, 1982). U-Pb crystallisation ages of sphene from the Bronson Hill Terrane in Connecticut indicate prograde Alleghanian (305 Ma) regional metamorphism occurred outside of the Avalon Composite Terrane and this event has been tentatively linked to the growth of staurolite related with the Bolton Syncline FIA trends (Wintsch et al., 2003). These age dates suggest that the period of garnet and staurolite metamorphism in the Merrimack Terrane, associated with the FIA orientations presented herein, occurred after the events described in Bell and Newman (2005) and before high grade metamorphism in the Narragansett Basin. The growth of porphyroblasts that define FIA trends in the Bolton Syncline and the Merrimack Trough are probably related to the same regional prograde metamorphic event.

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9. Discussion

9.1. Regional correlation of FIA trends

This regional comparison of New England FIA data sets reveals that some FIA trends, and thus directions of bulk shortening, have been repeated during Appalachian orogenesis. Those trends repeated are: an approximately W-E FIA trend, a NNW-SSE FIA trend and a SSW-NNE FIA trend. This demonstrates that FIA trends can not be correlated regionally by orientation alone and that FIA orientation alone can not discriminate between orogenic events. However, when a consistent succession in FIA trends has been identified, this can be correlated regionally. Bell et al. (1998a) verified that a regional correlation of FIA trend successions can be statistically valid. They assessed the degree of homogeneity between FIA data collected from an extended region around Springfield, Vermont, with FIA data from a much smaller area within the Spring Hill Synform but with a much greater sample density, to determine whether it was statistically valid to pool them. The FIA trends were compared using a χ^2 test for independence and the results suggested that the data from the two sample areas had similar characteristics and could be collated and analysed as a single data set. As the two data sets contained identical FIA successions, they were able to correlate the FIA data. Correlation of FIA trends across broadly separated regions has been completed by a number authors (Bell and Mares, 1999; Aerden, 2004; Bell and Newman, 2005).

The results of this study reinforce the importance of establishing a succession of FIA trends to provide an additional structural constraint on correlations. The succession of FIA trends measured from the Scotland Schist does not correlate with existing FIA data sets from Vermont, Massachusetts, Rhode Island or south central Connecticut. Correlation with the Bolton Syncline FIA succession would require additional age constraints.

9.2. Deformation within the Merrimack Synclinorium

The results of this FIA analysis provide some insight into the timing and extent of compressional deformation within the cover sequence away from the basement-cover boundary fault zone. Contrary to previous work which suggested post-Acadian metamorphism within the cover sequence was limited to narrow fault controlled zones (Moecher, 1999), high grade Pennsylvanian metamorphism appears pervasive throughout the Scotland Schist. NNE directed bulk orogenic flow accompanied high grade metamorphism during the earliest determined period of porphyroblast growth. WSW to NNE directed bulk orogenic flow accompanied high grade Pennsylvanian metamorphism. EW to NW shortening of Wintsch and Sutter (1986) from >310 Ma to *c*. 290 Ma (Moecher and Wintsch, 1994) appears to correlate with the Pennsylvanian bulk shortening identified by this study, however, the interpretation of S to E stacking of thrust nappes, loading eastern Connecticut and southwest Rhode Island (Wintsch and

Sutter, 1986; Wintsch et al., 2003), is hard to rationalise with the NNE to WSW directed bulk orogenic flow preserved in the Scotland Schist and Rhode Island Formation. The non-coaxial bulk shortening recorded in this study and the shearing and associated thrusting documented by previous workers (Wintsch, 1979; Getty and Gromet, 1992a) are characteristic of an orogenic margin (Bell and Johnson, 1989; Bell and Newman, 2005).

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Chapter 4. Partitioning of orogenesis across the boundary of Avalon with North America during the Alleghanian.

Abstract

Late Palaeozoic U-Th-Pb ages of monazite from rocks of the Merrimack Terrane in eastern Connecticut reflect an Alleghanian overprint on Acadian metamorphic rocks. The period of monazite growth was dated using an electron microprobe and has identified high grade metamorphism occurring in association with compressional deformation at 311 ± 3 Ma. High grade metamorphism was not restricted to shear controlled zones but affected the bulk of the vertical rock pile within the Merrimack Terrane during the Pennsylvanian. However, the late Alleghanian (Permian) deformation and metamorphism that affected the Narragansett Basin to the east had no impact on the Merrimack Terrane. This is strongly supported by the lack of correlation between the FIA sets for the two regions. As metamorphism increased to sillimanite grade within the Merrimack Terrane, deformation became increasingly coarsely partitioned until the Early Permian when the strain became localised along ductile shear zones at the Putnam-Avalon boundary. That is, collision related compressional deformation within the Narragansett Basin was partitioned entirely into the Honey Hill fault system during the early Permian.

1. Introduction

The boundary of the Avalon Composite Terrane with the deformed and intruded metasediments of the Acadian metamorphic belt is one of the most prominent tectonic features in the New England Appalachians (Fig. 1). However, the directions of motion and consequently, timing of juxtaposition of terrains across the boundary are uncertain.

Correlating structural elements across the boundary has proven problematical (Wintsch and Sutter, 1986; Reck and Mosher, 1988; Cogswell and Mosher, 1994). Three dimensional microstructural analyses of matrix foliations and structures preserved in porphyroblasts by Rich (2005) identified two extended periods of deformation and metamorphism about two differently trending foliation intersection/ inflection axes in porphyroblasts (FIAs) in Pennsylvanian age sediments within the Narragansett Basin. Another study identified four periods of deformation and metamorphism about three differently trending FIAs (Rich, Chapter 3) in Devonian age sediments within the Merrimack Terrane. The FIA data sets from the two regions do not correlate. This suggests that the Rhode Island set of FIAs has recorded a different period in the tectonic history to that preserved by the set of FIAs in the Merrimack Terrane. For the present study, chemical dating of monazite was undertaken to constrain the timing of high grade metamorphism and associated porphyroblast growth within metasediments of both regions.

Monazite is a light rare earth element phosphate [(LREE)PO_4] that is commonly found in many igneous, metamorphic and hydrothermally-altered rocks. Monazite incorporates appreciable amounts of Th and U, and is highly resistant to Pb-loss through either volume diffusion (Seydoux-Guillaume et al., 2002; Cherniak et al., 2004), or metamictisation (Ewing and Haaker, 1980; Meldrum et al., 1997). Consequently, it is widely used to date geologic events. Many techniques have been utilised to obtain ages from monazite. Those that tie ages to metamorphism and/or deformation to in-situ grains are advantageous because direct chronological links can be made with specific reactions, or microstructures. Since monazite contains little or no common Pb (Parrish, 1990), chemical dating on the electron probe microanalyser (EPMA) has become popular (e.g. Suzuki and Adachi, 1991; Montel et al., 1996; Rhede et al., 1996; Cocherie et al., 1998; Crowley and Ghent, 1999; Williams et al., 1999; Jercinovic and Williams, 2005; Pyle et al., 2005b). The advantages of using the EPMA include the small spatial resolution (down to 1 μm), minimal sample damage and the ability to get compositional data for each spot analysed. Thus monazite dating on the EPMA can play an important role in reconstructing the timing of specific events in complex petrogenetic sequences.

2. Background

2.1. Rhode Island field area

Sediments within the Narragansett Basin of Rhode Island and Massachusetts contain Pennsylvanian (post-Acadian; 325-295Ma) plant fossils (Lyons, 1984). The Rhode Island Formation pelites are the dominant rock type preserved within the basin, and, when porphyroblastic, were preferentially sampled. The basin has an unconformable or fault contact with the late Proterozoic meta-igneous rocks and Cambrian metasedimentary units of the Avalon basement. The structural history of the Narragansett basin is complex as early collisional deformation was overprinted by periods of wrench style tectonics. The general consensus of opinion on the tectonic history of this basin, summarised by Cogswell and Mosher (1994), suggests there were several generations of east-west directed compressional 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 upper amphibolite facies (Fig. 2). The area examined contains the Conanicut and Prudence islands within the central zone of the southern graben (Fig.2 inset). Cogswell and Mosher (1994) suggested that the south-central basin contains all the major early syn-metamorphic deformation events. Three dimensional microstructural analyses of both matrix foliations and structures preserved in porphyroblasts distinguishes two periods of deformation and metamorphism in metasediments of the Rhode Island Formation from the central zone of the Narragansett Basin (Table 1, Fig. 3a). Two axes of inclusion trail curvature trends are present. They consist of 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. Each FIA trend has a consistent asymmetry for the curved inclusion trails defining the FIAs (Rich, 2005). The asymmetries indicate that the sense of shear along matrix foliations when the porphyroblasts grew were directed top to the WNW and NNW for Set 1 and Set 2 respectively. Major fold axis orientations for the entire basin and FIA trends from the south-central zone are remarkably similar.

2.2. Merrimack Terrane field area, Connecticut

The Silurian-Devonian metasediments of the Merrimack Trough within Connecticut are bound to the west by the Bronson Hill anticlinorium and to the south and east by the Putnam-Nashoba terrane (Fig. 1). The rocks are primarily metapelitic and have been metamorphosed to amphibolite grade or higher (Zartman and Naylor, 1984). Felsic gneissic rocks and a mafic unit plus less common quartzites and marbles are present. Relative ages have been inferred mainly on the basis of rock type correlations and structural interpretations (Dixon and Lundgren, 1968; Wintsch, 1979). Rocks analysed for this work were sampled solely from the Scotland Schist (Fig. 4), which as a unit has consistently been interpreted as not bounded by any of the regional fault zones. Three dimensional microstructural analysis has revealed the following FIA succession: WNW-ESE, SW-NE, NNW-SSE and finally a repetition of the WNW-ESE FIA trend group (Rich, Chapter 3). The differentiation asymmetry preserved by the asymmetric curvature of inclusion trails in porphyroblasts (Bell et al., 2003) suggests NNW directed bulk orogenic flow accompanied high grade metamorphism during the earliest period of porphyroblast growth. WSW to NNW directed bulk orogenic flow accompanied subsequent high grade metamorphism.

3. Methods

3.1. *Monazite locating procedure and grain selection*

Monazite was identified using the secondary electron (SEM) mode combined with qualitative EDS spot analyses on the JEOL JXA-8200 Superprobe at James Cook University. Only a few samples contained monazite as inclusions in garnet and/or staurolite and from these only monazite grains larger than 10μm in diameter and with a sufficiently polished surface were deemed suitable for multiple analyses. A summary of the microstructural/textural setting of monazites analysed is given in Table 3. Backscatter electron (BSE) images were obtained for all monazites prior to quantitative analysis to identify compositional domains and/or assess zoning profiles and these suggest that the grains do not have complex compositional zoning (Figs. 4 and 5).

3.2. EPMA analysis

Sample thin sections were polished with 1 μm diamond paste and carbon-coated to approx 250 Å. Analyses (WDS) were conducted on the JEOL JXA-8200 Superprobe at James Cook University using a 2-3 μm beam diameter, accelerating voltage of 15 kV and Faraday cup current of 200 nA. The elements Si, P, Ca, Y, La, Ce, Pr, Nd, Sm, Gd, Dy, Pb, Th and U are measured in a single analysis, with extended count times on Pb, U and Th to optimise statistical precision for chemical age dating. Details of the setup are in Table 4. With the exception of ThMζ and YLγ on PbMα and ThMγ on UMβ, background positions avoid interfering peaks and were selected based on wavelength scans of 8 well-characterised monazites with Th concentrations ranging from 2 to 11 wt%. Two-point linear backgrounds were used as no curvature or abnormality above baseline was detected in the area between chosen background points. Collimators were opened to maximum (3mm), PHA settings were optimized and calibrations were performed on the standards at 15kV and 20nA. The Armstrong-CITZAF (phi-rho-z) matrix correction program (Armstrong, 1988, 1991) was used. Thorium and Y standards were analysed at "sample conditions" to correct for the interferences listed above (e.g. Scherrer et al., 2000; Pyle et al., 2002). The precision of each element in each individual analysis was calculated based on counting statistics using the equations in Scott et al. (1995) and Pyle et al. (2005a). In addition to the elemental standards, a fragment of 555 ± 1 Ma Manangotry monazite (Horstwood et al., 2003) was used as a "consistency age standard" and was routinely analysed prior to and after the unknown monazites. Results of these analyses are included with the results of the unknowns.

3.3 Monazite age and error calculation

BSE images, combined with quantitative elemental data are used to identify compositional domains in individual grains rather than elemental maps. In most cases compositional (Z) variation can be correlated with Th and/or Y zoning (e.g. Spear and Pyle, 2002). Where possible, multiple analyses were taken from within recognisable BSE domains, and once the quantitative data was available, individual points were re-allocated into different zones/domains if required. Individual dates were calculated for each point by inserting the Th, U, Pb concentrations into the age equation of Montel et al. (1996). Where compositional domains in a particular grain were either too small to adequately analyse, or the result of continuous compositional variation, the Y, Th and U composition of all analysed points were plotted with respect to their calculated dates (and associated 95% confidence interval counting statistical errors obtained via Monte Carlo simulation (Lisowiec, 2005). If no significant correlation existed between these components and the calculated date, then these points were allocated into a date-domain. A mean date was calculated for each domain and 95% confidence intervals

(CI) were generated by multiplying the standard error of the mean (SE) with the Student's-t value for (n-1) degrees of freedom (Siegel, 1988; Snedecor and Cochran, 1989).

Once the mean and confidence intervals were calculated for all domains, data from different monazite grains and/or domains were grouped together (if possible) based on additional information, such as chemical signature and/or textural setting. Where domains could be interpreted to be representative of a geologically significant event, the datasets were then combined via the weighted average procedure in Isoplot v3.10 (Ludwig, 2003).

4. Results

4.1. EMPA analyses Rhode Island

Five monazite grains were found in the matrix of samples taken within the south central zone of the Narragansett Basin in Rhode Island. No monazite was found included within porphyroblasts. Individual monazite chemical dates (n=50) span a 90 Ma interval between 210 and 300 Ma, with an average statistical uncertainty (2σ) of approximately ± 33 Ma for a single age determination. The weighted average (mean ± 95% CI Ma) for each grain is 264 ± 16 (n=9), 261 ± 15 (n=14), 270 ± 15 (n=10), 267 ± 17 (n=10) and 298 ± 18 (n=7; Table 5).

4.2. EMPA analyses Merrimack Terrane

Twenty four monazite grains from the Scotland Schist have been analysed with fourteen hosted by garnet and four by staurolite porphyroblasts plus six in the matrix. Individual monazite chemical dates (n=183) span a 120 Ma interval between 240 and 360 Ma, with an average statistical uncertainty (2σ) of approximately ± 23 Ma for a single age determination. The weighted average for each grain varies between 290 ± 19 Ma (n=8) and 325 ± 13 Ma (n=7; mean ± 95% CI; Table 6).

5. Interpretation

5.1 Age of the monazite from Rhode Island

Sample R225 contains two elongate monazite grains aligned parallel with the main matrix foliation, S_m, (Fig. 5). Another grain lies within a foliation lying at a high angle to S_m adjacent to a garnet porphyroblast and a forth grain sits within the strain shadow of a garnet porphyroblast. Sample R226 contains a monazite grain surrounded by quartz within the strain shadow of a garnet porphyroblast, but connected to the matrix by cracks (Fig. 6). The U, Th and Pb contents indicate that the four monazite grains from sample R225 have a weighted average age of 266 ± 8 Ma. Therefore, in spite of the variable structural locations of the monazite grains in this sample, they appear collectively to indicate a single resolvable event. The fifth grain from sample R226 has a weighted average age of 298 ± 18 Ma. The ages from the two samples are almost within statistical error. However, the close grouping of the mean ages for each grain from sample R225 suggests that the mean age of the grain from sample R226 does indicate a distinct geochronolgical event. In particular, the apparently older monazite grain from sample R226 lay within the strain shadow of a garnet porphyroblast. Since no monazite grains were found within porphyroblasts from the Rhode Island Formation, garnet grade metamorphism within the south-central zone of the Narragansett Basin probably began by the start of the Permian.

Comparative isotopic ages from the Narragansett Basin (Dallmeyer, 1982) using $^{40}Ar/^{39}Ar$ release spectra for biotite (245 Ma) and whole-rock phyllite (~255 Ma) are interpreted to date a period of postmetamorphic cooling. Combined with palaeontologic control on the deposition of the sediments at the Westphalian-Stephanian boundary (ca. 300 Ma, Bouroz, 1978), and post-compressional deformation emplacement of the Narragansett Pier Granite at 273 Ma (Zartman and Hermes, 1987; Reck and Mosher, 1988), a narrow time bracket, 295 to 275 Ma, is defined for attainment of peak metamorphic conditions (Dallmeyer, 1982). Comparative $^{40}Ar/^{39}Ar$ ages from the crystalline Avalon Composite Terrane basement presented by Wintsch et al.(1992) suggest Alleghanian metamorphism peaked near 280 Ma.

5.2. Age of the monazite from the Merrimack Terrane

The combined mean age for the twenty four monazite grains from the Scotland Schist is 311 ± 3 Ma. The mean age for monazite grains included within garnet (Fig. 7), staurolite (Fig. 8) or aligned within the matrix foliation (Fig. 9) is 311 ± 5 Ma, 306 ± 5 Ma and 314 ± 8 Ma, respectively. Thus, monazite shielded by porphyroblasts can not be statistically differentiated from the population of monazite aligned with the matrix foliation.

Two matrix monazite grains and a monazite grain included within the rim of a garnet porphyroblast were analysed from sample R40. The monazite grain included within garnet was connected to the matrix via a crack (Fig. 10). Combined the monazite grains from R40 have a mean age of 324 ± 7 Ma. This combined age is slightly older than any other monazite ages recorded in this study and is noteworthy because FIA analysis revealed that this sample did not record the final three phases of porphyroblast growth.

Porphyroblast growth within the Scotland Schist can be structurally correlated to four FIA controlled periods of bulk shortening and associated metamorphism. Unfortunately monazite was not found either included within the core of a garnet porphyroblast or within a domain defined by FIA set 1. This may have contributed to the analysis of monazite in this study being unable to statistically differentiate between FIA growth events. Apart from one deviant value (R98-Mz2; 290 ± 13 Ma), the weighted averages for each grain can be considered to be within statistical error of each other.

No comparative isotopic ages from Merrimack Terrane metasediments in Connecticut have been published. Ages have, however, been published from the Putnam-Nashoba, Avalon Composite and Bronson Hill terranes within south-central and eastern Connecticut. U-Pb analysis and 40Ar/39Ar step heating results for samples from the Putnam-Nashoba terrane are presented in Wintsch et al. (1992). Their data from Putnam Belt suggests cooling through 550°C around 350 Ma, and in addition, some samples from the southwestern part of the belt yield evidence of a later disturbance and/or cooling history around 275 Ma. Combined structural and geochronologic studies around the Willimantic Dome (Getty and Gromet, 1992b; Moecher and Wintsch, 1994) have established a sequence of metamorphic events. These consist of the regional metamorphism of the Putnam rocks during early Devonian (400 Ma). This was followed by middle Pennsylvanian (300-290 Ma) pervasive foliation of basement gneisses and shear controlled metamorphism of the Putnam Terrane plus early Permian extension related ductile deformation. U-Pb crystallisation ages of sphene from the Bronson Hill Terrane (Wintsch et al., 2003) indicate prograde Alleghanian (305 Ma) regional metamorphism occurred in New England outside of the Avalon Composite Terrane.

Porphyroblasts overgrow and preserve the minerals that define pre-existing matrix foliations (Bell and Rubenach, 1983). Monazite grains included within porphyroblasts are interpreted to preserve the age of the matrix foliation that predated this growth (Bell and Welch, 2002). This provides a maximum age on the phase of porphyroblast growth. Monazite grains included within garnet and staurolite porphyroblasts from the Scotland Schist have a mean weighted age of 310 ± 4 Ma. This does not, however, date peak metamorphism, as porphyroblasts of kyanite and sillimanite overgrow younger foliations. The monazite ages, therefore, define a period of garnet-staurolite grade metamorphism on the prograde metamorphic path.

5.3. Age of the monazite from the Rhode Island Formation versus the Scotland Schist

The monazite analysed from the matrix of sample R225 from the Rhode Island Formation and monazite in porphyroblasts and the matrix of samples from the Scotland Schist formed during different geochronologic periods. The monazite ages from sample R225 lie in the middle Permian while those from the Scotland Schist fall within the Pennsylvanian (Fig. 11). Deviant ages from both populations overlap and additional dates, particularly from the Rhode Island Formation, are required to determine whether this is of significance.

6. Discussion

6.1 Regional Orogenesis

Isotopic dating of rocks in Connecticut and Massachusetts has shown that the long held assumption that Alleghanian orogenesis was restricted to the Avalon Composite Terrane in New England is false (Getty and Gromet, 1992b; Robinson et al., 1992; Wintsch et al., 1992; Wintsch et al., 2003). Recent workers have suggested that Alleganian metamorphism was not penetrative into the vertical rock pile (Moecher, 1999), but was restricted to shear zone controlled areas of high strain (Bell and Kim, 2004). The results from this study suggest that compressional deformation and accompaning high grade metamorphism affected the bulk of the vertical rock pile within the Merrimack Terrane during the Pennsylvanian. This interpretation brings into doubt the correlation with Acadian orogenesis of the isograds mapped within eastern Connecticut. The chemical age dates suggest that the bulk of the rocks within the Merrimack Terrane did not experience the effects of late Alleghanian (Permian) deformation and metamorphism that is recorded within the Narragansett Basin to the east. This is strongly supported by the lack of correlation between the FIA sets for the two regions.

Evidence for orogenesis during the early Permian within eastern Connecticut is restricted to ductile shear controlled zones at and near the boundary between Avalon and the Putnam-Nashoba terrain. The Putnam-Nashoba terrain has recently been interpreted as a volcanic arc that formed off the leading edge of Avalonia which was subsequently deformed and metamorphosed at high grade during the Acadian (Acaster and Bickford, 1999). Two additional overprinting events have been reported, a high pressure prograde metamorphic event which peaked at *c*. 290 Ma. (Wintsch et al., 1992) and retrograde metamorphism that commenced shortly after the prograde metamorphic peak and attained muscovite closure at 250 Ma (Getty and Gromet, 1992b).

Similarities were noted in Rich (2005), between the change in bulk shortening direction recorded 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 in eastern Connecticut (Wintsch and Fout, 1982; Wintsch and Lefort, 1984). The peak metamorphism responsible for porphyroblast growth in the metasediments of the Narragansett Basin occurred during the Early Permian (Dallmeyer, 1982). This is coincident with the clockwise rotation of thrusting directions in eastern Connecticut from ESE at 290 Ma to due south at 250 Ma as proposed by Wintsch and Fout (1982). This relationship provides a tangible correlation between late Alleghanian orogenesis within the Narragansett Basin and continued but coarsely partitioned orogenesis in eastern Connecticut.

6.2. Partitioning of Orogenesis

Deformation within the Merrick Terrane oscillated between NNE and WSW directed bulk orogenic flow during the Pennsylvanian. As metamorphism within the eastern Connecticut increased to sillimanite grade, deformation was increasingly coarsely partitioned until the Early Permian when strain became localised at the Putnam-Avalon boundary along ductile shear zones. Subsequent clockwise rotation of thrusting along the Honey Hill fault system shear zones can be correlated with clockwise rotation of the compression direction in the Narragansett Basin. Finally, structural and isotopic evidence for the gravitational collapse of an overly thickened crust and resultant extension during the late Permian is present at the Willimantic Dome

(Getty and Gromet, 1992a, b) and is supported by cooling ages in the Narragansett Basin (Dallmeyer and Takasu, 1992).

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Conclusions

The results of this study are among the first in both the Narragansett Basin of Rhode Island and the Merrimack Terrane of eastern Connecticut to integrate the structural geology with the metamorphic evolution. Additionally, insitu dating of monazite using an electron microprobe had not previously been attempted in rocks from these regions.

"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. (Chapter 1)"

"Foliation intersection/inflection axes preserved in porphyroblasts (FIAs) from the Rhode Island Formation in the central zone of the Narragansett Basin preserve two distinct trends oriented NNE and ENE. Both trends occur in some samples and reveal a consistent succession from NNE to ENE. Each FIA trend is defined by asymmetric curved inclusion trails that in every case have an anticlockwise asymmetry looking NE. The two distinct trends and their consistent relative timing cannot be explained if the porphyroblasts had rotated. Therefore, a deformation history of progressive bulk inhomogeneous shortening with a consistent non-coaxial component of shear of top to the WNW followed by top to the NNW is required. This correlates with the macroscopic regional relationships suggested by the folds which verge WNW and provides a convincing demonstration that shear on cleavage corresponds with the differentiation asymmetry (curvature of a crenulated cleavage into differentiated crenulation cleavage). (Chapter 2)"

"High grade Pennsylvanian metamorphism appears pervasive throughout the Scotland Schist of the Merrimack Terrane in SE New England. This contrasts with previous work that has suggested post-Acadian metamorphism within the cover sequence was limited to narrow fault controlled zones. A three dimensional microstructural analysis of both matrix foliations and structures preserved in porphyroblasts defined four periods of deformation and metamorphism about differently trending foliation/ inflection axes (FIAs) in porphyroblasts. FIA sets 1 to 4 are oriented WNW-ESE, SW-NE, NNW-SSE and WNW-ESE, respectively. The bulk shortening recorded in this study was dominantly non-coaxial. NNE directed bulk orogenic flow accompanied high grade metamorphism during the earliest determined period of porphyroblast growth. WSW to NNE directed bulk orogenic flow accompanied high grade Pennsylvanian (310 Ma) metamorphism. Consistent NNE to WSW directed bulk orogenic flow in eastern Connecticut and southwest Rhode Island is not compatible with current models for loading of the Bronson Hill -Central Maine -Merrimack terranes by stacking thrust nappes towards the S and E. (Chapter 3)"

"Late Palaeozoic U-Th-Pb ages of monazite from rocks of the Merrimack Terrane in eastern Connecticut reflect an Alleghanian overprint on Acadian metamorphic rocks. The period of monazite growth dated using an electron microprobe identifies high grade metamorphism occurring in association with compressional deformation at 311 ± 3 Ma. High grade metamorphism was not restricted to shear controlled zones but affected the bulk of the vertical rock pile within the Merrimack Terrane during the Pennsylvanian. However, the effect of late Alleghanian (Permian) deformation and metamorphism that is recorded within the Narragansett Basin to the east was not recorded by the Merrimack Terrane. This is strongly supported by the lack of correlation between the FIA sets for the two regions. As metamorphism within the Merrimack Terrane increased to sillimanite grade, deformation was increasingly coarsely partitioned until the Early Permian when strain became localised at the Putnam-Avalon boundary along ductile shear zones. Thus, collision related compressional deformation within the Narragansett Basin was partitioning into the Honey Hill fault system during the early Permian. (Chapter 4)"

I conclude that the Alleghanian orogeny was responsible for the high-grade metamorphism in the rocks of the Rhode Island Formation, Rhode Island, and the Scotland Schist, eastern Connecticut. During this period the prevailing direction of bulk orogenic flow was to the NW throughout this region. Strain that had been distributed through the entire rock pile in eastern Connecticut the Pennsylvanian, became localised at the major lithotectonic boundaries, namely the Honey Hill, Willimantic, Lake Char and Clinton-Newbury fault systems during the early Permian. As a result, pervasive prograde metamorphism within the Merrimack terrane ceased while collision related deformation and associated metamorphism continued at shear controlled locations in eastern Connecticut and within the Avalon Composite Terrane.

Future work on the tectonic evolution of this region would benefit from further investigation of bulk orogenic flow directions. Such a study within the Putnam-Nashoba terrane to the east of the Merrimack terrane and around the Willimantic Dome could be particularly insightful. Determining the direction of bulk orogenic flow in this terrane may shed light on why the bulk orogenic flow direction within Merrimack and Narragansett Basin is hard to rationalise with the current model for loading of eastern New England by stacking thrust nappes towards the S and E. Figure 1 attempts to place the bulk orogenic directions measured for the Merrimack terrane into the generic model for orogenesis developed by Bell and Johnson (1989). This is not an effort to develop an integrated tectonic model but is used to schematically discuss the shear senses referred to in this study. Figure 1a shows how a top to the SE motion on the Putnam-Nashoba – Avalon boundary would be expected during the collision and emplacement of Avalon under the Putnam-Nashoba, Merrimack and Central Maine Terranes. At this time, the Merrimack terrane could experience N directed bulk orogenic flow, but this did not occur in response to stacking of thrust sheets from the NW. Figure 1b shows the arrival of Africa which would have dramatically changed the scale of the orogen. The core of the orogen would move in response to this scale change and the relationships between lithotectonic units and related shear senses could shift as a result. The bulk orogenic movement direction in the Merrimack terrane could be to the NW while the shear sense on the Putnam-Nashoba –Avalon boundary could have changed to top to the NW. In this example, with the Merrimack terrane now within the bottom half of the orogenic pile, stacking of thrust sheets from the NW does not create a shear sense quandary.

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