The microstructural and metamorphic history preserved within garnet porphyroblasts from southern Vermont and northwestern Massachusetts

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SECTION A

The orientation of textural discontinuities in garnets with complex spiral inclusion trails

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Abstract

Textural discontinuities are common within the complex inclusion trails of ‘snowball’ garnets in southern Vermont and north-western Massachusetts. Textural discontinuities may be truncations, where an inner foliation is truncated by a younger foliation in the rim of the garnet, commonly at a high angle, or deflection planes, where the inner foliation bends sharply before merging with the outer foliation at a low angle, resembling the transitions into differentiated crenulation cleavages. The orientation of over 500 discontinuities measured from six samples demonstrates that textural discontinuities are dominantly sub-vertical and sub-horizontal features. This is proposed to reflect the formation of multiple sub-vertical and sub-horizontal foliations during orogenesis. Measurement of the orientation of axes of spiral and other inclusion trail geometries within garnet porphyroblasts showed that they are dominantly shallowly plunging, supporting the hypothesis that they formed during the overprinting of a series of sub-horizontal and sub-vertical foliations. These observations are inconsistent with the non-rotational model of spiral inclusion trail formation. It is concluded that the complex spiral inclusion trails of southern Vermont and north-western Massachusetts were formed by the inclusion of a series of sub-horizontal and sub-vertical foliations during episodic garnet growth without porphyroblast rotation.

1. Introduction

Porphyroblastic minerals such as garnet commonly overgrow pre-existing foliations, preserving a portion of the foliation from destruction during younger deformation events. The garnet porphyroblasts of southern Vermont are well known for their inclusion trails as they commonly have spectacular spiral shapes (Rosenfeld, 1968; Hayward, 1992; Bell & Hickey, 1997). The issue of how these spiral trails developed has been controversial (Bell et al., 1992b; Bell et al., 1992c; Passchier et al., 1992; Johnson, 1993) and has been interpreted using two fundamentally opposing models. The first, more traditional, model proposes that the spiral shaped inclusion trails formed by **rotation** of the garnet crystals within a developing foliation. Rotation occurs both relative to the foliation and relative to any external reference frame. The second, more recently developed, model proposes that the spiral shape formed during successively developed, near orthogonal foliations without rotation of the garnet crystal relative to an external reference frame such as the geographic co-ordinates of the terrane at the time of deformation. This model is referred to as the **non-rotational** model. The reference frame is important because, as highlighted by Williams and Jiang (1999), the porphyroblasts may have rotated relative to present day geographical co-ordinates if the whole terrane subsequently rotated. In practice, measurements are made relative to present day geographic co-ordinates and the possibility that plate motion has moved the terrane relative to these geographic co-ordinates is considered separately. In the non-rotational model there is rotation of the garnet crystal relative to the foliation but it is the foliation that is rotating, relative to the external reference frame, not the garnet crystal, and the garnet crystals do not rotate relative to each other (Stallard, 1998).

1.1 Rotational Model

The fundamental tenet of this model is that “sigmoidal lines of inclusions…are due to the rotation of the crystal during growth” (Spry, 1963). It is presumed that the garnet crystals grew in a medium in which deformation took place by laminar flow (simple shear) along the foliation and that the garnets behaved as rigid spheres and rotated passively. An analogy is drawn with a snowball (hence the term “snowball garnets”). As a snowball rolls down a snow-covered slope it picks up more snow. The layer of snow envelops the points of contact between the ball and the slope and the locus of points of contact within the ball forms a spiral. These points of contact are seen as analogous to the inclusions with the garnet crystal. By this analogy, the nature of the spiral is controlled by the rate of growth and the rate of rotation. The situation becomes more complex if the garnet has been rotated during more than one period of deformation as it cannot be assumed *a priori* that all the rotations occurred around the same axis within the schistosity (Rosenfeld, 1968). If these rotations were indeed about different axes the later deformations would change the orientation of the earlier rotational axes, creating complex distributions in three dimensions and making it very difficult to “unravel” the spirals.

1.2 Non-rotational Model

The idea that curved inclusion trail patterns could be produced by rotation of the matrix rather than rotation of the porphyroblast was discussed by Ramsay (1962) after he observed than many apparently “rotated” porphyroblasts were growing in rocks where there was no evidence for slip on the primary bedding planes or folded schistosity. He suggested that in these rocks, where the deformation occurred by bulk shortening, the porphyroblasts remained relatively static while the matrix folded around them. Figure

A-1 illustrates how progressive flattening together with simultaneous progressive growth of the porphyroblast can produce curved inclusion trails. The porphyroblasts are non-compressible and differential flattening around these resistant particles will cause curvature of the surrounding schistosity. As the crystals increase in size, they preserve the curved foliation as inclusion trails. However, as Ramsay (1962) noted, this mechanism alone will not produce inclusion trails where the angle of curvature of internal schistosity is greater than 90° - to produce spiral trails his model would require successive non-parallel flattenings.

A somewhat similar line of thinking was developed by Bell and co-workers (Bell & Rubenach, 1983; Bell, 1985; Bell & Johnson, 1989) in the 1980's. They produced a deformation model of progressive bulk inhomogeneous shortening and then showed how spiral-shaped inclusion trails may result from "incremental porphyroblast growth during multiple stages of orthogonal crenulation cleavage development" (Bell & Johnson, 1989; Hayward, 1992). It was envisioned that garnet growth initiates during crenulation cleavage development and overgrows a portion of the pre-existing foliation (Figure A-1). The new foliation forms at a high angle to the earlier foliation and wraps around the porphyroblast so that the garnet overgrows a crenulation that has an anastomosing axial plane trace, creating a curved inclusion trail in a similar manner to that described by Ramsay (1962). During a later deformation the new foliation may, in turn, be crenulated and this may be accompanied by another phase of garnet growth. This growth may continue the inclusion trail to form a relatively smooth spiral, or abrupt truncations may occur. Smoothly curving inclusion trails occur when the crenulation cleavage does not develop to a penetrative foliation or a protuberance of the garnet crystal creates a strain shadow that protects a section of the crenulation cleavage from continued deformation (Bell et al., 1992b). Both truncational and smoothly curving inclusion trails may occur in the same porphyroblast as shown in Figure A-1.

Proponents of the non-rotation model suggest that each new foliation forms at a high angle to the preceding foliation and that numerous cycles of near-orthogonal foliation development occur during the development of an orogen (Bell & Johnson, 1989). This is supported by data from Johnson (1993) showing that total inclusion trail curvatures cluster in multiples of 90°. Johnson (1999b) reviewed the different mechanisms that could produce near-orthogonal foliations during orogenesis and concluded that three mechanisms are of general importance (Figure A-2). The first of these is the passage of thrust sheets over flats and ramps. Gently dipping foliations form when thrusting occurs across a nearly horizontal surface and steeply dipping foliations form when the rocks move over a ramp and undergo layer-parallel shortening (Beutener et al., 1988). Where stratigraphy allows the development of multiple flats and ramps sequential overprinting of steeply and gently dipping foliations may occur (Johnson, 1999b).

The second general mechanism for the production for near-orthogonal foliations is cycles of orogenic collapse. Bell and Johnson (1989) suggested that orogenesis initially involves horizontal crustal shortening, vertical thickening and the development of steep foliations. Eventually the thickened pile collapses and undergoes vertical shortening, resulting in a gently dipping foliation. According to the Bell and Johnson (1989) model, this cycle of compression and collapse is repeated many times during orogenesis, producing multiple sub-vertical and sub-horizontal foliations. Bell and Johnson (1989) primarily attribute the collapse to crustal overthickening and associated gravitational instability but other factors may play a role. These include changes in the strength of the rock medium, for example due to the addition of water or heat during metamorphism or magmatic activity, and changes in convergent velocity, either because of large scale changes in plate motion or smaller scale complexities related to the geometry of the margin. Means (1999) suggested that orogenic collapse could occur without reversal of the directions of maximum and minimum compressive stresses if the production of the vertical foliation renders the rock rheologically anisotropic enough and certain other stress conditions are met.

The final explanation presented by Johnson (1999b) for the common pattern of steeply dipping and gently dipping foliations is that foliations may not form orthogonally but that “back-rotation” of crenulation hinges during crenulation cleavage development produces a near-orthogonal relationship. “Back-rotation” could explain why near orthogonal foliation relationships are commonly preserved in porphyroblasts, which tend to grow in crenulation hinges.

1.3 Textural discontinuities within inclusion spirals

Inclusion trails within garnets commonly contain textural discontinuities that disrupt the spiral shape (Bell & Johnson, 1989; Bell et al., 1992c; Hayward, 1992). In this study two main styles of textural discontinuity were recognised (Figure A-3): i) truncations, where an inner foliation is truncated by a younger foliation in the rim of the garnet, commonly at a high angle. ii) deflection planes, where the inner foliation bends sharply before merging with the outer foliation at a low angle, resembling the differentiated zones of crenulation cleavages. In the later case the inner inclusion trails may merge continuously with the outer inclusion trails or a partial truncation may be present (Bell & Johnson, 1989; Hayward, 1992). Morphological gradations are observed between each style of discontinuity.

Textural discontinuities, such as those just described, are not consistent with the continuous rotational model as it was originally presented. However, the model can be modified to account for truncations by allowing for a pause in growth, with or without a pause in rotation (Johnson, 1993; Passchier & Trouw, 1998). This is illustrated in Figure A-4. The greater the amount of rotation and/or foliation development without further garnet growth the more abrupt the truncation. It is also possible that garnet growth does not cease completely but only slows relative to the rate of rotation and/or foliation development or that garnet growth stops only on some faces. Passchier and Trouw (1998) highlight the role of mica rich strain caps in producing deflection planes or truncations. No explanation has been given for what stops, or slows, garnet growth in the rotational model but it could be attributed to a change in any one of the factors necessary for a metamorphic reaction to continue such as the availability of reactants and the appropriate temperature and pressure conditions.

In the non-rotational model, garnet growth initiates during crenulation cleavage development and the porphyroblast grows in the crenulation hinge (Bell et al., 1986; Bell & Hayward, 1991). These microenvironments are favourable for porphyroblast nucleation and growth because the propensity for microfracturing in these zones provides access for fluids carrying the material needed for porphyroblast growth and the build-up of stored strain energy lowers the activation energy for nucleation (Bell et al., 1986; Williams, 1994). As development of the new foliation continues, the garnet porphyroblast is unable to continue growing out over the crenulation limbs because active shearing and dissolution is taking place in these zones (Bell et al., 1986; Bell & Hayward, 1991). If the crenulation cleavage continues to develop, forming a pervasive foliation that wraps around the porphyroblast, and especially if there is dissolution along the porphyroblast margins, a sharp truncation will form in the next phase of garnet growth (Figure A-4). Conversely, if the crenulation cleavage does not develop into a pervasive foliation, or the garnet crystal shape creates a strain shadow protecting the crenulation from continued deformation, the preserved discontinuity will be subtler and the spiral may appear to be smoothly curving (Bell et al., 1992b). According to Johnson (1993), the smoothness of spiral-shaped inclusion trails may be influenced by the rock type, the porphyroblast crystal-face geometry and the amount and the pattern of deformation partitioning in the rock.

In some cases, discontinuities develop in the matrix prior to being overgrown by garnet. For example a microfold bounded by differentiated crenulation cleavages may be overgrown and preserved by later garnet growth, unrelated to the formation of either foliation. In these cases the formation of the discontinuities is completely unrelated to garnet growth and/or garnet rotation and simply records the relationship of two overprinting foliations. It is, however, unlikely that a complex sequence of overprinting foliations, such as that observed in some porphyroblasts, would be preserved in the matrix as the greater the number of deformations, the greater the chance of a pervasive new foliation forming and destroying the record of previous foliations. In addition many garnet porphyroblasts record a change in chemical composition and/or inclusion mineralogy coincident with textural discontinuities (Karabinos, 1984; Bell & Johnson, 1989; Spiess & Bell, 1996; Stallard & Hickey, 2002; Section C of this thesis). This implies that the core of these porphyroblasts grew in a separate growth episode prior to the growth of the rim and that the textural discontinuities coincide with the pause in garnet growth rather than pre-dating all garnet growth.

1.4 Orientation of discontinuities

The first measurements of the orientation of textural discontinuities were made by Hayward (1992) in south-eastern Vermont and the present study aims to extend his pioneering work. Hayward's (1992) measurements indicate textural discontinuities in garnet porphyroblasts are predominantly sub-horizontal and sub-vertical features. However, several other studies discuss how discontinuities may form (Bell et al., 1992a; Bell et al., 1992c; Passchier et al., 1992; Johnson, 1993, 1999a). From these discussions it is clear a number of different factors could influence the orientation of included discontinuities and produce different patterns. One of the major aims of this study is to determine if there is any consistent pattern in the orientation of textural discontinuities in samples from this study and, if so, what this pattern might tell us about the processes operating when they formed.

If the garnet porphyroblasts were sub-spherical and rolling along the foliation in the manner of a snowball, there is no apparent mechanism by which porphyroblast orientation could be related to the pause in garnet growth needed to produce a discontinuity. Discontinuities could therefore, occur at any orientation and a random distribution would be expected. Alternatively, if the garnet porphyroblasts are idioblastic crystals, a rolling porphyroblast may tend to stop with one of its crystal faces parallel to the foliation. Garnet belongs to the cubic crystal system and commonly displays rhombododecahedral and icositetrahedral crystal forms. Most idioblastic garnet porphyroblasts in this study are hexagonal in cross-section and are therefore probably rhombdodecahrons. If a garnet crystal is a perfect rhombododecahedron it will have three fourfold axes of symmetry, four threefold axes, and six twofold axes (Figure A-5). When viewed along any of its fourfold axes it appears square in profile, while along any of its threefold axes it appears hexagonal. Therefore, if a garnet crystal rotated around one of its four-fold axes of symmetry, and stopped whenever one if its faces was parallel to the foliation, it would rotate in 90° increments. If the crystal rotated around one of its threefold axes of symmetry it would rotate in 60° increments and if it rotated around one of its twofold axes of symmetry it would rotate in 180° increments. If a discontinuity formed after each of these increments of rotation (or some multiple of these increments) then the discontinuities would tend to form 60°, 90° or 180° apart. If different garnet crystals in the sample rotated around different axes then a mixture of different discontinuity orientations would be present.

If the garnet porphyroblasts do not rotate and spiral trails reflect the inclusion of multiple foliations during episodic garnet growth, the orientation of the overprinting foliations will control the orientation of textural discontinuities. The Bell and Johnson (1989) model for spiral formation suggests that alternating sub-horizontal and sub-vertical foliations are formed during deformation. If this is correct then discontinuities will tend to be sub-vertical and sub-horizontal, as reported by Hayward (1992). If a newly formed foliation tended to wrap around a pre-existing porphyroblast, so that the portion of the foliation included in the next episode of growth was parallel to the garnet crystal faces, this may influence the orientation of textural discontinuities. Hayward (1992) concluded that the inclined discontinuities in his study resulted from the deflection of anastomosing matrix foliations around obliquely oriented crystal faces. As explained above, most idioblastic garnet crystals in this study are rhombododecahedrons with a dihedral angle of 120°. This means that the sections of foliation parallel to each crystal face will be at 60° to each other and will tend to form textural discontinuities 60° apart.

1.5 Geological setting

In southern Vermont and northwestern Massachusetts the Appalachian Orogen is made up of an array of paraautochthonous to allochthonous lithotectonic units (Stanley & Ratcliffe, 1985; Armstrong et al., 1992; Ratcliffe et al., 1992; Bell et al., 1998). Middle Proterozoic basement gneisses of the paraautochthonous Green Mountains Massif and the allochthonous Chester and Athens Domes are unconformably overlain by the allochthonous Late Proterozoic to Early Cambrian Hoosac Formation (Figure A-6). These rocks are overthrust by a sequence of Cambrian to Middle Ordovician calcareous, pelitic and semi-pelitic metasedimentary and metavolcanic and intrusive rocks of the Rowe-Moretown lithotectonic unit. The youngest unit in this area is the thick Siluro-Devonian sequence of the Connecticut Valley Belt, separated from the Cambro-Ordovician rocks to the west by an angular unconformity. Two major orogenic events are recognised in the area, the Ordovician Taconic orogeny and the Devonian Acadian orogeny (Sutter et al., 1985). The Taconic Orogeny is interpreted as the collision of a volcanic arc complex with the North American continent and the Acadian Orogeny is interpreted as a continental collision between North America and the microcontinent Avalonia (Stanley & Ratcliffe, 1985; Armstrong et al., 1992; Ratcliffe et al., 1998)

2. Methods

It has been shown that schists from the Appalachian Orogen in Vermont and north-western Massachusetts have undergone multiple phases of deformation and garnet growth and commonly preserve spiral-inclusion trails (Rosenfeld, 1968; Bell et al., 1998) so samples from this region should be suitable for a microstructural analysis based on inclusion trail geometry. All the samples in this study are garnet grade and are estimated to have experienced peak Acadian P-T conditions of around 500° C and 8 kbar (Spear et al., 2002).

2.1 Sample descriptions

Samples of pelitic schist were taken from the Cambrian-Precambrian Hoosac Formation, the Cambrian Rowe Formation and the Moretown Member of the Ordovician Missiquoi Formation. (In Vermont the units equivalent to the Rowe Formation in Massachusetts are mapped as three separate formations: the Pinney Hollow, the Stowe and the Ottauquechee.) These lithologies were chosen because they typically contain garnet porphyroblasts with good inclusion trails. Textural discontinuities were measured in six samples: BG11, BG15A and BG102B from the Missiquoi Formation and BG62, BG87 and BG107A from the Hoosac Formation. These samples were selected because they had inclusion trails that showed clear textural discontinuities and were representative of the different kinds of inclusion trails observed in the area (i.e quartz-rich vs. rutile-rich inclusion trails, truncated vs. deflection/differentiation style discontinuities). The samples were also selected to provide a geographic spread across the field area (Figure A-6).

BG15A is a garnet, biotite, muscovite, plagioclase, quartz schist with accessory opaque minerals (Figure A-3). BG102B has the same basic mineralogy but also has chlorite present. In both samples, garnet porphyroblasts are up to 3 mm in diameter with inclusions of quartz, muscovite and opaque minerals. Inclusions trails show up to 360° of apparent rotation and are typically relatively smoothly curving.

BG11 is a garnet, biotite, chlorite, muscovite, quartz schist with accessory opaque minerals. Garnet porphyroblasts are up to 2 mm in diameter. The inclusion trails are mainly defined by quartz with fine-grained epidote present in the cores but not the rims. The inclusion trails are generally smoothly curving sigmoids with up to 180° of apparent rotation is recorded in some porphyroblasts.

BG62 is a garnet, chlorite, muscovite, quartz schist with accessory ilmenite and tourmaline (Figure A-3). The garnet porphyroblasts are generally idioblastic but may be quite cracked, with alteration to chlorite and iddingsite along the cracks. The porphyroblasts are up to 3.5 mm in diameter with inclusions of quartz, plagioclase, rutile, chloritoid and opaque minerals. The inclusion trails are well defined and smoothly curving in the cores but are truncated in the rims and defined by sparse quartz and ilmenite. Up to 270° of apparent rotation is preserved in some porphyroblasts.

Sample BG87 is a chlorite, garnet, muscovite, plagioclase, quartz schist with accessory ilmenite, tourmaline, biotite and epidote. The garnet porphyroblasts are large (up to 25 mm) with distinct textural core and rim zones. The cores are darker pink in colour and inclusion rich. Typical inclusions in the core are quartz, chloritoid, chlorite, muscovite, ilmenite and epidote. The largest porphyroblasts contain abundant rutile inclusions in the innermost part of the core and may record up to 180° of apparent rotation. The sigmoidal inclusion trails in the rim are defined by ilmenite and appear to wrap around the garnet cores.

BG107A is a garnet, chlorite, biotite, muscovite, quartz, plagoiclase schist with accessory opaque minerals. The cores of the porphyroblasts are rich in inclusions, with quartz, plagioclase, chlorite, rutile, ilmenite and apatite defining smooth spiral trails with up to 180° of apparent rotation. The rims of the porphyroblasts have fewer inclusions, with opaque inclusions tending to form a ring around the garnet core.

2.2 Measuring textural discontinuities

The orientation of textural discontinuities within spiral inclusion trails was determined by measuring the pitch of discontinuities in 8 to 14 different vertical sections with strikes varying around the compass. Over 500 discontinuities were measured from 6 samples. Sample locations are indicated on Figure A-6 and grid references are given in Appendix 1. Figure A-3 illustrates the discontinuities in one vertical section from sample BG62 and one vertical section from BG15A. BG62 has euhedral garnet porphyroblasts with relatively fine-grained inclusions. Textural discontinuities in this sample tend to be truncational in nature, although some of inclusion trails do show deflection/differentiation style discontinuities. In sample BG15A the inclusion trails are dominated by quartz and tend to be more smoothly curving than those in sample BG62. Deflection/differentiation style discontinuities are most common in this sample.

For textural discontinuities that were straight or only slightly curved one measurement of the average orientation was recorded. For the small number of samples where discontinuities were more curved (acute angle between the tangents >15°), two measurements were recorded, one from each half of the curved trace. The porphyroblasts were examined under high magnification to ensure all the fine-grained inclusions were recognised and taken into account when interpreting inclusion patterns. In cases where inclusion density was insufficient in the garnet rims to clearly define inclusion trails, and therefore constrain discontinuity surfaces, no measurement was made.

The accumulated error in producing oriented thin-sections is estimated as +/- 8°. Error is introduced at five different stages: precision error in the compass used to mark orientation in the field +/- 1°; repositioning of the compass relative to orientation mark when back in the laboratory +/- 2°; precision error of the compass used to reorient sample in laboratory +/- 1°; error associated with cutting horizontal slabs +/- 2°; error in marking up and cutting vertical blocks +/- 2°. When measuring textural discontinuities an additional error of +/- 2° is introduced measuring the pitch of the discontinuity under the microscope. The total error in measuring textural discontinuities is therefore estimated as +/-10°.

2.3 Foliation Inflection/Intersection Axis (FIA) Analysis

Foliation Inflection/Intersection Axes within porphyroblasts (FIAs), measured as described by Bell et al.(1995), were used to identify the orientation of axes of spiral inclusion trails within garnet. Significantly, this technique makes no assumptions as to how the spirals formed or whether the axes identified are axes of rotation of the porphyroblast. The method used and estimated errors are described in Appendix 2. The complete orientation of the FIA (both trend and plunge) was only determined for nine samples due to the large number of thin-sections required. Production of the additional thin-sections required to constrain plunge was only possible for samples where a large volume of rock had been collected in the field, enabling vertical slabs to be cut as well as the standard horizontal slabs. Therefore, apart from sample BG102B, the samples chosen for FIA plunge analysis were not the same as those used to measure the orientation of textural discontinuities.

3. Results

The orientations of discontinuities for each of the measured samples are given in Appendix 3 and presented as equal-area rose diagrams in Figure A-7. The dominant trend is for textural discontinuities to be sub-horizontal and sub-vertical. This pattern agrees with that observed by Hayward (1992), who also measured discontinuities in garnets from southern Vermont. Sample BG62 shows the greatest spread in data, with each peak spread over an 80° range. BG62 also shows peaks at 60° and 160°.

FIA trend and plunge for the measured samples are shown in Table A-1. FIA trend is quite variable, with samples ranging from NW to SW to SE. The significance of this will be discussed in Section B of this thesis. In contrast FIA plunge is consistently shallow, with eight of the nine samples plunging between 15° and 25°. Only one sample, BG102B, has a moderate plunge of 45°.

4. Interpretation and Discussion

4.1 Textural Discontinuities

The observed pattern of sub-vertical and sub-horizontal discontinuities is not easily explained by the rotational model of spiral development. Rotation of an idioblastic garnet porphyroblast with a rhombododecahedral crystal form may produce a pattern of discontinuities with peaks 90° apart if rotation takes place around one of the fourfold axes of symmetry. However, it is difficult to explain why all the porphyroblasts in the sample would rotate around one of the fourfold axes of symmetry and not around one of the threefold axes. In fact, since threefold axes are more numerous and a hexagonal cross-section more closely resembles a circle, intuitively it would seem rotation around a threefold axis would be favoured. In addition, for the discontinuities to be sub-vertical and sub-horizontal, the porphyroblast must always be rolling along a sub-horizontal or sub-vertical foliation with a sub-horizontal axis of rotation.

Johnson (1999c) observed a near-orthogonal relationship between crenulation hinges and developing crenulation seams in metaturbidites and attributed this to “back-rotation” of the cleavage hinges preserved in garnet porphyroblasts. This “back-rotation” is significantly different to the snow-ball style rotation proposed for spiral-inclusion trail formation. In the scenario described by Johnson (1999b; 1999c) the production of spiral inclusion trails still relies on the preservation of overprinting crenulation cleavages in the manner described in the non-rotation model. Nevertheless, Johnson’s (1999c) observation that in some cases crenulation hinges rotate to obtain a near-orthogonal relationship with the developing cleavage seam provides one explanation for the development of orthogonal foliations and, therefore, orthogonal textural discontinuities. It does not, however, explain why these foliations would tend to be horizontal and vertical.

A pattern of vertical and horizontal discontinuities is predicted by the non-rotational model for spiral inclusion trail formation where overprinting foliations are produced by cycles of orogenic collapse. According to Bell and Johnson (1989) the cycle of overprinting vertical and horizontal events would produce a pattern of sub-horizontal and sub-vertical discontinuities within garnet porphyroblasts that were growing episodically across the alternating foliations. The pattern of textural discontinuities observed in the present study is consistent with the orientation of discontinuities in these rocks being primarily controlled by the formation of sub-vertical and sub-horizontal foliations. However, it is possible that in some situations the near-orthogonal relationship of the foliations is enhanced by “back-rotation” of the porphyroblasts (Johnson, 1999c). The development of sub-horizontal and sub-vertical foliations is attributed to cycles of orogenic collapse in a manner similar to that described by Bell and Johnson (1989). It is not known whether collapse is related to crustal overthickening, as suggested by Bell and Johnson (1989), or to rheological anisotropy, as suggested by Means (1999), or to some other factor. The development of sequential sub-vertical and sub-horizontal foliations by the passage of thrust sheets over multiple flats and ramps (Johnson, 1999b), is not considered relevant because ramp-flat style thrusting is not significant at the time of garnet growth in this area.

When samples are examined in detail under the microscope, it is clear that crystal shape also plays a role in the orientation of discontinuities. Sample BG62 contains numerous idioblastic garnet crystals with hexagonal cross-sections and it is clear that in some cases the discontinuities parallel the crystal faces (Figure A-3). This could either be due to rotation in increments from one crystal face to another or the tendency for foliations to wrap the crystal faces and be included as discontinuities. In this sample the presence of sub-vertical and sub-horizontal maxima, in addition to the peaks at 60° and 160°, supports the hypothesis that the discontinuities are formed by overprinting sub-vertical and sub-horizontal foliations that have wrapped around the porphyroblasts. This agrees with the conclusion of Hayward (1992) that the inclined discontinuities in his study resulted from the deflection of anastomosing matrix foliations around obliquely oriented crystal faces. Although the foliation may wrap around all the crystal faces, foliation intensification will be greatest against faces that are favourably oriented (that is either sub-horizontal or sub-vertical faces depending on the foliation orientation) and this is recorded in the predominance of sub-horizontal and sub-vertical discontinuities.

4.2 Mineral Preferred Orientations

It has been reported that garnet crystals commonly show a lattice preferred orientation which means that the crystal will tend to grow with a crystal face parallel to the foliation and this is attributed to the role of micas in assisting garnet nucleation (Powell, 1966). This lattice preferred orientation will not fundamentally influence the pattern in truncation orientations - it controls the garnet porphyroblast orientation relative to the original foliation rather than to any subsequent foliations that form truncations. However, in a situation where multiple orthogonal foliations have developed, later foliations will parallel the original foliation. The tendency for later foliations to lie parallel to the original foliation, and therefore parallel to one set of garnet crystal faces, may create a situation where truncations are commonly parallel to crystal faces even though the orientation of crystal faces is not the dominant control on the orientation of the truncations.

4.3 FIA Analysis

The wide range in FIA trend indicates that the samples come from a number of different FIA sets (Bell & Hickey, 1997; Section B of this thesis). However, for almost all the samples, the FIA plunge is shallow. The tendency for all FIAs to be shallow, whatever FIA set they belong to, agrees with the work done by Bell et al. (1995) in the Alps, Bell and Hickey (1997) in Vermont and Aerden (2004) in the Iberian Massif.

If the spiral inclusion trails were formed by rotation, the FIAs would represent axes of rotation. For all the FIAs to have a dominantly shallow plunge then almost all porphyroblasts must have rotated around a sub-horizontal axis. While this is possible in an area where all the shear planes are horizontal, it is very unlikely in areas where shear planes are inclined or variably oriented. However the tendency for FIAs to have a shallow plunge can be readily explained if the FIAs formed during the crenulation of a series of sub-horizontal and sub-vertical foliations during cycles of horizontal and vertical compression (Bell & Johnson, 1989). When horizontal and vertical foliations intersect, the line of intersection (FIA) is always horizontal.

The exception to the general trend is sample BG102B, which has a FIA that plunges at 45°. Close analysis of this sample shows that the inclusion trails are consistent with the porphyroblasts first growing during horizontal compression. This is important because if the first phase of porphyroblast growth occurs during horizontal compression the dip of the pre-existing foliation controls the plunge of the FIA. This is because the plunge of the line of intersection between a vertical foliation and any other foliation depends on the dip of the other foliation. If the porphyroblasts in BG102B grew during horizontal compression of a moderately dipping foliation then the FIA would be moderately plunging. Rotation and reactivation of a pre-existing horizontal or vertical foliation during deformation could easily change the dip by 45° (Bell, 1986) and crenulation of this dipping foliation during later horizontal compression would produce a FIA plunging at 45°. The dip of the pre-existing foliation is only relevant when a porphyroblast grows for the first time during a horizontal shortening event - a FIA formed during vertical shortening, such as associated with extensional collapse, will always be sub-horizontal, whatever the orientation of the pre-existing foliation. This is because the line of intersection between a horizontal plane and any other plane is always horizontal.

4.4 Rotation vs. Non-rotation

The strong evidence for sub-horizontal and sub-vertical foliation events, provided by the geometric analysis of textural discontinuities and the observation that apparent rotation axes are commonly shallowly plunging, supports the non-rotational model for spiral formation in these rocks. While orthogonal discontinuities can be explained by porphyroblast rotation in 90° increments or by "back-rotation" of crenulation hinges, sub-vertical and sub-horizontal textural discontinuities and shallowly plunging FIA can only be explained by rotation if the axis of rotation for every porphyroblast was always sub-horizontal, whatever the shear plane, and this is considered very unlikely. In contrast, sub-vertical and sub-horizontal discontinuities and shallowly plunging FIA are readily explained in the non-rotational model by the overprinting of successive sub-horizontal and sub-vertical foliations. It can be difficult to find a single criterion by which to determine if a porphyroblast has rotated or not as the two models produce very similar inclusion geometries (Johnson, 1993; Stallard et al., 2003). However, in this case, the non-rotational model best explains the observed features.

5. Conclusions

1. Textural discontinuities are common within the spiral inclusion trails of ‘snowball’ garnets in southern Vermont and north-western Massachusetts.
2. Textural discontinuities are dominantly sub-vertical and sub-horizontal, consistent with the previous study of Hayward (1992).
3. Textural discontinuities are interpreted to reflect the formation of multiple, overprinting, sub-vertical and sub-horizontal foliations during orogenesis.
4. FIAs (foliation intersection/inflection axes) are dominantly shallow plunging, supporting the hypothesis that they also formed during the crenulation of a series of sub-horizontal and sub-vertical foliations.
5. The inclusion of multiple sub-vertical and sub-horizontal foliations during episodic garnet growth is best explained by the non-rotational model of spiral inclusion trail formation.

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SECTION B

Foliation Intersection/Inflection Axes in garnet porphyroblasts and the relationship between garnet growth and deformation

Table of Contents

Abstract

Garnet porphyroblasts in schists from the Appalachian Orogen in southern Vermont and northwestern Massachusetts preserve complex inclusion trails indicating a history of multiple phases of deformation and garnet growth. **F**oliation **i**nflection/**i**ntersection **a**xes preserved in garnet porphyroblasts (FIAs) in 62 samples of garnet schist show a systematic change in the direction of principal horizontal bulk shortening across the area through time and the six FIA sets identified in this study correlate well with previous work in adjacent areas. The spatial distribution of samples containing this succession of FIA sets shows no evidence to suggest that garnet growth began in the east and moved west to the current location of the garnet isograd. That is, both young and old FIAs are found throughout the area. This suggests that lateral migration of temperature and/or pressure conditions was not the primary control on garnet growth, which was both heterogeneous and episodic across the area. Such a distribution can be explained by deformation partitioning occurring at different scales throughout Acadian orogenesis and acting as a control on garnet growth. Repartitioning of the distribution of progressive shearing and shortening during successive deformation events resulted in a heterogeneous spatial distribution of garnet growth through time. The absolute age of the different phases of garnet growth is not known and it was not possible to distinguish between Taconic (Ordovician) and Acadian (Devonian) garnet growth on the basis of microstructural evidence alone.

1. Introduction

Schists from the northern Appalachian Orogen contain exceptional examples of garnet porphyroblasts with complex spiral inclusion trails (Rosenfeld, 1968; Bell et al., 1998). It is difficult to absolutely date garnet growth and garnet growth in southern Vermont and northwestern Massachusetts could have occurred in the Acadian or the Taconian or during both events. The most commonly quoted evidence for Taconic garnet growth in southern Vermont comes from the microstructural work of Rosenfeld (1968). Rosenfeld (1968) identified the apparent axis of rotation for complex spiral inclusion trails preserved in garnet and related this to the direction of shearing that caused what he assumed was 'rotational' behaviour of the porphyroblasts. Based on the observation of a strong textural unconformity between the core and rim of some porphyroblasts from the Pinney Hollow Formation, Rosenfeld (1968) suggested that the cores of these garnet porphyroblasts were Taconic and predated the two Acadian deformations he had observed elsewhere in southern Vermont. Karabinos (1984), studied similar garnet porphyroblasts from the Hoosac Formation, which also preserve two different garnet growth stages, and suggested that the cores were Taconic and the rims Acadian, but acknowledged that both growth stages may have been Acadian. As discussed in Section A of this thesis, recent work has suggested that spiral inclusion trails in garnet porphyroblasts may not have formed by garnet rotation, as was presumed by Rosenfeld (1968), but instead may result from the inclusion of multiple sub-horizontal and sub-vertical foliations during episodic garnet growth (Hayward, 1992; Bell et al., 1998). This reinterpretation of the origin of spiral-shaped inclusion trails, and recognition that multiple phases of garnet growth must have taken place to preserve such complex trails, presents problems for Rosenfeld's conclusions regarding the timing of garnet growth in Vermont. In particular, the widely accepted interpretation of two Acadian deformations, the first associated with westward-directed thrusting and the second with doming, appears not to be correct (Bell et al., 2003; Bell et al., 2004).

The aim of the present study was to identify different phases of garnet growth in southern Vermont and northwestern Massachusetts using microstructural analysis. Based on the spatial distribution of these growth phases, the study set out to define the movement of the garnet isograd through time and the fundamental controls on garnet growth. The possibility of discriminating between Taconic (Ordovician) and Acadian (Devonian) garnet growth using microstructural evidence was also investigated.

1.1 Geological setting and metamorphic history

In southern Vermont and northwestern Massachusetts the Appalachian Orogen is made up of an array of paraautochthonous to allochthonous lithotectonic units (Stanley & Ratcliffe, 1985; Armstrong et al., 1992; Ratcliffe et al., 1992; Bell et al., 1998). Middle Proterozoic basement gneisses of the paraautochthonous Green Mountains Massif and the allochthonous Chester and Athens Domes are unconformably overlain by the allochthonous Late Proterozoic to Early Cambrian Hoosac Formation (Figure B-1). These rocks are overthrust by a sequence of Cambrian to Middle Ordovician calcareous, pelitic and semi-pelitic metasedimentary and metavolcanic and intrusive rocks of the Rowe-Moretown lithotectonic unit. The youngest unit in this area is the thick Siluro-Devonian sequence of the Connecticut Valley Belt, interpreted to be separated from the Cambro-Ordovician rocks to the west by an angular unconformity.

The Appalachian Orogen is believed to have experienced several phases of metamorphism associated with the closure of Iapetus, the ocean that separated Laurentia and western Eurasia in the Paleozoic. In southern Vermont and northwestern Massachusetts two major metamorphic produced the present distribution of terranes and isograd. The Taconic Orogeny is interpreted as the collision of a volcanic arc complex with Laurentia and the Acadian Orogeny is interpreted as a continental collision between Laurentia and the microcontinent Avalonia (Stanley & Ratcliffe, 1985; Armstrong et al., 1992; Ratcliffe et al., 1998). These two phases of collision had a very similar distribution in central New England and their metamorphic effects overlap (Laird et al., 1984; Sutter et al., 1985; Hames et al., 1991; Armstrong et al., 1992). Interpreting the history of polymetamorphic areas can be very difficult and it was not until the 1980's that the extent and high grade of the earlier Taconic metamorphism in southern Vermont and northwestern Massachusetts was recognised. At this time new radiometric age data (K-Ar and Ar-Ar) helped define the distribution of Taconian versus Acadian metamorphic effects and maps showing different isograds for each of the periods of metamorphism were constructed (Laird et al., 1984; Sutter et al., 1985). If the Taconic garnet isograd proposed by Sutter et al. (1985) is projected northwards it should lie slightly to the east of the Acadian garnet isograd but to the west of the Chester-Athens Dome in southern Vermont (Figure B-1). This means that garnet growth in southern Vermont and northwestern Massachusetts could have occurred in the Acadian or the Taconian or during both events.

1.2 Complex spiral inclusion trails and FIAs

As discussed in Section A of this thesis, the interpretation of the mechanism of formation of spiral-shaped inclusion trails is currently controversial (Bell et al., 1992a; Bell et al., 1992b; Passchier et al., 1992; Johnson, 1993) and has been interpreted using two fundamentally opposing models – the rotational model and the non-rotational model. The axes identified in spiral inclusion trails provide important information about the kinematics of deformation and how this is interpreted is significantly affected by the mechanism by which spiral-shaped inclusion trails formed. Rosenfeld (1968) interpreted the spiral axes as axes of rotation and used them to infer the direction of shear during deformation. The non-rotational model argues these axes formed by the overprinting of alternating steep and flat foliations and are actually foliation inflection/intersection axes that are preserved within the porphyroblasts (FIAs). According to this hypothesis, where a horizontal foliation is crenulated by horizontal compression, the trend of the FIA preserved by garnet growth during that event will tend to lie at a high angle to the direction of bulk shortening, especially where a previous porphyroblast has formed (Bell & Johnson, 1989; Bell & Wang, 1999). Where a vertical foliation, which has developed against a previously formed porphyroblast, is crenulated by vertical shortening, the trend of the FIA preserved by subsequent growth of that porphyroblast will parallel the strike of the vertical foliation. The strike of the vertical foliation preserved against the porphyroblast reflects the direction of bulk horizontal shortening during the event that formed the foliation. Therefore, the trend of FIAs produced by the crenulation of alternating vertical and horizontal foliations that have formed against pre-existing porphyroblasts should always lie at a high angle to the direction of bulk horizontal shortening. According to this hypothesis, if the direction of bulk horizontal shortening changed within the period of garnet growth a garnet porphyroblast may preserve one FIA trend in the core and a different FIA trend in the rim and the preservation of such core-rim relationships allows the relative age of different FIA trends to be determined (Bell et al., 1998). FIAs commonly preserve a regular succession of consistent orientations over distances of tens to hundreds of kilometres, allowing FIAs to be correlated regionally (Bell et al., 1998; Bell & Mares, 1999; Bell et al., 2004).

1.3 FIAs and the garnet isograd

As demonstrated by Barrow in the Scottish Highlands, metamorphic zones can be mapped out based on differences in the mineral assemblages of pelitic rocks (Barrow, 1893). Zonal boundaries are defined by isograds, representing the first appearance of key index minerals such as garnet (Barker, 1998). Generally, isograds are mapped without breaking the succession down into various periods of growth. However, measurement of successive FIAs allows the relative timing of different phases of porphyroblast growth to be established, potentially enabling the delineation of an isograd for each change in FIA trend. Isograds are usually interpreted as directly reflecting the pressure-temperature history in a rock. However, additional factors that can influence the growth of a mineral such as garnet are the bulk composition of the rocks and the deformation history (Bell & Hayward, 1991; Bell et al., 2003; Bell et al., 2004). As discussed in Section D of this thesis, mineral assemblages, rather than a single mineral, form the most reliable approach to evaluating P-T conditions in any detail.

2. Methods

Samples were taken from three major lithological units (Figure B-1). In Massachusetts, using the terminology of Zen et al. (1983), these are referred to as the Hoosac, the Rowe and the Moretown Formations. In Vermont, using the terminology of Doll et al. (1961), the Moretown is a member of the Missisquoi Formation and the Rowe is equivalent to three separate formations: the Pinney Hollow, the Stowe and the Ottauquechee. These lithologies were chosen because they are typically aluminous or contain graphitic schists and are likely to contain garnet porphyroblasts with good inclusion trails.

2.1 FIA Analysis

FIA analysis, as described by Bell et al. (1995), was used to determine the orientation of axes of spiral inclusion trails within the garnet porphyroblasts in all samples where this was possible. Of the 120 samples collected, 61 were suitable, as they contained porphyroblasts with curved inclusion trails and sufficient garnet was present to allow detailed analysis. The location of these 61 samples is shown on Figure B-1 and grid-references are given in Appendix 1. FIAs were determined using the asymmetry-switch method as described in Appendix 2.

The successful application of this method is dependent on FIAs within individual porphyroblasts being non-randomly oriented and having a restricted range in orientation within a sample. Stallard et al. (2003) reported that it is quite common to find both anti-clockwise and clockwise geometries within thin sections oriented close to the FIA, showing that the switch in asymmetry occurs over an angular range rather than at a discrete point. This is interpreted to reflect the curvilinear geometry of FIAs within individual porphyroblasts and variation in orientation within porphyroblasts within a sample. However, in this study, very few samples had thin sections where two asymmetries were present. In cases where one section had two asymmetries present, and the sections either side had a single asymmetry, the FIA was defined as the orientation of the section with two asymmetries. In cases where two sections had two asymmetries present, and the sections either side had a single asymmetry, the FIA was defined as the mid-point between the two sections with two asymmetries. No sample with a single FIA had two asymmetries present in more than two sections (i.e. over more than a 20° range). In multi-FIA samples the complete deformation history may not be preserved in all porphyroblasts and it is extremely important to separate inclusion trail data related to different episodes of garnet growth (i.e. core vs. rim). When this is done correctly the asymmetry switch for each FIA is found to occur over no more than a 20° range.

3. Results

From the 61 samples analysed 71 FIAs were determined. Eight samples contained two FIAs and one sample preserved three FIAs. The FIA trends are compiled in Table B-1. Where two or more FIAs were determined, the core FIA trend is listed first, followed by the median FIA trend (if present) and, finally, the rim FIA trend. The total FIA trend data are presented as an equal-area rose diagram in Figure B-2.

3.1 Multi-FIA Samples

The succession of differently trending FIAs preserved from core to rim in multi-FIA samples provides relative timing for the FIA trends preserved in single-FIA samples and offers a way of distinguishing distinct populations in the data. The nine samples that contained two or more FIAs are shown at the bottom of Table B-1.

The following patterns of relative FIA timings are present in the data:

- E-W FIA followed by a NNW-SSE FIA followed by a N-S FIA (BG108)
- E-W FIA followed by a N-S FIA (BG15A, BG32)

- NNW-SSE FIA followed by N-S FIA (BG104, BG105A)
- NW-SE FIA followed by a N-S FIA (BG21)
- N-S FIA followed by a NE-SW FIA (BG60, BG62)
- ENE-WSW FIA followed by a NNE-SSW FIA (BG87)

4. Interpretation and Discussion

4.1 Defining FIA sets and correlating with previous studies

Based on major peaks in the FIA data, at least two FIA sets are present, oriented approximately E-W and N-S. However, from the multi-FIA samples it can be seen that the data are more complex and additional FIA sets are present. With the exception of BG87 and BG62, the FIAs show a progression from E-W to NNW-SSE to N-S. BG62 has a N-S FIA followed by a NE-SW one, suggesting that the next FIA in the progression is NE-SW. The relative timing of the FIA sets is therefore determined as E-W followed by NNW-SSE followed by N-S followed by NE-SW (Figure B-3). This correlates well with the data of Bell and Hickey (1997) and Bell et al. (1998), who used the same FIA technique on samples they collected around Chester and Athens domes in south-eastern Vermont. Their field area partially overlaps the eastern margin of the field area for this study and the FIA trends identified in their area show an E-W to NNW-SSE to N-S to NE-SW progression through time, similar to that identified in the present study (Figure B-3). Their data also show a similar density distribution, with the greatest proportion FIAs oriented approximately N-S (Figure B-2).

Sample BG87 does not appear to fit within the FIA progression established from the other samples, showing an ENE-WSW FIA followed by a NNE-SSW. Given the small number of multi-FIA samples in the present study it was not possible to fully resolve the FIA progression from this data set alone. Bell and Hickey (1997) and Bell et al. (1998) found 33 multi-FIA samples (Table B-2 and Figure B-3). These data show another FIA set is clearly present, pre-dating those identified in multi-FIA samples in this study, and with a NE-SW trend. This additional FIA set could explain the progression preserved in sample BG87 with the core FIA from the sample coming from this earlier NE-SW FIA set and the rim FIA coming from the later NE-SW FIA set.

The core FIA from sample BG21 is also somewhat problematic. It is the only sample with a FIA at 125° and it is not clear whether it should be allocated to the NNW-SSE FIA set, or the E-W FIA set, or to another FIA set altogether. Bell et al. (1998) did not have any samples with a 125° FIA trend and indeed report no FIAs between 110° and 140°. Recent detailed re-examination of the core of one of their samples led Bell to revise the core FIA to 136° but FIAs around this orientation are still believed to be rare in this area (Bell et al., 2004). In contrast, Ham (2001), working around the Pomfret Dome, NNE of the Chester Dome, reported a relatively large data set of FIAs between 120° and 140°. The multi-FIA data of Ham (2001) shows that FIAs of 120°-140° only occur in porphyroblast cores and are generally followed by an NE-SW FIA or an E-W FIA. One sample has a NW-SE core FIA followed by a NE-SW median FIA followed by an E-W rim FIA. If the core of BG 21 belongs to the early NW-SE FIA set of Ham (2001), it must predate all the other FIAs, including the NE-SW FIA set 1 of Bell et al. (1998). This early NW-SE FIA set has also been recorded by Newman (2001) and Kim (2000; 2001). Bell et al. (2004) suggest that very little porphyroblast growth occurred in the Chester Dome area at the time when the early NW-SE FIA set formed because deformation was partitioned around a mass of gneiss lying under the domes, and without deformation garnet growth did not occur. BG21 lies slightly to the north of the Chester Dome and, based on Figure 13 of Bell et al. (2004), would lie on the margin of the zone where deformation was more intensely developed during the formation of the early NW-SE FIA. This may explain why BG21 records the early NW-SE FIA but it is not present in any other samples from this study.

In accordance with the multi-FIA data, the single-FIA samples from this study were allocated to one of six FIA sets based on their trend (Table B-1):

Set 0 - NW-SE - 120° to 130°

Set 1- NE-SW - from 030° to 050°

Set 2 - E-W - from 065° to 105°

Set 3 – NNW-SSE - from 140° to 165°

Set 3.5 - N-S - from 170° to 015°

Set 4 - NE-SW - from 025° to 045°

The FIA set terminology follows that established by Bell et al. (2003). The data from the present study shows a population peak oriented N-S, close to the boundary between FIAs Set 3 and Set 4 as defined by Bell et al. (1998). Based on the sequences preserved in multi-FIA samples (e.g. BG60, BG62, BG15A) this population is recognised as a separate set called FIA Set 3.5 to fit with the established naming system.

The boundaries between FIA sets are somewhat arbitrary and given the natural variation in FIA orientation, and that each measurement is only accurate to +/- 8 degrees at best, some overlap between categories would be expected. In particular, FIA sets 3, 3.5 and

4 could be thought of as a continuum with three peaks rather than as three discrete FIA sets. An equal area rose diagram for each FIA set from this study is shown in Figure B-3.

4.2 Continuity between matrix and inclusion trails

Bell et al. (1998) evaluated whether inclusion trails were continuous with the matrix or not and used this to separate FIA sets with a similar orientation. This approach is based on the interpretation that matrix foliations would tend to truncate inclusion trails in earlier formed porphyroblasts, whereas, the youngest grown porphyroblasts should have inclusion trails continuous with the matrix foliation. However, in the area covered by this study, particularly towards the Green Mountains, overprinting foliations are not well developed. In many areas regional mapping suggests that the dominant foliation preserved in the matrix is S_2, the strong second generation 'Taconian' foliation, despite several deformation events that postdate D_2 and evidence for younger crenulation cleavages locally preserved (Ratcliffe, 1993, 1997; Ratcliffe & Armstrong, 1999). Unlike the Bell et al. (1998) study, several FIA with E-W and NNW-SSE trends observed in this study appear continuous with the matrix foliation at the thin-section scale (Table B-1). Spirals that are continuous with the matrix and preserve an E-W trending apparent axis of rotation have also been reported by Ratcliffe (1997). It is possible that in some samples, older matrix foliations are preserved due to regional scale deformation partitioning, with the area between the Green Mountain Massif and the Chester Dome being partially shielded from the effects of later deformation. Alternatively, Bell et al. (2004) suggest that around the Pelham Dome and the Pomfret Dome, where FIA sets 3 and 4 are less developed, the presence of earlier grown porphyroblasts may have increased the competency of rocks and therefore reduced the pervasiveness of deformation partitioning through the rock mass in later events. This may also apply to the present study area, particularly where the porphyroblasts tend to be quite large or densely concentrated, and explain why later foliations are less pervasively developed. It is also possible that the apparent continuity between inclusion trails and the matrix may be due to foliation “reactivation”, reuse of an older foliation in an a younger event. In the area of the West Dover and Jacksonville Quadrangles, Vermont, an $S_{4.5}$ foliation is supposedly very strongly developed, but it forms a composite foliation with the S_2 foliation (Ratcliffe & Armstrong, 1999). Consequently, garnet porphyroblasts that include the older foliation may still appear continuous with the matrix foliation.

Continuity with the matrix is not, therefore, considered an appropriate criterion for generally distinguishing between FIA sets in this study. However, an exception was made for FIA sets 1 and 4. FIA sets 1 and 4 have the same orientation but have different relative ages based on the multi-FIA data described above. As set 4 is the youngest FIA set present, one could expect all the samples in this set to be continuous with the matrix. The two samples with a NE-SW FIA truncated by the matrix were therefore allocated to FIA set 1 based on this criterion. It is accepted that some of the continuous spirals allocated to FIA set 4 may actually also preserve the older FIA but it is not possible to determine which, if any, samples fall in to this category. It is assumed that, if present, such samples would form a minority.

4.3 Taconic vs. Acadian FIA sets

As discussed in the introduction, garnet growth in southern Vermont and northwestern Massachusetts could have occurred in the Acadian or the Taconian or during both events. It is difficult to absolutely date garnet growth but FIA sets provide a relative chronology for garnet growth, and when combined with techniques such as radiometric dating of inclusions, can be used to infer absolute age.

Microstructural analysis of schists from the Chester Dome region of Vermont revealed that porphyroblast growth could be grouped into four sets based on FIA trend and core-rim relationships (Bell & Hickey, 1997; Bell et al., 1998). The same FIA relationships were preserved in Cambro-Ordovician lithologies as in the Siluro-Devonian rocks, suggesting that all the garnet growth was Acadian in age. Monazite dating of grains preserved in included foliations constrained the age of porphyroblast growth and led to the conclusion that episodic garnet growth occurred from some time before 425Ma to 340 Ma (Bell & Welch, 2002). Hames et al. (1991) presented Ar-Ar data that indicated that the Taconian thermal maximum was about 445 Ma and the Acadian thermal maximum was about 390 to 400 Ma. This is consistent with the ages of Taconic arc magmatism presented by Ratcliffe et al. (1998) and suggests that the bulk of garnet growth recorded by Bell and Welch (2002) was related to Acadian metamorphism, although garnet growth may have initiated in the Taconic. The oldest monazite dated by Bell and Welch (2002) was 432Ma, which could be considered late Taconic rather than Acadian, and Bell and Welch (2002) suggested that metamorphism in this area may have been effectively continuous from the Taconic through to the Acadian, rather that forming two discrete episodes. A similar prolonged metamorphic evolution was suggested by Hames et al. (1991) based on work from southwestern New England.

In the area of the present study, northward projection of the Taconic garnet isograd of Sutter et al. (1985) suggests Taconic garnet porphyroblasts should be present as well as the later, Acadian, garnet (Figure B-1). Sutter et al. (1985) also identified a Taconian staurolite isograd in north-western Massachusetts. This parallels the garnet isograd and if projected northwards should pass through the Rayponda-Sadawga Dome, meaning that samples collected to the west of the Rayponda-Sadawga Dome lie in an area that could contain both Taconic garnet and staurolite (Figure B-1). However, none of the samples collected in this study contain staurolite. The sample locations all lie below the Acadian staurolite isograd and either staurolite did not grow in this area during the Taconian metamorphic event or it was completely destroyed by the overprinting effects of the later Acadian metamorphism.

Two samples in the study area (BG104 and BG 105A), lie well west of the Acadian garnet isograd of Sutter et al. (1985) and, therefore, the garnet porphyroblasts they contain could potentially be pre-Acadian (Figure B-1). BG104 comes from a para-autocthonous sliver of the Hoosac formation just to the west of the area in northwest Massachusetts where the Taconian and Acadian isograds are inferred to intersect. BG105A comes from a highly aluminous unit in the Devils Den area on the eastern flank of the Green Mountains, close to Weston in Vermont. There is disagreement as to the age of this unit and whether it should be mapped as part of the Middle Proterozoic Mt Holly Complex or the Cambrian Cavendish Formation (Karabinos et al., 1999). If it is part of the Mt Holly Complex, it may have experienced both Grenvillian and Taconian metamorphism.

Two FIAs were identified for each of these samples: a core FIA at 145° and a rim FIA at 175°. These data introduce the possibility of two older FIA sets that have trends parallel to Sets 3 and 3.5 as defined above, but which are Taconian and pre-date **all** the

FIAs identified by Bell et al. (1998). It is also possible that only the cores of the garnets are Taconian. If so, the cores may belong to an expanded FIA set 0, rather than to FIA set 3, while the rims remain part of FIA set 3.5. Although the age of FIA set 0 is not known, FIAs with this orientation from the study by Ham (2001) are preserved in rocks of Silurian age (Bell et al., 2004). Consequently, it is probable that the FIAs from BG104 and BG105A predate FIA set 0. However, it is also possible that samples BG105A and BG104 record the same history of deformation and metamorphism as the rest of the study area and the isograds here are Acadian rather than Taconic.

If Taconian garnet is present in the field area east of the Green Mountains, there should be porphyroblasts that preserve Taconian FIA orientations (145° and 175°) in their cores and Acadian FIAs in their rims. Samples BG60 and BG62 both preserve a N-S FIA in their cores and NE-SW FIA in their rims, consistent with a progression from FIA set 3.5 to FIA set 4. However, it is also possible that the cores of these porphyroblasts preserve the Taconic N-S FIA rather than the Acadian N-S FIA as previously assumed. Armstrong et al. (1992) describe the leading edge of the Taconic accretionary wedge, sometimes referred to as the Ordovician cryptic suture or Cameron’s Line, as roughly coinciding with the line between dominantly Taconic and dominantly Acadian regional metamorphic effects. Both BG60 and BG62 are from the Hoosac formation and lie to the west of Cameron’s Line, as defined by Sutter et al. (1985). Six other single FIA samples from the Hoosac Formation in the west of the field area also contain garnet porphyroblasts with inclusion trails that are not continuous with the matrix and preserve FIAs close to the possible Taconian FIA orientations (BG48, BG53, BG54, BG55, BG57B and BG107A). These samples may contain “suspect” Taconic garnet porphyroblasts. However, there are currently no suitable criteria by which to definitively separate possible older NE-SW and N-S FIAs from the younger FIA set 3 and FIA set 3.5 samples. Only the dating of monazite grains that lie within the included foliation allowed the absolute age of individual FIA samples to be determined in previous studies (Bell & Welch, 2002). Unfortunately, monazite has not been identified, either as inclusions or as matrix grains, in the "suspect" samples from this study, possibly because these rocks have not reached high enough grade (Wing et al., 2003).

In summary, the absolute age of the FIA sets identified in this study is not known, but, based on work to the east (Bell et al., 1998; Bell & Welch, 2002) they could be older than 425Ma and range down to 360 Ma. Taconic garnet (~440Ma) may be present in the study area but it is not possible to distinguish it from later mineral growth on the basis of microstructural data alone.

4.4 Spatial distribution of FIAs and implications for metamorphism

The relative porphyroblast ages established using FIAs should make it possible to define the western limit of each phase of garnet growth and construct approximate garnet isograds for each FIA set. However, FIA sets 1 through 4 are found throughout the field area (Figure B-4) and the garnet isograd for all the phases of garnet growth appears to lie close to the mapped isograd (Figure B-1). It should be noted that the small number of samples in the oldest FIA sets in this study (FIA Set 0 – one sample; FIA Set 1 – three samples) limits the interpretation of the extent of the very earliest garnet growth. While it is possible that the very earliest core growth was not identified in some samples, this is unlikely given the large number of thin-sections cut.

The same FIA sets found in the present study are interpreted to be present around the Chester-Athens Dome to the east, the Pomfret Dome to the north east and the Pelham Dome to the south east (Bell et al., 1998; Kim, 2000; Ham, 2001; Kim, 2001; Bell et al., 2004). Yet, there is no pattern in the spatial distribution of the FIA data to indicate that garnet growth started in the east of the field area and moved westward to the current location of the garnet isograd. This is a surprising observation. Over the lengthy history of garnet growth preserved in these rocks, heat should have migrated through the crust and the garnet reaction front would be expected to follow this pathway, with the youngest period of garnet growth defining the isograd mapped in the field. Given the consistency between the FIA succession determined from this study and that determined from similar studies in adjacent areas it is not plausible that the succession is coincidental and the different FIA sets must represent a true chronology (Bell et al., 2004). It is possible that garnet growth did migrate laterally, at least to some extent, and that later shearing ‘mixed’ the isograds corresponding to successive garnet generations so that their discrimination is now extremely difficult. However, as discussed below, it appears that the controls on garnet growth were much more complex than a simple dependence on the migration of heat through the crust.

The progression of FIAs suggests that garnet growth across the area was episodic and spatially heterogeneous. No multi-FIA sample contains all FIA sets and adjacent samples from the same lithology do not necessarily preserve the same FIA sequence. The hypothesis of episodic garnet growth is supported by the compositional zoning anomalies in some samples, as discussed in Section C of this thesis, and by the truncational relationship between core and rim inclusion trails described in Section A of this thesis.

Changes in P-T can stop and start garnet growth but these processes act at a regional scale and could not produce the heterogeneity observed in the present study. Subtle variations in bulk rock composition can also control whether a garnet crystal grows in one location and not another. This could explain why garnet porphyroblasts in one location preserve a different FIA sequence than porphyroblasts in another location. For example, if one bulk composition effectively lowered the P-T range for garnet growth so that growth initiated earlier in that area, then those porphyroblasts would preserve older FIA information. However, in some cases, garnet growth appears to have stopped in one location (e.g. BG87) whilst continuing in adjacent areas (e.g. BG83, BG86, BG62) and then later resumed and preserved the same young FIA orientation as adjacent samples. This more complex switching on and off of garnet growth is difficult to rationalise in terms of compositional variation alone. Modelling of P-T pseudosections and the relationship between bulk composition and garnet growth is discussed in Section D of this thesis.

The heterogeneous distribution of FIA sets is suggests that P-T conditions and bulk composition were not the only limiting factors for the growth of garnet. The progress of garnet producing reactions could also depend on the availability of reactants, the ability of the phase to nucleate and/or the access of reactants to the nucleation site. Previous studies have shown that all of these factors can be linked to deformation (Bell & Rubenach, 1983; Bell et al., 1986; Bell & Hayward, 1991; Williams, 1994; Spiess & Bell, 1996). For example, it has been proposed that zones of progressive shortening, such as crenulation hinges, are favourable environments for porphyroblast nucleation and growth because the propensity for microfracturing provides access for fluids carrying the material needed for porphyroblast growth and the build-up of stored strain energy lowers the activation energy for nucleation (Bell & Hayward, 1991; Spiess & Bell, 1996; Bell et al., 2004). Dempster and Tanner (1997) have also highlighted the role of deformation in facilitating major element diffusion in white micas. In their study, the biotite isograd reaction is shown to preferentially take place in areas that are more strongly deformed because mica in these areas reacts more easily. Deformation may place a similar role in the present study, facilitating the breakdown of those phyllosilicates, such as muscovite and chlorite, that are involved in garnet producing reactions.

If, as suggested by Bell and Hayward (1991), the development of successive crenulations can essentially turn garnet growth on and off, then at a larger scale the repartitioning of deformation will control where garnet growth occurs (Bell et al, 2004). Deformation partitioning can operate at any scale and could certainly explain the heterogeneity in garnet growth observed across the field area. Repartitioning would inevitably occur through time as orogenesis proceeded and could produce the complex pattern of garnet growth turning on and off described above. During the earlier deformation events regional scale deformation partitioning around the Chester Dome gneiss, as proposed by Bell et al. (2004), would have been important in controlling where deformation was taking place but as orogenesis proceeded, and temperature increased, deformation would be more easily partitioned through the gneiss. Early regional scale deformation partitioning around the Chester Dome, as shown in Figure 13 of Bell et al. (2004), would explain why FIA set 0 is only present in one location, to the north of the Chester Dome, and why FIA set 1 is relatively rare, occurring in just three locations to the south of the Chester Dome.

5. Conclusions

1. Foliation inflection/intersection axes (FIAs) preserved in garnet porphyroblasts from southern Vermont and northwestern Massachusetts can be separated into six FIA sets. Based on the sequences preserved in multi-FIA samples these sets can be ordered chronologically. From oldest to youngest the FIA sets are:

   Set 0 - NW-SE - 120° to 130°

   Set 1- NE-SW - from 030° to 050°

   Set 2 - E-W - from 065° to 105°

   Set 3 - NNW-SSE - from 140° to 165°

   Set 3.5 - N-S - from 170° to 015°

   Set 4 - NE-SW - from 025° to 045°

2. Although the different FIA sets are interpreted to represent a progression through time, there is no pattern in their spatial distribution to indicate that garnet growth migrated westward with time, as all sets of FIAs are found throughout the area. This suggests that P-T conditions were not the only control on garnet growth.
3. Garnet growth was spatially heterogeneous, presumably due to variation in the distribution of deformation partitioning from FIA set to FIA set controlling the sites of garnet growth. Deformation partitioning appears to be a primary control on garnet growth in southern Vermont and northwestern Massachusetts.

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SECTION C

Chemical zoning anomalies in garnet porphyroblasts displaying multiple phases of growth: their formation and relationship to textural discontinuities

Table of Contents

Abstract

Garnet porphyroblasts from the Hoosac Formation in southern Vermont have distinct textural core and rim zones, the boundary of which is marked by a 50-100 µm wide zone exhibiting a spectacular increase in manganese and by variable changes in calcium and magnesium zoning patterns. Previous studies have attributed the manganese enrichment at the core-rim boundary to diffusion of manganese following garnet breakdown. Of the four samples studied in detail, three show clear evidence for dissolution around the margin of the core but one sample does not. The latter suggests that either manganese enrichment occurred without significant garnet breakdown or that garnet dissolution occurred parallel to crystal faces, maintaining a euhedral crystal form and leaving no textural evidence for the dissolution. In three samples a narrow zone depleted in calcium accompanies the manganese enrichment. This observation is inconsistent with diffusion as a mechanism for manganese enrichment. A solution-reprecipitation mechanism is favoured to explain the calcium depletion, accompanied by crystal scale metasomatism. This is consistent with oxygen isotope studies that suggest fluids infiltrated the rocks in this region at around the same time as the core-rim discontinuity formed. The infiltrating fluids may have introduced boron, explaining the relatively coarse-grained tourmaline preserved in the garnet porphyroblast rims and matrix of several samples.

1. Introduction

Schists from the Appalachian Orogen in Vermont and north-western Massachusetts have undergone multiple phases of deformation and garnet growth and commonly preserve spiral-inclusion trails with textural discontinuities (Rosenfeld, 1968; Bell et al., 1998). Detailed work using the microprobe has shown that schists from the Hoosac Formation in this region also preserve unusual zoning patterns and, in particular, an anomalous Mn-enriched zone at the textural core-rim boundary (Karabinos, 1984a, b). Manganese enrichment near garnet grain rims is generally believed to be characteristic of a resorption process (de Bethune et al., 1975; Hwang et al., 2003). Accordingly, previous studies have attributed the manganese-rich zone in the Hoosac garnets to diffusive modification of the manganese concentration, accompanying garnet dissolution between the core and rim growth (Karabinos, 1984a, b). However, the samples examined in the present study indicate that manganese enrichment occurred at relatively low temperatures (<550°C) and may be accompanied by a narrow zone depleted in calcium, inconsistent with diffusive alteration. The aim of this paper is to describe the different styles of zoning anomaly observed in four Hoosac garnets and, using these examples, consider the role of open versus closed system behaviour in developing the zoning anomalies and the relationship between zoning anomalies and the formation of textural discontinuities.

1.1 Manganese Zoning Anomalies

Several different theories have been put forward to explain chemical zoning “anomalies” or “reversals” where the rim of the garnet crystal (or the core-rim boundary in porphyroblasts that have experienced two phases of growth) shows enrichment in manganese. The most common explanation is that manganese enrichment occurs during garnet dissolution. Manganese liberated by the breakdown of garnet is unable to enter any other mineral phase present and remains in the garnet structure by diffusing inwards, modifying the pre-existing zoning profile and creating a reversal (de Bethune et al., 1975; Karabinos, 1984b). Most studies interpret garnet dissolution as occurring during retrogression but Thompson et al. (1977) suggest the dissolution may occur during a prograde reaction such as garnet, chlorite and muscovite breaking down to form staurolite and biotite.

The second option, in cases where the zoning anomaly appears to occur between two phases of garnet growth, is that garnet breakdown produces a manganese-enriched retrograde assemblage of minerals such as chlorite. A manganese-rich intermediate garnet rim then forms from this assemblage at a very early stage in the second episode of garnet growth in the rock (Robinson, 1991).

Not all porphyroblasts that show manganese reversals have clear textural evidence of garnet resorption. An explanation for manganese reversals without resorption was put forward by Banno and Chii (1978). Their model assumes that garnet is formed by the breakdown of zoned chlorite and that the material released by this process is increasingly manganese rich. This is reflected in the increasing manganese content of garnet rims. Yang and Rivers (2002) described similar manganese annuli in garnets from Labrador, Canada, and attributed their formation to the breakdown of epidote grains with manganese rich cores. Some authors have suggested kinetic mechanisms that may lead to rings of high yttrium or calcium content in garnets (Lanzirotti, 1995; Chernoff & Carlson, 1997, 1999). It is possible that similar processes can also produce manganese enrichment.

A fourth possible explanation for the increase in manganese content is that manganese has been introduced to the system. This could result from an influx of manganese rich fluids coming off an igneous intrusion or from the breakdown of garnet or other manganese rich minerals in nearby lithological units.

1.2 Textural Discontinuities

The inclusion trails within Hoosac garnets are not usually smoothly curving spirals but contain textural discontinuities that disrupt the spiral shape. The most obvious textural discontinuities are truncations, where an inner foliation is truncated by a younger foliation in the rim of the garnet, commonly at a high angle. The formation of textural discontinuities is discussed in the context of both the rotational and non-rotational model for spiral inclusion trail development in Section A of this thesis. In the non-rotational model, discontinuities represent a pause in garnet growth, during which time a new foliation develops along the margins of the porphyroblast, truncating the inclusion trails (Bell & Hayward, 1991). During a subsequent phase of growth the new foliation is included in the garnet and the discontinuity is preserved. Interpretations based on the rotational model suggest that the discontinuities usually form when there is a pause in growth, with or without a pause in rotation (Johnson, 1993; Passchier & Trouw, 1998). The greater the amount of rotation and/or foliation development without further garnet growth, the more abrupt the truncation. It is also possible that garnet growth does not cease completely but only slows relative to the rate of rotation and/or foliation development or that garnet growth stops only on some faces. Under both the rotational and non-rotational models the formation of a textural discontinuity is not necessarily accompanied by garnet dissolution but is always accompanied by a pause or a slowing in garnet growth (Bell & Hayward, 1991; Johnson, 1993). In some cases it has also been suggested that discontinuities develop in the matrix prior to being overgrown by garnet. In these cases the formation of the discontinuities is completely unrelated to garnet growth and there should not be any change in chemical composition and/or inclusion mineralogy coincident with textural discontinuities.

2. Sample Descriptions

Four samples from the Hoosac Formation with distinct microstructural core and rim zones were selected and analysed with the aim of relating the major element zoning patterns to the preserved deformation history (Figure C-1). Twelve thin-sections were prepared for each sample, in addition to the polished thin-sections required for microprobe work. For each sample the Foliation Intersection/Inflection Axis (FIA) was determined for the core and rim using the technique developed by Bell et al. (1995). The inclusion trail relationships are shown for a garnet porphyroblast from each sample in Figures C-2, C-3, C-5, C-6 and C-7.

2.1 BG62

Sample BG62 is a garnet, chlorite, muscovite, quartz schist with accessory ilmenite and tourmaline. Some of the garnet porphyroblasts, up to 3.5 mm in diameter, are euhedral but many are quite cracked and fragmented. They contain inclusions of quartz, plagioclase, rutile, chloritoid and ilmenite. The inclusion trails are well defined and smoothly curving in the cores but truncated in the rims and defined by sparse quartz and ilmenite. Figure C-2 shows a porphyroblast with a well-developed core but which does not preserve much of the rim growth visible in other porphyroblasts from this sample. The core FIA trends at 005° (Set 3.5) and the rim FIA trends at 045° (Set 4). Chlorite is present as clots around the margins of garnet porphyroblasts. The matrix also contains large zoned tourmaline grains, up to 3 mm in length, and saussuritized plagioclase grains.

2.2 BG87

Sample BG87 is a chlorite-garnet-muscovite-plagioclase-quartz schist with accessory ilmenite, tourmaline, biotite and epidote. The garnet porphyroblasts are large (up to 25 mm) with distinct textural core and rim zones (Figure C-3, C-4 and C-5). The cores are a darker pink than the rims. Typical inclusions in the core are quartz, chloritoid, chlorite, muscovite, ilmenite and epidote. The largest porphyroblasts contain abundant rutile inclusions in the inner most part of the core, but these are rare or absent from the rest of the core. The core inclusions form sigmoidal trails with FIA at 030° (Set 1). The rims of the porphyroblasts also preserve inclusions. These are typically quartz, plagioclase, ilmenite, muscovite, tourmaline and sparse chlorite. The inclusion trails in the rim are defined by ilmenite and are sigmoidal, appearing to wrap around the garnet cores (Figure C-3). Rim trails are continuous with the matrix and have a FIA of 050° (Set 4). The matrix is dominated by muscovite, with some large grains up to 5 mm in size cutting across the foliation. Large plagioclase grains in the matrix appear to be overgrown by muscovite in some places and other grains show saussuritization. Chlorite in the matrix locally forms clots, suggesting a retrogressive origin, but in other places appears to follow the foliation and may be primary. Biotite is rare but where present is always associated with chlorite. Accessory ilmenite, toumaline and apatite are also present in the matrix. Tourmaline grains in the matrix can be up to 3 mm in length and are commonly zoned. Chloritoid is absent from the garnet rims and the matrix.

2.3 BG107A

Garnet porphyroblasts in sample BG107A are plentiful and up to 10 mm in diameter. The porphyroblasts are anhedral and are commonly cracked and fragmented. The cores of the porphyroblasts are rich in inclusions, with quartz, rutile and ilmenite defining smooth spiral trails (Figure C-6). Plagioclase, chlorite and apatite are also present as inclusions. The FIA defined by these inclusions trends at 140° (Set 3). The rims of the porphyroblasts generally have fewer inclusions, with slightly larger ilmenite grains tending to form a ring around the garnet core. The matrix contains chlorite and biotite, both parallel to and crosscutting the foliation. These two minerals are commonly intergrown and generally surround garnet porphyroblasts. There is also abundant muscovite and large plagioclase grains, some of which show saussuritisation.

2.4 BG108

Sample BG108 is chloritoid-chlorite-garnet-muscovite-quartz-plagioclase schist with accessory tourmaline, ilmenite and apatite. The matrix is crenulated and quartz rich bands are interlayered with chloritoid-white mica rich bands. Spectacular crenulation hinges, rich in chloritoid, are preserved locally. Chlorite is present but tends to form clots rather than aligning with the foliation. Garnet porphyroblasts are up to 10 mm in diameter, with the larger ones tending to be idioblastic and hexagonal in cross-section. Smaller porphyroblasts appear cracked and fragmented with embayed edges. Some have clots of chlorite around them and alteration to iddingsite occurs locally along the cracks. The cores of the porphyroblasts are rich in inclusions, with quartz, plagioclase, chloritoid, chlorite, apatite, rutile and ilmenite defining smooth spiral shaped inclusion trails with a core FIA trending at 090° (Set 2). The rims of the porphyroblasts have fewer inclusions, with ilmenite inclusions tending to form a ring around the garnet core

(Figure C-7). The rim trails are not continuous with the matrix foliation and the rim FIA trends at 175° (Set 3.5). Quartz, plagioclase, white mica, chlorite, chloritoid, tourmaline, ilmenite and apatite are present as inclusions in the rim and in the matrix but rutile is not.

3. Compositional zoning

Compositional maps were obtained for garnet porphyroblasts from each sample using the electron microprobe facilities at the Advanced Analytical Centre (AAC), James Cook University. Samples BG62, BG87 and BG107A were analysed using energy dispersive spectrometry (EDS) on the JEOL 8200 Superprobe. The porphyroblast in sample BG62 was mapped as a 500 x 400 pixel image and the porphyroblasts in samples BG87 and BG107A were mapped as 500 x 500 pixel images. Sample BG108 and the enlarged area of sample BG87 were analysed using the JEOL-840A microprobe. Ca, Mg and Mn were analysed using wavelength dispersive spectrometers (WDS) and Fe using the EDS detector. Porphyroblasts were mapped as 512 x 512 pixel images. In each case step size was determined according to the size of the area being mapped. The results are shown in Figures C-2, C-3, C-4, C-5, C-6 and C-7. Point analyses of garnet composition were made using the JEOL-840A. Average values of the garnet compositions obtained are given in Table C-1 and the full point analysis data are given in Appendix 5.

3.1 BG62

In sample BG62 (Figure C-2), Mn decreases outward from the core to the core-rim boundary. This boundary is marked by a distinct Mn high that is roughly hexagonal and similar to the inner crystal shape, but is embayed in places along cracks and inclusions.

Beyond this boundary Mn drops to zero at the garnet rim. Ca is higher in the core of the porphyroblast, decreasing towards the core-rim boundary. This boundary is marked by a distinct step up in Ca. Ca is relatively high in the inner part of the rim, which is richer in inclusions, and decreases towards the outer rim. Mg is uniformly low in the core of the porphyroblast and increases towards the core-rim boundary. At this boundary there is a distinct step down in Mg. Mg increases across the rim. Fe increases outward from the core. There is a step down at the core-rim boundary, beyond which Fe increases.

3.2 BG87

In sample BG87 (Figures C-3, C-4 and C-5), Mn decreases moving outwards from the core until reaching the core-rim boundary. This boundary is marked by a distinct Mn high that appears to follow the crystal faces. Beyond this boundary, Mn again decreases outward. Ca is patchy in the core of the porphyroblast, increasing towards the core-rim boundary. This boundary is marked by a sharp Ca low, which mirrors the Mn high. Ca is relatively high in the inner part of the rim, which is richer in inclusions, and decreases towards the outer rim. Mg is high in the core of the porphyroblast and decreases towards the core-rim boundary before increasing again towards the rim. Unlike Ca and Mn, there is no sharp change in Mg content at the core-rim boundary, but rather a broad area of relatively low Mg content that generally matches the inner rim zone marked by higher Ca and Mn. Fe is low in the core of the porphyroblast and increases in the outer rim, matching the decrease in Ca. Figure C-4 shows an enlargement of the core-rim boundary in the bottom right corner of the porphyroblast in Figure C-3. The higher resolution compositional mapping in this area shows that the Mn high and the Ca low at the core rim boundary are matched by a slight increase in both Mg and Fe.

3.3 BG107A

In sample BG107A (Figure C-6) the zoning is very patchy. Mn is highest in several patches close to the centre of the porphyroblast and these areas appear to represent the original garnet core. The upper left hand part of the porphyroblast also appears to be unaltered and shows a gradual decrease in Mn moving outward from the core along the spiral arm before reaching an irregular zone of enriched manganese. Surrounding the areas of relatively high Mn, and beyond the irregular enriched zone, are patches of very low Mn. The Ca zoning has a very similar pattern to Mn and is higher in the "core" patches and decreases outward. The Ca zoning around the core areas is sharper than the Mn zoning and shows several steps down to low Ca areas with the same distribution as the low Mn areas. The irregular Mn high in the porphyroblast rim appears to match a very narrow band of low Ca. Mg is low in the "core" patches and increases outwards. The surrounding areas are comparatively high in Mg. Fe is also low in the "core" patches and increases slightly outward. The surrounding areas are significantly higher in Fe.

3.4 BG108

In sample BG108 (Figure C-7), the Mn content decreases outward from the core to the core-rim boundary, which is marked by a distinct Mn high. The boundary is wavy and irregular in character. Beyond this boundary Mn tends to decrease toward the edge of the porphyroblast with patchy zones ringed by Mn highs. Ca is higher in the core of the porphyroblast with a distinct step down at the core-rim boundary. Ca does not show the patchy distribution in the rim that is evident in the Mn and Mg maps. However, close examination of the patchy area in the bottom left corner of the porphyroblast suggests that a narrow zone of depleted Ca matches the ring of enriched Mn in this area. Mg is low in the core of the porphyroblast but higher in the rim with a distinct step up at the core-rim boundary. The rim contains patchy areas where Mg is low and these match the areas ringed by Mn highs. Fe is slightly lower in the core than in the rim, stepping up at the core-rim boundary.

4. Interpretation and Discussion

Karabinos (1984a; 1984b) studied similar garnet porphyroblasts from the Jamaica area of the Vermont Appalachians and concluded that the zoning anomalies present in his samples reflect “limited diffusive alteration of garnet during retrogression”. According to his model, garnet porphyroblasts were partially resorbed during a relatively rapid change in metamorphic conditions. The mineral assemblage tried to equilibrate by diffusive exchange and reaction with an outer garnet shell of finite thickness, creating a rim relatively enriched in manganese. There are several problems in applying Karabinos’ model to the garnets described in this study and these problems will be discussed in detail in the following sections.

4.1 Garnet dissolution and manganese enrichment

Samples BG62 and BG108, like the samples described by Karabinos, show areas where garnet has broken down to form chlorite and the manganese-rich band at the core-rim boundary is embayed and irregular, consistent with a dissolved margin (Figures C-2 and C-7). As there is no staurolite in these samples the prograde reaction suggested by Thompson et al. (1977):

garnet + chlorite + muscovite → staurolite + biotite

was not significant and all garnet dissolution appears to result from retrogressive reactions. Sample BG107A contains evidence of more extensive garnet resorption and compositional modification. The compositional zoning maps show an irregular manganese-rich band in the rim of the porphyroblast similar to that in sample BG108 but the interior of the garnet has also been significantly altered along cracks and inclusions. This suggests that fractures in the garnet porphyroblast have at some stage allowed the porphyroblast interior to react with matrix phases in a manner similar to that described by Whitney (1996) and this resulted in more extensive dissolution and re-precipitation of garnet.

In contrast to the other samples, sample BG87 does not show any evidence of significant garnet resorption between the growth of the cores and the rims. The cores of the porphyroblasts are clearly visible in transmitted light microscopy, appearing slightly pinker than the porphyroblast rims, and show mostly pristine crystal faces with no evidence for significant dissolution. Chlorite is present within the porphyroblasts but appears to be primary, preserved as inclusions, rather than forming the retrogressive clots described by Karabinos (1984b). The manganese-rich band at the core-rim boundary appears to parallel the faces of the idioblastic garnet core.

Calculations to estimate the amount of garnet dissolution required to produce the observed manganese anomaly in this sample, and in sample BG62, suggest that the amount of garnet dissolved would be small, relative to the size of the porphyroblasts (Appendix 6). For sample BG87 dissolution of a garnet shell 0.32 mm wide would be sufficient to provide the amount of manganese observed in the anomaly peak. Given the small amount of resorption required it is possible that the dissolution simply occurred parallel to crystal faces and did not produce the embayed textures considered typical of a dissolved margin. Figure 18 from Pyle and Spear (1999) shows a garnet where resorption paralleled the crystal face over a distance of 0.5 mm.

4.2 Manganese enrichment without garnet dissolution

Banno and Chii (1978) put forward a model that specifically attempted to explain garnet rim manganese enrichment without garnet dissolution while maintaining a closed system. The scenario described, where zoned chlorite grains break down to form garnet, requires an unusual situation where there is not sufficient time for chlorite to homogenise before it starts to breakdown. As acknowledged by these authors, such a steep dT/dt is probably more appropriate to the conditions surrounding a thermal aureole than to regional metamorphism. In the rocks examined in the present study there is no evidence for zoned chlorite or for a particularly rapid change in temperature. While the Banno and Chii (1978) model cannot be dismissed, it does not appear to be appropriate to the metamorphic conditions of this area.

Other authors have suggested kinetic mechanisms may lead to rings of high yttrium or calcium in garnets (Lanzirotti, 1995; Chernoff & Carlson, 1997, 1999). Lanzirotti (1995) suggested that if the supply of yttrium to the growing garnet face were diffusion limited in the matrix, then a decrease in the garnet growth rate would result in an increase in the yttrium content of the garnet. However, Spear and Daniel (2001) suggested that manganese diffusion in the matrix, like iron and magnesium diffusion, is faster than calcium diffusion. If this is so, any enrichment in manganese due to slower garnet growth should be accompanied by some enrichment in iron and magnesium and considerable enrichment in calcium. Such enrichment is not observed for the samples from the present study, however, and for samples BG87, BG107A and BG108 the manganese high is actually accompanied by a calcium low. Diffusion limited garnet growth does not, therefore, seem a likely explanation for the manganese enrichment in this case.

Chernoff and Carlson (1997; 1999) postulated that depleted zones develop around growing garnets where diffusion of elements such as calcium and yttrium through the matrix is not sufficient to keep up with garnet growth. When these zones overlap, the depletion is sufficient to cause calcium and yttrium bearing accessory phases in the matrix to become unstable and breakdown, releasing additional calcium and yttrium that is then taken up by garnet. A similar mechanism could be postulated to explain manganese-zoning spikes but, unlike calcium, very little manganese is held in accessory matrix phases in these rocks. Also, as stated above, manganese diffusion is believed to be more efficient that calcium diffusion and depleted manganese zones would not form as readily as calcium and yttrium depleted zones.

Yang and Rivers (2002) suggested that the high manganese annuli in samples from Labrador were related to the sporadic local breakdown of piemontite (Mn-rich epidote). It is possible that the manganese in sample BG87 was released by breakdown of a similar accessory manganese-bearing mineral rather than from garnet dissolution. However, manganese is preferentially taken up by garnet and so it is unlikely that dissolution of an accessory phase would release a sufficiently large total amount of manganese to produce the high observed at the core-rim boundary. For example, chloritoid is the most abundant mineral, other than garnet, to contain manganese but the chloritoid grains preserved in the core of sample BG87 contain only 0.35wt% Mn. Ilmenite has been suggested as another possible source of manganese but ilmenite grains are as large and abundant in the garnet rims as they are in the cores, ruling out significant breakdown of this mineral (Figure C-8).

The only other explanation for the manganese-enrichment without garnet dissolution is that the system was not closed and that manganese, and potentially other elements, were added to the system. This may have been associated with an influx of fluid, as will be discussed further below, or alternatively, it may have been controlled by deformation. Bell and Hayward (1991) argue that all garnet growth is micrometasomatic and that the components needed for garnet growth may be transported to the growth site by diffusion along actively shearing phyllosillicates. The pattern of deformation partitioning controls where dissolution and deposition take place. If shearing is concentrated more strongly in one lithology dissolution will be enhanced in that location and the material could be carried along cleavage seams to locations where dissolution is limited. If material was primarily being transported diffusively along cleavage seams manganese could be transported from the sites of mineral breakdown to the sites of garnet growth without the bulk rock "seeing" the material (Bell & Cuff, 1989). In sample BG87, as discussed above, there is no evidence for significant manganese-rich mineral breakdown in the rock itself. The manganese may, however, have come from minerals breaking down in a nearby rock volume and been transported along cleavage seams to the garnets in sample BG87. The manganese would only be released from the cleavage seams where there is microfracturing and this would tend to occur in locations where a porphyroblast pulls away from matrix in strain shadow regions. Manganese is preferentially partitioned into garnet so any manganese released along these microfractures on porphyroblast boundaries will be taken up by the garnet rather than any other mineral. The relationship between zoning anomalies and deformation will be discussed further below.

4.3 Regional evidence for fluid infiltration

Fluid infiltration through the garnet schists in Eastern Vermont in the Acadian has been studied by Young and Rumble (1993) and Chamberlain and Conrad (1991) who conducted oxygen isotope studies on samples from the Gassett Schist member of the Hoosac formation. Young and Rumble (1993) used a sample from the Chester Dome that preserved textural unconformities similar to those described by Karabinos (1984a; 1984b), whereas Chamberlain and Conrad (1991) used a sample from the Townshend Dam at the northern end of the Athens Dome. Both studies showed that the garnet porphyroblast cores had higher $\delta^{18}O$ values than the garnet porphyroblast rims and attributed this zoning to infiltration by a fluid depleted in $\delta^{18}O$ relative to the schist. This appears to have occurred at approximately the same time as the textural discontinuity formed in the garnet porphyroblasts.

Chamberlain and Conrad (1993) published a more detailed oxygen isotope study looking at garnets from the Pinney Hollow Formation, Townshend Dam. Their study showed that the Pinney Hollow garnet porphyroblast cores had lower $\delta^{18}O$ values than the garnet porphyroblast rims and attributed this zoning to infiltration by a fluid enriched in $\delta^{18}O$ relative to the schist garnets. Chamberlain and Conrad (1993) conclude that in this case the infiltrating fluid was derived from the dehydration of nearby pelites, mainly from the breakdown of chlorite to form garnet, and that fluid flowed downwards into structurally deeper, higher-grade rocks such as the Hoosac

Formation. Such a metamorphic origin for the fluid is consistent with the fluid inclusion work of Irwin (1994).

In contrast to the study presented by Chamberlain and Conrad (1993) another study of oxygen isotope zoning in Pinney Hollow garnets from the Townsend Dam by Kohn and Valley (1994) concluded that the zonation observed is inconsistent with pervasive fluid flow across strike. Kohn and Valley (1994) suggest that either the rocks essentially behaved as a closed system or the isotope interaction between adjacent rocks was largely accommodated through diffusion in an interconnected grain boundary fluid.

In conclusion, while there is evidence that these rocks interacted with fluids at the time that the garnet porphyroblasts were growing, there is debate as to the extent of the fluid-rock interaction, the scale of fluid circulation and the source of the fluid (Ferry, 1994; Kohn & Valley, 1994). It should be emphasised that none of the studies suggest that the infiltrating fluid carried manganese or that fluid infiltration significantly altered the major element chemistry of the rocks in this area.

4.4 Open vs. closed system metamorphism: textural evidence

Some mineralogical changes observed in the samples support the suggestion that new material entered the system after garnet core growth. In samples BG62, BG87, and BG108, abundant large tourmaline grains are present in the matrix and tourmaline inclusions are preserved in the garnet rims of samples BG87 and BG108 but not in the garnet cores (Figure C-8). The growth of tourmaline supports the suggestion that the bulk composition changed between core and rim growth. Other mineralogical changes between the core and rim of the garnet suggest changes in pressure and temperature conditions, and changes in the mineral reactions taking place as a result. For example, chloritoid is present in the core of BG87 and BG62 but absent from the rim and matrix (Figure C-8). Karabinos (1985) suggested that chloritoid is part of an important garnet forming reaction in the chlorite-chloritoid schists of the Hoosac formation in the Jamaica area:

$$\text{qtz} + \text{ctd} + \text{chl} \rightarrow \text{gt} + H_2O$$

The absence of chloritoid from the garnet rims and matrix of sample BG87, coupled with the decrease in the number of chlorite inclusions between the garnet core and rim, suggests this reaction took place in sample BG87 and ultimately removed all the chloritoid from the rock. Rutile is another mineral that is present in the core of the garnets but not in the rim or matrix. The absence of rutile in the rims in other studies of Hoosac garnets has been attributed to a decompression reaction where rutile was consumed and ilmenite produced (Karabinos, 1985; Vance & Holland, 1993). This reaction probably also occurred in samples from the present study. In particular, in samples BG108 and BG107A, ilmenite grains appear larger and coarser on the rim side of the core-rim boundary, consistent with increased ilmenite growth accompanying rutile breakdown. Section D of this thesis will further address the question of open vs. closed system metamorphism, using the thermodynamic modelling software THERMOCALC.

4.5 Intra-crystalline diffusion in garnet

A problem with the model of diffusive alteration during retrogression, as acknowledged by Karabinos (1984b), is that the rocks are chloritoid-bearing, with no evidence that the chloritoid has broken down to staurolite. This suggests that these rocks probably did not reach temperatures above about 550°C (Karabinos, 1984b; Barker, 1998). P-T work by Ratcliffe and Armstrong (1999) on adjacent samples suggests peak metamorphic conditions in this area of 7.5 kbar and 530 °C. At these temperatures, intra-crystalline diffusion of Fe, Mg, Mn, and particularly Ca, in garnet is not very efficient. The length scale of diffusion, *h*, depends upon the diffusion coefficient, *D*, and the time scale, *t*, according to the relationship $h = (Dt)^{0.5}$ (Spear, 1993). Calculations based on the experimental values for tracer diffusion published by Chakraborty & Ganguly (1992) give a diffusion coefficient for manganese of $2.48\times10^{-23}\ m^2s^{-1}$ at 530 °C (Appendix 6). This means that at 530°C it takes 12.8 million years for manganese to diffuse 0.1 mm, the width of the manganese anomaly in sample BG87. However, most of the diffusion probably occurred at temperatures lower than the peak metamorphic conditions and therefore would have been even slower. Karabinos (1984b) suggested that grain boundary diffusion along inclusion boundaries may enhance diffusion. However, this could only be effective if all the inclusions were connected, yielding a permeability network. Similar “defect-mediated” resorption processes have recently been described by Hwang et al. (2003). Samples BG62 and BG107A show evidence for greater alteration along cracks and inclusions and this may be related to enhanced diffusion along grain boundaries in these areas (Figures C-2 and C-6).

Robinson (1991) attempted to explain the features described by Karabinos (1984a; 1984b) without invoking diffusion. He suggested that when the garnet broke down a manganese-enriched retrograde assemblage of minerals such as chlorite was produced and the manganese-rich intermediate garnet rim then grew by prograde growth from this assemblage. Close analysis of the garnets from this study, however, shows that the Mn-high lies inward of the textural discontinuity that marks the boundary between core growth and rim growth and is not related to the main prograde rim growth (Figure C-4).

4.6 Manganese enrichment accompanied by calcium depletion

Samples BG87, BG107A and BG108 all show evidence that a narrow calcium low mirrors the manganese enrichment. Sample BG62 has such low calcium values approaching the core-rim boundary that a similar narrow calcium low in that porphyroblast could not be easily detected. Depletion in calcium accompanying enrichment in manganese cannot be explained by diffusive exchange. When manganese enters the garnet lattice by diffusion it would be expected to displace mostly iron and magnesium ions rather than calcium ions (de Bethune et al., 1975). The garnet profile published by Karabinos (1984b) shows a calcium low similar to the samples from the present study but this feature is not mentioned in his discussion. In all the samples from this study the manganese high is broader than the calcium low, suggesting manganese diffused out of this thin shell to create a wider zone of enrichment and that the calcium low on the compositional map defines the width of the original enrichment.

Hames and Menard (1993) proposed that manganese rim enrichment in dissolved garnets from central Vermont and north-western Connecticut was related to crystal-scale metasomatism in addition to diffusion. Thermobarometry from these rocks suggested that the dissolution was also taking place at temperatures of around 550 °C and intra-crystalline diffusion could not adequately explain the observed compositional change. Hames and Menard (1993) suggested that reaction with a metamorphic fluid was also involved. According to this hypothesis garnet with disequilibrium compositions was dissolved and garnet with a composition in equilibrium with the metamorphic fluid and the evolving matrix assemblage was reprecipitated. Hames and Menard (1993) reported than the manganese, magnesium and iron were enriched in the rims of their samples but calcium was depleted. The decrease in calcium was attributed to open system behaviour and metasomatic loss of calcium from the rock. A similar fluid interaction could explain the manganese enrichment and the accompanying calcium depletion observed in samples from this study. As discussed above, there is regional evidence for fluid infiltration at about the time the zoning anomalies formed. However, as discussed in Section D of this thesis, THERMOCALC modelling suggests the bulk rock composition has not changed significantly so any calcium lost from the garnet was probably taken up by some other mineral phase rather than being lost from the system completely.

4.7 The relationship between zoning anomalies and deformation

As discussed in the introductory section, textural discontinuities are important indicators of a change in deformation conditions during garnet growth. In samples BG62 and BG87, manganese enrichment and other zoning changes take place at a distinct core-rim boundary, which is also marked by textural changes such as the size and abundance of inclusions and truncations between the inner and outer inclusion trails. However, Figure C-6 shows that in sample BG107A the manganese enrichment does not coincide with the ring of larger ilmenite inclusions that marks the textural discontinuity in porphyroblasts from this sample, and it appears that the manganese enrichment post-dates the formation of this discontinuity. Other zoning changes in Figure C-6 cut directly across the inclusion trails in the inner part of the porphyroblast. Sample BG108 (Figure C-7) shows manganese enrichment around the margin of the textural core-rim boundary but there are also other patchy areas of manganese enrichment in the porphyroblast rim. Inclusion trails in the rim appear to be continuous across the areas of patchy compositional zoning. The continuity of the inclusion trails across patchy zoning in both samples BG107A and BG108 suggests that, if the manganese enrichment is related to a period of garnet dissolution and reprecipitation, either there was no active foliation development between garnet dissolution and regrowth, or the existing foliation was protected from new crenulation cleavage development by the strain shadow produced by the remaining garnet. If the first option is correct, then it implies that the formation of the zoning anomalies was not directly associated with a deformation event.

4.8 Timing the manganese enrichment

Rosenfeld (1968) and Karabinos (1984b) proposed that the cores of these garnets formed during the Ordovician Taconian Orogeny and the rims during the Devonian Acadian Orogeny. It is possible, however, that both growth stages are Acadian (Karabinos, 1984b). The period of manganese enrichment occurred either at the very end of the first growth phase or after the first phase of growth ended. It may, therefore, be either Taconic or Acadian in age. An attempt has been made to date the relative age of porphyroblast growth phases in southern Vermont and northwestern Massachusetts using FIAs (Bell et al., 1998) and monazite crystals included in garnet porphyroblasts (Bell & Welch, 2002). Based on the relationship between the zoning anomalies and the microstructure discussed above the enrichment must have occurred after the development of all the inclusion trails preserved in samples BG107A and BG108. Samples BG62 and BG87 provide further constraints because in those samples the enrichment must have occurred between the time the core grew and the time the rim grew. Based on FIA succession data (Section B of this thesis), the core of sample BG62 is contemporaneous with the rim trails in sample BG108 and younger than the core of sample BG87 and sample BG107A. The rim of sample BG62 is contemporaneous with the rim of sample BG87. Taken together this data indicates that the manganese enrichment occurred between FIA set 3.5 and FIA set 4. Combined with the monazite dating work of Bell and Welch (2002), these results suggest that the manganese enrichment occurred at approximately 360-380 Ma (late Acadian). However, as discussed in Section B of this thesis, unless monazite is found and dated in these samples the possibility remains that the FIA preserved in the core of sample BG62 belongs to a Taconic FIA set with the same orientation as FIA set 3.5.

5. Conclusions

1. All the samples of Hoosac Schist from this study record a zone of manganese enrichment at the core-rim boundary but the character of the compositional zoning anomaly is quite different in each sample. Samples BG62, BG107A and BG108 show clear evidence for dissolution around the margin of the core but sample BG87 does not. This suggests that either garnet dissolution occurred parallel to crystal faces, maintaining a euhedral crystal form and leaving no textural evidence for the dissolution, or manganese enrichment occurred without significant garnet breakdown for one sample and manganese was introduced from outside the system. The possibility of euhedral garnet dissolution is significant for P-T studies, where it is essential to identify which minerals are in equilibrium, and reinforces the importance of collecting compositional zoning maps for garnets used for geothermobarometry.
2. In samples BG62 and BG87 the manganese enrichment coincides with a textural discontinuity but in samples BG107A and BG108 the enrichment does not appear to be related to an episode of deformation.
3. Previous studies have attributed manganese enrichment to diffusive alteration during retrogression. However, diffusive alteration of garnet would not be very efficient at metamorphic temperatures of around 530ºC because the rate of intra-crystalline

manganese diffusion in garnet is very slow. Also, the depletion in calcium accompanying enrichment in manganese cannot be explained by diffusive exchange. To explain the observed anomalies a solution-reprecipitation mechanism is favoured, accompanied by metasomatism at the crystal scale.

4. The manganese enrichment appears to have occurred between the FIA set 3.5 and FIA set 4. Based on the monazite dating of Bell and Welch (2002) this is late Acadian (~360-380Ma).

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SECTION D

Pressure and temperature conditions during garnet growth in southeastern Vermont

Table of Contents

Abstract

P-T pseudosections, constructed using THERMOCALC from major element compositions for seven samples of pelitic garnet schist from the Hoosac formation of southeastern Vermont, predict mineral assemblages in good agreement with the observed mineralogy. They also successfully model the garnet core compositions measured in six out of the seven samples. The three garnet compositional isopleths intersect at a point, allowing the P-T conditions at the time of garnet core growth to be estimated at between 4.4 kbar and 7.7 kbar and 500 °C and 540 °C. These values are lower than estimates of peak metamorphic P-T previously established from the equilibrium between garnet and matrix minerals, suggesting that there was a general trend of increasing pressure and temperature during garnet growth in southeastern Vermont. Although, garnet compositional zoning is generally consistent with growth during heating and compression several samples have zoning patterns suggesting a more complex history with some periods of cooling and/or decompression. In some samples, this cooling and/or decompression was accompanied by garnet dissolution. Foliation Intersection/Inflection Axes in porphyroblasts (FIA) are used to provide relative ages for the garnet growth from sample to sample. However, there does not appear to be a clear relationship between the P-T data and the FIA data in this study, suggesting that the preservation of different FIAs is not simply a function of P-T conditions and that P-T conditions are not the only control on garnet growth. In samples that appear to be overstepped, deformation may have played a crucial role in garnet nucleation and growth, and these samples indicate a progressive increase in pressure through the different phases of orogenesis.

1. Introduction

Understanding the processes of orogenesis requires a combined approach of metamorphic and structural studies. Links occur between all the processes involved in deformation and metamorphism, and to truly understand the changes in the conditions of metamorphism across an orogen, the history of temperature and pressure changes must be related to the deformation history that accompanies these changes. As discussed in Section A of this thesis, six different FIA sets have been identified in garnet porphyroblasts from southeastern Vermont, reflecting different episodes of garnet growth. This study aims to combine the FIA data with geochemical modelling and relate different episodes of garnet growth to the pressure-temperature conditions at the time they formed.

1.1 Previous P-T path work in the New England Appalachians

The majority of P-T path work done in the New England Appalachians focuses on the Acadian orogeny and the differences in the P-T-t evolution of the different New England tectonic belts at this time (Armstrong et al., 1992; Spear et al., 2002). The present study area lies in the eastern Vermont belt, which is characterized by dominantly clockwise P-T-t paths, while the Merrimack belt is characterized by dominantly counter-clockwise paths. The intervening Bronson Hill belt has more complex P-T-t paths (Spear et al., 2002). The clockwise paths recorded in southeastern Vermont and adjacent Massachusetts suggest that Acadian metamorphism in this area occurred purely as a result of tectonic/sedimentary overthickening followed by thermal relaxation and advective heating during rapid unroofing, with virtually no contribution from magmatic heating (Armstrong et al., 1992). In western New England, the Acadian metamorphism overprinted an older Taconian metamorphism that is also thought to have followed a clockwise P-T-t path and involved overthickened crust, thermal relaxation, uplift, erosion and advective heating (Armstrong et al., 1992). Available age data suggest that Acadian metamorphism occurred 30-50 Ma after the attainment of Taconian peak metamorphic conditions and that rocks in the zone of overprinting were probably still at temperatures well above an equilibrium geothermal gradient at the time of the second metamorphism (Armstrong et al., 1992). P-T data based on various different geothermobarometers suggests that peak metamorphic conditions in the garnet zone of south-eastern Vermont ranged from approximately 6.5 kbars and 475°C to 8.5 kbars and 590°C (Laird & Albee, 1981; Kohn & Spear, 1990; Ratcliffe et al., 1992; Ratcliffe & Armstrong, 1999).

1.2 Foliation Intersection/Inflection Axes (FIAs)

The relative time aspect for P-T-t paths is based on identifying mineral assemblages of sequential age to determine the pressures and temperatures at different times. Sometimes it is possible to obtain an absolute date on a mineral from the assemblage (e.g. monazite; Bell and Welch, 2002) but not all minerals can be dated radiometrically. Relative chronology may be combined with absolute chronology to extract the complete chronology of mineral growth. For example the minerals trapped as inclusions in the cores of porphyroblasts preserve the mineralogy of the sample at the time of porphyroblast growth. Inclusions in the rim of the porphyroblast give an indication of the matrix mineralogy after the core grew and any changes in the mineral assemblage may reveal a change in P-T conditions. Potentially erroneous P-T conditions may be calculated from an inferred assemblage that did not equilibrate contemporaneously. It is, therefore, essential to identify the minerals present in a sample and describe their microstructural position and textural characteristics. These techniques allow a P-T-t path to be drawn for a single sample but it is difficult to correlate the different parts of that path between samples.

Work over the last fifteen years has shown that the spiral inclusion trails in garnets from Vermont have formed by the inclusion of alternating steep and flat foliations during episodic garnet growth (Bell & Johnson, 1989; Bell & Hickey, 1997; Bell et al., 1998; Bell et al., 2003; Section B of this thesis). According to this hypothesis the **f**oliation **i**nflection/**i**ntersection **a**xes within the porphyroblasts (FIAs), about which foliations curve or intersect, provide important information about the kinematics of deformation as they should form at a high angle to the direction of bulk shortening (Bell et al., 1995; Bell et al., 1998). Where a horizontal foliation is crenulated by horizontal compression, the trend of the FIA preserved by garnet growth during that event will tend to lie perpendicular to the direction of bulk shortening, especially where a previous porphyroblast has formed (Bell & Wang, 1999). Where a vertical foliation is crenulated by vertical shortening, the trend of the FIA preserved by garnet porphyroblasts that grow during that event, will parallel the strike of the vertical foliation. The strike of the vertical foliation preserved against the porphyroblast reflects the direction of bulk horizontal shortening during the event that formed the foliation. Therefore, the trend of FIAs produced by the crenulation of alternating vertical and horizontal foliations that have formed against pre-existing porphyroblasts should always lie at a high angle to the direction of bulk horizontal shortening. If the direction of bulk horizontal shortening changed within the period of garnet growth a garnet porphyroblast may preserve one FIA trend in the core and a different FIA trend in the rim and the preservation of such core-rim relationships allows the relative age of different FIA trends to be determined (Bell et al., 1998). In Vermont and Massachusetts a sequence of six FIA sets has been established, based on the FIA trend and other microstructural relationships (Section B of this thesis). From oldest to youngest the FIA sets are:

Set 0 - NW-SE – from 120° to 130°

Set 1- NE-SW - from 030° to 050°

Set 2 - E-W - from 065° to 105°

Set 3 - NNW-SSE - from 140° to 165°

Set 3.5 - N-S - from 170° to 015°

Set 4 - NE-SW - from 025° to 045°

Foliation inflection/intersection axes therefore allow the age of different inclusion assemblages to be bracketed and correlation to be made between samples from different locations across the area (Bell et al., 1998). New dating techniques can be used to determined the age of any monazite grains that may be preserved in the included foliations or in the matrix and to provide absolute age brackets for each FIA set (Bell & Welch, 2002).

1.3 THERMOCALC and P-T pseudosections

THERMOCALC is thermodynamic calculation software designed to tackle mineral equilibria problems. The programme calculates mineral equilibria involving solid solutions by solving simultaneous non-linear equations and, ultimately, allows the construction of phase diagrams (Powell et al., 1998). THERMOCALC uses the internally consistent thermodynamic dataset of Holland and Powell (1990; 1998 and subsequent upgrades).

A commonly constructed phase diagram is the P-T projection, showing all the stable invariant points and univariant lines for a given chemical system (e.g. NCMnKFMASH). A special variant of this diagram is the P-T pseudosection. Pseudosections show only those portions of the full system grid that are stable for a given bulk composition. A P-T pseudosection therefore shows the pressure and temperature at which different mineral assemblages are stable for a rock of known composition (Powell et al., 1998). By comparing the observed mineralogy to the fields calculated by THERMOCALC, estimates of the P-T conditions at the time the assemblage formed can be made. If textural relationships within the rock allow different equilibrium assemblages to be identified (e.g. inclusions within porphyroblasts) then it is possible to identify a number of different P-T points which the rock in question must have passed through and construct a P-T path for the sample. A more quantitative assessment of the P-T conditions when a particular mineral formed can be determined by measuring the mineral compositions and using these data to plot compositional isopleths on the pseudosection. The intersection of the measured compositional isopleths gives an estimate of the P-T at which that mineral composition was stable (Vance & Mahar, 1998).

Several fundamental assumptions are made when using P-T pseudosections to construct P-T paths. First, the mineral assemblage considered must be in equilibrium. A judgement regarding this assumption is usually based on textural evidence that the minerals were growing simultaneously. However, it is possible that disequilibrium crystallisation is taking place and that minerals growing together are not in equilibrium, or that all the minerals present are not part of the same equilibrium assemblage.

Secondly it is assumed that metamorphism is isochemical and that the bulk composition of the rock does not change during metamorphism. While this may not be generally true in schistose rocks it is a common assumption in metamorphic modelling. Textural and geochemical evidence suggests that there is significant material loss during regional metamorphism of pelites, particularly during crenulation cleavage formation, and that the majority of the loss is SiO_2 (Ague, 1991; Williams et al., 2001). However, during most modelling in THERMOCALC, quartz is assumed to be present in excess and therefore changes in the amount of quartz present will not generally affect the topology of the P-T pseudosections (Vance & Mahar, 1998). A more concerning issue is that porphyroblasts, such as garnet, growing in the rock will take material into their crystal lattice as they grow and that this material will essentially be removed from the reacting system and effectively change the bulk composition (Vance & Holland, 1993; Stüwe, 1997; Vance & Mahar, 1998; Marmo et al., 2002). Whole rock XRF data may not, therefore, provide a suitable measure of the effective bulk composition of the reacting system. The effective bulk composition is the composition of the volume of rock in which the equilibration of minerals is achieved and maintained at a given stage in the metamorphic evolution (Stüwe, 1997). For example only the outer rim of a garnet porphyroblast is necessarily in equilibrium with the minerals growing in the matrix and therefore the contribution of the garnet cores should ideally be removed from the whole bulk composition when calculating the effective bulk composition for the matrix mineral assemblage (Marmo et al., 2002). However, this does not take into account mineral grains occluded by the growing porphyroblasts and, therefore, also effectively removed from the bulk composition. If the porphyroblasts are rich in inclusions the material isolated within the garnet may not be that different from the bulk composition, so that the effective bulk composition is not significantly changed by garnet growth

(Vance & Mahar, 1998). Estimating the proportion of minerals that are inferred to have equilibrated with each other and combining this with the composition of the minerals can approximate the effective bulk composition for a given matrix assemblage (Zeh, 2001). However, it is more difficult to estimate, for example, the effective bulk composition at different stages during porphyroblast growth. Porphyroblasts may capture some matrix phases as inclusions but the included population will probably not represent the relative proportions of these minerals in the matrix at the time the porphyroblast grew. Given the difficulties in accurately estimating the different effective bulk compositions experienced by a sample it is often best to use the whole rock bulk composition from XRF analyses as a first approximation when constructing pseudosections but consider the possibility of changing bulk composition through time when interpreting these sections (Stüwe & Powell, 1995).

Thirdly, it is assumed that fluid (H_2O) is also present in excess. This is generally true during prograde metamorphism because of the water produced by prograde reactions, but may not be true during retrogression and therefore caution should be exercised when interpreting the retrograde part of the P-T path from the pseudosections (Vance & Mahar, 1998; Guiraud et al., 2001).

2. Sample Descriptions

Seven samples of pelitic garnet schist from the Proterozoic/Cambrian Hoosac Formation in southeastern Vermont were used in this study (Figure D-1). The mineral assemblages observed in each sample are summarised in Table D-1. In all the samples the garnet porphyroblasts have good inclusion trails and these were used to measure the FIAs (Section B of this thesis). The selection of samples chosen included two samples with a core FIA from FIA set 1, two samples with a core FIA from FIA set 2, one sample with a core FIA from FIA set 3 and two samples with a core FIA from FIA set 3.5. This range of FIAs was chosen to provide a microstructural history against which the P-T history could be compared. The samples were also selected because their mineralogy changed either between the core inclusion assemblage and the rim inclusion assemblage or between the inclusion assemblage and the matrix assemblage. These changes in the stable mineral assemblage provide additional constraints on the P-T path for a sample.

2.1 BG53

Sample BG53 contains large garnet porphyroblasts, up to 10 mm in diameter, which are typically cracked and altered to chlorite and iddingsite around their margins. The porphyroblasts are rich in inclusions with quartz, plagioclase, chloritoid, apatite and ilmenite present defining inclusion trails with a FIA trending at 015° (Set 3.5). Rutile needles are present in the cores of the porphyroblasts but not in the rims. The matrix contains quartz, plagioclase, muscovite and chloritoid and crenulations of the chloritoid and muscovite are common. Small staurolite laths are present in the matrix along with accessory tourmaline and coarse ilmenite grains (up to 3 mm). Small amounts of biotite are present (less than 1% modal abundance), associated with retrograde chlorite clots.

2.2 BG58B

Sample BG58B contains large (up to 12 mm) garnet porphyroblasts, which are commonly cracked and altered with chloritisation around the margins. Inclusions of rutile, chloritoid, chlorite and muscovite define inclusion trails with a FIA trending at

035° (Set 1). Plagioclase and quartz are also present as inclusions. The matrix contains large plagioclase porphyroblasts (up to 4 mm), some of which are saussuritized, as well as quartz, muscovite, tourmaline and ilmenite. Chlorite in the matrix forms “clots” and is commonly associated with biotite.

2.3 BG59

Sample BG59 contains large (<10 mm) garnet porphyroblasts with inclusions of chloritoid, plagioclase, muscovite, apatite, rutile and quartz. The inclusions define relatively smooth spiral trails with a FIA trending at 075° (Set 2). The matrix contains muscovite, quartz, plagioclase, chloritoid, tourmaline, biotite and clots of chlorite.

2.4 BG62

Sample BG62 is a garnet, chlorite, muscovite, quartz schist with accessory ilmenite and tourmaline. The garnet porphyroblasts are generally idioblastic but may be quite cracked and altered. The porphyroblasts are up to 3.5 mm in diameter with inclusions of quartz, plagioclase, rutile, chloritoid and ilmenite. The inclusion trails are well defined and smoothly curving in the cores but truncated in the rims. The core FIA trends at 005° (Set 3.5) and the rim FIA trends at 045° (Set 4).

2.5 BG87

The garnet porphyroblasts in sample BG87 are large (up to 25 mm), with distinct textural core and rim zones. Typical inclusions in the core are quartz, chloritoid, chlorite, muscovite, ilmenite and small amounts of epidote. The largest porphyroblasts contain abundant rutile inclusions in the inner most part of the core, but these are rare or absent from the rest of the core. The core inclusions form sigmoidal trails with FIA at 030° (Set 1). The rims of the porphyroblasts also preserve inclusions. These are typically quartz, plagioclase, ilmenite, muscovite, tourmaline and sparse chlorite. Inclusion trails in the rims of the porphyroblasts are continuous with the matrix and have a FIA of 050° (Set 4). Large plagioclase grains in the matrix appear to be overgrown by muscovite in some places and other grains show saussuritisation. Chlorite in the matrix sometimes forms clots, suggesting a retrogressive origin, but in other places appears to follow the foliation and may be primary. Biotite is rare, and where present is always associated with chlorite. Accessory ilmenite, tourmaline and epidote are also present in the matrix. Tourmaline grains in the matrix can be up to 3 mm in length and are commonly optically zoned. Chloritoid is absent from the garnet rims and the matrix.

2.6 BG107A

Garnet porphyroblasts in sample BG107A are up to 10 mm in diameter. The cores of the porphyroblasts are rich in inclusions, with quartz, plagioclase, chlorite, rutile, apatite and ilmenite defining smooth spiral trails. The FIA defined by these inclusions trends at 140° (Set 3). The rims of the porphyroblasts have fewer inclusions, with ilmenite tending to form a ring around the garnet core. The matrix contains biotite, crosscutting the foliation, and large plagioclase grains, some of which show saussuritisation.

2.7 BG108

The garnet porphyroblasts in sample BG108 are up to 10 mm in diameter. The larger ones tend to be idioblastic, with classic hexagonal cross-sections. Smaller porphyroblasts appear cracked and fragmented with embayed edges. Some have clots of chlorite around them and show alteration to iddingsite along cracks. The cores of the porphyroblasts are rich in inclusions, with quartz, plagioclase, chloritoid, chlorite, rutile, ilmenite and minor apatite defining smooth spiral shaped inclusion trails with a core FIA trending at 090° (Set 2). The rims of the porphyroblasts have fewer inclusions, with ilmenite tending to form a ring around the garnet core. The rim trails are not continuous with the matrix foliation and the rim FIA trends at 175° (Set 3.5). Quartz, plagioclase, muscovite, chlorite, chloritoid, tourmaline, ilmenite and apatite are present as inclusions in the rim and in the matrix but rutile is not.

3. P-T Pseudosections

THERMOCALC 3.21 was used to calculate P-T pseudosections in the system NCMnKFMASH. Calculations were performed using the October 2002 dataset and the datafile in Appendix 8. The mineral phases considered were garnet (gt), staurolite (st), biotite (bi), chlorite (chl), chloritoid (ctd), kyanite (ky), sillimanite (sill), andalusite (and), plagioclase (pl), zoisite (zo), muscovite (mu), quartz (qz) and water (H_2O). For all samples, except BG53, quartz, muscovite and water were considered to be in excess. Quartz and water were also considered to be in excess for sample BG53 but muscovite was found to react out of the system and is absent from two low-pressure fields on the pseudosection.

The bulk composition for each sample was obtained from whole rock XRF analysis (Appendix 9). These data were entered into the THERMOCALC datafile as oxide molar values for Na_2O, CaO, MnO, K_2O, FeO, MgO, and Al_2O_3 (Table D-2). A P-T pseudosection for each sample was then constructed as described by Powell et al.

(1998). Compositional isopleths were calculated for measured garnet compositions. In the system NCMnKFMASH garnet composition is expressed as the mole fraction of Fe, Mn and Mg:

$F(g) = FeO/(FeO+MnO+CaO+MgO)$

$M(g) = MnO/(FeO+MnO+CaO+MgO)$

$C(g) = CaO/(FeO+MnO+CaO+MgO)$

The intersection of the three isopleths occurs at the P-T conditions for which that garnet composition was in equilibrium with the bulk composition (Vance & Mahar, 1998). For each sample, the garnet core composition was measured using the microprobe and compositional isopleths were plotted on the pseudosections. Manganese zoning maps were used to locate the compositional core of the porphyroblast and 3-4 microprobe analyses from the core were averaged. The average core composition for each sample is given in Table D-3 and full point analysis data is given in Appendix 5. The pseudosections and compositional isopleth intersections for each sample are shown in Figures D-2 to D-8. Compositional isopleths were not plotted for garnet rim compositions because the effect of fractionating material, particularly manganese, into the growing garnets means that the effective bulk composition at the time the garnet rims grew was significantly different from the bulk composition used in the pseudosection modelling (Vance & Mahar, 1998). This means either the measured rim compositions cannot be plotted at all, because those values are not found on the pseudosection, or the isopleths can be plotted but they do not intersect and do not provide any meaningful information.

THERMOCALC performs error propagation on all calculations based on the errors on the activities of the end-members and on the thermodynamic data. Typically the 2σ

uncertainty on lines separating areas of stability of different mineral assemblages is +/- 10-20 °C or 0.4-1.0 kbars. This uncertainty does not include any error in the XRF data used to determine the bulk composition for the pseudosection. For clarity the uncertainty on lines between different fields is not shown on the pseudosections in Figures D-2 to D-8. However, the 1σ uncertainty calculated by THERMOCALC for the compositional isopleth lines is shown. This uncertainty does not include any error in the XRF data or in the microprobe data used to determine the garnet compositions (Appendix 10).

3.1 Comparing pseudosections for different samples

The topology of a pseudosection is determined by the bulk-composition of the sample considered. The samples considered in this study are all highly aluminous pelites and therefore have grossly similar pseudosection topologies. However, the pseudosections can be separated into three sub-groups based on variations in the stability of different minerals.

3.1.1 BG58B and BG107A

Samples BG58B and BG107A (Figure D-3 and D-7) have the greatest area of plagioclase stability. In these sections plagioclase does not react out until pressures around 3kb higher than in sample BG59 and around 5kb higher than in samples BG53, BG62, BG87, and BG108. The increased plagioclase stability in samples BG58B and BG107A is probably related to their high total Na_2O+K_2O+CaO (Table D-2).

Samples BG58B and BG107A have the smallest area of chloritoid stability. The chloritoid-in line lies entirely above the plagioclase-out line, at pressures up to 15 kbar higher than in samples from BG53, BG62, BG87, and BG108. Samples BG58B and BG107A also have the largest areas of biotite stability and the most restricted staurolite stability, with the biotite-out reaction line lying at higher temperatures and pressures than the staurolite-out line in both sections. The chlorite-out line also lies at slightly higher temperatures than in any of the other samples. The relative stability of all these ferro-magnesian minerals is probably determined by the relatively high Mg/Fe ratio in sample BG58B and BG107A (Table D-2).

3.1.2 BG53, BG62, BG87, and BG108

This group of samples has relatively reduced plagioclase stability, with the plagioclase-out line roughly bisecting the pseudosection diagonally (Figures D-2, D-5, D-6 and D-8). This can be related to the relatively low total Na_2O-K_2O-CaO in these samples, compared to samples BG58B, BG59 and BG107A (Table D-2).

Samples BG53, BG62, BG87, and BG108 also have relatively large areas of staurolite stability. Within the group, samples BG53 and BG108 have the greatest area of staurolite and BG62 has the least. This can be correlated with the Mg/Fe ratio, which is lowest in samples BG53 and BG108 and highest in sample BG62 (Table D-2). The Mg/Fe ratio also appears to be control the biotite stability, which is greater in BG62 than in the other samples from this group. Similarly chlorite is more stable in BG62 than in the other samples.

BG53 (Figure D-2) differs from the other samples in this group because muscovite is unstable in the high-temperature low-pressure area of the pseudosection. This area of muscovite absence is probably related to the low K_2O content of this sample combined with the very high Al_2O_3. Below the muscovite-out line the garnet-in line changes trend and garnet is stable at lower pressures than on the other pseudosections from this group.

3.1.3 BG59

The pseudosection for sample BG59 (Figure D-4) is very similar to samples BG87, BG108, BG62 and BG53 but has some important points of difference. Firstly, garnet has a greater area of stability in sample BG59 and in particular is stable at low pressures for all temperatures. This enhanced garnet stability is probably related to the high manganese content. However, across all the samples studied, the sample with the most restricted garnet stability, sample BG53, does not have the lowest manganese value. CaO is very low in sample BG53 suggesting than Ca content is also important in determining garnet stability, particularly at low temperatures. The relatively high CaO content in sample BG59 supports this.

Sample BG59 has a relatively restricted area of chloritoid stability. However, unlike samples BG107A and BG58B, the chloritoid is not confined to high pressure, low temperature areas but is stable in a wedge-shaped area at temperatures less than 560° and pressures less than 8kb. This area lies entirely below the plagioclase-out line. The plagioclase-out line is slightly elevated in this sample, probably due to the relatively high total Na_2O+K_2O+CaO (Table D-2). The reason for the absence of chloritoid from the low temperature, high-pressure areas of the pseudosection is unclear but it may be related to MnO content and the associated increase in garnet stability.

3.2 Comparing the pseudosections to observed mineralogy

As J.B. Thompson stated nearly fifty years ago, “a pelitic schist is not a simple chemical system and the mineralogic variations that have been observed do not lend themselves readily to graphical analysis” (Thompson, 1957). The pseudosections modelled in this study are, by necessity, a simplification of the chemistry of the real samples.

It should be noted that the simplified chemical system used to model the mineralogy of these samples (NCMnKFMASH) does not take into account the ferric iron content of the samples and for the purposes of modelling all the iron in the samples is assumed to be Fe^{2+}. This is particularly significant when considering epidote group minerals where the substitution of Fe^{3+} may be important in determining mineral stability (Tinkham et al., 2001). The modelled chemical system also does not take into account the titanium content of the samples. This means the pseudosections do not show the areas of relative stability of rutile and ilmenite. Expanding the chemical system to include TiO_2 may provide further constraints on the P-T evolution of those samples where rutile is present in the garnets cores but absent from the rims and matrix. Phosphates are also absent from the modelled chemical system, meaning that the importance of apatite as a calcium-bearing phase in some samples cannot be considered. Finally, boron is not considered and therefore tourmaline, which occurs as very large grains in some samples, is not modelled on the pseudosections. The presence or absence of tourmaline in these samples may influence the availability of materials such as Na, Al, Fe, Mn or Mg needed for the formation of other mineral species.

3.2.1 BG53

Inclusions of quartz, plagioclase and chloritoid are preserved in the cores of garnet porphyroblasts in this sample. Garnet, plagioclase and chloritoid are only stable together in one field on the pseudosection, at 530-565 °C and 7.2-8.2 kbar (Figure D-2). Chlorite and muscovite are also predicted to be stable in this field but neither of these minerals is preserved as an inclusion in garnet. The matrix assemblage contains chlorite, chloritoid, muscovite, quartz, plagioclase, garnet and small laths of staurolite. According to the pseudosection, chloritoid, garnet, plagioclase and staurolite are stable together only in an extremely narrow field between 4.2-7.0 kbar at 550-560 °C. It is possible that the small staurolite laths grew later than the chloritoid in the matrix and that the final equilibrium matrix assemblage was chl-g-st-pl-mu. This assemblage is stable over a much larger area of the pseudosection between 4.2-9.0 kbar and 550-610 °C. It should also be noted that the chlorite in the matrix appears to be largely retrogressive, forming clots and fringes around garnet, and may not have been stable at the same time as all the other phases. Small amounts of biotite are associated with the chlorite suggesting this is also a late phase, possibly replacing chlorite.

3.2.2 BG58B

Inclusions of muscovite, plagioclase, quartz, chlorite and chloritoid are present in garnet porphyroblasts in both these samples. However the pseudosection (Figure D-3) predicts that chloritoid and plagioclase are not stable together and that chloritoid is not stable until pressures greater than 13.5 kbar. Chloritoid is absent from the matrix, leaving an assemblage of chl-g-pl, which is predicted to be stable over a large area of pseudosection between 6.5-14.0 kbar and 500-600 °C. Biotite is stable at slightly lower pressures, consistent with its appearance as a later phase in the matrix assemblage, associated with retrogressive chlorite.

3.2.3 BG59

This sample contains large garnet porphyroblasts with inclusions of chloritoid, plagioclase, muscovite and quartz. This assemblage, with the addition of chlorite, is predicted to be stable in a relatively large area of the pseudosection between 3.5-8.0 kbar and 495-565 °C (Figure D-4). The matrix contains chloritoid, plagioclase, chlorite, biotite, muscovite and quartz. According to the pseudosection this assemblage is stable in a restricted field at slightly lower pressures (3.3–3.7 kbar) than the inclusion assemblage.

3.2.4 BG62

Inclusions of quartz, plagioclase and chloritoid are preserved in the cores of garnet porphyroblasts in this sample. Garnet-plagioclase-chloritoid, with the addition of chlorite and muscovite, is predicted to be stable on the pseudosection in a field between 3.5-9.0 kbar and 510-560 °C (Figure D-5). Chloritoid is absent from the matrix but the loss of this phase does not appear to have been accompanied by the growth of staurolite, as would be expected from the pseudosection. The pseudosection does not predict the observed matrix assemblage of chlorite-garnet-plagioclase-muscovite-quartz at all.

3.2.5 BG87

Garnet porphyroblasts in this sample preserve inclusions of quartz, plagioclase chloritoid, chlorite, muscovite and epidote in the cores. This assemblage is predicted to be stable on the pseudosection between 5.3-8.0 kbar and 480-525 °C (Figure D-6). The same assemblage is present in the garnet rims and matrix with the exception of chloritoid. According to the pseudosection, zoisite is only stable when chloritoid is present and this means that the rim/matrix assemblage is not predicted to be stable at all. If epidote with a greater compositional range was considered this might change the stability field. However, previous studies suggest that zoisite has a larger stability field than clinozoisite and that zoisite therefore provides the best estimate of the maximum stability of an epidote group mineral, in the system NCMnKFMASH, over the pressure and temperature range considered in this study (Tinkham et al., 2001). The failure of the pseudosection to correctly predict the stability of epidote in this sample may reflect the influence of Fe^{3+} in increasing epidote stability. As was observed in sample BG62, the absence of chloritoid from the matrix does not appear to have been accompanied by the growth of staurolite, as may be expected from the pseudosection. Instead the rock probably passed through the chl-pl-g field. The small amounts of biotite present in the matrix are typically associated with retrogressive chlorite clots and probably represent a last phase of growth and the rock moving into the chl-g-bi-pl field.

3.2.6 BG107A

Quartz, plagioclase and chlorite are present as inclusions in garnet porphyroblasts in this sample. This assemblage, with the addition of muscovite, is predicted to be stable on the pseudosection in a broad field between 5.25-14.0 kbar and 490-610 °C (Figure D-7). The matrix assemblage, chl-g-bi-pl is stable at slightly lower pressures across a similar temperature range.

3.2.7 BG108

The cores of garnet porphyroblasts in this sample preserve inclusions of quartz, plagioclase, chloritoid and chlorite and the same minerals are also present in the matrix. This mineral assemblage is stable in the chl-ctd-g-pl field, between 4.0-7.5 kbar and 510-555 °C (Figure D-8).

3.3 Isopleth intersections

3.3.1 BG58B, BG62, BG87 and BG108

The measured compositional isopleths for sample BG58B intersect at the junction of the chl-g-pl field and the chl-g-bi-pl field at 6.4 kbar and 532°C (Figure D-3, Table D-4). The three isopleths intersect closely and the small triangle formed by the three intersection points lies well within the area of overlap of the 1σ errors. At the intersection of the isopleths, the modal proportion of garnet calculated by THERMOCALC is 0.005 +/- 0.012.

The measured compositional isopleths for samples BG62, BG87 and BG108 intersect in the chl-ctd-pl-g field at 5.5 kbar and 525°C, 4.7 kbar and 520°C, and 7.0 kbar and 507°C respectively (Figures D-5, D-6 and D-8, Table D-4). In sample BG108, the three isopleths intersect closely and the triangle formed by the three intersection points lies well within the area of overlap of the 1σ errors. For sample BG87, the intersection is not as tight but the triangle of intersection still lies with the area of overlap of the 1σ errors. For sample BG62, the triangle of intersection is even larger and lies partially outside the area of overlap of the 1σ errors.

At the intersection of the isopleths for sample BG108, the modal proportion of garnet is 0.006 +/- 0.014. For samples BG87 and BG62 the modal abundance of garnet increases across the triangle of intersection. For BG87 at the intersection of the C(g) and the M(g) isopleths and the F(g) and the M(g) isopleths the modal proportion of garnet calculated is 0.008 +/- 0.016 and at the intersection of the F(g) and the C(g) isopleths the modal proportion of garnet calculated is 0.010 +/- 0.020. For sample BG62 at the intersection of the C(g) and the M(g) isopleths and the F(g) and the M(g) isopleths the modal proportion of garnet calculated is 0.002 +/- 0.020 and at the intersection of the F(g) and the C(g) isopleths the modal proportion of garnet calculated is 0.012 +/- 0.024.

The intersection, within error, of the compositional isopleths for these four samples, combined with the relatively small values of garnet abundance at the compositional isopleth intersection points, support the inference that the garnet core compositions were in equilibrium with the modelled bulk composition for these samples and that the measured isopleths represent the garnet composition at the very start of garnet growth.

3.3.2 BG59 and BG107A

The measured compositional isopleths for sample BG59 intersect in the chl-ctd-g-pl field at 5.7 kbar and 524°C (Figure D-4, Table D-4). The three isopleths intersect closely and the small triangle formed by the three intersection points lies well within the area of overlap of the errors. At the intersection of the isopleths, the modal proportion of garnet is 0.028 +/- 0.020.

The measured compositional isopleths for BG107A intersect in the chl-g-pl field at approximately 7.3 kbar and 520°C (Figure D-7, Table D-4). Although the isopleths do intersect, within error, the triangle formed by the three intersection points is relatively large and lies partially outside the area of overlap of the 1σ errors. At the intersection of the C(g) and the M(g) isopleths and the F(g) and the M(g) isopleths the modal proportion of garnet calculated is 0.017 +/- 0.012. At the intersection of the F(g) and the C(g) isopleths the modal proportion of garnet calculated is 0.028 +/- 0.012.

The relatively high modal abundance of garnet at the intersection of the compositional isopleths in samples BG59 and BG107A suggests that the core garnet composition measured for these samples does not represent the very earliest possible garnet growth. The garnet growth in these samples may be "overstepped", with the first growth occurring at (the "garnet-in" line). Reasons for this apparent overstepping are discussed further below.

3.3.3 BG53

The manganese content measured from garnet cores in this sample has an M(g) value of 0.078. This value is much higher than is calculated at any point on the pseudosection. The inclusion mineralogy for this sample suggests that garnet growth initiated in the chl-ctd-g-pl field. Based on the microprobe measurements F(g) and C(g) compositional isopleths can be calculated for the chl-ctd-pl-g and chl-ctd-g fields as shown in Figure D-2. However, along the garnet-in line of the chl-ctd-g-pl field the highest value of M(g) predicted by THERMOCALC is only 0.03, much lower than the measured value. It appears that the bulk rock composition used to prepared the pseudosection for this sample is not representative of the effective bulk composition at the time the garnet porphyroblasts grew and that the effective bulk composition at that time was enriched in manganese relative to the measured bulk rock composition. It seems unlikely that there has been an absolute decrease in the manganese content in these rocks since the time that the garnet porphyroblast growth began, as most of the manganese in the rock would be sequestered inside garnet crystals and there is no textural evidence for significant garnet dissolution. However, it is possible that material has been added to the rock, causing a *relative* decrease in the amount of manganese. The pseudosections are relatively insensitive to changes in SiO_2 content, due to the excess of quartz, (Vance & Mahar, 1998) but metasomatism involving the introduction of Al_2O_3, for example, would have a significant effect on the calculated stability of aluminosilicates and their predicted composition. Sample BG53 is exceptionally aluminous and if a proportion of this Al_2O_3 were added after garnet growth it would effectively dilute the MnO content of the sample.

4. Garnet zoning

Compositional maps were obtained for garnet porphyroblasts from each sample using the electron microprobe facilities at the Advanced Analytical Centre (AAC), James Cook University. These maps were used to identify any changes in composition that may be related to changes in P-T conditions and to distinguish the core of the porphyroblast before doing point analyses.

4.1 BG62, BG87, BG107A and BG108

Compositional zoning maps for samples BG62, BG87, BG107A and BG108 are presented in Section C of this thesis and point analyses are given in Appendix 5. Generally the garnet porphyroblasts show normal prograde compositional zoning patterns in the cores of the porphyroblasts with decreasing Mn and Ca and increasing Mg. However, a narrow zone of Mn-enrichment and Ca-depletion marks the core-rim boundary. Across this boundary there is a step up in Ca and a step down in Mg. Normal zoning with decreasing Ca and Mn and increasing Mg continues in the garnet rims.

4.2 BG53 and BG58B

Samples BG53 and BG58B show prograde compositional zoning patterns with depletion in Ca and Mn from core to rim accompanied by enrichment in Mg (Figures D-9 and D-10; Appendix 5). In both samples the Fe content does not change across the porphyroblast. Sample BG58B shows enrichment of Mn in the very outer rim of the garnet and there is evidence for dissolution at the garnet margin, suggesting that the garnet was attempting to maintain equilibrium via net transfer reactions with the matrix.

4.3 BG59

Sample BG59 shows the most complex zoning pattern out of the seven samples studied (Figure D-11; Appendix 5). Compositionally the garnet appears to be made up of three different layers – the core, the inner rim and the outer rim. Mn decreases slightly moving outwards from the core until reaching the core-inner rim boundary. This boundary is marked by a slight increase in Mn. Beyond the core-inner rim boundary Mn continues to decrease outward, approaching zero at the boundary between the inner and outer rim zones. In the outer rim, Mn increases slightly towards the very edge of the garnet where there is a thin layer of manganese enrichment. Ca is patchy in the core of the porphyroblast, increasing slightly towards the core-inner rim boundary. This boundary is marked by a sharp drop in Ca. Ca is relatively depleted in the inner part of the rim but increases at the boundary between the inner rim and the outer rim. The very outermost part of the garnet is again slightly depleted in calcium. Mg is relatively low in the core of the porphyroblast and decreases further at the boundary between the core and the inner rim. At the boundary between the inner rim and the outer rim, there is a zoning reversal and Mg is relatively high in the outer rim of the garnet. Fe is relatively low in the core of the porphyroblast but increases sharply at the boundary between the core and the inner rim. Fe is high in the inner rim but it decreases slightly at the boundary between the inner and outer rim zones.

5. P-T History

5.1 P-T and Compositional Zoning

The interpretation of compositional zoning using pseudosections is limited because the fractionation of material into the growing garnet will change the effective bulk composition and, therefore, a pseudosection prepared using the bulk rock composition determined by XRF analysis cannot accurately predict the composition of garnet grown late in the rock's history (Vance & Mahar, 1998). However, some general trends regarding changing garnet composition can be recognised from the compositional isopleths on pseudosections and these will be discussed below.

The prograde compositional zoning observed in sample BG58B, and in the cores of garnets of samples BG62 and BG108, is consistent with fractionation of material into the porphyroblasts during garnet growth and may or may not have been accompanied by changes in P-T conditions (Frost & Tracy, 1991). For example in Sample BG58B the M(g) isopleths across the chl-g-pl and chl-g-bi-pl fields have a gentle to moderate negative slope and the manganese content of garnet decreases with increasing pressure and temperature. Across the chl-g-pl field the C(g) isopleths are nearly vertical and calcium content would tend to decrease with increasing temperature. In the chl-g-bi-pl field, however, the C(g) isopleths have a steep to moderate positive slope and the calcium content would increase slightly with increasing pressure and decrease with increasing temperature.

The distinct break in compositional zoning at the core-rim boundary of samples BG87, BG108, BG107A and BG62 suggests that there was a period during the evolution of these samples in which garnet growth stopped and in some samples garnet was unstable and began to break down. There is regional evidence that the garnet breakdown was associated with fluid infiltration and the change in chemical zoning at the core-rim boundary may be partly related to a change in the bulk composition of the rock (Section C of this thesis). However, the intersection of the core compositional isopleths for these samples suggests that the cores of the garnet porphyroblasts are in equilibrium with the modelled bulk rock compositions and, therefore, there cannot have been significant metasomatism of the rocks. Instead the changes in garnet zoning at the core-rim boundary may be been related to a change in P-T conditions. This means that even though it appears that there has been an overall increase in temperature and pressure conditions from the time the garnet cores grew up to the peak of metamorphism, the P-T path may be more complex than a simple heating and compression with time. For garnet dissolution to occur it is not necessary for the samples to have moved completely outside the field of garnet stability. The garnet dissolution may simply reflect a change in P-T conditions that leads to the sample moving into an area of the pseudosection where a smaller modal proportion of garnet is stable. This means some garnet will dissolve so its components can be used by the other stable mineral species. The pseudosections for these samples have not been contoured for garnet abundance but generally garnet abundance parallels the manganese content because this element is so strongly partitioned into garnet (Spear et al., 1991; Vance & Mahar, 1998) . In all these samples in the field where garnet growth began the M(g) isopleths have a moderate negative slope. This means that if garnet growth continued within that field a decrease in pressure and/or temperature would be needed for garnet dissolution to occur. This agrees with Karabinos' (1984) conclusion that garnet from the Jamaica area, close to the location of samples BG107A and BG108, had experienced dissolution during a period of retrogression before completing growth under prograde conditions. The break in the zoning profile is analogous to an unconformity in a sedimentary section and represents a period of time for which there is no record preserved. It is, therefore, very difficult to know how long the break was without being able to date the garnet material on either side. Rosenfeld (1968) and Karabinos (1984) have suggested that the cores of these "unconformity" garnets formed during the Ordovician Taconic Orogeny and the rims during the Devonian Acadian Orogeny. However, recent monazite dating by Bell and Welch (2002) suggests that the garnet growth in this area is mostly Acadian in age, although there must have been some pre-425 Ma garnet growth. The possibility that the early garnet growth in these samples could be Taconic is discussed further in Section B of this thesis.

Sample BG59 shows reversals of compositional zoning but, unlike the samples discussed above, garnet growth appears to have been continuous across the porphyroblast. First the garnet core shows an increase in calcium and a decrease in manganese, while iron remains constant. Again this is consistent with fractionation and may or may not have been accompanied by changes in P-T conditions (Frost & Tracy, 1991). Within the chl-ctd-g-pl field the M(g) isopleths have a moderate negative slope and M(g) decreases with increasing pressure temperature. The C(g) isopleths have a moderate positive slope and C(g) increases with increasing pressure and decreasing temperature. For the garnet core to show an increase in calcium and a decrease in manganese, the temperature would have to be fairly constant as the core grew but pressure may have been increasing. The F(g) isopleths are sub-vertical so an increase in pressure would not be expected to significantly change the iron content, which is consistent with the flat Fe zoning observed in the core. At the boundary between the core and rim there is a major decrease in calcium and an increase in iron. This change in composition is consistent with a step up in temperature. There is no decrease in manganese, however, and the core-rim boundary actually shows a slight enrichment in manganese. This suggests that the temperature increase was probably accompanied by a slight decrease in pressure, roughly parallel to the M(g) contours or moving towards slightly higher M(g) values. The outer rim has higher calcium and lower iron than the inner rim and increasing manganese. This suggests that there was a decrease in temperature during the final stage of garnet growth.

5.2 P-T conditions during FIA development and the role of overstepping

There does not appear to be a clear relationship between the P-T data and the FIA data in this study (Figure D-12). There is no obvious pattern of increasing or decreasing pressure or temperature across the FIA sets and the only trend shown by the P-T data is a progressive increase in pressure going from south to north across the field area. In fact, samples with the same core FIA do not appear to have grown under the same P-T conditions. Samples BG87 and BG58B both preserve core FIAs from FIA set 1 but sample BG58B appears to have grown at P-T conditions 1.5 kbar higher and 12 °C higher than sample BG87. Similarly samples BG108 and BG59 both preserve FIA set 2 but sample BG108 appears to have grown at P-T conditions 1.3 kbar higher and 17 °C lower than sample BG59. This suggests that the preservation of different FIAs is not simply a function of P-T conditions and that P-T conditions were not the primary control on garnet growth. However, as discussed in Appendix 10, the errors in calculating the intersection points may be as much as +/- 1 kbar and +/- 20 °C, and, if the errors are that large, the isopleth intersections shown on Figure D-12 may simply represent a single point in P-T space.

For samples BG59 and BG107A the P-T intersection point for the compositional isopleth lies above the garnet-in line on the pseudosection and for sample BG87 the isopleth intersection is also somewhat above the garnet-in line, although, within error, the modal proportion of garnet at that point is zero. When crystal growth does not initiate in metamorphic rocks until temperature and/or pressure conditions higher than the minimum P-T conditions predicted for stability of that mineral, the mineral reaction is described as being “overstepped”. There are several possible reasons for the apparent overstepping of the garnet reaction in these samples BG59, BG107A and BG87. Firstly, the overstepping may not be real. When the errors in position of the garnet-in line as well as the errors in the compositional isopleth intersections are considered the garnet-in line does lie within error of the isopleth intersection point for all three samples.

Secondly, although every effort was made to record the most primitive garnet values from each sample, it is possible that the polished section did not pass directly through the core of the garnet and the area of garnet probed was not the true centre of the garnet. This does not seem to be a likely explanation, however, as compositions outside the garnet core area would be expected to show evidence of fractionation and the compositional isopleths would not intersect closely.

Thirdly, fractionation of the effective bulk composition caused by the garnet growth itself, may have made the early garnet crystals unstable. Vance and Mahar (1998) observed samples in which the compositional isopleths for the initial garnet grown intersected at P-T above the garnet isograd and attributed this to changes in effective bulk composition caused by the fractionation of material, particularly manganese, into the growing garnet. The change in effective bulk composition would cause the newly grown garnet to become unstable and be resorbed, releasing the manganese back into bulk composition and triggering a cycle of repeated garnet growth and resorption before becoming properly established. According to Vance and Mahar (1998), this could lead to the eventual garnet core indicating conditions within the garnet stability field rather than at the garnet isograd.

Finally, the garnet-in reaction in these rocks may have been truly overstepped and garnet growth may not have initiated until well above the pressure and temperature conditions of chemical equilibrium. The growth of garnet, like other minerals, depends on the ability of the phase to nucleate and the access of reactants to the nucleation site. Previous studies have shown that both of these factors can be linked to deformation (Bell et al., 1986; Williams, 1994; Spiess & Bell, 1996; Williams et al., 2001). It is possible that, in the three samples that appear to be overstepped, garnet growth was primarily controlled by deformation. That is, even though the bulk composition and the pressure and temperature conditions were appropriate, garnet growth could not occur until the rocks were deformed because deformation was necessary to allow nucleation and/or efficient transport of reactants. For example, Bell and Hayward (1991), argued that crenulation hinges are favourable sites for porphyroblast nucleation and growth because the propensity for microfracturing in these zones provides access for fluids carrying the material needed for porphyroblast growth and the build-up of stored strain energy lowers the activation energy for nucleation. If deformation plays an essential role in garnet nucleation and growth then the samples that are overstepped record the P-T conditions at the time that the rocks were deformed. In the samples that are not overstepped deformation was presumably occurring prior to garnet growth and therefore growth of this phase was controlled by the bulk composition of the rock. In those cases the isopleth intersections simply record the P-T conditions at which the rock entered a field where garnet was stable.

Reassessment of the data, considering the possibility that only garnet growth in the "overstepped" samples was controlled by deformation, shows that there is a progressive increase in pressure from FIA 1 to FIA 3 in the "overstepped" samples. For samples BG58B and BG108, which are not overstepped, garnet growth occurred at pressures higher than that for the overstepped sample with the same FIA but lower than that of the subsequent FIA set.

Sample BG62 (FIA set 3.5) is not overstepped and records lower pressure conditions than sample BG107A (FIA set 3). This is not consistent with a general trend of increasing pressure through time. It is possible that there was a drop in pressure between FIA set 3 and FIA set 3.5. As discussed below there is evidence for garnet dissolution between core and rim growth in several samples and the dissolution may have been associated with a change in pressure and/or temperature conditions.

However, sample BG62 records this dissolution so any change metamorphic conditions associated with dissolution must have occurred after the core growth in FIA set 3.5 rather than between FIA set 3 and FIA set 3.5 (Section C of this thesis). It is also possible that the core of sample BG62 is Taconic rather than Acadian, as discussed in Section B of this thesis. In that case, the core P-T would record part of an earlier metamorphic event. Absolute dating, for example using monazite inclusions, would be necessary to determine whether the core is Taconic or Acadian (Section B of this thesis).

When interpreting P-T conditions during FIA development it should be noted that this study compared a very small number of samples and not all the FIA sets identified in southeastern Vermont are included. A much larger dataset, preferably constrained by absolute dating techniques, would be needed to evaluate if there really is a relationship between FIA sets and P-T conditions in overstepped samples. In addition, the errors associated with P-T estimates from isopleth intersections are very large and the isopleth intersections shown on Figure D-12 may essentially represent a single point in P-T space (Appendix 10). This technique may simply be unable to resolve any changes in P-T conditions associated with the different FIA sets.

5.3 Comparing garnet cores with peak P-T from matrix assemblages

The P-T values determined in this study are different from most other P-T values quoted for south-eastern Vermont because they give the P-T at the time that garnet began to grow rather than at the peak of metamorphism. Vance and Holland's (1993) study on a single garnet from the Gassetts Schist, approximately 25 km north of the present study, also determined P-T conditions at the time of garnet core growth using compositional isopleths. They found the garnet core to have grown at 9.7 kbar and 540 °C (Figure D-12). These pressure conditions are much higher than for any of the samples in the present study. However, this is consistent with the trend of increasing pressure towards the north observed in Figure D-12 and the proximity of this sample to the axis of the Chester and Athens Domes. By comparing the P-T conditions from the garnet core with those from the rim and matrix Vance and Holland (1993) determined that garnet growth occurred during heating through 95 °C and a decompression of about 2.5 kbar.

In the present study P-T conditions could not be determined from the composition of the garnet rims using isopleth intersections because of the effects of fractionation. Generally, peak metamorphic P-T conditions can be determined using conventional geothermobarometry, based on the equilibrium between co-existing minerals. Thermobarometers that are commonly used for garnet schists include garnet-biotite, garnet-chlorite, garnet-biotite-muscovite-plagioclase or garnet-rutile-ilmenite-plagioclase-quartz (Spear, 1993). Unfortunately the samples from this study could not be used for this type of thermobarometry because the plagioclase grains in the matrix were saussuritized, biotite was either absent or present in only very small amounts and chlorite grains typically cross-cut the foliation, indicating it was retrograde and not part of the peak metamorphic assemblage. However, several other studies have determined peak metamorphic conditions in this area based on the equilibrium between garnet rims and various matrix minerals (Figures D-1 and D-12). These studies indicate that peak P-T conditions in this area ranged from approximately 6.5 kbars and 475 °C to 8.5 kbars and 590 °C (Laird & Albee, 1981; Kohn & Spear, 1990; Ratcliffe et al., 1992; Ratcliffe & Armstrong, 1999). These values are generally higher in both pressure and temperature than the values determined for the garnet cores. In the northern part of the field area (samples BG107A and BG108) temperatures calculated from the matrix are up to 80 °C higher than those from the garnet cores and pressures calculated from the matrix are around 1 kbar higher than those from garnet cores. In the southern part of the field area (samples BG58B, BG59, BG62 and BG87) temperatures calculated from the matrix are similar to those calculated from the garnet cores but at pressures are up to 2.5 kbars higher. These results suggest that, unlike the garnet of Vance and Holland (1993), the garnet porphyroblasts in the present study grew under both increasing pressure and temperature conditions. This increase in pressure and temperature is consistent with the results of Kohn and Valley (1994) who looked at garnets from the Townshend Dam, Vermont (Location 118D Figure D-1). Their study used the Gibbs method and estimated that the P-T path involved an increase in temperature of 40-85 °C and an increase in pressure of 1.0-1.7 kbars. However, it should be noted that this method relies on making major assumptions regarding the mineral assemblage equilibrating with garnet during the growth of the porphyroblasts. Without the additional constraint of well-preserved inclusions, such as plagioclase and biotite, any P-T trajectory determined from zoning patterns will have substantial uncertainty (Frost & Tracy, 1991).

6. Conclusions

1. The mineral assemblages predicted by geochemical modelling in this study are generally in good agreement with the observed mineralogy of the samples. However, there are two exceptions. Firstly, the stability area calculated for epidote in sample BG87 does not include an area where chloritoid is absent, meaning that the matrix assemblage observed for this sample is not stable on the calculated pseudosection. Secondly, the stability area calculated for chloritoid in sample BG58B is restricted to relatively high pressures and consequently the inclusion assemblage observed for this sample is not stable on the calculated pseudosection.
2. Compositional isopleths based on the composition of garnet cores intersect, within error, for all the samples except BG53. Sample BG53 is interpreted to have experienced some degree of metasomatism since the garnet core growth, effectively diluting the manganese content of the sample.
3. Isopleth intersections indicate that the garnet cores grew at pressures between 4.4 kbar and 7.7 kbar and at temperatures between 500 °C and 540 °C. These values are lower than the estimates of peak metamorphic P-T conditions from nearby samples in previous studies.
4. Garnet compositional zoning is generally consistent with growth during heating and compression. However, several samples have zoning patterns that suggest a more complex history with some periods of cooling and/or decompression. In some samples, this was accompanied by garnet dissolution.
5. There does not appear to be a simple relationship between the P-T data and the FIA data in this study. This suggests that the preservation of different FIAs is not primarily a function of P-T conditions. In "overstepped" samples, deformation may have played an essential role in garnet nucleation and growth, and these samples

indicate a progressive increase in pressure through the different phases of orogenesis.

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