SECTION D

RECONCILING THE STRUCTURAL AND METAMORPHIC RECORD OF OROGENY IN CENTRAL WESTERN NEW HAMPSHIRE VIA FIA AND GARNET ISOPLETH THERMOBAROMETRY

ABSTRACT

A new method based on weighted averages is used to appraise a large dataset of Foliation Intersection Axes (FIA) preserved in porphyroblasts from the Orford-Piermont and Garnet Hill-Salmon Hole Brook regions, central western New Hampshire. This method determines modal peaks in orientation within the FIA dataset in a manner that accounts for imprecision in each FIA measurement. Four distinct, major populations (~015, ~050, ~090 and ~160; orientations A, B, C and D respectively) and one minor population (~135, orientation E) of FIA were found, but no explicit solution to the relative timing of these populations could be determined. At least two of these orientations developed twice during the metamorphic history of the region. Whilst no unique relative timing solution could be found on the strength of the data in this study, the data is consistent with that from other studies in New England. If the relative timing determined from those studies is used, then the FIA succession is EBCDABC, or FIA 0-6 respectively.

P-T paths for both regions have been determined for 17 samples using compositional isopleths from garnet calculated in a continuously fractionating system. FIA from garnet used in the *P-T* path calculations have been plotted onto the *P-T* paths to observe any correlation between the relative timing of FIA development as determined from petrography, and the order of occurrence of the different FIA through the *P-T* path. Throughout the whole *P-T* path, different, often nearly orthogonal FIA were observed forming in different samples over the same region of *P-T* space. Given the inherent uncertainty in the petrographically derived relative timing scheme for FIA development, and the lack of a clear progression of FIA orientation through *P-T* space, it is concluded that in this region FIA are of very limited use as indicators of relative timing of porphyroblast growth. The *P-T* path calculations, in conjunction with mapping have been used to generate a new tectonic model for the Bronson Hill Belt that resolves several serious problems with many of the existing models. This new model integrates well with existing crustal-scale models of the Acadian Orogeny developed through numerical modelling and deep seismic reflection interpretation. The Bronson Hill Anticlinorium and the western half of the Central Maine Synclinorium are interpreted as being part of an east-verging, eastward migrating imbricate thrust system. The granitoids of the New Hampshire Plutonic Suite were emplaced along successive generations of thrust-planes within this system. Metamorphism in the area is the result of isothermal doming along the west-dipping basal detachment that is related to, but post-dates thrusting and granite emplacement.

1. INTRODUCTION

Much work has been done in recent years studying the significance of inclusion trails within porphyroblasts (Bell et al., 1998; Stallard & Hickey, 2001a; Stallard & Hickey, 2001b; Bell et al., 2003; Timms, 2003). **F**oliation **I**ntersection **A**xes preserved within porphyroblasts (FIA) tend to cluster in populations of particular orientations, and those different orientations have been found to consistently occur in a particular order on an orogen-wide scale (Adshead-Bell & Bell, 1999; Aerden, 2004; Bell et al., 2004). It has been proposed that the structural history of a region can be defined in terms of the succession of orientations of FIA populations, and that the orientation of FIA can be used to place porphyroblast growth in a relative timing framework that can be correlated across an orogen (Bell et al., 1998; Bell et al., 2004). Two *a priori* assumptions about the nature of foliation formation at both the microscopic and orogenic scales are implicit in this model for FIA formation:

1. Foliations form at a high angle to the direction of bulk shortening by the mechanism of Progressive Bulk Inhomogeneous Shortening (Bell, 1981), and porphyroblasts only overgrow a pre-existing foliation in the early stages of development of a subsequent deformation, before a new cleavage begins to develop in the immediate vicinity of the porphyroblast (Bell & Hayward, 1991).
2. The direction of bulk shortening is consistent in orientation at all sub-orogenic scales, over the time-scale of foliation development, and is controlled by the direction of relative plate movement (Bell et al., 1995).

This model for FIA formation explains the occurrence of distinct populations of FIA orientations that are regionally consistent in orientation and relative timing. Consequently, it is very important to critically assess whether FIA data *is* in fact regionally consistent in orientation and relative timing. Methods are developed in the early part of this paper that do just that.

Because FIA potentially provide very good relative timing criteria for porphyroblast growth, they are particularly well suited to integration with thermobarometric studies. The combination of these two approaches provides constraints on the relative accuracy of each technique, and additionally yields a detailed and multifaceted view of the thermal, baric and structural dynamics of orogens. *P-T* path calculations used in this study are derived from intersecting compositional isopleths for garnet calculated for a fractionating system (Evans, 2004). This approach yields *P-T* estimates for the growth of garnet that are based on electron probe microanalyses of garnet composition, and the XRF analyses of the composition of the bulk rock. The *P-T* paths that are generated have a very high spatial resolution, and can be correlated directly to textural features within the garnet, such as FIA measurements.

The purpose of this study is to asses how well the independent techniques of FIA analysis and isopleth thermobarometry correlate in the determination of *P-T-d* paths. The Salmon Hole Brook, Garnet Hill and Orfordville-Piermont areas have been chosen for this study as they contain large tracts of garnet staurolite grade metapelites. Additionally, the difficult and time consuming process of measuring FIA has been done by Timms (2002) in the Orfordville-Piermont region, and his data is used *en bloc*, and reinterpreted in this research.

2. GEOLOGY

2.1. Regional Geology

The geology of the New Hampshire Appalachians has been studied for well over 100 years. The detailed geological mapping undertaken in the first half of the 20th century remains a highly relevant and useful database (Billings, 1937; Hadley, 1942). The gross crustal architecture is the result of Middle to Late Devonian deformation accommodating the accretion of Avalon and related terranes from the southeast onto the Laurentian plate during the Acadian orogeny (Figure 1). Sediments from the Siluro-Devonian Basins that separated Avalon and Laurentia and rocks from the Bronson Hill Magmatic Arc, an Ordovician island arc that lay submerged on the Laurentian margin during the Silurian and Devonian, have been extensively deformed, metamorphosed and intruded by granite as they were caught between the colliding continents. Rocks from the Bronson Hill magmatic arc now form the Bronson Hill anticlinorium and are exposed as a series of domes extending from Connecticut to New Brunswick. Intrusion of the New Hampshire Plutonic Suite to the east of the Bronson Hill Anticlinorium accompanied Acadian metamorphism in central New Hampshire. The Bethlehem Granodiorite is regarded as the oldest member of the New Hampshire Plutonic Suite

(Dorais, 2003), having intruded metasediments of the westernmost Central Maine Terrane early in the Acadian at 410±5Ma (Lyons et al., 1997). The Kinsman Quartz-Monzonite was emplaced at 413±5 (Barreiro & Aleinikoff, 1985) to the east of the Bethlehem Granodiorite. The Kinsman Quartz Monzonite is chemically very similar to the Bethlehem Granodiorite (Dorais, 2003), and was probably derived from the same source, albeit one that was more evolved, hotter and less hydrous (Thompson et al., 1968). It is less deformed than the Bethlehem Granodiorite, and in spite of the two being geochronologically indistinguishable, the Kinsman Quartz Monzonite is considered to have been emplaced after the Bethlehem Granodiorite based on the structural and chemical differences between the rocks (Dorais, 2003). This relative timing implies an eastward migration of plutonism during the Acadian in western New Hampshire.

There is continuing debate over the interpretation of the geology in the northern Appalachians; some current tectonic models proposed for the region are based on the classic models of Thompson et al. (1968), involving the transport and stacking of multiple thrust-nappes from the east to the west (Spear et al., 2002; Dorais, 2003). Other tectonic models propose the westward migration of a foreland basin and deformation front ahead of the advancing Acadian Orogen (Bradley et al., 2000; Eusden et al., 2000). Deep seismic reflection profiling across southern New Hampshire (Ando et al., 1984) and across western Maine (Stewart, 1989) show prominent sub parallel reflectors that dip west at around 30˚ throughout the Bronson Hill Anticlinorium and the Central Maine Synclinorium. It is difficult rationalise the Thompson (1968) model in the light of this seismic data, and it is difficult to rationalise the Bradley et al. (2000) and Eusden et al. (2000) models in view of the eastward migration of plutonism in the region. The numerical modelling Beaumont & Quinlan (1994) presents a compelling solution to the seismic reflector geometry across New Hampshire. They suggest that the Bronson Hill Anticlinorium and Central Maine Synclinorium are part of a distributed thrust belt in the prowedge of the Acadian Orogen, formed during the west-dipping subduction of the Avalonian lithospheric mantle beneath the Laurentian margin. The observed geometry, kinematics and eastward migration of deformation within these regions supports their interpretations.

2.2. Geology of the Salmon Hole and Garnet Hill Synclines

2.2.1. Introduction

This region was first mapped by Billings (1937) and his work remains the basic geological resource for the area. Florence et al. (1993) conducted isograd mapping and detailed *P-T* work within the region, pioneering recently developed techniques in *P-T* path calculation. These workers developed a tectonic history based on the ideas of Thompson (1968) and the modelling of Thompson & England (1984). They suggested that the Salmon Hole Brook and Garnet Hill synclines were hot thrust sheets that had been emplaced from the east, over the cooler basement rocks of the Orford-Piermont region.

2.2.2. Geological setting

The Salmon Hole Brook and Garnet Hill synclines are located on the eastern flank of the Bronson Hill Anticlinorium. They are tight to isoclinal, plunge at ~30° towards 260°, overturned to the southeast, and separated by the northwest-dipping Northy Hill fault (Figure 2). The dominant matrix foliation is typically axial plane to the both synclines. However, a later, sub-horizontal crenulation cleavage with a consistent top-to-the-southeast shear-sense is widely developed.

The Garnet Hill and Salmon Hole Brook synclines are composed of a sequence of Silurian to Devonian metasediments that unconformably overly Ordovician felsic volcanics and metasediments. The Clough conglomerate is the basal unit to this sequence, but outcrops discontinuously around the synclines. The Silurian Fitch formation, a package of calcareous schist, calc-silicate and marble, overlies the Clough and occurs in thicknesses ranging from 7 to 600m (Billings, 1937). The Devonian Littleton formation, a package of pelitic, psammitic and carbonaceous schist and amphibolite overlies the Fitch formation and makes up the bulk of each syncline. It typically contains euhedral staurolite porphyroblasts (up to 10cm) and small (~2mm) euhedral garnets in a muscovite-quartz matrix with either biotite or chlorite. Chloritoid occurs in more aluminous layers with garnet, biotite and chlorite, and locally with staurolite.

The Bethlehem Granodiorite, a foliated sheet-like body that intrudes the southernmost tip of the Garnet Hill syncline, appears to have been emplaced along the Northy Hill fault. There is no change in metamorphic index minerals in the Littleton Formation adjacent to the Bethlehem Granodiorite; it contains garnet, staurolite and biotite throughout the Garnet Hill Syncline. However, there is a region around the contact with the Bethlehem Granodiorite that is highly depleted in carbonaceous material with respect to the rest of the Littleton Formation in the Garnet Hill and Salmon Hole Brook Synclines. The Northy Hill Fault truncates this depleted zone to the northwest, whilst its northeastern margin is diffuse. Large, inclusion-rich porphyroblasts of garnet and staurolite are characteristic of the rocks in the carbon-depleted zone, with the amount of carbonaceous material present increasing steadily to the north. Biotite is the dominant matrix mineral in this zone whereas muscovite and chlorite are dominant in the carbonaceous rocks.

2.3. Geology of the Orford-Piermont region

2.3.1. Introduction

The geology of the Orford-Piermont region has been mapped in detail many times over the past 60 years (Hadley, 1942; Rumble, 1969; Moench, 1990; Timms, 2002). Vigorous debate has surrounded the interpretation of the geology, particularly over the existence of the Piermont Allochthon (Moench, 1989; Billings, 1992; Moench, 1992; Timms, 2002). The structural model for the region used herein is based on the mapping of Timms (2002). This region displays significantly greater structural complexity than the Garnet Hill-Salmon Hole Brook region at all scales, and has been metamorphosed to a higher grade.

2.3.2. Structure

The Orford-Piermont region lies on the eastern flank of the Bronson Hill Anticlinorium, along strike to the SW from the Salmon Hole Brook region (Figure 1). The map-scale structure is dominated by a doubly plunging, NNE trending anticline-syncline pair with steep to NW-dipping axial planes (Figure 3). The Piermont allochthon, a thrust-slice of Silurian metapelite and metaconglomerate was emplaced across the Bean Brook Fault early in the deformational history, structurally above the parautochthonous Ordovician basement (Timms, 2002). The contact between the Siluro-Devonian successions of Clough, Fitch and Littleton Formations, and the Ordovician Orfordville Formation has previously been interpreted as an unconformity. However, here it is interpreted as the continuation of the Northy Hill Fault. This interpretation is supported by the highly schistose character of the Littleton Formation and the attenuated pods of Clough and Fitch Formation along the contact.

2.3.3. Metamorphism

Kyanite and staurolite isograds have been mapped across the Orford-Piermont region (Figure 3). Metamorphic grade increases to the northwest, with the highest-grade parts of the region displaying the assemblage kyanite staurolite biotite garnet muscovite, and the lowest-grade regions displaying the assemblage garnet chlorite muscovite.

3. METHODS

3.1. Measuring, grouping and correlating FIA

A FIA is an axis of curvature of a foliation that has been overgrown by a porphyroblast. It is interpreted to represent the line of intersection between two differently oriented schistosities. The angular range of each FIA measurement is determined by observing multiple, oriented, vertical thin sections cut at 10° intervals around the compass, and noting the range over which the inclusion trail asymmetries switch from clockwise to anticlockwise for a particular microstructural domain within a porphyroblast. The overwhelming majority of FIA measured in this and other studies are subhorizontal in orientation, because they generally represent the intersection between a subvertical and subhorizontal foliation (Bell & Hickey, 1997). The trend of the FIA is always controlled by the subvertical foliation, regardless of whether the subhorizontal or subvertical foliation formed first. This means that only FIA that have developed from a subvertical foliation overprinting a subhorizontal foliation can be used reliably as relative timing indicators. The orientation of FIA that have formed during a subhorizontal foliation development will be controlled by the potentially much older subvertical foliation.

Timms (2002) ignored FIA ranges when grouping the FIA into sets, basing all of his correlations between samples on the median value of the measured FIA range. His method allowed FIA with overlapping ranges to be grouped in separate sets, introducing unjustifiable complexity into his measured FIA populations. A simple statistical approach is introduced here to determine where distinct populations of FIA occur, taking the precision of each FIA measurement into account. The dataset of Timms (2002) was plotted as summed, weighted averages, whereby weighting was given to each FIA measurement proportional to the precision of that measurement. For example, a FIA with a range of 10° was given a weighting of 1.0 over the 10° interval, whereas a FIA with a range of 30° was given a weighting of 0.3 over the 30° interval (Figure 4). All of the FIA measurements were plotted on a 360° "radar chart", where overlapping ranges accumulate to generate modal peaks (FIA populations) in the angular data. The angular range of each population was specified, and every FIA measurement was ascribed to one of the populations if its measured range fell entirely within the range of the FIA population. Samples containing two or more non-overlapping FIA were used to constrain the relative timing of the development of the FIA sets. This was accomplished by determining the relative timing relationship between each FIA set preserved in the sample, principally by noting which FIA occur in porphyroblast cores, and which occur in the rims.

3.2. *P-T* path determination

The intersecting isopleth method (Vance & Mahar, 1998; Marmo et al., 2002; Evans, 2004) was used exclusively to determine the *P-T* conditions of garnet growth. In this method, THERMOCALC is used to calculate the *P-T* conditions of equilibration between garnet of a particular composition and the bulk composition of the rock in which it was growing. Garnet composition is measured by electron microprobe point-analysis, allowing very small volumes of garnet at specific locations within a porphyroblast to be used in the equilibrium calculations. This means that the *P-T* history of garnet growth can be defined at a high spatial resolution within the garnet. *P-T* paths for individual samples were generated using intersecting isopleths from a series of analyses from the core to the rim of garnet, using a modified version of the methods of Evans (2004). This generated a *P-T* path that describes the growth history of garnet. The techniques described in Evans (2004) have been modified in two important ways:

1. The concept of the "reactive rim" has been dispensed with. This concept was hard to justify in the face of the fact that compositional zoning in garnet is so well preserved. In the modified method, the most manganiferous garnet analysis is now assumed to be the earliest grown garnet. K_d values are calculated based on this assumption, from the equation:

   $$K_d = \frac{3X_{Spss}}{8X_{Mn-bulk}}$$

   Where X_{spss} is the molar proportion of spessartine in the most manganiferous garnet analysis, and $X_{Mn\text{-}bulk}$ is the molar proportion of MnO in the bulk rock composition. This equation is derived from the assumption that the molar proportion of MnO in garnet will be equal to 3/8 of the spessartine content of the garnet, based on the chemical formula for almandine-type garnet $(Fe,Mg,Ca,Mn)_3Al_2Si_3O_{12}$.

2. A complete error analysis is now incorporated into the calculations, including propagation of analytical error, assessment of "geological error" (Worley & Powell, 2000), and calculation of the thermodynamic error. These various error types are separated so that their contributions towards the relative and absolute uncertainty of positions of points within the *P-T* path can be seen.

Figure 5 shows an example of the output of the modified technique, illustrating both the sources and the relative magnitudes of the different error contributions.

4. RESULTS

4.1. FIA results

4.1.1. Orford-Piermont Region

All FIA measurements for this region are from the study of Timms (2002), and are reproduced here in table 1. Four distinct populations of FIA were apparent in the data, and were termed sets A, B, C and D (Figure 6a). Individual FIA measurements were then assigned to each set on the criterion that the range of the FIA measurement was entirely within the range of one of the sets. The relative timing of the sets was investigated by observing the microstructural position of FIA from samples that contained two or more different sets. Of the 191 FIA measurements taken from 91 samples, there are 19 instances of different FIA occurring between the core and rim of particular porphyroblast species within individual samples (Table 2). There is no unique solution to the relative timing of FIA development contained within this data. However, it is clear that at least two of the modal peaks are built from multiple FIA-forming events, i.e., FIA have formed along the same orientation at different times during orogenesis. It is impossible to say which of the populations are composed of multiple generations of FIA on the strength of the relative timing data. The oldest FIA found in eastern Vermont and north central Massachusetts, set 0 at 120-150 (Bell et al., 2004), is not present as a significant population in the dataset. However, five occurrences of this orientation of FIA (orientation E) were measured, all within garnet.

4.1.2. Garnet Hill-Salmon Hole Brook Region

An investigation of FIA was undertaken in this area, but was hindered by the generally poor preservation of inclusion trails within porphyroblasts. All measurements for this region are shown in figure 6b, and table 3. Orientation B dominates the data, however A and C are also evident. Two multiFIA samples provide some limits on the relative timing of FIA development, suggesting that the ordering of the sets is ABC (Table 4).

4.2. *P-T* results

P-T pseudosections and *P-T* paths for each sample used in this study are shown in Appendix 4. The spreadsheets used to calculate the evolving effective bulk compositions for each *P-T* path are presented in Appendix 5. Appendix 2 illustrates the microprobe analysis locations on each garnet used in the *P-T* path calculations.

4.2.1. Orford-Piermont Region

The summary of the *P-T* path calculations for the Orford-Piermont region is presented in Figure 7(b). The orientation of the FIA preserved in the garnet from which the *P-T* path was calculated is plotted on each point. The *P-T* history of garnet growth is characterised by heating from 515 to 590˚C with burial from ~3.8 to 7kbar. The bulk of the pressure increase appears to occur at relatively lower temperatures, with the latter part of the history being near isobaric. The occurrence of the assemblage staurolite-kyanite-garnet-biotite-muscovite constrains the metamorphic peak for those samples to 620-650˚C and 6.6 to 8.5 kbar.

4.2.2. Garnet Hill-Salmon Hole Brook Region

The summary of the *P-T* path calculations for the Salmon Hole Brook-Garnet Hill region is presented in figure 7(a), with the orientation of FIA contained within studied samples plotted on each *P-T* point. The *P-T* history of this region is characterised by heating from 520 to 560˚C with compression from 4.8 to 6.0 kbar, followed by continued heating from 560 to 590˚ with decompression from 6 to 4.6kbar. The widespread abundance of staurolite and the absence of aluminosilicate broadly constrain the peak *P-T* conditions to the region outlined in green on Figure 8(a).

5. DISCUSSION

5.1. Relative timing constraints on FIA development

No unique solution to the relative timing of FIA development could be found on the strength of the data presented herein. However, the relative timing scheme for FIA development derived in Vermont and Massachusetts (Bell et al., 2004) does fit the FIA data used in this study provided two new sets are added to the scheme. The new relative timing scheme described in terms of the FIA orientation populations defined above is EBCDABC, where the repeats of orientations B and C (FIA 5 and 6 respectively) are new to the scheme. The strength of the modal peaks in the FIA data presented here, and their consistency with modal peaks obtained in other FIA studies provides compelling evidence for both the non-rotation of porphyroblasts during deformation, and for the orogen-scale consistency, and hence the plate-scale controls on FIA orientation. However, the lack of unequivocal relative timing constraints on the development FIA successions, coupled with the conclusion that at least two orientations of FIA have each formed at least twice calls into question the usefulness of these structures for generating relative timing frameworks for metamorphism.

5.2. *P-T* path calculations

The problems and limitations of this method of calculating P-T paths have been discussed in detail in the previous sections of this thesis, and will only be briefly restated here. It is immediately obvious that there is significant variation in the *P-T* paths recorded across the two regions. The causes for this variation are potentially numerous, and explicitly identifying and eliminating them is problematic. Some potential contributors to the apparent imprecision are small-scale, transient thermal heterogeneity during metamorphism, and non-systematic error contributions by parameters that are assumed to be systematic (e.g. highly non-ideal solid solution behaviour). If the former has contributed significantly to the apparent imprecision of the *P-T* paths, then this method provides an important insight into the thermal behaviour of the crust during metamorphism. This was discussed in depth in the previous section. If the latter has contributed significantly to the results, then serious flaws exist in the structure of the modelling performed here, and all of the *P-T* path results are highly questionable. However, although mixing models are regarded as a potentially very large source of error in thermobarometric calculations, they are typically regarded as being systematic whether they are ideal or not (Hodges & Mckenna, 1987; Kohn & Spear, 1991; Worley & Powell, 2000). Additionally, there are some technical limitations to the method of *P-T* path calculation used here that should be kept in mind when interpreting the results. Garnet growth appears limited to a *T* window of 510-590˚C. This means that *P-T* paths derived purely from garnet zoning record only this *T*-window within the path. Estimates of the peak conditions for the path are constrained by the calculated *P-T* field of the peak assemblage in each sample for the fractionated rock composition. This introduces further potential sources of error from the petrographical interpretation of the peak mineral assemblage, and very often leads to a very imprecise account of the peak conditions. However, the fact that the *P-T* paths calculated from garnet composition and those calculated from peak mineral assemblages are derived within the same computational system, and from the same experimental data at least gives an increased level of confidence in the relative accuracy of the results.

5.3. FIA and *P-T* paths

5.3.1. Garnet Hill-Salmon Hole Brook region

The progression of FIA orientation with *P-T* change in the Salmon Hole Brook-Garnet Hill region appears to go from NNE trending at lower temperatures to WNW-WSW at higher temperatures (figure 7a). Whilst the general trend of the FIA and *P-T* data does suggest an ABC FIA progression with heating, there is enough overlap in this data to cast doubt on the hypothesis that particular FIA orientations form at distinct intervals in the metamorphic history of a region. The relative timing constraints in the FIA successions in the Salmon Hole Brook-Garnet Hill region are based on only two samples. DL-36 provides evidence for an A to B transition, whilst DL-64 provides evidence for the B to C transition. The lack of relative timing data does not inspire a great deal of confidence in the proposed FIA succession for this region.

Garnet porphyroblasts have grown during subhorizontal foliation development in many of the samples, and always preserve consistently oriented inclusion trail asymmetry, here interpreted to indicate a top to the SE shear sense during foliation formation and porphyroblast growth. Subhorizontal foliations form during the gravitational collapse of an orogenic pile (Bell & Johnson, 1989). The orogen should tend to collapse outwards, parallel to the maximum regional topographic gradient, generating sub-horizontal structures with consistent shear senses. The consistent top to the SE shear sense implies that the topographic high of the orogen lay to the NW of the Garnet Hill-Salmon Hole Brook region during this period.

It is noteworthy that in the latter stages of the *P-T* path calculated here, decompression occurs during the development of subvertical foliations. Subvertical foliations are formed during crustal shortening sub-perpendicular to the direction of relative plate motion (Bell et al., 1998; Bell et al., 2004). Accordingly, they are widely associated with crustal thickening, and should form during burial. If there is any crustal thickening occurring in this region during the formation of the foliations defining FIA 5-6, it is apparently outstripped by the effects of denudation. This could reflect a lack of any large-scale thrust emplacement over the region during the metamorphic peak, and suggests that crustal thickening associated with crenulation cleavage formation at this time is negligible on the tectonic scale. Importantly, the bulk of the crustal thickening in this region occurred prior to garnet-growth, predominantly before the development of FIA 4.

5.3.2. Orford-Piermont region

The progression of FIA orientations with the *P-T* path in this region is complex and is not unequivocally consistent with the regional FIA succession defined by Bell et al. (2004). The early part of the path is characterised by compression from ~3.8 to 5.5kbar during heating from 510 to 560˚C contains FIA 0 to 2. Sets 0 and 1 occur with no clear ordering in *P-T* space, but set 2 only occurs at the end of this early portion of the path. Sets 3 and 4 occur throughout the same portion of the regional *P-T* path, during near isobaric heating from 540 to 590˚C at ~6kbar. Set 5 is absent within the samples used for *P-T* path calculations, but set 4 and 6 occur within coexisting kyanite and staurolite, implying that they formed at ~630˚C and ~7kbar.

In the Orford-Piermont region, it appears that differently oriented FIA have developed over the same range of *P-T* space during orogenesis. This has occurred within all portions of the *P-T* path, whether characterised by compression, by isobaric heating, or by peak mineral assemblages. There is a broad correlation between the *P-T* path and FIA formation, where groups of different orientation of FIA have formed during particular windows in the *P-T* path. This suggests that these groups of orientations are developing repeatedly within the particular *P-T* window, and that switches in FIA orientation may be occurring over a much smaller time-scale than previously suggested (Bell & Welch, 2002). This would account for the occurrence of distinct populations of FIA orientation, but implies that any relative timing constraints derived from the succession of those orientations is questionable.

5.4. Temporally linking metamorphism between the two areas via FIA and *P-T* paths

The only FIA evident in the Salmon Hole Brook-Garnet Hill region are orientations A, B and C. The limited relative timing information available for these FIA, combined with their distribution in *P-T* space, suggests that they developed in the order ABC, and are equivalent to FIA 4, 5 and 6 from the Orford-Piermont region. This correlates well with the metamorphic data from the Orford-Piermont region. In both regions, FIA 4, 5 and 6 occur during heating up to the thermal peak, with little to no pressure increase. The decompression recorded in the Garnet Hill-Salmon Hole Brook region may reflect along-strike variation in syntectonic erosional patterns. At the time of the formation of FIA 0-3, the Salmon Hole Brook-Garnet Hill region must have been too cool to grow garnet, whilst the Orford Piermont region was just reaching garnet-grade temperatures. Additionally, the bulk of crustal thickening in both regions occurred prior to the formation of FIA 3-6; it is partially recorded in FIA 0-2 garnets in the Orford-Piermont region, but is not recorded in any garnets from the Salmon Hole Brook-Garnet Hill region. Figure 8 shows the correlated portions of the *P-T* paths from the two regions based on the FIA data and the overall shape of the paths.

5.5. Thermo-tectonic synthesis

5.5.1. Key observations

The six observations listed below are regarded as centrally important to formulating a model for the tectonic development of the Bronson Hill and western Central Maine terranes.

1. The Salmon Hole Brook-Garnet Hill region was both shallower and cooler than the Orford-Piermont region throughout the prograde metamorphic cycle.
2. Peak metamorphism for both areas was accompanied by little or no crustal thickening
3. Deep seismic reflection studies show west-dipping structures throughout the Bronson Hill and Central Maine terranes
4. There is an eastward younging trend for successive generations of magma from the New Hampshire Plutonic Suite.
5. The New Hampshire Plutonic Suite has been emplaced between regions that do not appear to be structurally continuous, effectively dividing the western portion of the Central Maine Synclinorium into discrete structural blocks.
6. Peak metamorphic temperatures tend to increase and peak pressures tend to decrease to the east on the scale of the structural blocks

5.5.2. Interpretation

- Based on 1,5 and 6, the heat-source for metamorphism lies below the region, but gets shallower to the east
- Based on 3, 4 and 5, the New Hampshire Plutonic Suite has been emplaced along a series of east-verging thrust faults, obscuring original shear-zone textures. The thrust system has propagated eastward in the manner of "piggyback thrusting" (Bell, 1983), with successive generations of granite being emplaced along new thrusts.
- The pressure increase measured in the Orford-Piermont area from 4 to 6 kbar was probably stimulated by thrust emplacement over the region along the Ammonoosuc Fault. Based on 2, burial rates slowed with respect to heating rates towards the peak of metamorphism because thrusting and associated crustal thickening was occurring to the east of the region at this time.
- Based on 1, 2, 3and 6, crustal isotherms for this region appear to have been strongly influenced by magma generation and ascent within the basal detachment of the thrust system.

It is proposed that what has been previously called the Bronson Hill Anticlinorium is actually the core of an east verging imbricate thrust complex that propagated eastward during the Acadian Orogeny. Additionally, it is suggested that the New Hampshire Plutonic Suite was transported and emplaced along successive generations of thrust surfaces as the complex propagated to the east (Figure 9). The previously unrecognised Mt Clough and Cardigan Thrusts are introduced to account for structural discontinuity between metasediments on either side of the granitoids, and are named for the plutons that intruded along them.

The low temperature compression recorded in FIA 0-2 in the Orford-Piermont region is interpreted to reflect burial due to thrusting along the Ammonoosuc Fault. Near-isobaric heating seen during the development of FIA 3-6 reflects the upward migration of isotherms along the basal detachment of the thrust system during and after the emplacement of the New Hampshire Plutonic Suite. The peak of metamorphism and the development of FIA 4-6 are interpreted to post-date thrusting on the Ammonoosuc and Northy Hill Faults, but are potentially synchronous with thrusting and/or plutonism along the Mt Clough and Cardigan Thrusts.

Brown & Solar (1999) suggested that in reverse fault systems granite will initially be transported by percolative flow during active deformation up the shear zone, and on the cessation of deformation will be transported by fracture assisted channelised flow further up the shear zone. Accordingly, they predict that granite will be tend to be emplaced along shear zones in the upper crust after the cessation of thrusting. This model of the timing of magmatism with respect to thrusting is consistent with the observations made in this study. The peak of metamorphism in the Salmon Hole Brook and Garnet Hill blocks occurred after the cessation of reverse movement along the Clough Thrust, and was possibly synchronous with the emplacement of the Kinsman Quartz Monzonite. This model implies that the metamorphic field gradient for the region was the result of an isothermal anticline forming along the basal detachment of the thrust system, lagging behind each subsequent pulse of granite emplacement. Post Acadian extension reactivated the Northy Hill Fault and the Ammonoosuc Fault, resulting in normal displacement across those structures, eliminating the prograde reverse displacement, obscuring prograde kinematic indicators, and juxtaposing the chlorite-grade rocks NW of the Ammonoosuc Fault with the staurolite-grade rocks to the SE.

The cross-section presented here bears a strong similarity to that proposed by Rodgers (1981) for a region in north Connecticut ~200km along strike to the south, lending support to the notion that the Bronson Hill Anticlinorium is, in its entirety, the eroded core of an east-verging, imbricated thrust complex. Deep seismic reflection profiling of southern New Hampshire shows strong, east-dipping reflectors that surface in the vicinity of the Rowe-Hawley Belt and the Connecticut Valley Synclinorium that underlie and truncate the weaker west-dipping reflectors throughout the Bronson Hill and Central Maine Belts (Ando et al., 1984). The reflector geometry in this region has been closely replicated by numerical modelling (Beaumont & Quinlan, 1994). In this modelling, the Rowe-Hawley Belt and the Connecticut Valley Synclinorium are interpreted as being within the retrothrust system, whilst the Bronson Hill and Central Maine Belts are interpreted as part of the prowedge. The model of Beaumont & Quinlan (1994) accurately predicts the vergence, kinematics and eastward, piggyback-style migration of the Bronson Hill Thrust system described in this study, and additionally concurs broadly with the conclusions of Rodgers (1981), that the Acadian Orogeny was stimulated by the partial subduction of the Avalon plate beneath the Laurentian plate.

6. CONCLUSIONS

The simple statistical approach to appraising FIA populations employed here revealed irreconcilable complexity within a large FIA dataset. Although no unique relative timing solution could be defined for the history of FIA development, the relative timing scheme developed for surrounding areas in Bell et al. (2004) was consistent with the data. The Bell et al. (2004) scheme was employed, and FIA development was correlated with the *P*-*T* paths calculated from garnets containing known FIA orientations. In general, the older FIA (sets 0-2) occurred in the early parts of the P-T path and younger FIA (sets 3-6) occurred later in the path, towards the thermal peak. Within these general groupings of older and younger FIA, no consistent ordering of occurrence in *P-T* space could be defined. Consequently, FIA alone are of limited use in developing a relative timing scheme for porphyroblast growth.

If FIA do record the direction of relative plate motion during orogenesis, then measuring these structures is essential to developing a complete tectonic model of the growth of a mountain belt. In this region, the changes in relative plate motion described by FIA measurement imply a very complex tectonic history during the Acadian Orogeny. Indeed, the results from the integration of FIA and *P-T* path calculations suggest that only small portion of the total microstructural history is revealed in this detailed study. Geochronological studies that utilise a technique with a high spatial and analytical resolution, such as nanosims or electron microprobe dating of monazite, appear to be the best method of clarifying the complexity revealed by FIA studies.

What has been referred to in the literature the Bronson Hill Anticlinorium is actually an east verging, eastward migrating imbricate thrust system. The domes exposed along its length are hanging wall block anticlines that formed during thrusting. The strain regime in the Bronson Hill Belt is consistent with the interpretation of the COCORP seismic reflection data and numerical modelling of Beamont & Quinlan (1994). In this context, the west dipping reverse faults represent a prothrust system that overlay the west-dipping subduction of the Avalonian lithospheric mantle beneath Laurentia.

RECONCILING THE STRUCTURAL AND METAMORPHIC RECORD OF OROGENY IN CENTRAL WESTERN NEW HAMPSHIRE VIA FIA AND GARNET ISOPLETH THERMOBAROMETRY

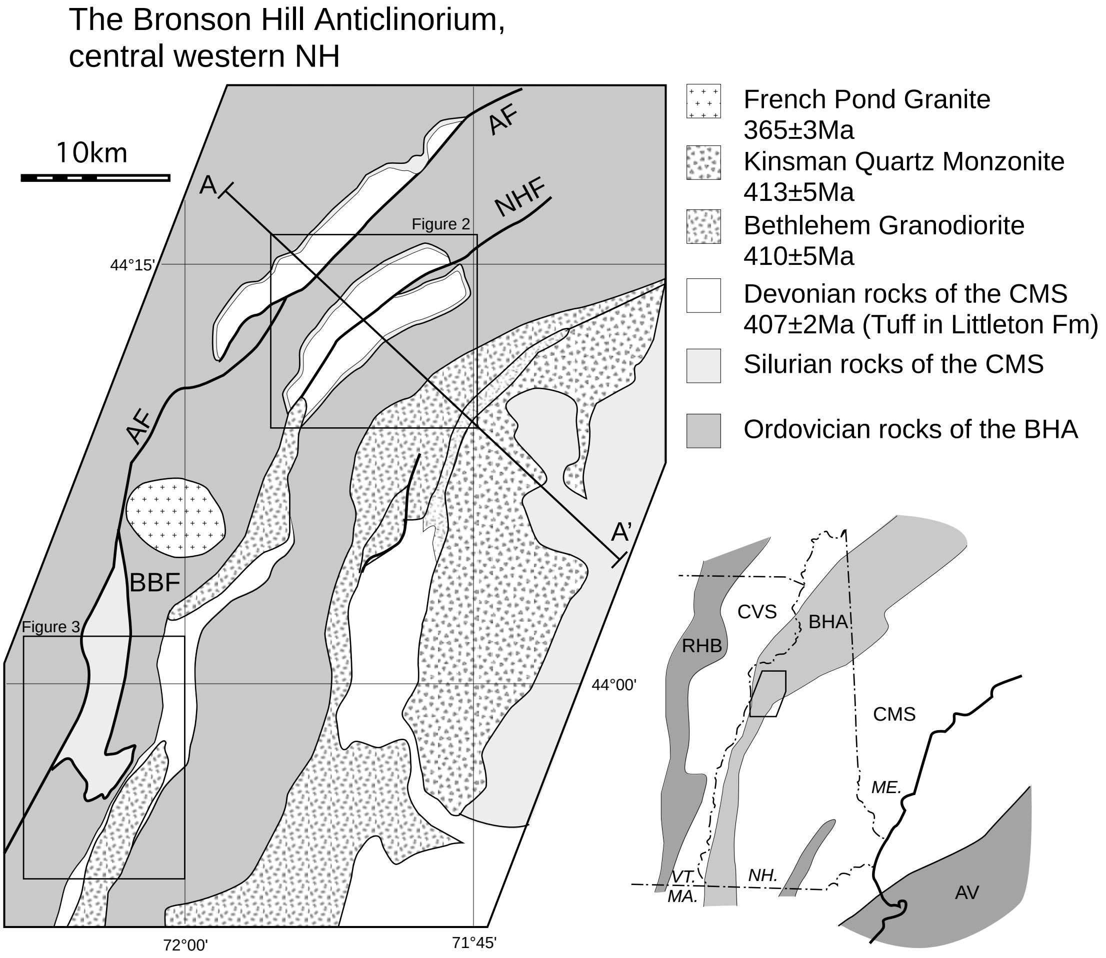

Figure 1. Geological map of the Littleton-Orfordville region, central western New Hampshire, with a tectonic map of NH inset. Figure 2 and 3 locations are shown. Abbreviations in tectonic map: RHB, Rowe-Hawley Belt; CVS, Connecticut Valley Synclinorium; BHA, Bronson Hill Anticlinorium; CMS, Central Maine Synclinorium; AV, Avalon. Abbreviations on geological map: AF, Ammonoosuc Fault; NHF, Northey Hill Fault; BBF, Bean Brook Fault.

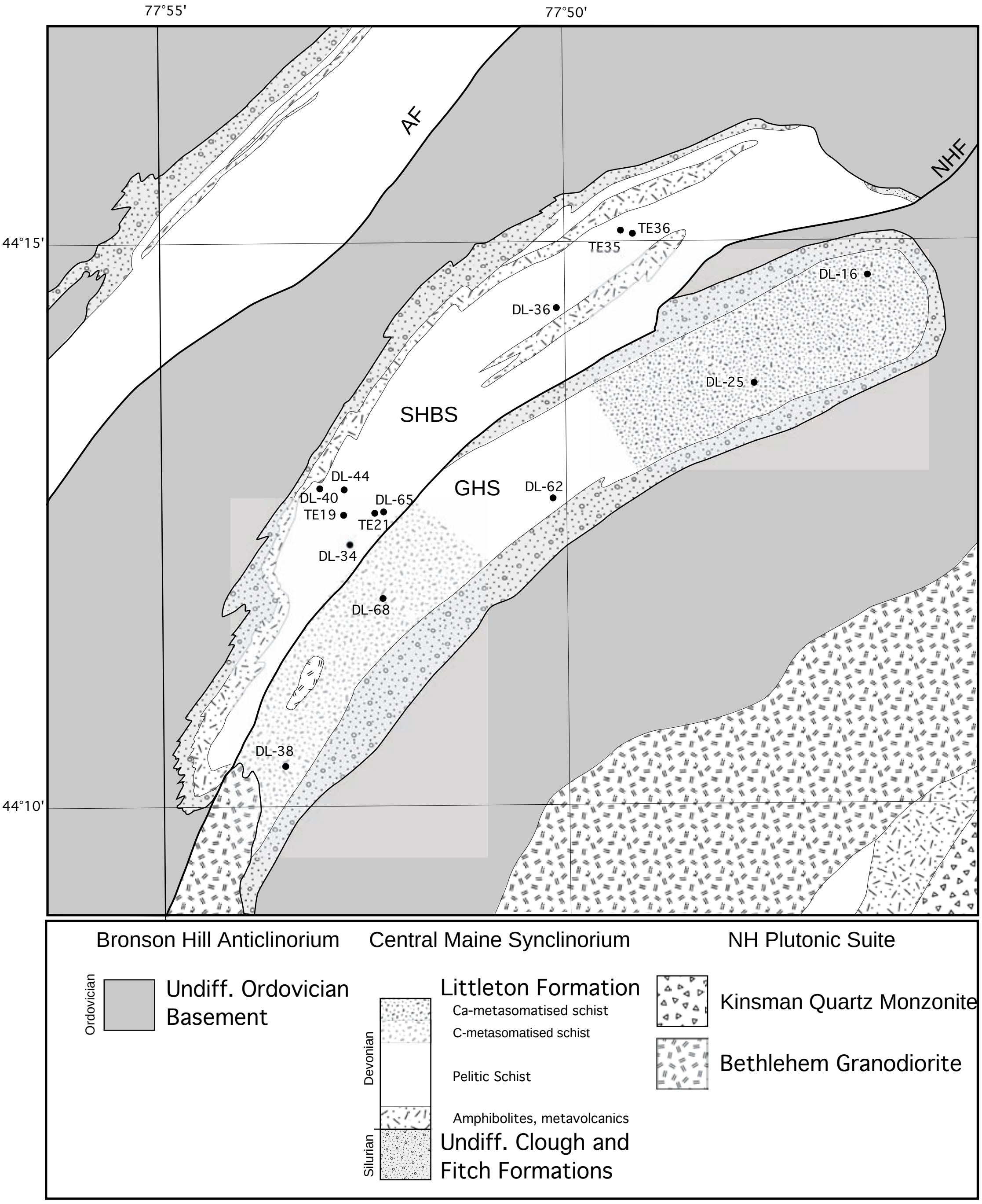

Figure 2. Geological map of the Garnet Hill-Salmon Hole Brook region. Locations of samples use in this study are shown

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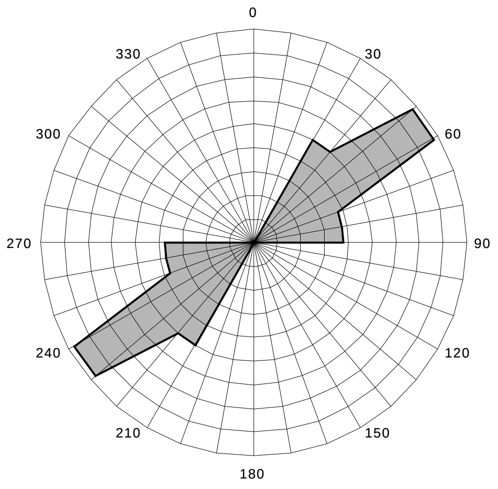
Figure 3. Geological map of the Orford-Piermont region. Map by Timms (2002) Locations of samples used in this study are shown



n=2

Figure 4. Example of the weighted averages plot for FIA ranges. Plot shows two hypothetical FIA measurements, one ranging from 30-60, the other ranging from 50-90. Note how the overlapping portions of each FIA range reinforce to generate a peak.

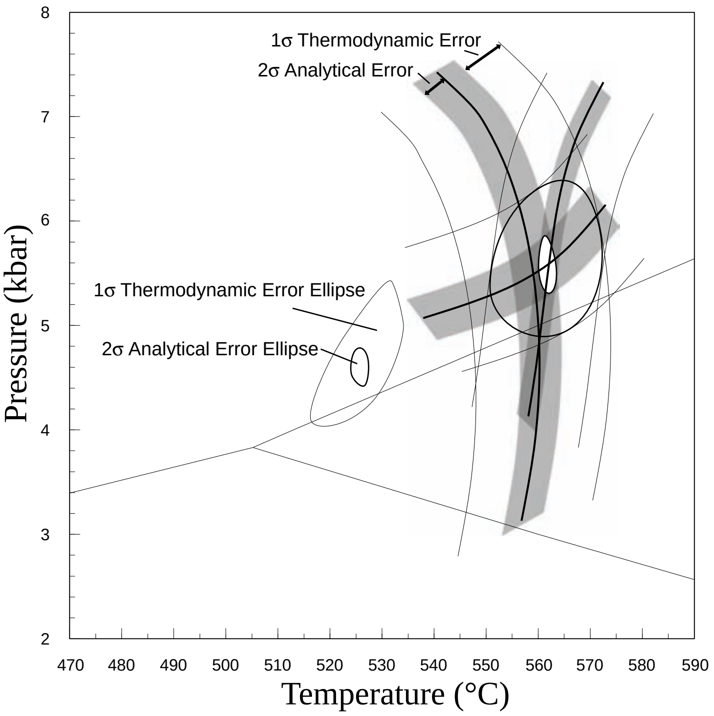
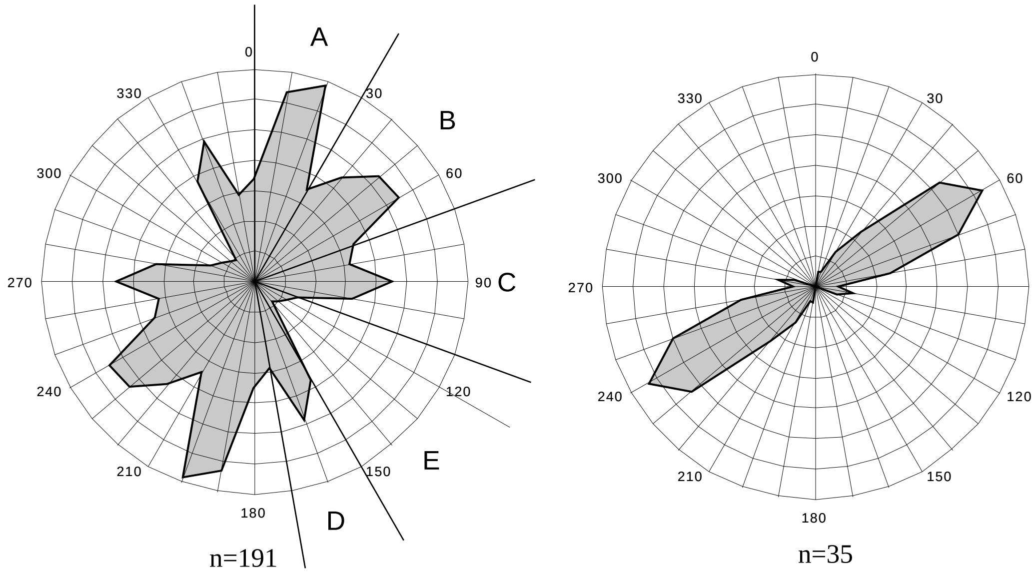


Figure 5. Error contributions in isopleth thermobarometry. Ellipses represent the overlap of the estimable random and systematic error contributions. The tightness of the intersection of the isopleths provides an assessment of the accuracy of the assumption of equilibrium between the garnet and the chemical system in which it is interpreted to be growing



(a) Orford-Piermont Region

(b) Garnet Hill-Salmon Hole Brook Region

Figure 6. FIA results for the **(a)** Orford-Piermont region, and **(b)** Garnet Hill-Salmon Hole Brook region. Boundaries between populations A-E are marked on **(a)**.

Table 1.

Sample No.	Lithology	type	median	plus/minus
NT3	Orfordville fm	garnet core	50	10
NT3	Orfordville fm	garnet core	15	5
NT4	Orfordville fm	chlorite	60	10
NT5	Orfordville fm	garnet core	15	15
NT5	Orfordville fm	staurolite core	15	15
NT6	Orfordville fm	garnet core	45	5
NT7	Orfordville fm	garnet core	40	10
NT8	Littleton fm	garnet core	45	5
NT8	Littleton fm	garnet core	175	5
NT11	Albee fm	garnet core	25	5
NT16	Albee fm	garnet core	65	5
NT24	Rangely fm	garnet core	65	15
NT37	Albee fm	garnet core	50	10
NT38	Albee fm	pFIA	145	5
NT38	Albee fm	garnet core	5	5
NT44	Rangely fm	staurolite core	170	10
NT44	Rangely fm	kyanite	170	10
NT46	Rangely fm	garnet core	85	5
NT46	Rangely fm	staurolite core	85	5
NT49	Albee fm	pFIA	45	5
NT49	Albee fm	garnet core	170	10
NT49	Albee fm	staurolite core	165	5
NT49	Albee fm	staurolite rim	165	5
NT50	Albee fm	pFIA	155	5
NT50	Albee fm	garnet core	90	20
NT51	Rangely fm	garnet core	160	10
NT52	Rangely fm	garnet core	15	5
NT53	Rangely fm	pFIA	155	5
NT53	Rangely fm	garnet core	165	5
NT53	Rangely fm	pFIA	155	5
NT53	Rangely fm	staurolite core	165	5
NT53	Rangely fm	staurolite rim	55	5
NT54	Rangely fm	pFIA	165	15
NT54	Rangely fm	garnet core	15	5
NT54	Rangely fm	pFIA	5	5
NT54	Rangely fm	staurolite core	30	10
NT55	Rangely fm	pFIA	155	5
NT55	Rangely fm	garnet core	155	5
NT55	Rangely fm	pFIA	155	5
NT57	Rangely fm	pFIA	165	15
NT58	Rangely fm	garnet core	45	5
NT61	Albee fm	pFIA	30	10
NT61	Albee fm	garnet core	85	5
NT62	Albee fm	pFIA	35	15
NT62	Albee fm	garnet core	70	10
NT63	Albee fm	pFIA	65	5
NT63	Albee fm	garnet core	125	5
NT65	Albee fm	pFIA	150	10
NT65	Albee fm	garnet core	155	5
NT67	Albee fm	pFIA	15	5
NT67	Albee fm	garnet core	35	15

Table 1 cont.

Sample No.	Lithology	type	median	plus/minus
NT67	Albee fm	staurolite core	70	10
NT69	Albee fm	garnet core	50	10
NT69	Albee fm	garnet core	50	10
NT69	Albee fm	staurolite core	50	10
NT70	Albee fm	garnet core	155	5
NT70	Albee fm	garnet core	55	5
NT71	Albee fm	garnet core	5	5
NT72	Albee fm	garnet core	30	10
NT72	Albee fm	garnet core	70	10
NT74	Albee fm	garnet core	85	5
NT81	Albee fm	pFIA	95	5
NT81	Albee fm	garnet core	85	5
NT81	Albee fm	garnet core	15	5
NT83	Albee fm	pFIA	65	5
NT83	Albee fm	garnet core	95	5
NT86	Albee fm	pFIA	45	5
NT86	Albee fm	garnet core	65	5
NT86	Albee fm	garnet core	165	5
NT86	Albee fm	staurolite core	110	40
NT87	Albee fm	pFIA	50	10
NT87	Albee fm	garnet core	15	5
NT87	Albee fm	garnet core	90	10
NT90	Rangely fm	pFIA	100	20
NT93	Rangely fm	pFIA	15	15
NT95	Rangely fm	garnet core	15	5
NT95	Rangely fm	pFIA	15	5
NT95	Rangely fm	staurolite core	100	10
NT95	Rangely fm	kyanite	100	10
NT96	Rangely fm	garnet core	75	15
NT99	Rangely fm	pFIA	55	5
NT102	Albee fm	pFIA	15	5
NT102	Albee fm	garnet core	15	5
NT103	Albee fm	pFIA	155	5
NT103	Albee fm	garnet core	145	5
NT104	Albee fm	garnet core	105	15
NT105	Rangely fm	pFIA	115	25
NT105	Rangely fm	garnet core	140	10
NT110	Rangely fm	pFIA	105	15
NT110	Rangely fm	garnet core	85	5
NT114	Albee fm	pFIA	95	5
NT114	Albee fm	garnet core	20	10
NT114	Albee fm	garnet core	85	5
NT115	Albee fm	pFIA	5	5
NT117	Albee fm	pFIA	70	10
NT118	Albee fm	pFIA	25	25
NT118	Albee fm	pFIA	115	15
NT118	Albee fm	staurolite core	145	15
NT125	Albee fm	garnet core	65	25
NT126	Albee fm	pFIA	10	10
NT126	Albee fm	garnet core	10	10
NT126	Albee fm	garnet core	20	10

Table 1 cont.

Sample No.	Lithology	type	median	plus/minus
NT127	Albee fm	pFIA	105	5
NT127	Albee fm	garnet core	75	5
NT130	Albee fm	pFIA	95	5
NT130	Albee fm	garnet core	25	5
NT130	Albee fm	garnet core	75	5
NT132	Albee fm	garnet core	30	10
NT132	Albee fm	staurolite core	175	5
NT133	Albee fm	pFIA	5	5
NT133	Albee fm	garnet core	20	10
NT133	Albee fm	staurolite core	15	5
NT134	Albee fm	pFIA	50	10
NT134	Albee fm	garnet core	95	5
NT134	Albee fm	pFIA	50	50
NT136	Albee fm	pFIA	160	10
NT136	Albee fm	garnet core	155	5
NT137	Albee fm	pFIA	25	25
NT137	Albee fm	garnet core	130	10
NT138	Albee fm	pFIA	85	5
NT138	Albee fm	pFIA	135	15
NT138	Albee fm	garnet core	175	5
NT141	Albee fm	pFIA	155	5
NT141	Albee fm	garnet core	155	5
NT141	Albee fm	garnet core	15	5
NT141	Albee fm	staurolite core	15	5
NT142	Albee fm	garnet core	15	15
NT142	Albee fm	garnet core	15	15
NT143	Albee fm	pFIA	55	5
NT143	Albee fm	garnet core	165	15
NT143	Albee fm	garnet core	165	5
NT144	Albee fm	garnet core	95	5
NT147	Albee fm	garnet core	95	5
NT152	Albee fm	garnet core	50	10
NT152	Albee fm	staurolite core	45	15
NT153	Rangely fm	pFIA	105	15
NT155	Rangely fm	garnet core	165	5
NT160	Rangely fm	pFIA	75	15
NT160	Rangely fm	garnet core	15	5
NT160	Rangely fm	staurolite core	15	5
NT161	Albee fm	garnet core	15	5
NT161	Albee fm	garnet core	5	5
NT162	Albee fm	garnet core	90	30
NT180	Rangely fm	pFIA	90	10
NT180	Rangely fm	garnet core	45	5
NT185	Orfordville fm	garnet core	50	10
NT186	Orfordville fm	garnet core	125	5
NT186	Orfordville fm	garnet core	105	5
NT188	Orfordville fm	garnet core	55	15
NT190	Albee fm	pFIA	65	5
NT190	Albee fm	garnet core	10	10
NT191	Albee fm	garnet core	25	5
NT191	Albee fm	garnet core	50	20

Table cont.

Sample No.	Lithology	type	median	plus/minus
NT194	Albee fm	pFIA	10	10
NT194	Albee fm	garnet core	65	5
NT197	Albee fm	garnet core	55	5
NT197	Albee fm	garnet core	25	5
NT200	Albee fm	garnet core	25	5
NT201	Albee fm	pFIA	20	10
NT201	Albee fm	garnet core	45	5
NT202	Albee fm	pFIA	175	5
NT202	Albee fm	garnet core	25	5
NT203	Albee fm	pFIA	55	15
NT203	Albee fm	garnet core	55	5
NT204	Albee fm	pFIA	120	10
NT204	Albee fm	garnet core	15	5
NT204	Albee fm	garnet core	95	5
NT206	Albee fm	pFIA	65	5
NT206	Albee fm	garnet core	70	10
NT206	Albee fm	garnet core	85	15
NT212	Rangely fm	pFIA	15	15
NT212	Rangely fm	kyanite	15	15
NT213	Albee fm	garnet core	100	10
NT213	Albee fm	staurolite core	100	10
NT214	Albee fm	pFIA	55	15
NT214	Albee fm	garnet core	45	5
NT214	Albee fm	pFIA	45	5
NT214	Albee fm	staurolite core	45	5
NT216	Albee fm	pFIA	15	5
NT216	Albee fm	garnet core	65	5
NT216	Albee fm	garnet core	105	15
NT217	Albee fm	pFIA	20	10
NT217	Albee fm	garnet core	155	5
NT217	Albee fm	staurolite core	20	20
NT219	Albee fm	pFIA	35	5
NT219	Albee fm	garnet core	65	5
NT219	Albee fm	pFIA	55	5
NT219	Albee fm	staurolite core	55	5

Table 1. FIA data for the Orford-Piermont region. pFIA designates the orientation of curvature of a foliation within a porphyroblast where the formation of that curvature pre-dates porphyroblast growth.

Table 2.

		FIA in porphyroblast rim				
	FIA sets	A	B	C	D	E
FIA in porphyroblast core	A	3	1	4	0	0
	B	2	1	0	2	0
	C	1	0	0	0	0
	D	1	2	0	2	0
	E	0	0	1	0	0

Table 2. Core-rim FIA orientation transitions for the Orford-Piermont region.

Table 3.

Sample No.	Lithology	type	median	plus/minus
te33	Littleton fm	garnet core	60	10
te34	Littleton fm	garnet core	60	10
dl-16	Littleton fm	garnet core	70	10
dl-16	Littleton fm	biotite	70	10
dl-16	Littleton fm	staurolite core	50	10
dl-25	Littleton fm	garnet core	70	10
dl-25	Littleton fm	staurolite core	45	5
dl-25	Littleton fm	biotite	70	10
dl-30	Littleton fm	garnet core	60	10
dl-30	Littleton fm	garnet core	60	10
dl-30	Littleton fm	biotite	60	10
dl-36	Littleton fm	chloritoid	20	10
dl-36	Littleton fm	garnet core	60	10
dl-36	Littleton fm	biotite	60	10
dl-38	Littleton fm	garnet core	70	10
dl-38	Littleton fm	staurolite core	70	10
dl-44	Littleton fm	garnet core	45	15
dl-62	Littleton fm	garnet core	100	10
dl-62	Littleton fm	staurolite core	105	5
dl-65	Littleton fm	garnet core	60	10
dl-65	Littleton fm	staurolite core	60	10
dl-68	Littleton fm	garnet core	20	10
dl-68	Littleton fm	garnet core	40	10
dl-68	Littleton fm	staurolite core	40	10
te19	Littleton fm	garnet core	60	10
te19	Littleton fm	staurolite core	60	10
te21	Littleton fm	garnet core	70	10
te21	Littleton fm	garnet core	70	10
te36	Littleton fm	chloritoid	50	10
te36	Littleton fm	garnet core	50	10
te36	Littleton fm	garnet core	50	10
dl-64	Littleton fm	garnet core	60	10
dl-64	Littleton fm	garnet core	90	10
dl-64	Littleton fm	staurolite core	90	10
dl-40	Littleton fm	garnet core	45	15

Table 3. FIA data for the Garnet Hill-Salmon Hole Brook region.

Table 4.

		FIA in porphyroblast rim				
	FIA sets	A	B	C	D	E
FIA in porphyroblast core	A	0	1	0	0	0
	B	0	2	1	0	0
	C	0	0	0	0	0
	D	0	0	0	0	0
	E	0	0	0	0	0

Table 4. Core-rim FIA orientation transitions for the Garnet Hill-Salmon Hole Brook region.

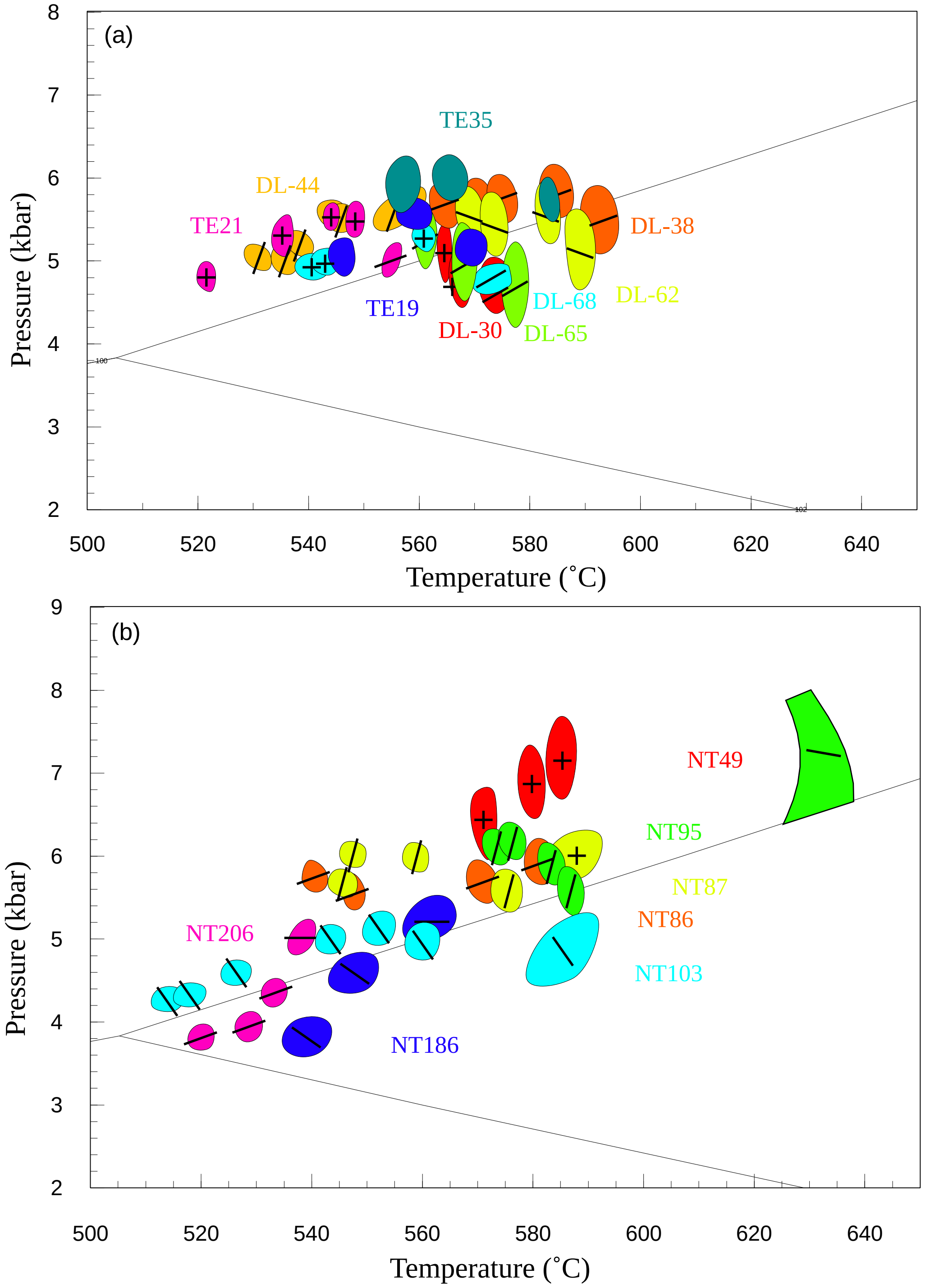


Figure 7. P-T paths for samples from **(a)** the Salmon Hole Brook-Garnet Hill region and **(b)** the Orford-Piermont region. Lines on each P-T point illustrate the orientation of the FIA in which analyzed garnet grew, a cross indicates that the garnet grew during subhorizontal cleavage formation. The green area at high P-T shows the stability field calculated for staurolite + kyanite for NT95 with the st and ky FIA plotted within it.

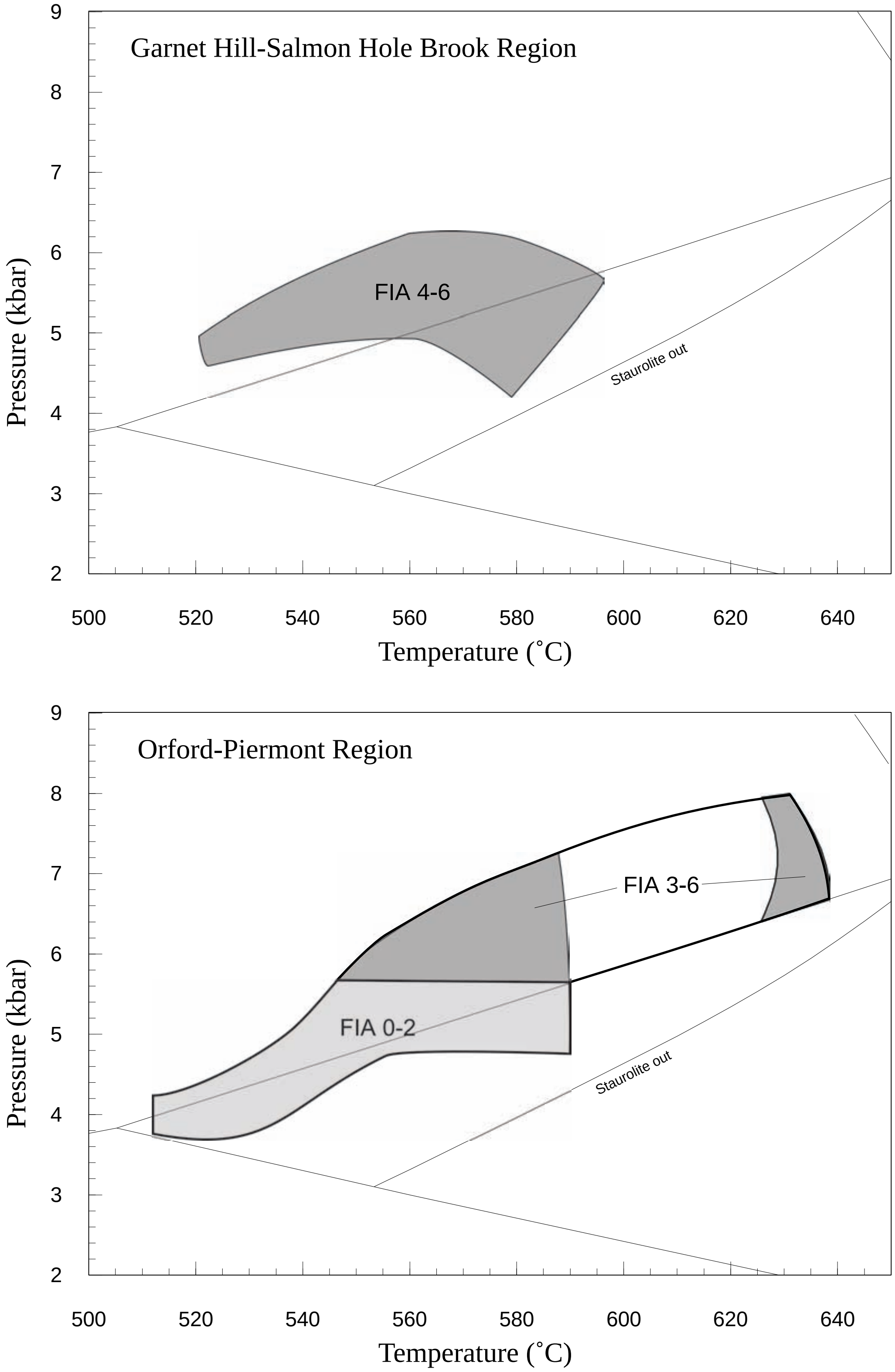


Figure 8. Comparison of calculated P-T paths correlated by FIA and P-T trajectory. The dark shaded area is interpreted to temporally correlate between regions. The line marked “staurolite out“ represents the likely highest temperature possible for the stability of staurolite in the sillimanite and kyanite-bearing fields.

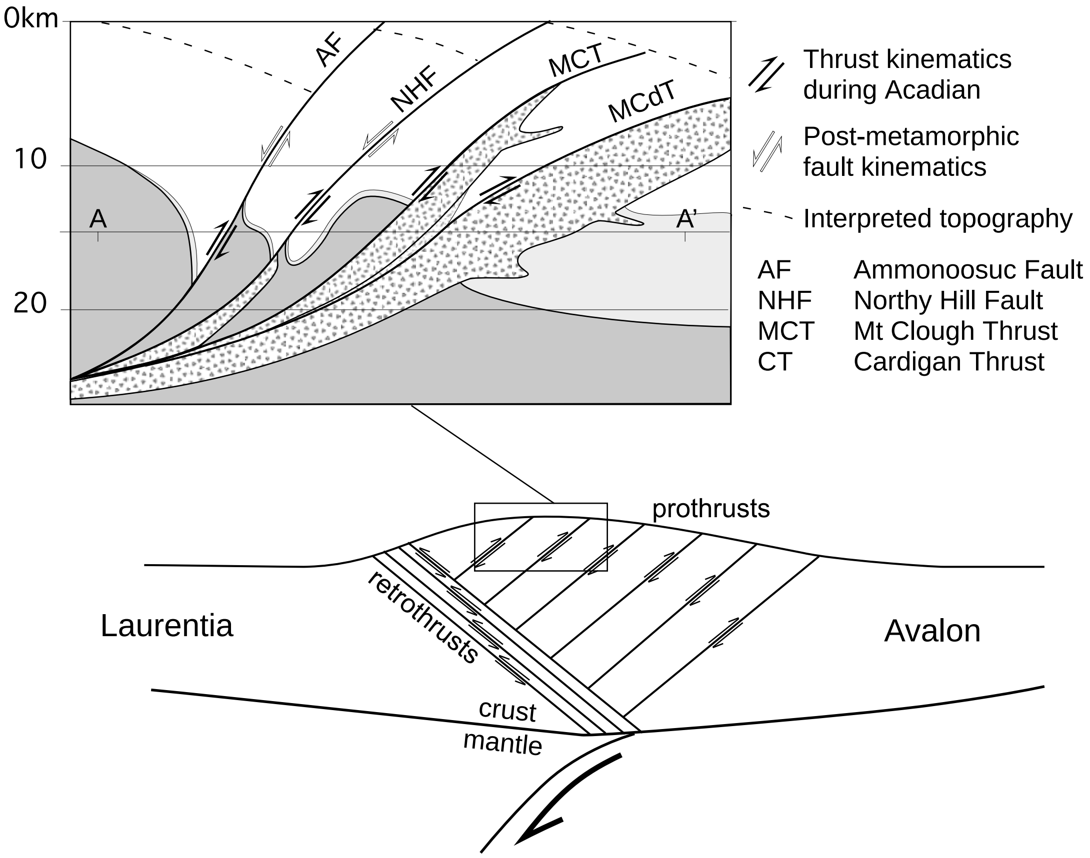


Figure 9. Interpretative cross-section A-A’ on figure 1, showing the prograde and retrograde fault kinematics leading to the current arrangement of crustal blocks in the Bronson Hill Belt. The Ammonoosuc Fault is the oldest thrust, the Cardigan Thrust is the youngest. Approximate current ground level is marked by the line A-A’. The cross section is interpreted to be part of a distributed prothrust belt, after the modelling of Beaumont & Quinlan (1994)