Journal of Structural Geology 26 (2004) 2157–2174

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

The drawbacks of sectioning rocks relative to fabric orientations in the matrix: A case study from the Robertson River Metamorphics (Northern Queensland, Australia)

M. Cihan

School of Earth Sciences, James Cook University, Townsville, Queensland 4811, Australia

Received 28 December 2003; received in revised form 4 June 2004; accepted 4 July 2004

Abstract

Understanding the relationships of inclusion trail geometries in porphyroblasts relative to matrix foliations is vital for unravelling complex deformation and metamorphic histories in highly tectonized terranes and the approach used to thin sectioning rocks is critically important for this. Two approaches have been used by structural and metamorphic geologists. One is based on fabric orientations with sections cut perpendicular to the foliation both parallel (P) and normal (N) to the lineation, whereas the other uses geographic orientations and a series of vertical thin sections. Studies using P and N sections reveal a simple history in comparison with studies using multiple-vertical thin sections. The reason for this is that inclusion trails exiting the porphyroblasts into the strain shadows in P and N sections commonly appear continuous with the matrix foliation whereas multiple vertical thin sections with different strikes reveal that they are actually truncated. Such truncations or textural unconformities are apparent from microstructures, textural relationships, compositional variations and FIA (foliation intersection axis) trends. A succession of four FIA trends from ENE–WSW, E–W, N–S to NE–SW in the Robertson River Metamorphics, northern Queensland, Australia, suggests that these truncations were formed because of the overprint of successive generations of orthogonal foliations preserved within porphyroblasts by growth during multiple deformation events. At least four periods of orogenesis involving multiple phases of porphyroblast growth can be delineated instead of just the one previously suggested from an N and P section approach.

Keywords: Robertson River Metamorphics; Truncation; Inclusion trails; Porphyroblast growth; Reactivation

1. Introduction

Thin section examination of inclusion trails in porphyroblasts is an important tool used to elucidate the relative timing of porphyroblast growth and deformation. Establishing such relationships is vital if the complex deformation and metamorphic history of highly tectonized terranes is to be resolved. Recent studies (e.g. Vernon et al., 1993; Bell and Hickey, 1999; Paterson and Vernon, 2001) have debated conflicting interpretation of microstructures and the deformation history that in part have resulted from different approaches to thin sectioning. One is based on fabric orientations in the matrix whereas the other is based on geographic directions around the compass. Most structural and metamorphic geologists over the past 30 years have cut their thin sections with respect to fabric orientations in the matrix. This is called the P–N approach for brevity and the thin sections are cut parallel to lineation but perpendicular to foliation (P), and perpendicular to lineation and foliation (N; Bell and Rubenach, 1983; Fig. 1). A major ongoing controversy, partly raised because of these different approaches, is whether rotation or non-rotation of porphyroblasts is the applicable model. For the first model, a major factor has been continuity of inclusion trails with the matrix, suggesting the interpretation that porphyroblasts have rotated causing the internal foliation (Si) to change orientation relative to external foliation or shear plane (Se). This geometry is very typical in P and N sections but commonly does not hold true when multiple vertical thin sections have been cut. The latter commonly reveal that porphyroblast inclusion trails are truncated in 3-D by the

E-mail address: mustafa.cihan@jcu.edu.au.

0191-8141/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2004.07.001

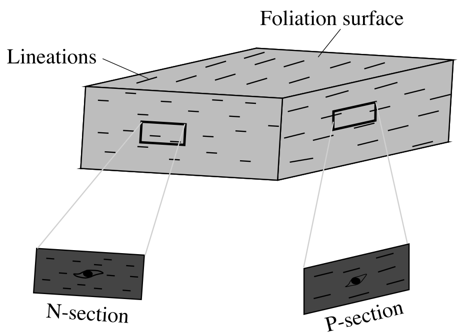

Fig. 1. Sketch showing a P section (perpendicular to foliation plane and parallel to lineation) and an N section (perpendicular to foliation and lineation).

matrix foliation and that the porphyroblasts have not necessarily rotated. Understanding which model is a more reliable paradigm regarding porphyroblast behaviour for a specific area has important inferences for solving deformation histories. This has been tested in a number of studies (e.g. Bell and Hayward, 1991; Hayward, 1992; Johnson, 1992; Bell et al., 1995; Johnson and Vernon, 1995; Bell and Hickey, 1999; Bell and Chen, 2002) by measuring the foliation intersection axes (FIAs) preserved within porphyroblasts. The reason for this difference between the interpretations resulting from the two thin sectioning approaches is that P and N sections generally contain strain shadows around the porphyroblasts relative to the matrix foliation in which the inclusion trails exiting the porphyroblasts appear continuous with the matrix foliation. This problem is illustrated using the Robertson River Metamorphics where early studies using P and N sections revealed a relatively simple history of porphyroblast growth. Multiple vertical thin sections with different strikes have revealed a far more complex history than expected from the relative apparent continuity of inclusion trails with the matrix foliations initially observed.

2. Robertson River Metamorphics

The Robertson River Metamorphics lie within the Georgetown Inlier, which is one of the largest exposures of Precambrian rocks in Northern Queensland (Fig. 2a). It is separated by Phanerozoic rocks from other inliers such as the Yambo, Coen, Woolgar and Mt. Isa. These inliers have been linked to similar sequences in North America that drifted apart nearly one billion years ago during the break-up of the supercontinent Rodinia (Blewett et al., 1998; Karlstrom et al., 1999). The area described herein includes intrusive rocks as well as highly deformed metamorphic rocks such as phyllites, pelitic schists, quartzites and amphibolites, which underwent prograde metamorphism (Fig. 2c). These metamorphic rocks contain a greenschist to amphibolite facies metamorphic transition that has resulted in extensive porphyroblast growth with well-developed inclusion trails. Two stratigraphic units, the Dead Horse Metabasalt and Cobbolt Metadolerite, outline the major structural features, which are an ENE–WSW- to E–W-trending overturned antiform and synform. N–S- and NE–SW-trending folds refolded these structures.

Bell and Rubenach (1983) proposed that there were six deformational events in the Robertson River Metamorphics. The first two events, dated as D_1 1570 ± 20 Ma and D_2 ~1550 Ma (Black et al., 1979, 1998), created penetrative foliations associated with prograde metamorphism, whereas the last four produced local crenulations and are commonly associated with retrograde metamorphism. Bell and Rubenach (1983) used P and N sections and claimed that porphyroblasts grew over S_1 during D_2 since curving inclusion trails exiting the porphyroblasts appeared continuous with the penetrative schistosity they called S_2 in the matrix (Davis, 1995). They recognized that in some sections S_1 was a differentiated crenulation cleavage and, therefore, that there was potential for an extra deformation pre S_1. Subsequent comparison of P–N sections with multiply oriented vertical thin sections has revealed that many inclusion trails exiting porphyroblasts, which appear to be continuous with matrix foliation, are in fact truncated in 3-D and a much more extensive history of porphyroblast growth has now been recognized.

3. Study methods

Sixty-eight spatially oriented samples collected from the study area were reoriented in the laboratory and horizontal rock slabs were marked and cut. Multiple vertical blocks around the compass were cut from these slabs (Fig. 3a). The matrix–porphyroblast relationships were examined using 8–10 vertical thin sections cut by this approach. The FIAs were measured for each rock sample from these thin sections as described by Hayward (1990) and Bell et al. (1995, 1998). Initially these sections were cut from blocks with 30° increments and then two more were prepared at 10° intervals between the two in which the curvature of inclusions (clockwise/anticlockwise) switched one to another when viewed from the one direction. The FIAs were then determined as lying between the 10° sections where the asymmetry changed (Fig. 3b). This is shown in Fig. 4 where vertical thin sections cut from the same rock sample are presented. When they are examined from the one direction, inclusion trails indicate the same clockwise asymmetries within the core of the garnet porphyroblasts in all but the 170° section (Fig. 4g), which contains some symmetric shaped inclusions and the 180° striking thin section (opposite view of 000° section; Fig. 4h), which shows an anticlockwise symmetry. The FIA should lie around 170° or very close to it; for this sample the FIA was determined to be at 175°. FIA trends are detached from the assumption of whether porphyroblasts rotate or not. If the porphyroblasts rotate, the FIA will be a rotation axis and lie perpendicular to the shearing direction (Rosenfeld, 1970;

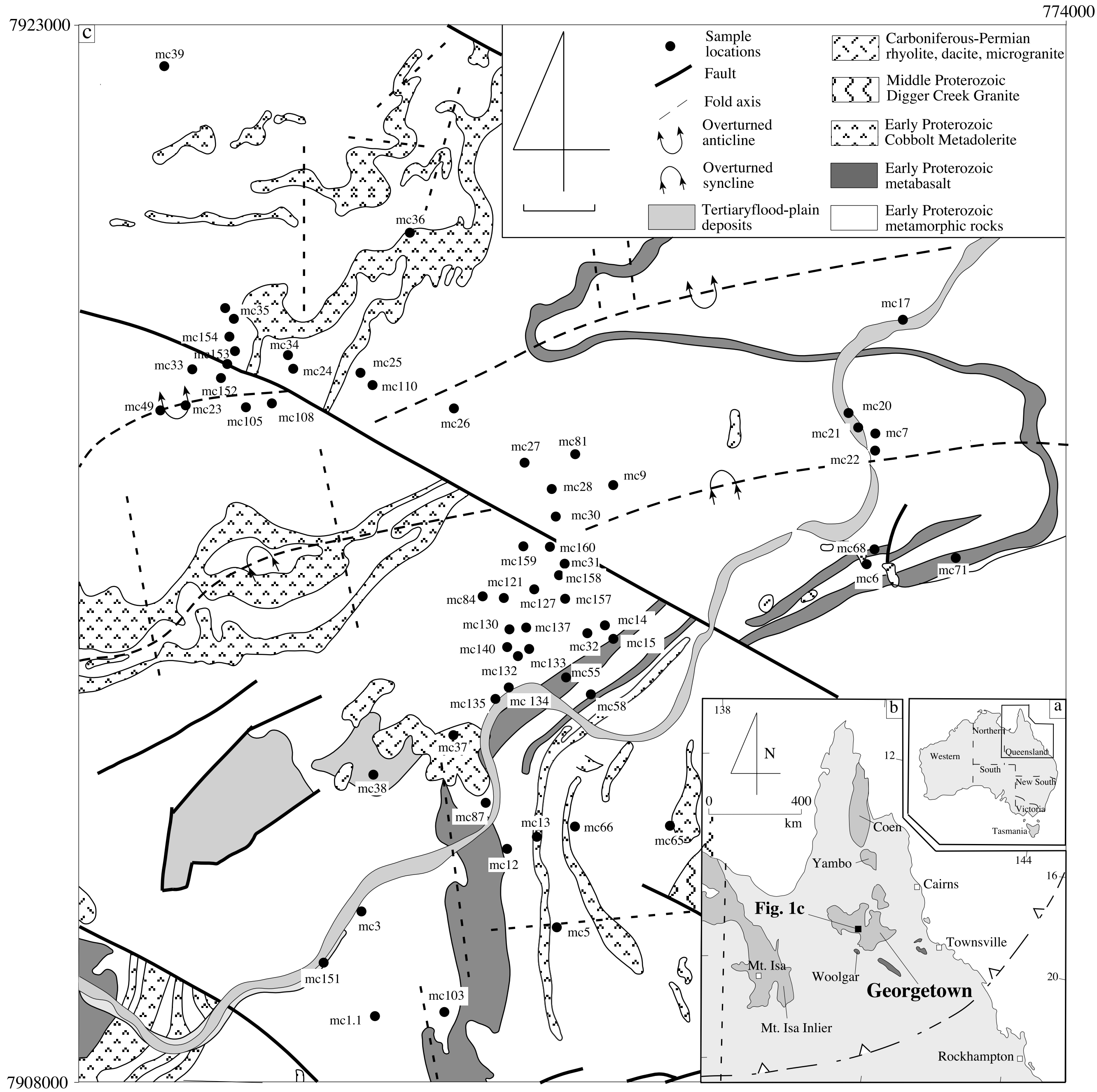

Fig. 2. Location maps of major regional geological features ((a) and (b)) in which geological map of the area (c) is outlined by a rectangular box.

Schoneveld, 1979). If they do not, the FIA trend will lie perpendicular to the direction of bulk shortening (Bell et al., 1995). P and N sections were also prepared from representative rock samples where the matrix truncates the inclusion trails of early porphyroblasts in vertical thin section orientations. In addition to these, a representative garnet porphyroblast was analysed to check compositional anomalies across the truncation boundary or textural disconformity. This analysis is based on X-ray maps plus line traverses across the porphyroblast. X-ray maps were generated on a JxA-8200 electron microprobe. These maps were created by a 512×512 stage scan analysis made with both WDS and EDS spectrometers at 100 nA beam current, 15 kV and 80 ms count times. Line traverses include 54 analyses taken at 20 μm spacing. These were acquired with EDS by a JxA-840A microprobe.

4. FIA data

One hundred and twelve FIA measurements were determined from both garnet and staurolite porphyroblasts

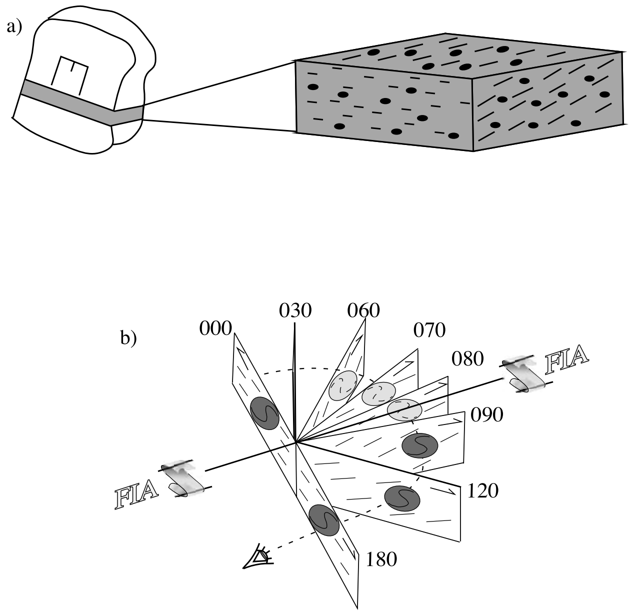

Fig. 3. Sketches of the oriented rock sample marked and cut into a horizontal slab (a) and multiple-vertical thin sections (b). FIA is the foliation intersection/inflection axis preserved within porphyroblasts.

in 68 spatially oriented rock samples. The succession of FIAs was decided based on the changes in trend from the core to rim of porphyroblasts plus the textural link between garnet and staurolite porphyroblasts in places where the former is preserved as inclusions within the latter. The core must grow earlier than the rim and the growth of garnet appears to occur earlier than staurolite in all rock samples. This usually provides relative timing for the two or three different FIA trends present in the same rock sample. Four dominant peaks (Fig. 5a) with ENE–WSW, E–W, N–S and NE–SW directions can be distinguished on a rose diagram. These data were also separated into garnet versus staurolite FIAs (Fig. 5b and c). The nearly ENE–WSW (FIA1)- and E–W (FIA2)-trending FIAs were observed dominantly in the core and rim of the earliest garnet porphyroblasts, whereas only in a few samples were FIA2 (E–W) trends recorded within staurolite porphyroblasts. FIA1 (ENE–WSW) trends range from 50° to 70° but FIA2 (E–W) trends vary between 80° and 130°. This was followed by nearly N–S (FIA3; 170°–020°N)-trending FIAs that are common in both garnet and staurolite porphyroblasts. The last FIA trend (FIA4; NE–SW, 20°–45°) is only present within staurolite porphyroblasts. To determine whether the trends observed within both porphyroblasts are from the same population statistically, the X^2 test (e.g. Upton, 1992; Bell et al., 1998) was also applied. The X^2 values (55.2; 37.3) for this comparison are far higher than the critical values of 5.99 and 9.49 for two and four degrees of freedom, respectively (Table 1). This suggests that these two groups of data contain two different populations.

5. Compositional data

Compositional maps of a garnet porphyroblast from sample mc37 include the Xgrs (Ca), Xpyr (Mg), Xsps (Mn) and Xalm (Fe) components. The typical zoning patterns (Fig. 6) suggest a boundary between the core and rim of the porphyroblast. Xpyr and Xalm distinctly increase in the rim, whereas other components, Xsps and Xgrs decrease. The boundary between core and rim is marked by a sharp decrease in Xsps from core to rim, yet an increase in Xpyr and Xgrs, as shown with vertical dash lines that refer to a truncation zone on the line traverses (Fig. 6). This boundary is characterized by zoning reversals (e.g. Xalm, Xgrs, Xpyr in Fig. 6) and steepened compositional gradients (e.g. Xsps in Fig. 6). The typical zonation patterns are generally attributed to growth zoning and/or diffusion zoning (e.g. Spear, 1993). The growth zoning occurs where compositional differences arise during the growth of a crystal due to changing external conditions such as changing P–T conditions, or a change in the local bulk composition of the rock. The diffusion zoning, on the other hand, requires modification of the pre-existing garnet composition in the absence of growth or consumption of the crystal by the volume diffusion because of the external conditions. Although, the examples presented here classically suggest growth rather than diffusion zoning, requiring a more homogeneous distribution and gradient of the compositions

Table 1
X^2 test of independence of the null hypothesis that the distribution of the variables (FIA trends) is from the same population. Test results are assessed at the 0.05 level of significance. The outcome of the test suggests that garnet and staurolite FIAs differ significantly from each other

Three groups			Using five rather than three groups		
Actual	Garnet	Staurolite	Actual	Garnet	Staurolite
127°–020°	24	18	180°–030°	7	6
021°–50°	5	17	031°–070°	17	15
051°–126°	45	3	071°–120°	29	3
			121°–160°	5	0
			161°–179°	16	14
	74	38		74	38
$X^2=$	55.2003		$X^2=$	37.2494	
d.f.=2	$X^2_{0.05}=5.99$		d.f.=4	$X^2_{0.05}=9.49$	
P=	6.2228×10^{-12}		P=	1.6003×10^{-7}	

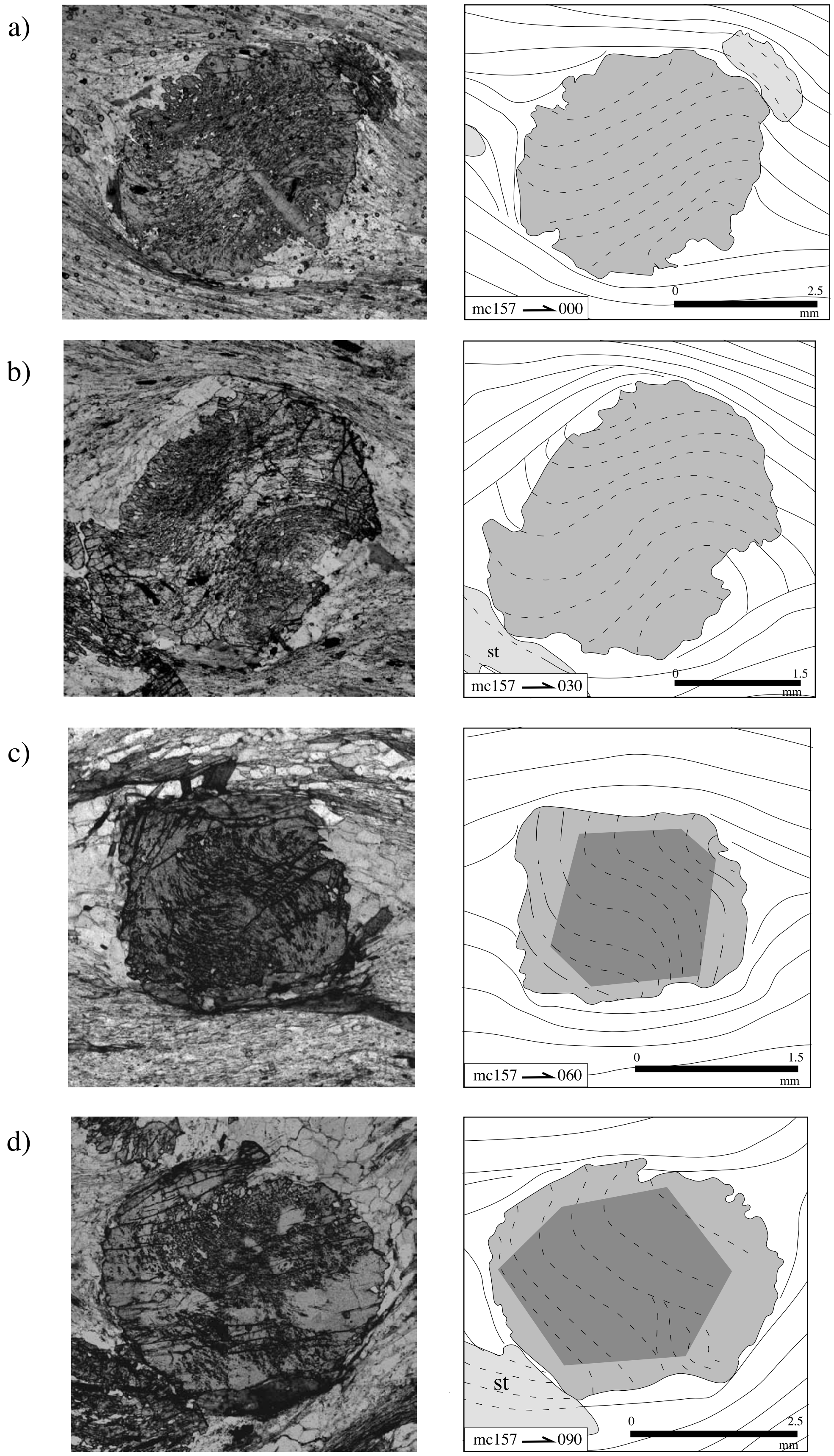

Fig. 4. Photographs and line diagrams ((a)–(g)) of garnet porphyroblasts taken from vertical thin sections in different orientations around compass. Shaded areas at the core of the porphyroblasts in (c)–(f) represent early growth of these and can only be observed in these orientations.

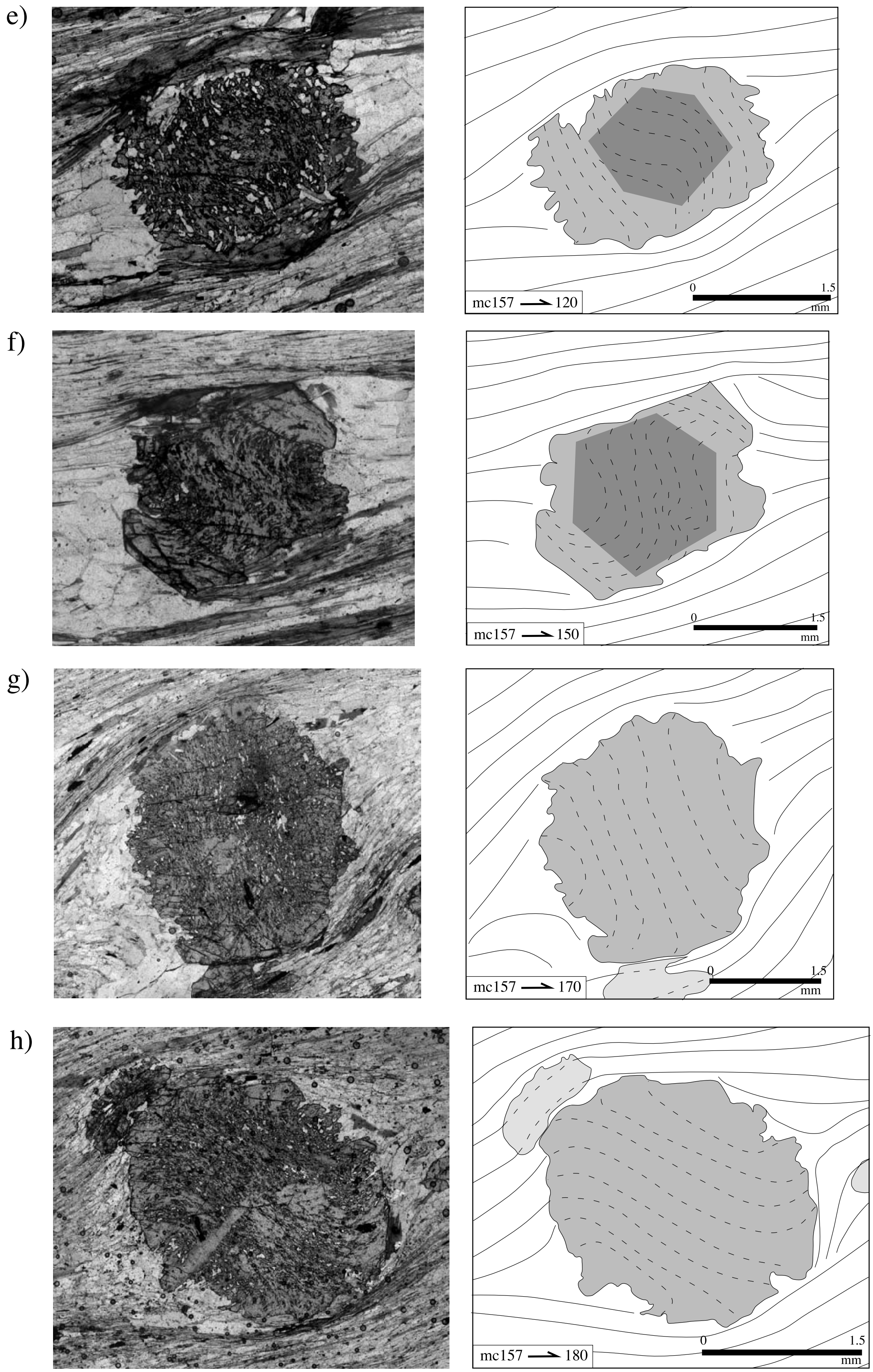

Fig. 4 (*continued*)

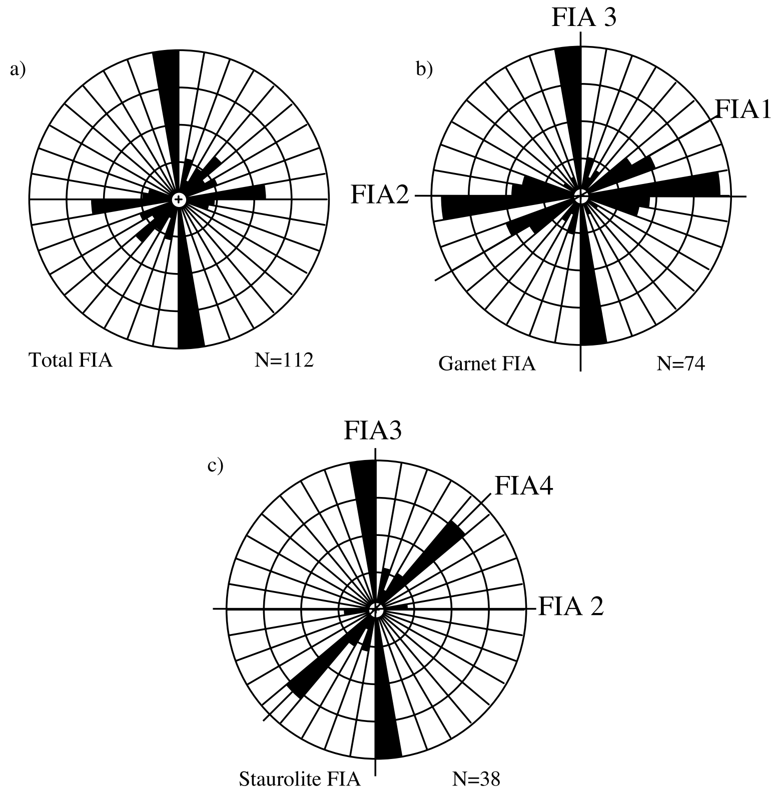

Fig. 5. Rose diagrams of total FIA trends (a), garnet FIAs (b) and staurolite FIAs (c).

throughout the porphyroblasts, diffusion effects cannot be completely excluded but should be negligible (Cihan, 2004).

6. Inclusion trails in porphyroblasts

The inclusion trails, which are well preserved in garnet and staurolite porphyroblasts, include mainly elongate quartz grains as well as plagioclase, graphite, mica and epidote. These inclusion trails are usually sigmoidally shaped and abruptly deflect adjacent to the matrix foliations (Fig. 4c–f). These textural discontinuities are very common within garnet porphyroblasts between the core and the rim as well (Figs. 7 and 8). In some thin section orientations, especially the ones that are parallel to the FIA, more symmetric shaped inclusions (Fig. 4g) are present. Garnet is commonly overgrown by staurolite porphyroblasts that contain inclusion trails. These trails truncate those within the garnet or lie parallel to the rim inclusions (Fig. 8). Although inclusions within garnet porphyroblasts look continuous in P–N sections with the matrix foliation (Fig. 9) in other thin section orientations they are truncated or partly continuous (Fig. 4c–f). Since the inclusion trails in staurolite porphyroblasts are continuous with the matrix, they can be correlated with matrix foliations. There are three types of inclusion trail geometries trapped in staurolite porphyroblasts, which are characterized by different generations of staurolite growth and which are only recognizable with the help of multiple vertical thin sections. One type is preserved as differentiated crenulation cleavages, the long limbs of which are generally curved and continuous with the dominant matrix foliation (Fig. 10). The second type is slightly sigmoidal or curved defining the crenulation hinge (Fig. 11), and the last type is usually straight and parallel to the matrix foliation (Fig. 8).

7. Truncation or truncation zones

Truncation zones or truncations in porphyroblasts and/or at the matrix–porphyroblast boundary have been described as a textural 'hiatus' or 'unconformity' (Rosenfeld, 1970; Karabinos, 1984) or as truncational foliations (Bell and Hayward, 1991) that are the result of overprinting relationships between two sets of inclusion trails and/or foliations. There is a general consensus that these truncations or truncation zones can form in two ways. The first is as older foliations preserved in the porphyroblast core that are surrounded by the younger matrix foliation, which is then overgrown in a subsequent event. The second is as crenulations in microfold hinges, bounded by differentiated crenulation cleavages overgrown by porphyroblast rims during a younger event (Bell and Johnson, 1989; Bell and Hayward, 1991; Jones, 1994; Passchier and Speck, 1994; Williams, 1994; Spiess and Bell, 1996; Bell et al., 1998). Truncations can be distinguished based on smooth (partly continuous) or sudden changes in orientation, texture,

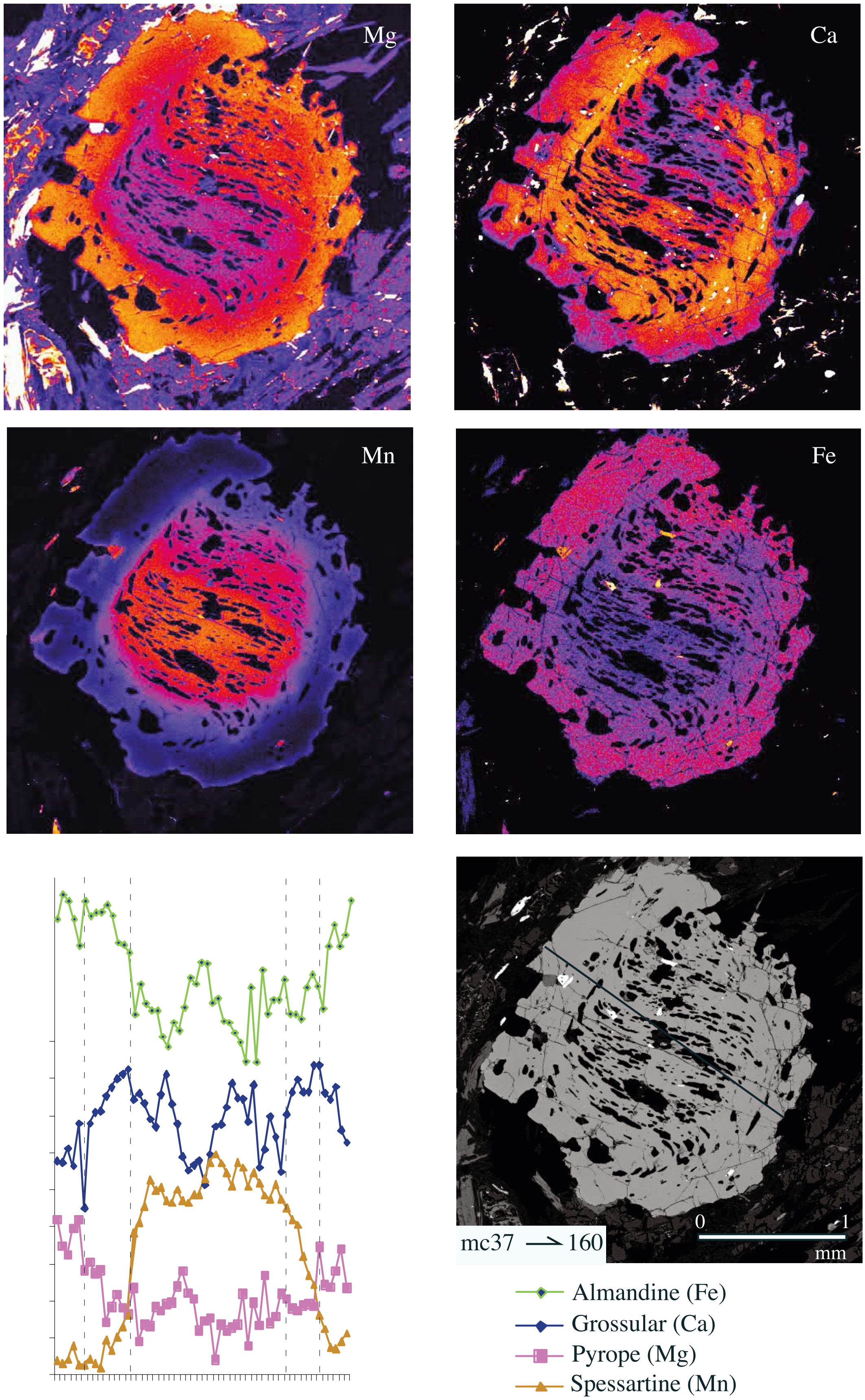

Fig. 6. Compositional maps (Mg, Ca, Mn, Fe) of a garnet porphyroblast from sample mc37.

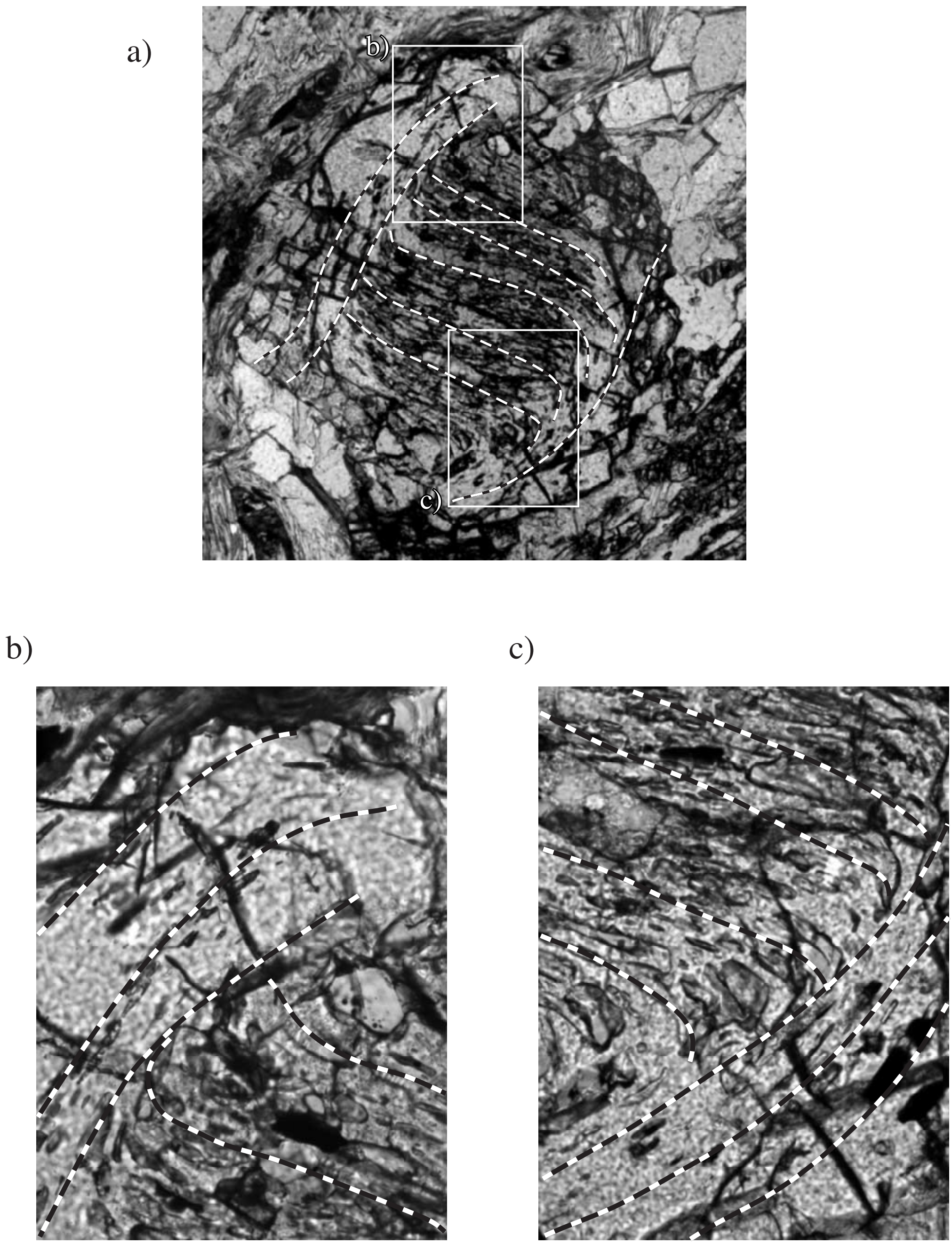

Fig. 7. Photograph of the same garnet porphyroblast in Fig. 6 containing sigmoidal type inclusion trails (a). Close-up views show flat lying inclusions truncated sharply by the rim inclusions (b) and (c). Boxes A and B show the positions of the close-up views.

composition and asymmetry of inclusions. Bell and Johnson (1989) suggested that inclusion trails are commonly not continuous but truncated from core to rim of garnet porphyroblasts generating complex, staircase or spiral shaped trails and are arranged orthogonally or near orthogonally in cross-section. This was supported by the pitch measurements of the truncations using absolute orientations (Bell and Hayward, 1991; Hayward, 1992; Aerden, 2003). Similar observations can be seen in Figs. 4 and 7, where orthogonal relationships between the inclusion trails in the core and rim of the porphyroblasts are visible. In Fig. 4c, the gently dipping core inclusions smoothly curve towards the steeply dipping rim inclusions. A truncation boundary can also be observed with the matrix foliation, in this case with a more sharply defined character. In another example inclusion trails suddenly change their orientation from core to rim (Fig. 7a–c). In these examples textural changes are also recognizable at the truncation zones. Fine-grained quartz and opaque minerals in the rim are orthogonally arranged with respect to the coarser quartz

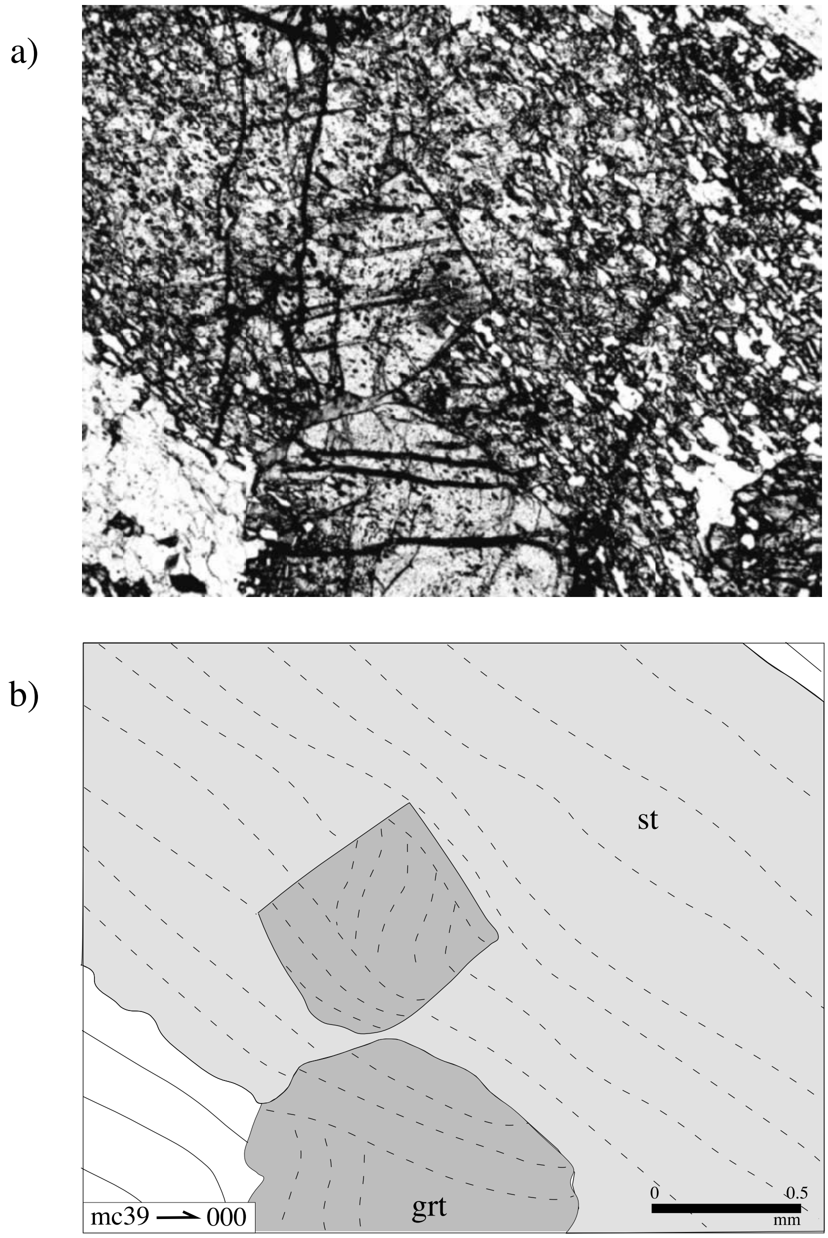

Fig. 8. Photograph and a line diagram showing a staurolite (st) porphyroblast containing two garnet (grt) porphyroblasts. The inclusion trails within staurolite porphyroblasts are continuous with the matrix and rim inclusions, whereas the ones in the core of garnet porphyroblasts are truncated.

grains in the core. It has been reported that these relationships can be coincident with compositional zoning patterns in garnets (Powell and Vernon, 1979; Bell and Johnson, 1989; Hayward, 1992; Stallard and Hickey, 2002). Indeed, compositional X-ray maps of these samples (Fig. 6) showed that the compositional modification from core to rim is consistent with the microstructural truncations and also textural relationships, as evident from Fig. 7. This suggests that following the growth of a core, a hiatus in growth, accompanied by garnet dissolution (e.g. Karabinos, 1984; Ikeda, 1993), occurred at the boundary with the older matrix. After that, growth continued in a subsequent deformation event, which developed orthogonal in cross-section to the previous one. Such characteristics result in FIA trends that can change from core to rim for a sample such as shown in Figs. 4, 7 and 8 (data are available from the author upon request).

8. Implications of FIA trends

FIA data enables one to test whether the porphyroblasts have been rotated in a specific area. This illuminates the nature of the mechanism of truncation and the different porphyroblast growth phases. The four FIA trends formed successively in NNE–SSW, E–W, N–S and NE–SW orientations and suggest that the porphyroblasts have not

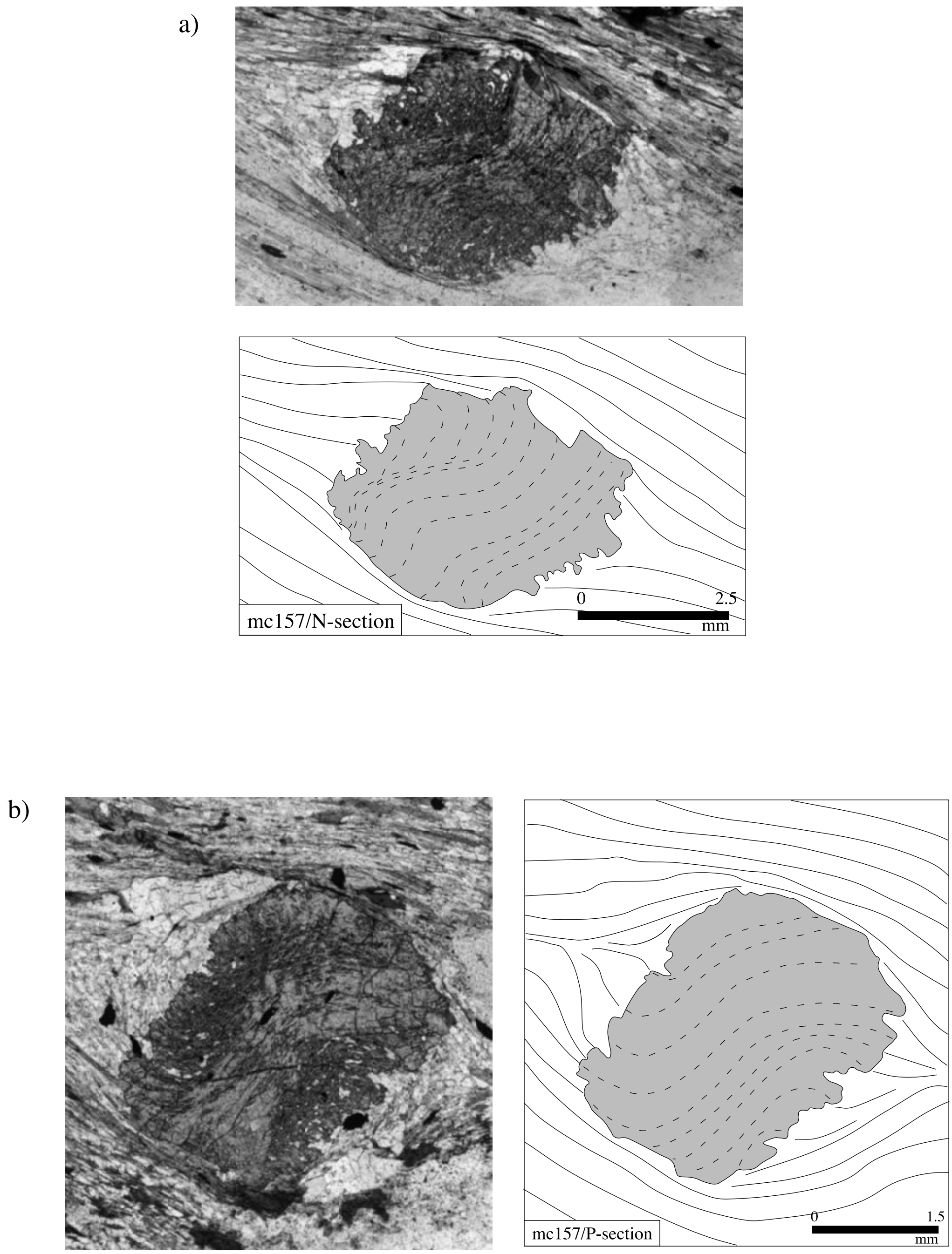

Fig. 9. Photographs of garnet porphyroblasts from N (a) and P (b) sections. In both sections the inclusion trails are continuous into the strain shadows and superficially appear to be continuous with the matrix foliation.

been rotated during the deformation. If they had been rotated they would have random trends rather than the succession of dominant orientations observed. For example, if E–W FIA2 trend was formed after an NNE–SSW FIA1 trend, and if rotation of the porphyroblasts were the cause, the FIA1 trend should have been rotated around the E–W axis as shown in Fig. 12a. In the same way, if both FIA1 (NNE–SSW) and FIA2 (E–W) porphyroblasts were rotated around the N–S-trending FIA3 axis, they could have lain in any direction individually based on the amount of apparent rotation with respect to a fixed matrix (Fig. 12a), depending on the size of the porphyroblasts and type of flow (Williams and Jiang, 1999). If FIA4 (NE–SW) was a rotation axis, they could be oriented in any direction from N to E and S to W (Fig. 12b). Since this is not the case, it appears that the porphyroblasts have not rotated during the ductile deformation that affected the area investigated.

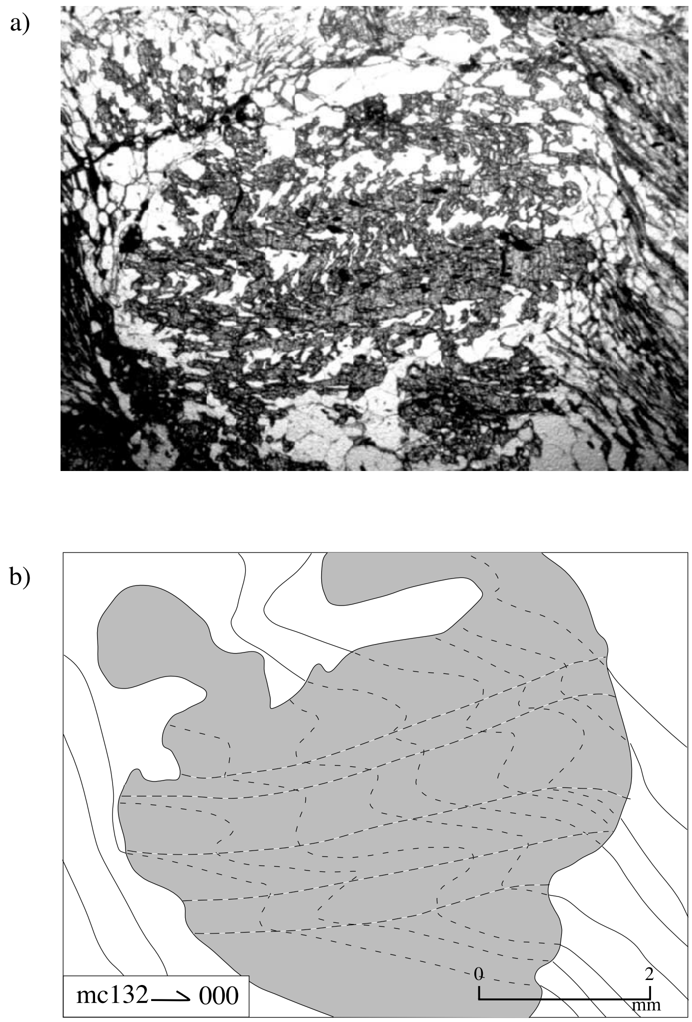

Fig. 10. Photograph of a staurolite porphyroblast overgrowing differentiated crenulation cleavage, whose trails are continuous with the matrix foliation.

9. Multiple phases of porphyroblast growth in the Robertson River Metamorphics

The four FIA trends signify a sequence of porphyroblast growth with time. The earliest garnet porphyroblasts preserve FIA1 (NNE–SSW) and FIA2 (E–W), whereas FIA3 (N–S) was observed in both garnet and staurolite porphyroblasts. The FIA4 (NE–SW) was only found in staurolite porphyroblasts where the inclusions are continuous with and sub-parallel to the matrix. These different generations of FIAs indicate at least four periods of multiple phases of episodic porphyroblast growth that accompanied multiple deformation events and this is supported in single garnet porphyroblasts by the microstructures and compositional maps (Figs. 6 and 7). This also suggests that the bulk shortening direction has changed with time from NNW–SSE to N–S to E–W and finally to NW–SE, which produced macro-scale structures mimicking the FIA trends as shown in Fig. 2.

10. Discussion

10.1. Implications of compositional and FIA data for truncational relationships and phases of porphyroblast growth and their mechanisms

Consistency between microstructures and compositional variation has been previously reported from other metamorphic terrains (e.g. Karabinos, 1984; Ikeda, 1993; Stallard and Hickey, 2002). In these studies, zoning reversals observed at the truncation boundaries were attributed to resorption due to exchange reactions (e.g. Spear, 1993) producing chlorite and mica minerals at the expense of garnet. During these reactions because of Fe/Mg exchange, Xalm and Xpyp within the garnet porphyroblasts commonly increase from core to rim. Fig. 6 shows that just after the core formed, these components suddenly and then gradually increased. This suggests episodic growth of the porphyroblast because, following the growth of the core, a)

b)

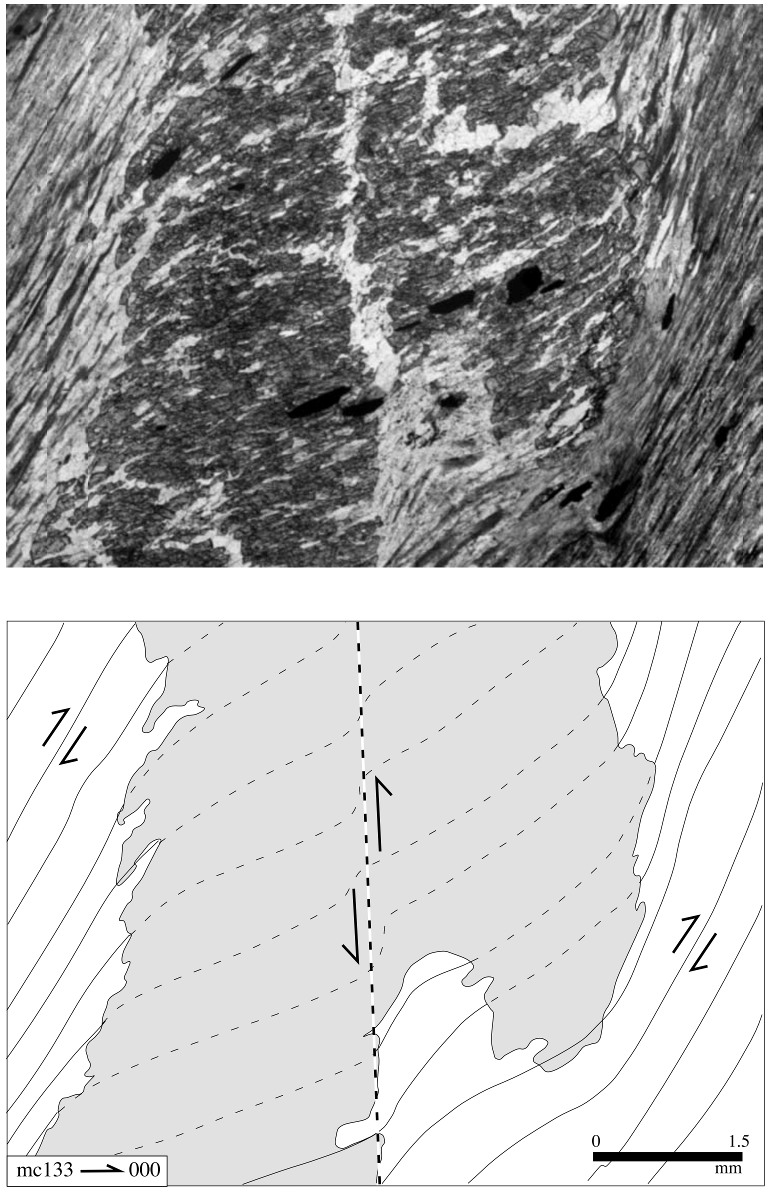

Fig. 11. Photograph and a line diagram showing two staurolite porphyroblasts, which have grown adjacent to one another with sigmoidal type inclusions, which are continuous with the matrix (a). The porphyroblasts preserve between them a steep crenulation cleavage (thick vertical dash lines on a line diagram), in which clockwise (sinistral) shear sense was acting (b). This steep foliation has been destroyed in the matrix by reactivation. The shear senses, operating during development of the crenulation cleavage and during reactivation are shown with barbed arrows.

mica and chlorite minerals were formed in earlier mica domains during the resorption, and then these minerals were dissolved to grow the rim during a subsequent deformation event. The resorption or dissolution of the porphyroblasts apparently occurred against the limbs of crenulations or differentiated crenulation cleavages (mica domains) where high progressive shearing strain was active (e.g. Marlow and Etheridge, 1977; Bell et al., 1986). This indicates that the first phase of porphyroblast growth occurred on the hinge of a crenulation cleavage at the beginning of deformation during stage 2 of crenulation cleavage development (fig. 4 in Bell and Rubenach, 1983; Bell et al., 1986). Porphyroblast growth occurs in zones of progressive shortening (Bell, 1981; Bell et al., 1986; Bell and Hayward, 1991) early in the deformation history when the strain is relatively low in the matrix (Bell et al., 2003, 2004). As the deformation intensifies, these hinges are generally destroyed unless they are trapped within porphyroblasts (Bell et al., 1992). As the porphyroblasts nucleate and grow in the progressive shortening sites (Fig. 13a), shearing becomes more active along the progressive shearing domains and porphyroblasts may begin to dissolve (Bell et al., 1986). A new phase of growth occurs only when a differently oriented phase of deformation is partitioned through the rock (e.g. Bell and Hayward, 1991; Bell and Welch, 2002; Bell et al., 2003). This is supported by the FIA trends, which change from core to rim of the porphyroblasts for some of the rock samples (e.g. Fig. 7). These changes in

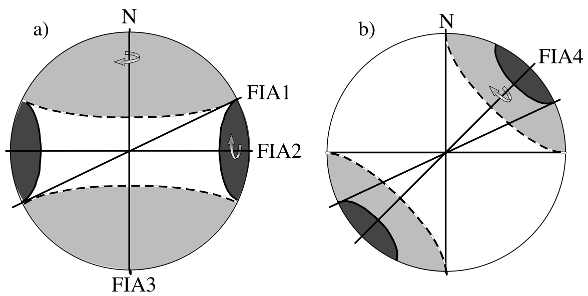

Fig. 12. Steorenet projections of the FIA1–4 showing the effect of rotation around the mean trend of the next FIA in the succession. In (a), rotation effect of FIA1 around E–W axis; FIA2, shown with darker shaded area. FIA1 trend would lie in that shaded area in any orientation with gentle plunges, if they were rotated around FIA2. Apart from that the rotation of both FIA1 and FIA2 are shown around FIA3 as well. They would lie in the range shown by shaded areas in northern and southern quadrants, if they were again rotated. In (b) the rotation of FIA1–3 is shown around FIA4 axis. If they were rotated, FIA1 would lie in darker shaded area, and FIA2 and FIA3 would lie in any orientation in NE–SW quadrants.

FIA trend suggest that the direction of the bulk shortening causing orogenesis changed with time. Around the same FIA trend, more than two successively formed near vertical and near horizontal foliations can develop (Bell and Welch, 2002) and this is common in staircase and spiral garnets (e.g. Bell and Chen, 2002). In this case the growth continues episodically during the early stages of deformation partitioning accompanying successive phases of deformation (Bell and Hayward, 1991; Bell et al., 2003).

During repartitioning of the deformation, earlier formed foliations in the matrix may rotate around the porphyroblasts towards the compositional layering because of reactivation of the bedding (e.g. Bell et al., 2003). Where this happens, the near orthogonal foliations observed within porphyroblasts have rotated closer towards parallelism in the matrix (e.g. Figs. 11 and 13b). This geometry is one of the main reasons why porphyroblasts were originally suggested to be a product of rotation when one just used P–N sections (Fig. 9).

10.2. Reactivation and rotation of the earlier foliations around porphyroblasts

In multiply deformed terrains, old or intermediate events are commonly obscured by the effects of younger deformations due to reactivation of the bedding or old foliations, unless they are trapped as inclusion trails in porphyroblasts. Reactivation (Bell, 1986) is simply antithetic shear occurring on pre-existing foliations and bedding where it has an orientation compatible for this to occur in conjunction with synthetic shear on a newly developing axial plane cleavage (e.g. Bell, 1986; Bell et al., 2003). During reactivation, synthetic progressive shear on the developing foliation (S_2 in Fig. 14a) switches to antithetic shear on compositional layering (S_0 in Fig. 14a and b). At this stage, the newly formed foliation (e.g. S_2 in Fig. 14a and b) is destroyed, and remnants of earlier oblique foliations

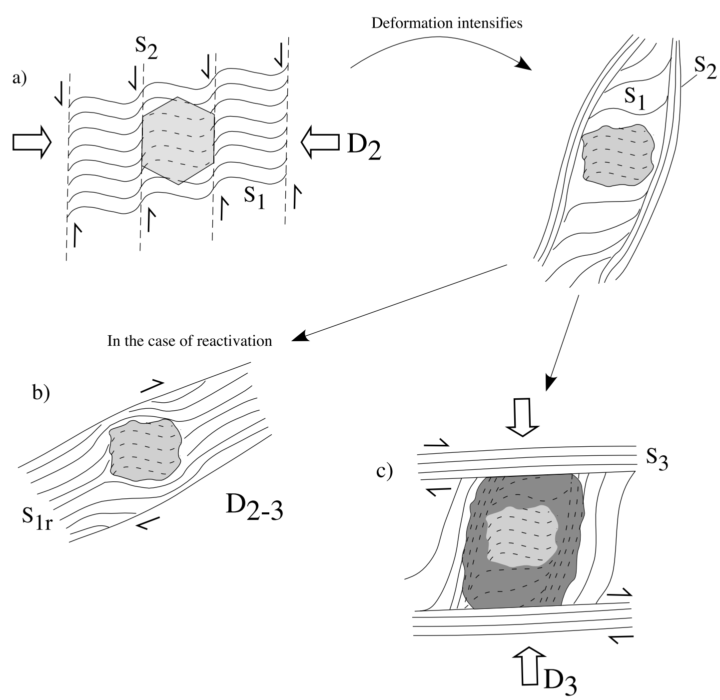

Fig. 13. Simplified sketch showing the growth of a porphyroblast. In (a), deformation partitions into progressive shearing and shortening domains as represented by crenulation cleavage and hinge of a crenulation, respectively. The first porphyroblast growth occurs on a hinge of crenulation cleavage (progressive shortening domain) at the beginning of D_2 event. In (b), if reactivation occurs, S_1 is decrenulated and rotated towards compositional layering in the matrix (S_{1r}). In (c), deformation repartitions during D_3, and the growth of rim occurs. The earlier foliation, S_2 or S_{1r} in the case of reactivation, which intensified in the matrix during the late stages of D_2, is trapped as inclusion trails.

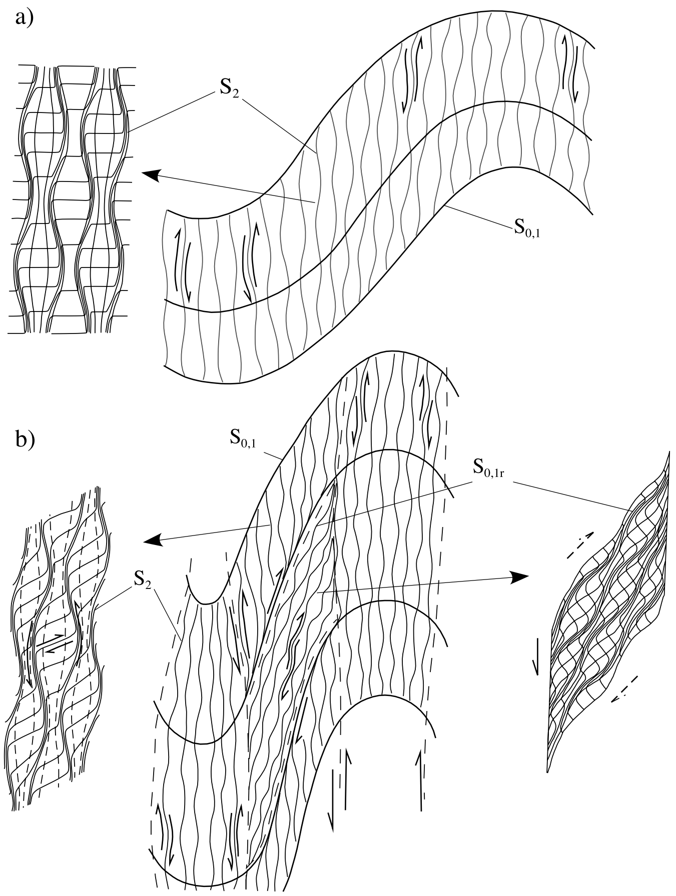

Fig. 14. Sketches showing the effect of reactivation (modified from Bell et al. (1986)). In (a), anastomosing S_2 foliations formed with synthetic sinistral shear sense parallel to the axial plane of newly developing fold. The inset shows the strain field diagram in which deformation partitions into progressive shearing and shortening domains. In (b), as the deformations continue, the fold tightens more and bedding ($S_{0,1}$) reactivates. During this stage, synthetic shear sense acting on S_2 switches to antithetic shear sense along the bedding in a reactivated area in which S_2 is destroyed, and the earlier foliation, S_1, decrenulates and rotates towards the bedding.

such as S_1 are rotated towards the bedding (e.g. $S_{0,1}$ in Fig. 14b). For instance, in Fig. 11 the two adjacent staurolite porphyroblasts preserve between them a differentiated crenulation cleavage that has been destroyed in the matrix elsewhere by reactivation. These porphyroblasts formed early during the development of the deformation that produced steep crenulation cleavage on which anticlockwise shear was acting.

10.3. Timing of porphyroblast growth through P–N and multiple-vertical thin sectioning approaches

Correct interpretation of the timing of porphyroblasts relative to deformational history is derived from correct identification of foliations trapped as inclusions in porphyroblasts. Reactivation of foliations around porphyroblasts and the continuity of inclusion trails into strain shadow regions relative to the matrix foliation will result in conflict in the timing of porphyroblast growth relative to deformation events unless they are observed in multiple vertical sections. For instance, P and N sections in Fig. 15 suggest porphyroblasts grew during D_2 since they overgrow S_1 and the inclusions appear continuous with S_2. What appear to be the effects of D_2 and S_2 are actually those of D_3 and S_3 when viewed using a series of vertical thin sections (Fig. 15c).

The garnet porphyroblasts in Fig. 4 have undergone at least two phases of growth. Yet in P–N sections (Fig. 9) this growth appeared to occur as one or more phases during the formation of the matrix foliation. Clearly, P and N sections reveal little of the growth history because of the strain shadow caused by the matrix foliation and this appears to be the case elsewhere such as California (Bell and Hickey (1999) versus Paterson and Vernon (2001)), and the Appalachian Orogen in southeast Vermont (Rosenfeld (1970) versus Bell et al. (1998) and Bell and Welch (2002)).

It is also worthwhile to note that the lack of critical geometrical relationships between inclusion trails in porphyroblasts and matrix in P and N sections can lead to misinterpretation of the shear senses used for the kinematic analysis within an orogen. The main reason here is that both shear senses can be obtained if porphyroblasts predate the matrix and if the FIA axis is sub-parallel to the P-section orientation.

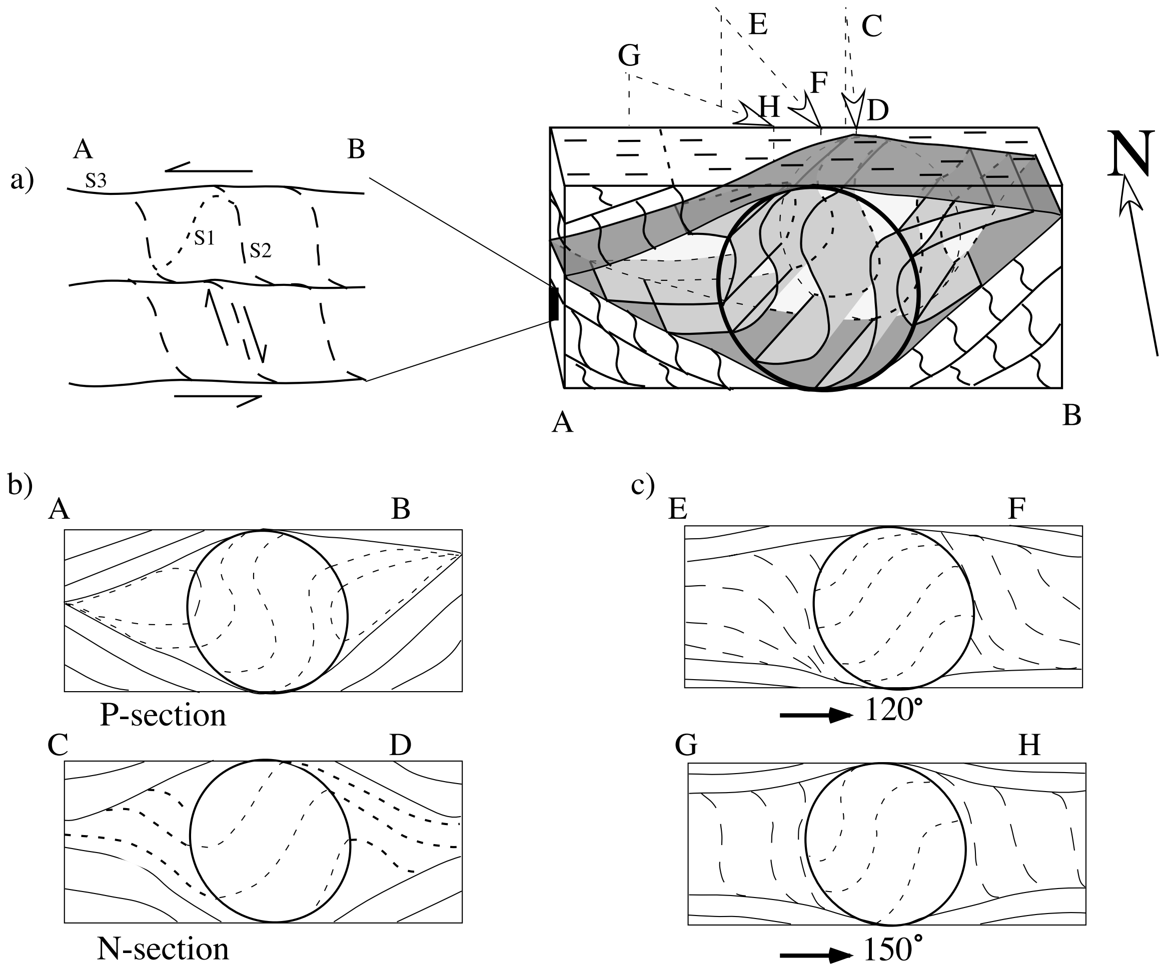

Fig. 15. 3-D sketch of a porphyroblast having inclusions that are oblique to, and truncated by, the matrix foliation planes, with the detailed view along A–B orientation showing the relationship of S_1, S_2 and S_3 (a). P and N sections cut from 3-D block sketch show the continuation of the inclusion trails with matrix. In these sections, inclusions trapped in the strain shadows, especially in the N section, are misinterpreted as S_1, but in fact it is S_2 (b). However, in multiple-vertical thin sections in 120° and 150° orientations, inclusion trails are truncated by the matrix foliations. S_1 is the earliest foliation trapped as inclusion in porphyroblast; S_2 is the earlier matrix foliation; S_3 is lately formed foliation; Barbed arrows show shear senses; A–B, C–D, E–F, G–H show the positions of sections; N is true north.

11. Conclusions

Inclusion trail geometries in porphyroblasts, which are vital for understanding the deformation history in highly tectonized rocks, can only be fully analysed using multiple-vertical thin sections. Studies of the inclusion trails using a P–N section approach will regularly result in the misinterpretation of the timing of porphyroblast growth and the number of deformational and metamorphic events. The Robertson River Metamorphics contain at least four periods of porphyroblast growth accompanying different directions of orogenic shortening and multiple deformation events compared with the one phase proposed previously. Such multiple phases of growth versus simple histories have been recognized in other highly deformed terranes such as the Foothills of the Sierra Nevada in California (Bell and Hickey, 1999; Paterson and Vernon, 2001), Haast Schist, New Zealand (Johnson, 1990), Cooma Complex (Johnson, 1992; Johnson and Vernon, 1995) and the Appalachian Orogen in southeast Vermont (Rosenfeld, 1970; Bell et al., 1998; Bell and Welch, 2002). In these regions, multiple vertical thin section approaches have revealed much more complex deformation histories than proposed previously where sections were cut only orthogonal to the matrix foliation.

Acknowledgements

I thank Prof. Tim H. Bell, Dr Tom Blenkinsop and Dr Andrew Ham for their critical comments and assistance in improving the language of an early version of this manuscript. I also appreciate Dr Scott Paterson's critical review, which greatly improved the quality of the manuscript.

I would also like to acknowledge Marco Herwegh and an anonymous referee for their constructive criticism, suggestions and comments. Many thanks are also due to Prof. Joao Hippertt for his invaluable effort for dealing with the manuscript.

References

Aerden, D.G.M., 2004. Correlating deformation in Variscan NW-Iberia using porphyroblasts; implications for the Ibero–Armorican Arc. Journal of Structural Geology 26, 177–196.

Bell, T.H., 1981. Foliation development: the contribution, geometry and significance of progressive, bulk inhomogeneous shortening. Tectonophysics 75, 273–296.

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

Bell, T.H., Chen, A., 2002. The development of spiral-shaped inclusion trails during multiple metamorphism and folding. Journal of Metamorphic Geology 20, 397–412.

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

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

Bell, T.H., Johnson, S.E., 1989. Porphyroblast inclusion trails: the key to orogenesis. Journal of Metamorphic Geology 7, 279–310.

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

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

Bell, T.H., Johnson, S.E., Davis, B., Forde, A., Hayward, N., Wilkins, C., 1992. Porphyroblast inclusion-trail orientation data: eppure non son girate!. Journal of Metamorphic Geology 10, 295–307.

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

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

Bell, T.H., Welch, P.W., 2002. Prolonged Acadian Orogenesis: Revelations from FIA controlled monazite dating of foliations in porphyroblasts and matrix. American Journal of Science 302, 549–581.

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

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

Black, L.P., Bell, T.H., Rubenach, M.J., Withnall, I.W., 1979. Geochronology of discrete structural–metamorphic events in a multiply deformed Precambrian terrain. Tectonophysics 54, 103–137.

Black, L.P., Gregory, P., Withnall, I.W., Bain, J.H.C., 1998. U–Pb zircon age for the Etheridge Group, Georgetown region, north Queensland: implications for relationship with the Broken Hill and Mt. Isa sequences. Australian Journal of Earth Sciences 45, 925–935.

Blewett, R.S., Black, L.P., Sun, S.-s., Knutson, J., Hutton, L.J., Bain, J.H.C., 1998. U–Pb zircon and Sm–Nd geochronology of the Mesoproterozoic of North Queensland: implications for a Rodinian connection with the Belt supergroup of North America. Precambrian Research 89, 101–127.

Cihan, M., 2004. Constraining pressure–temperature-deformation path using P–T pseudosections combined with FIA data in the Robertson River Metamorphics, Northeastern Australia. Journal of Metamorphic Geology, in review.

Davis, B.K., 1995. Regional-scale foliation reactivation and re-use during formation of a macroscopic fold in the Robertson River metamorphics, north Queensland, Australia. Tectonophysics 242, 293–311.

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

Hayward, N., 1992. Microstructural analysis of the classical spiral garnet porphyroblasts of south-east Vermont: evidence for non-rotation. Journal of Metamorphic Geology 10, 567–587.

Ikeda, T., 1993. Compositional zoning patterns of garnet during prograde metamorphism from the Yanai district, Ryoke metamorphic belt, southwest Japan. Lithos 30, 109–121.

Johnson, S.E., 1990. Deformation history of the Otago Schists, New Zealand from progressively developed porphyroblasts/matrix microstructures: cyclic uplift—collapse orogenesis and its implications. Journal of Structural Geology 12, 727–746.

Johnson, S.E., 1992. Sequential porphyroblast growth during progressive deformation and low-P high-T (LPHT) metamorphism, Cooma Complex, Australia: the use of microstructural analysis to better understand deformation and metamorphic histories. Tectonophysics 214, 311–339.

Johnson, S.E., Vernon, R.H., 1995. Stepping stones and pitfalls in the determination of an anticlockwise P–T–t deformation path: the low-P, high-T Cooma Complex, Australia. Journal of Metamorphic Geology 13, 165–183.

Jones, K.A., 1994. Progressive metamorphism in a crustal-scale shear zone: an example from the Leon region, north-west Brittany, France. Journal of Metamorphic Geology 12, 69–88.

Karabinos, P., 1984. Polymetamorphic garnet zoning from southeastern Vermont. American Journal of Science 284, 1008–1025.

Karlstrom, K.E., Williams, M.L., McLelland, J., Geissman, J.W., Ahall, K., 1999. Refining Rodinia: geological evidence for the Australia–Western U.S. connection in the Proterozoic. GSA Today 9, 1–7.

Marlow, P.C., Etheridge, M.A., 1977. Development of a layered crenulation cleavage in mica schist of the Kanmantoo Group near Macclesfield, South Australia. Geological Society of America Bulletin 88, 873–882.

Passchier, C.W., Speck, J.H.R., 1994. The kinematic interpretation of obliquely transected porphyroblasts: an example from the Trois Seigneurs Massif, France. Journal of Structural Geology 16, 971–984.

Paterson, S.R., Vernon, R.H., 2001. Inclusion trail patterns in porphyroblasts from the Foothills Terrane, California: a record of orogenesis or local strain heterogeneity? Journal of Metamorphic Geology 19, 351–372.

Powell, C.McA., Vernon, R.H., 1979. Growth and rotation history of garnet porphyroblasts with inclusion spirals in a Karakoram schist. Tectonophysics 54, 25–43.

Rosenfeld, J.L., 1970. Rotated garnets in metamorphic rocks. Geological Society of America Special Paper, 129.

Schoneveld, C., 1979. The geometry and significance of inclusion patterns in syntectonic porphyroblasts. PhD thesis, University of Leiden, 125pp.

Spear, F.S., 1993. Metamorphic Phase Equilibria and Pressure–Temperature–Time Paths, Mineralogical Society of America Monograph 1993. 799pp.

Spiess, R., Bell, T.H., 1996. Microstructural controls on sites of metamorphic reaction: a case study of the inter-relationship between deformation and metamorphism. European Journal of Mineralogy 8, 165–186.

Stallard, A., Hickey, K., 2002. A comparison of microstructural and chemical patterns in garnet from the Fleur de Lys Supergroup, Newfoundland. Journal of Structural Geology 24, 1109–1123.

Upton, G.J.G., 1992. Fisher's exact test. Journal of the Royal Statistical Society, A 192, 395–402.

Vernon, R.H., Paterson, S.R., Foster, D., 1993. Growth and deformation of porphyroblasts in the Foothills terrane, central Sierra Nevada, California: negotiating a microstructural minefield. Journal of Metamorphic Geology 11, 203–222.

Williams, M.L., 1994. Sigmoidal inclusion trails, punctuated fabric development, and interactions between metamorphism and deformation. Journal of Metamorphic Geology 12, 1–21.

Williams, P.F., Jiang, D., 1999. Rotating garnets. Journal of Metamorphic Geology 17, 367–378.