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The internal inclusion trail geometries preserved within a first phase of porphyroblast growth

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Abstract

The inclusion trail geometry within a first phase of porphyroblast growth can differ significantly from that preserved by further enlargement because the porphyroblast forms a rigid mass up against which the rock preferentially strains during ensuing events. The geometry of the first overgrown inclusion trails is affected by their primary orientation, including any pre-existing curvature, combined with any heterogeneous rotation of this foliation about the developing stretching lineation. This can impact the apparent timing of foliation intersection/inflection axes preserved within porphyroblasts (FIAs) that nucleated during the development of a sub-horizontal foliation, but is readily resolved. 3-D computer analysis of sigmoidal inclusion trails reveals that the asymmetry method for FIA determinations is unaffected by the cut location relative to the porphyroblast core. Significantly, perfect spiral inclusion trail geometries can be produced from a sigmoidal shape in cuts up 30° away from the FIA. Therefore, since FIAs in most porphyroblasts bear no relation to matrix structures, there is a 17% chance that thin-sections cut relative to the foliation lie within 30° of a FIA and could contain such an apparent spiral. FIAs maintain consistent trends for the first phase of porphyroblast growth accompanying horizontal bulk shortening but may vary in plunge. FIAs have sub-horizontal plunges for porphyroblasts nucleating during gravitational collapse, but may vary in trend. For all periods of porphyroblast regrowth the data available indicates that FIAs remain consistently trending and sub-horizontal until the relative direction of plate motion causing orogenesis changes.

Keywords: Porphyroblast nucleation; Porphyroblast growth; Crenulation cleavage; Shear sense

1. Introduction

Over a decade has passed since measurements were first made on the orientation of foliation intersection/inflection axes in porphyroblasts (FIAs). For some years now this data has been providing extended structural histories that have been lost from the matrix due to repeated shearing or reactivation of the bedding (e.g. Ham and Bell, 2004), extended metamorphic *P–T–t* paths (e.g. Sayab, 2005), quantitative correlation of metamorphic and structural data around oroclines and along and across orogens (e.g. Aerden, 2004), and a means for dating periods of deformation associated with the successive changes in relative plate motion that accompany extended orogenesis (e.g. Bell and Welch, 2002).

One feature of this data has not received much attention. A first phase of porphyroblast growth does not necessarily behave like the later phases in terms of the internal inclusion trail geometry preserved within. This occurs because, once a porphyroblast has grown, it forms a rigid mass against which the rock preferentially deforms during ensuing events, preventing reactivation of the compositional layering as shown in Fig. 1. Subsequent porphyroblast growth can entrap the foliations that have formed against the porphyroblast rim and they maintain predominantly sub-vertical and sub-horizontal orientations (e.g. Hayward, 1992). However, the first phase of porphyroblast growth overgrows a crenulation hinge as it begins to develop in a pre-existing foliation; such crenulations or foliation inflections may have a large range of orientations depending on the orientation of this earlier-formed foliation. For example, if the porphyroblast grows in a deformation event that forms a sub-vertical foliation, then the resulting FIA will have a

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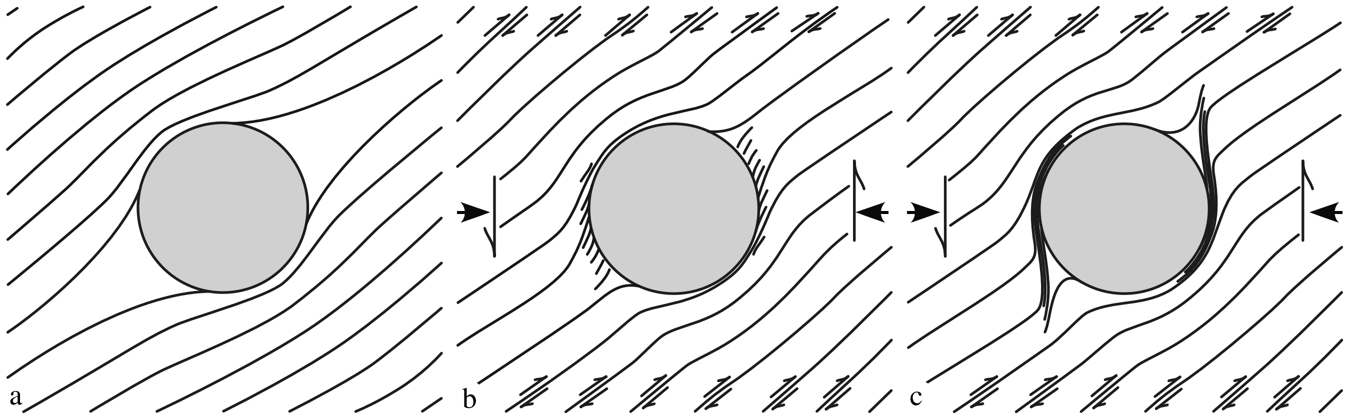

Fig. 1. (a) Vertical cross-section through a porphyroblast within an obliquely dipping foliated matrix. (b) Progressive bulk inhomogeneous shortening involving a component of anticlockwise shear causes antithetic (clockwise shear) on the oblique foliation. The presence of the rigid porphyroblast causes synthetic clockwise axial plane shear to localize against its margins. (c) Clockwise synthetic shear develops a differentiated foliation against the porphyroblast margin.

trend consistent with those measured from porphyroblasts that contain earlier formed cores, but a variable plunge (Fig. 2; Bell and Wang, 1999). If the porphyroblast grows in a deformation event that forms a sub-horizontal foliation, then the resulting FIA will have a sub-horizontal plunge but potentially a trend that is not consistent with those measured from porphyroblasts with earlier formed cores (Fig. 3). If there has been a previous crenulation event that was not accompanied by porphyroblast growth, then other geometries are possible.

To demonstrate the geometric consequences and significance of these effects we:

1. Examine the variation in inclusion trail geometry and FIA trend within different porphyroblastic phases in the same layer, as well as within the same phase in different layers, from two adjacent samples from the one outcrop; in these samples there is a remarkable consistency of FIA trends between porphyroblasts showing multiple phases of growth and those that grew during the development of a sub-vertical foliation. This contrasts dramatically with those that only grew during the development of a sub-horizontal foliation.
2. Examine the 3-D geometry of sigmoidally shaped inclusion trails obtained by high-resolution X-ray

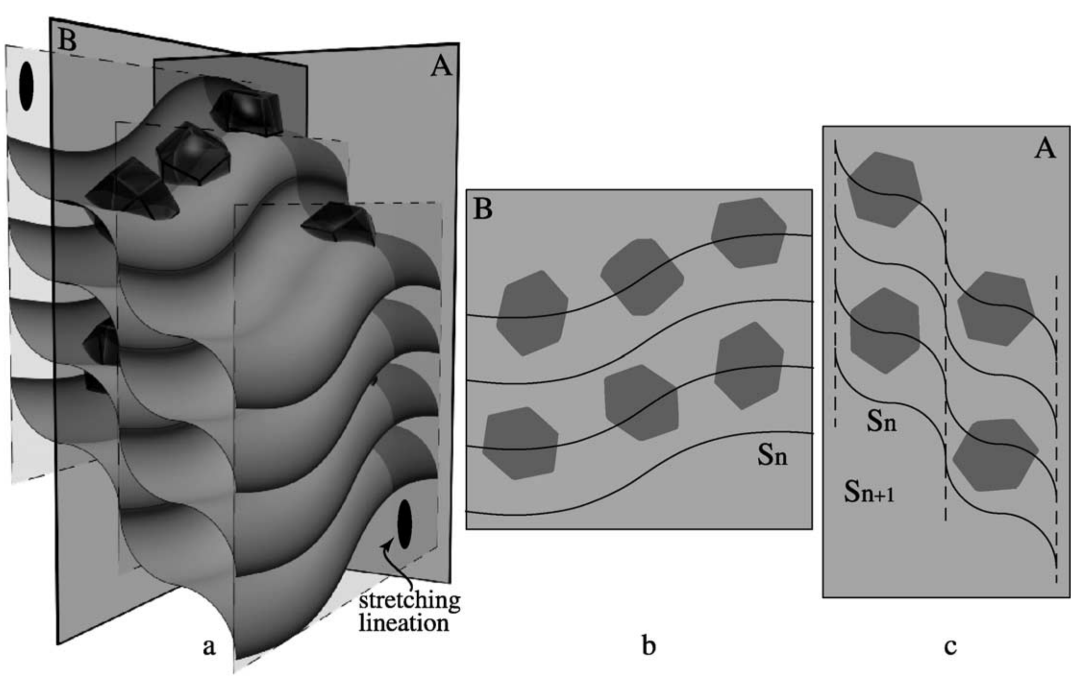

Fig. 2. (a) 3-D sketch showing the location of the 2-D longitudinal section (b) and cross-section (c). Porphyroblasts that grew in crenulation hinges during a deformation event that formed a sub-vertical foliation S_{n+1} ((a) and (c)) contain FIAs with the same trend but variable plunges ((a) and (b)).

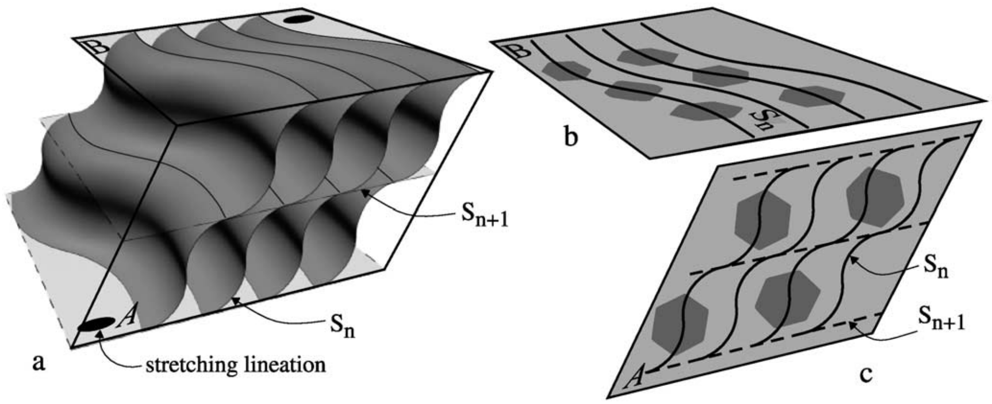

Fig. 3. (a) 3-D sketch showing the location of the 2-D horizontal section (b) and cross-section (c). Porphyroblasts that grew in crenulation hinges during a deformation event that formed a sub-horizontal foliation S_{n+1} ((a) and (c)) contain FIAs with the same plunge but variable trends ((a) and (b)).

computed tomography (X-ray CT) of a garnet porphyroblast that reveals significant aspects of the variation of inclusion trails that are possible within a first phase of porphyroblast growth, which need to be taken into account when attempting to time porphyroblasts microstructurally.

3. Discuss the significance and implications of these phenomena for structural geologists and metamorphic petrologists working with porphyroblastic rocks.

2. FIA trend variation within samples from the Tommy Creek Block

2.1. The samples

Samples TC1365 and TC1365i were taken from adjacent thin pelitic bands in an outcrop of the Tommy Creek Block, Mount Isa Province of Queensland, Australia (Fig. 4; Lally, 1997). Three different pelitic bands within these samples contain:

A. garnet porphyroblasts (layer A; sample TC1365i).
B. garnet plus andalusite porphyroblasts (that locally replace staurolite; layer B; sample TC1365i).
C. garnet and staurolite porphyroblasts (layer C; sample TC1365).

2.2. Timing of porphyroblast growth and FIA trend

The FIAs preserved in these porphyroblasts were measured separately for each porphyroblastic phase in each compositional layer. The foliations and phases of growth preserved within these porphyroblasts, plus the FIA trends they define, are as follows:

1. Layer A—garnet porphyroblasts preserve up to six stages of growth (Fig. 5) that occurred during D_2 (S_2 sub-vertical, S_3 sub-horizontal) through D_7 (S_7 sub-horizontal). All have a FIA trending at 350°.
2. Layer B—garnet porphyroblasts in the andalusite bearing layer (Fig. 6a) contain sub-vertical S_4 with a clockwise asymmetry (looking NE) into sub-horizontal S_5 and the FIA trends at 45°. Local relics of staurolite porphyroblasts preserved within masses of andalusite have very similar inclusion trail geometries to garnet, preserving sub-vertical S_4 with a clockwise asymmetry into sub-horizontal S_5 (Fig. 6b). The FIA was not determined for staurolite because relics of this phase are only present in a few thin sections, but we expect it to be similar to that in garnet. Andalusite porphyroblasts grew early during the development of a matrix crenulation with a sub-vertical axial plane (S_6), and then during the development of another with a sub-horizontal axial plane (S_7); the FIA for andalusite trends at 350°.
3. Layer C—garnet and staurolite porphyroblasts in layer C (Fig. 7) contain FIA trending at 350 and 45°, respectively. Garnet grew predominantly during the development of sub-vertical S_4, with some rim growth during the development of sub-horizontal S_5 (Fig. 7c,d), whereas staurolite grew predominantly during the development of sub-horizontal S_5 (Fig. 7a,b).

2.3. Interpretation

Layer A contains garnet porphyroblasts preserving multiple phases of growth that accompanied up to six different deformation events. Once garnet had formed, any foliations that developed against its rim were preserved by subsequent phases of growth in the orientation in which they were produced, as shown in Figs. 5 and 8b. The FIA trend of 350° is controlled by the strike of the sub-vertical foliation S_2 that predated porphyroblast growth as well as the strike of S_4 and S_6 that accompanied it, independent of any rotational effects or reactivation in the matrix. There was no rotation of L_3^2 towards the stretching lineation L_3^3, such as

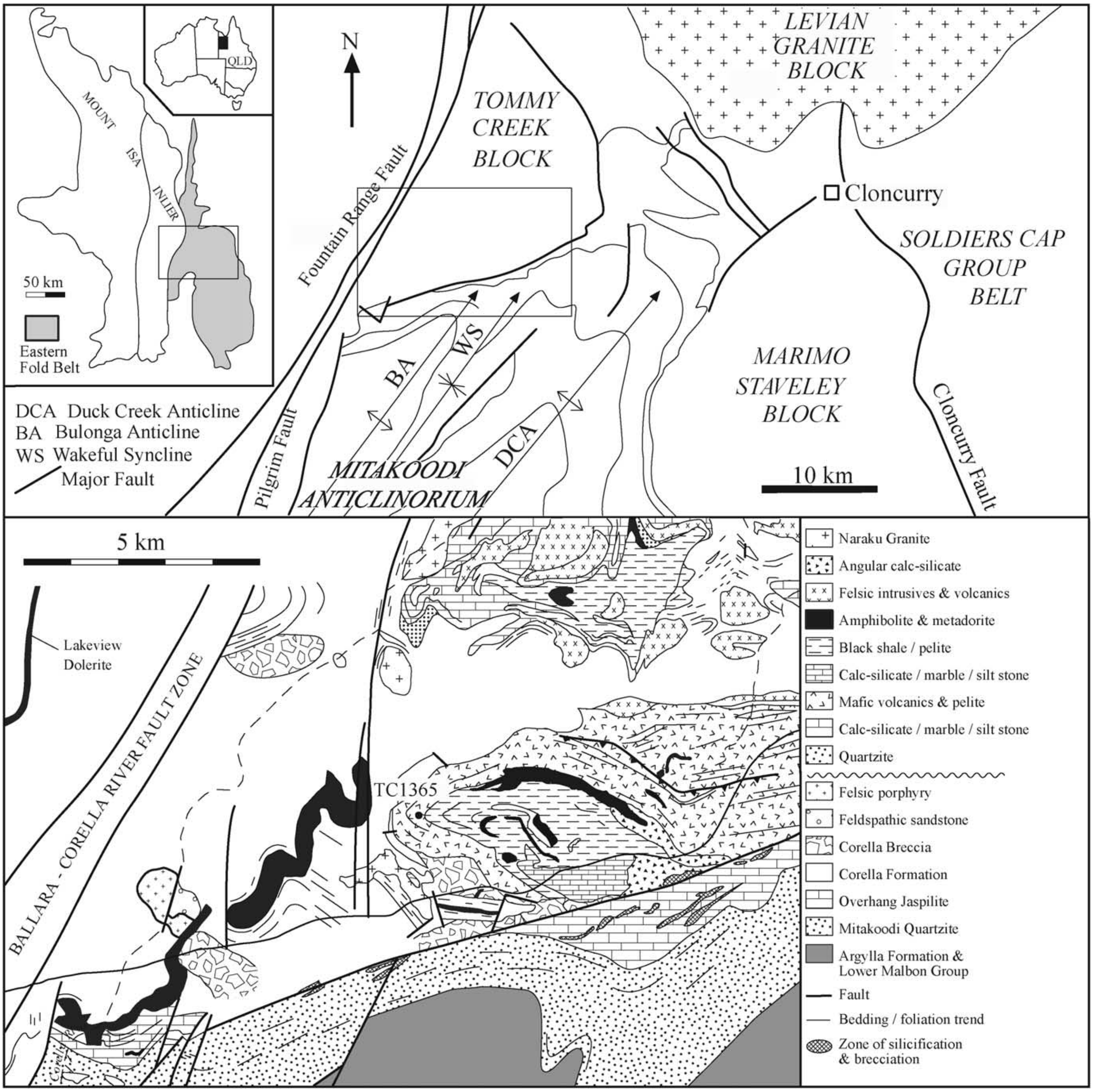

Fig. 4. Location of samples TC1365 and TC1365i from adjacent thin pelitic bands in the Tommy Creek Block of the Mount Isa Province of Queensland, Australia.

that shown in Fig. 2, prior to porphyroblast nucleation in the very early stages of D_3.

In layer B, garnet only grew during development of sub-horizontal S_5 (Figs. 6a and b and 8d). The regionally coarsely partitioned nature of D_5 (Bell and Hickey, 1998) caused the L_5^4 intersection lineation to rotate towards the W–E-trending L_5^5 mineral elongation lineation, such as shown in Fig. 3, at a scale much bigger than a porphyroblast. Where garnet nucleation accompanied reduction in the scale of deformation partitioning, it overgrew portions of rock where L_5^4 had been rotated from 350° towards the L_5^5 stretching lineation to a trend of 45° (Figs. 3 and 8d). Andalusite first nucleated in D_6, which produced sub-vertical S_6 (Fig. 8e). It then grew during development of a weak sub-horizontal S_7. The 350° FIA trend in andalusite is controlled by the 350° striking sub-vertical S_6. This FIA could vary in plunge from the horizontal if rotation of L_6^5 towards the steeply pitching L_6^6 occurred in a similar manner to that which affected L_5^4 (such as shown in Fig. 3); however, such rotation does not affect the primary 350° FIA trend. The weak character of D_7 meant that the 350° FIA was maintained in any andalusite that did not nucleate on

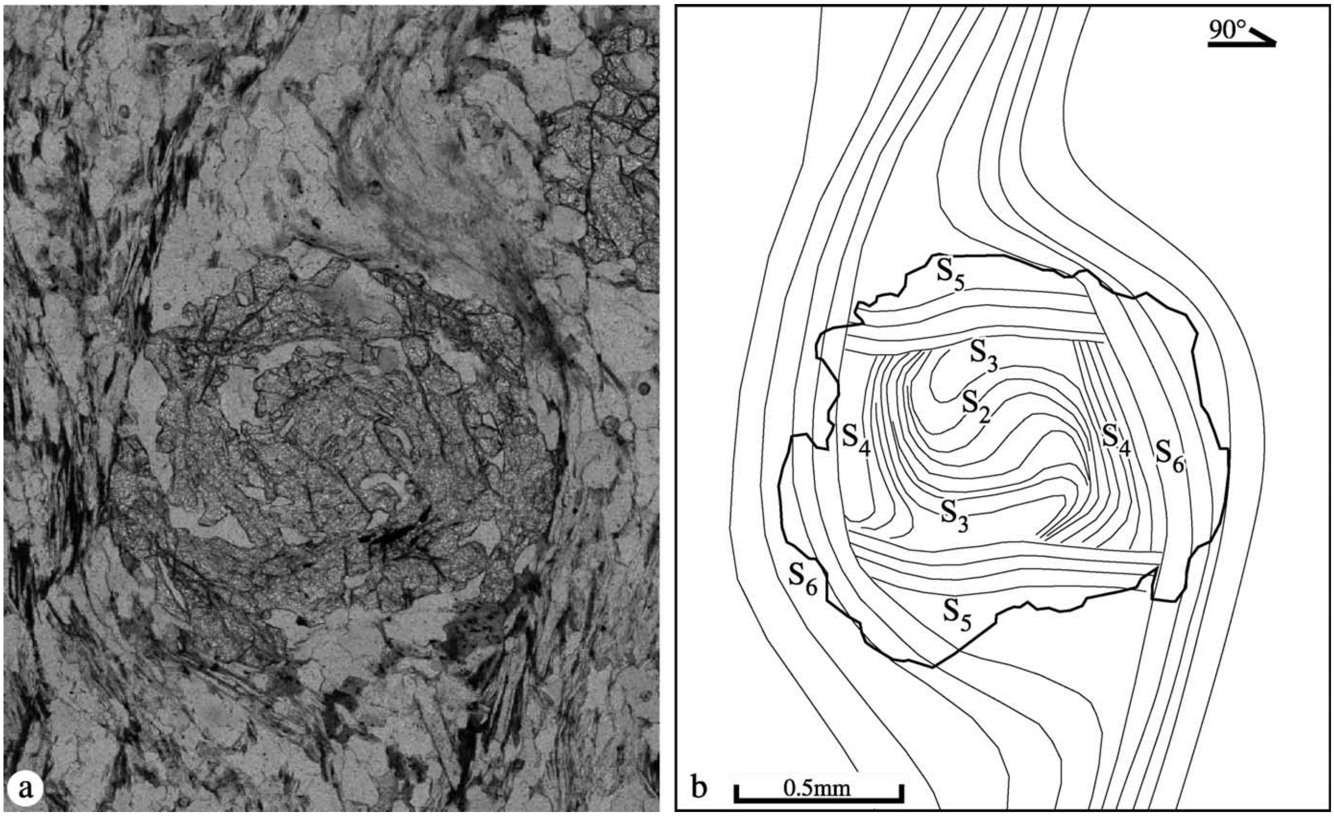

Fig. 5. Spiral-shaped inclusion trails (a) and line diagram (b) of a garnet porphyroblast from layer A in sample TC1365i. Vertical section strikes 90° with single barbed arrow showing strike and way up. The relics of four foliations are preserved with the fifth (S_6) being continuous with the matrix foliation. The overgrowth of S_6 took place during a weak crenulation event with a sub-horizontal axial plane (S_7). Note the truncational character of S_4, S_5 and S_6. Plane polarized light.

previously formed porphyroblasts. Very locally, andalusite has replaced staurolite (Fig. 6c and d) and in these locations could preserve the staurolite FIA trend.

In layer C, where garnet porphyroblasts first grew early during the development of sub-vertical D_4, the 350° FIA trend is controlled by the strike of sub-vertical S_4 (Fig. 8a and c; see also Fig. 2) There was no rotation of S_4 preserved in the D_5 strain shadows of the porphyroblasts (Fig. 7d) during minor rim growth that accompanied the development of sub-horizontal S_5 and so the FIA defined by L_5^4 remained at 350°. Staurolite grew predominantly during the development of sub-horizontal D_5, which as described in point (2) above, caused rotation of L_5^4 towards L_5^5 prior to porphyroblast nucleation and resulted in the 45°-trending FIA (Fig. 8d).

These observations from adjacent layers reveal that variation in FIA trend is possible during a single sub-horizontal foliation producing deformation event for a first phase of porphyroblast growth in some layers versus a second or later phase in others. For example, the different FIA trends in garnet porphyroblasts that grew during D_5 in layers A and B can be readily interpreted via the effects that the presence of a porphyroblast has on the development and preservation of foliations in the matrix against it. Furthermore, the parallelism of FIA trends in garnet and andalusite porphyroblasts that grew for the first time during a sub-vertical foliation producing deformation event, with those in garnet in layer A overgrowing earlier formed cores, has resulted from the only variation that is possible due to heterogeneous strain being in the vertical plane around a steep stretching lineation (Fig. 2).

Thus the variation in FIA trend from phase to phase and layer to layer can be readily interpreted when the timing of porphyroblast development is examined with regards to whether the foliation that accompanied growth developed sub-horizontally or sub-vertically. Where foliations preserved in porphyroblasts are successively sub-vertical and sub-horizontal, the FIA trends are controlled by the strike of sub-vertical foliations as shown in Fig. 8a. Once a porphyroblast has formed, sub-vertical foliations that formed against it are preserved in its strain shadow from the effects of rotation due to subsequent deformation or reactivation of bedding. Any foliation pre-dating porphyroblast growth can be rotated by the effects of prior deformation, or locally by that accompanying porphyroblast nucleation.

3. Inclusion trail geometries in 3-D

A significant quantity of data has been published on the measurement and analysis of FIA orientations with the

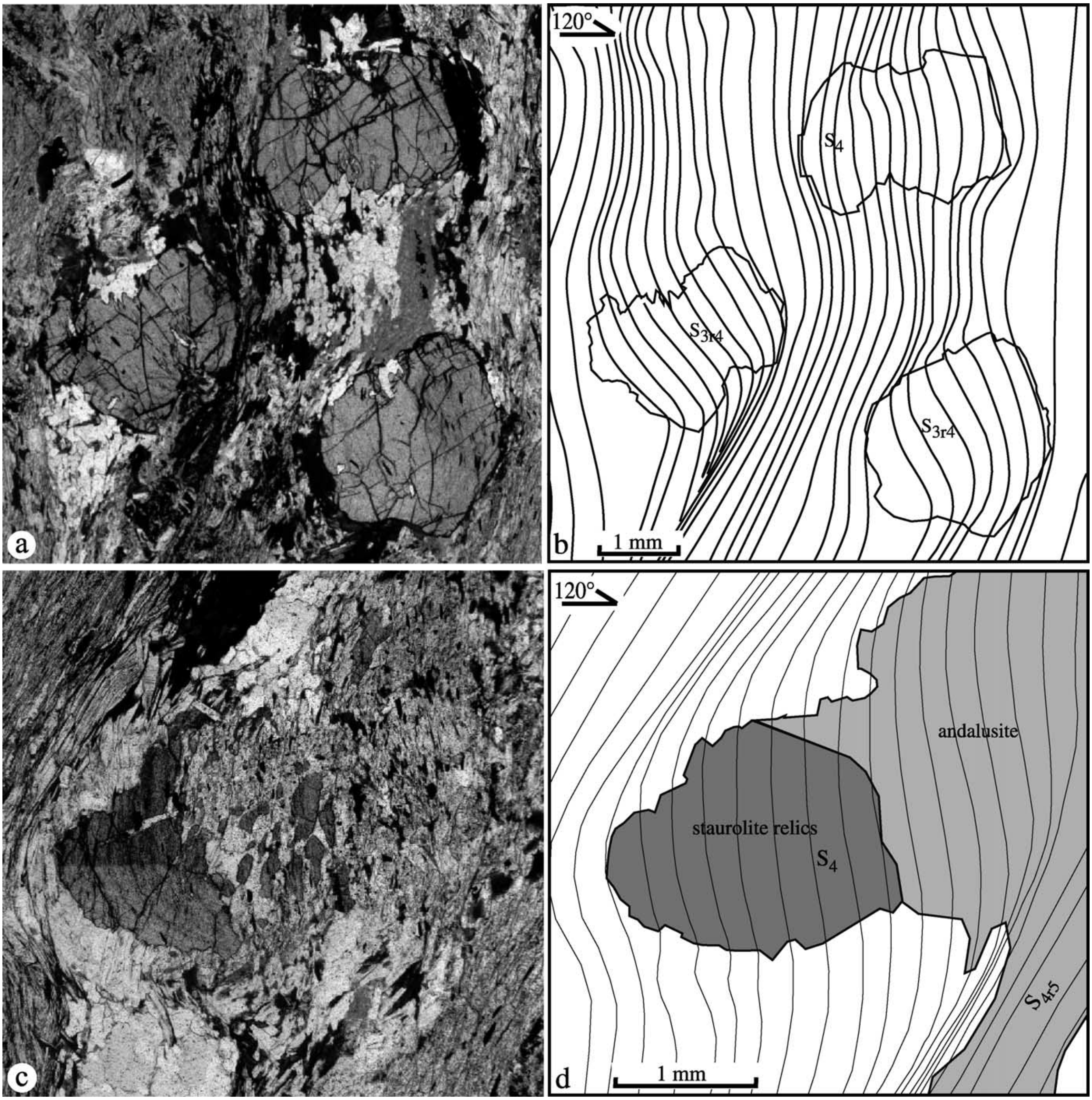

Fig. 6. (a) and (b) Shows straight to slightly sigmoidal shaped inclusion trails in garnet porphyroblasts that grew during the development of a crenulation with a sub-horizontal axial plane S_5 in layer B in sample TC1365i. Vertical section strikes 120° with single barbed arrow showing strike and way up. Plane polarized light. (c) and (d) Shows a staurolite porphyroblast that grew during the development of a crenulation with a sub-horizontal axial plane S_5 in layer B in sample TC1365i. The staurolite was partially replaced by andalusite in a younger steep event S_6. Partial evidence for this is the remains of S_4, reactivated during D_5, preserved in the andalusite extremities. Vertical section strikes 120° with single barbed arrow showing strike and way up. Plane polarized light.

majority of this work carried out using the approach established by Hayward (1990) of cutting multiple vertical thin sections around the compass. This method averages the asymmetry of the inclusion trails in a large population of porphyroblasts from a single rock sample using several differently oriented thin sections. Reconciliation of the structures observed in differently oriented thin sections into a complete 3-D presentation of the inclusion trail geometry is generally impractical because each porphyroblast is cut somewhere between its centre and edge. This does not change the inclusion trail asymmetry for one stage of growth but it may change the shape (e.g. compare Fig. 9a–c). In particular, it may reveal curvature of inclusion trails, in some porphyroblast cores, which pass towards the horizontal

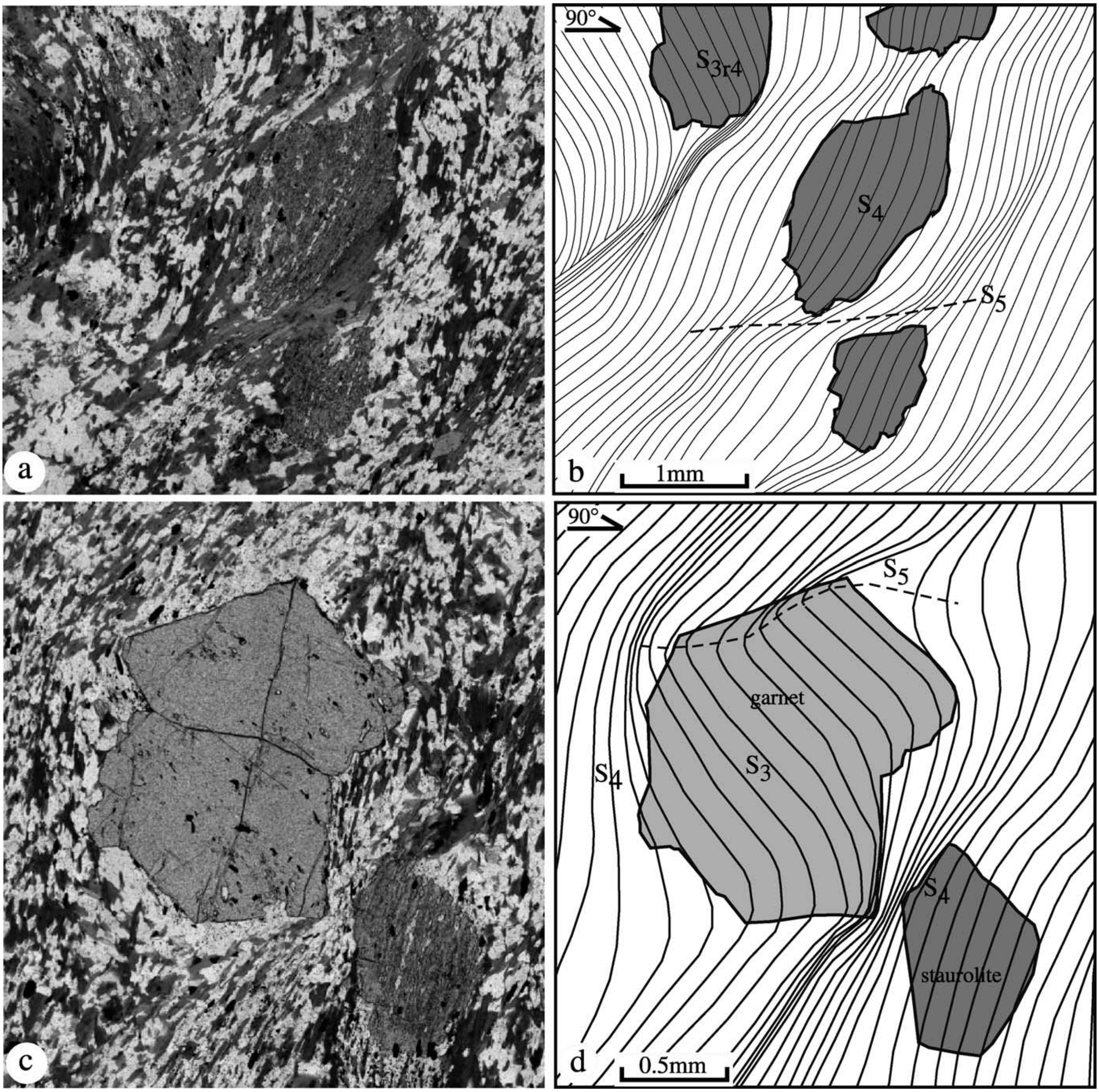

Fig. 7. (a,b) Staurolite grown in flat D_5 event in layer C in sample TC1365. Vertical section strikes 90° with single barbed arrow showing strike and way up. Plane polarized light. (c,d) Bulk of garnet overgrew S_3 in steep D_4 event in layer C in sample TC1365 (vertical S_4 intensifies at lower RH garnet rim). Upper and lower garnet rims grew in D_5. Vertical section strikes 90°with single barbed arrow showing strike and way up. Plane polarized light.

(Fig. 9a and b) or vertical; such curvature has significance (see Discussion).

Numerous studies have attempted to predict the geometry of inclusion trails based on the process by which they form (e.g. Schoneveld, 1977; Bell and Johnson, 1989; Masuda and Mochizuki, 1989; Williams and Jiang, 1999), but relatively little data has been presented on the 3-D geometry of inclusion trails preserved in real rocks. A doubly curving non-cylindrical geometry of 'simple' sigmoidal inclusion trails has been described by several studies (e.g. Johnson, 1993) utilising a serial sectioning approach in which the inclusion trails were reconstructed from tracings of several parallel thin sections made through a single large porphyroblast. Marschallinger (1998) employed a precision serial lapping and scanning technique to aid in similar reconstructions.

The advent of high-resolution X-ray CT has permitted the actual 3-D geometry of curved inclusion trails in garnet

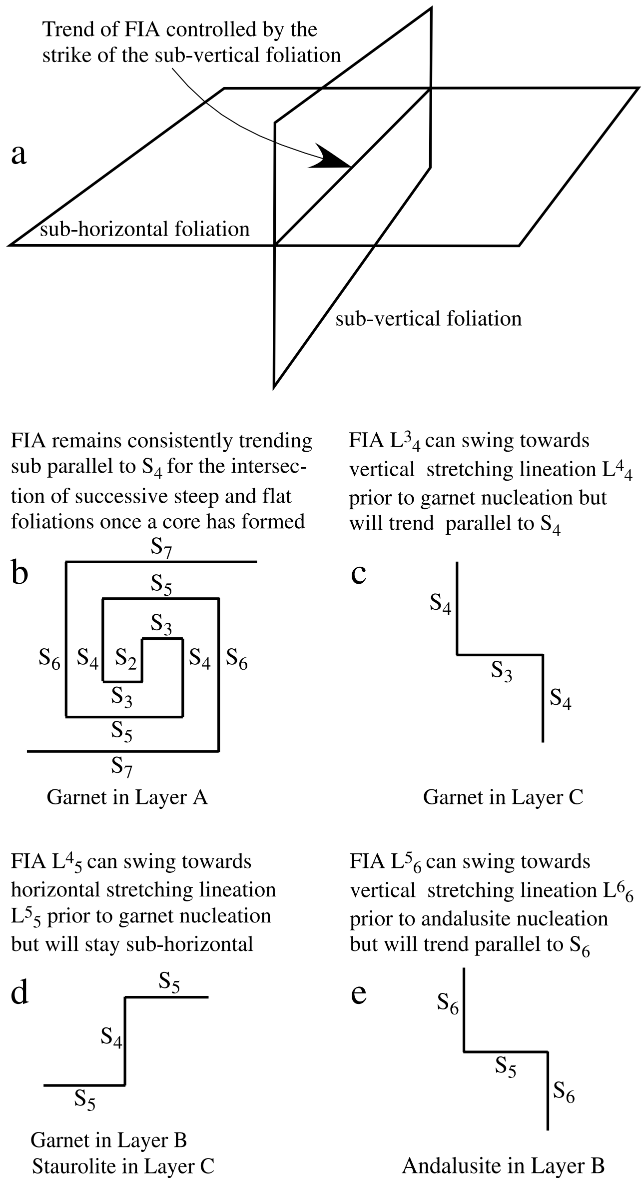

Fig. 8. (a) Shows how FIA trend is controlled by the strike of the sub-vertical foliation. (b)–(e) Skeletal inclusion trail geometries drawn as vertical cross-sections for each porphyroblast phase in each layer. The foliations represent those preserved within the porphyroblasts and can be correlated from layer to layer. (b) The FIA defined by L_4^3, L_5^4, L_6^5 and L_7^6 in the garnet from layer A remain consistently oriented throughout porphyroblast growth at 350°. (c) The FIA defined by L_4^3 in garnet from layer C formed during the development of a sub-vertical foliation and trend at 350°. (d) The FIA defined by the L_5^4 intersection lineation were rotated towards L_5^5 during the development of sub-horizontal S_5 in garnet and staurolite in layers B and C, respectively, and trend at 45°. (e) The FIA defined by the L_6^5 intersection lineation in andalusite in layer B may have been rotated towards the steeply plunging L_6^6 during the development of the sub-vertical S_6 but the trend remains at 350°.

porphyroblasts to be studied in detail for the first time (Ikeda et al., 2002; Huddlestone-Holmes and Ketcham, in press). The combination of attenuation data with thin section and microprobe data allows inclusion phases to be distinguished and separated. The 3-D model of a single garnet porphyroblast produced by Huddlestone-Holmes and Ketcham (in press) provides the actual geometry of a doubly curving single sigmoidal quartz-rich inclusion trail that runs through the centre of the porphyroblast, paralleled by numerous ilmenite inclusions. Their model serves as the template for this study as the geometry of inclusion trails preserved throughout this porphyroblast can be examined and computer derived 2-D cuts made through it in any orientation to quantify and thus understand the significance of inclusion trail cut effects through a single porphyroblast.

3.1. Establishing a model porphyroblast

The 3-D inclusion trail geometry, produced from the high-resolution X-ray CT by Huddlestone-Holmes and Ketcham (in press) on a sample of Cram Hill Formation from south-eastern Vermont, is shown in Fig. 10a. This representation was imported into and manipulated in the 3-D modelling, animation and rendering package Discreet 3ds Max™. This software allows individual phases (garnet, quartz, ilmenite, etc.) or even individual inclusions to be treated and managed separately. It is possible to turn individual parts of the model on or off to highlight aspects of interest. We stripped away garnet and crack-fill material to reveal the central quartz inclusion trail (light coloured) along with higher attenuation opaques (ilmenite) inclusions (Fig. 10b). For clarity, we removed isolated quartz inclusions around the periphery of the garnet because this study is concerned with structures preserved during the first phase of porphyroblast growth and these inclusions were overgrown very late. The central quartz inclusion trails were traced in three dimensions by adjusting the vertex points of a flat, box-shaped primitive object in 3ds Max. Adjustments were made so that the resultant continuous inclusion trail passes through the centres of the quartz inclusions (Fig. 10c), resulting in a continuous representation of the inclusion trail geometry. Removing the central quartz trails reveals that the dark ilmenite inclusions are parallel to the central continuous trail in Fig. 10d. Additional trails were made by extrapolation of the central trail, using the ilmenite inclusions as a guide and adjusting as necessary to create a satisfactory fit (Fig. 10e). We then replaced the garnet around the periphery that was established by the original X-ray CT to produce the final model (Fig. 10f). The inclusion trails in this model offer the advantage that they contain no breaks or gaps. A section cut through the garnet at any orientation or position will always intersect the trails and produce a continuous trace.

3.2. Slicing the model

The trend of the FIA is usually found by looking for the flip in inclusion trail asymmetry in a set of radial vertical thin sections. Fig. 11 illustrates the inclusion trail geometries encountered in a set of such radial sections made through the centre of the model porphyroblast. In

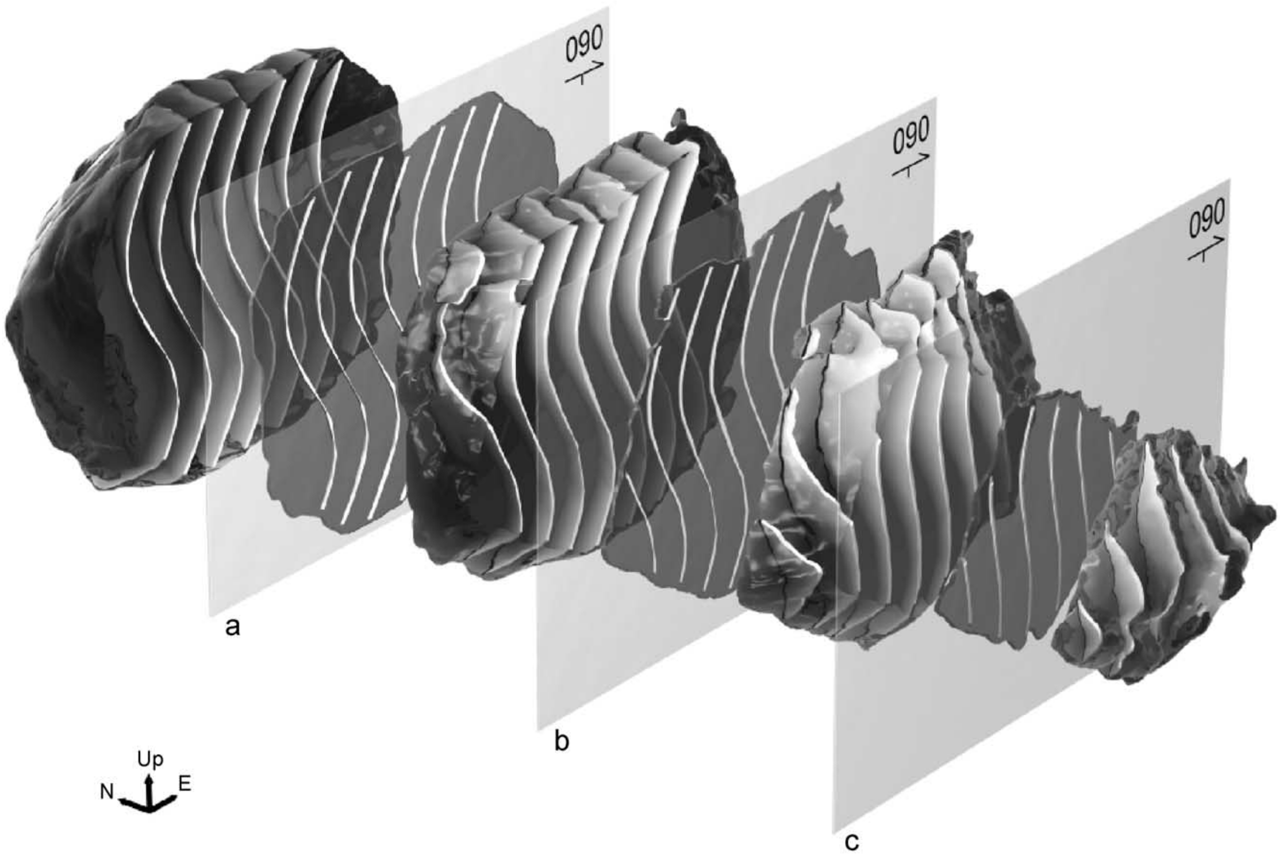

Fig. 9. Shows how reconciliation of the structures observed in differently located thin sections into a complete 3-D presentation of the inclusion trail geometry is impractical because thin sections commonly cut each porphyroblast represented somewhere between its centre and edge.

reality, we need only cut sections at 0, 30, 60, 90, 120 and 150° to get this information. Sections at 180, 210, 240, 270, 300 and 330° can be examined simply by reversing the initial set of six sections. It can be seen that the flip in asymmetry from 'Z' to 'S' shaped occurs at, or very close to, 0° (000° or 180° section). Consequently, the FIA for this sample is oriented approximately N–S. The trend of the FIA can be further constrained by cutting additional sections close to 000° (Fig. 12). These additional sections confirm that the flip in asymmetry occurs very close (± 5°) to 0°.

Fig. 11 shows that the sections cut perpendicular to the FIA (090° and 270°) display the least apparent curvature of the trails. These sections, passing through the centre of the porphyroblast, provide true profiles of the inclusion trail geometry. Sections cut in the remaining orientations display an increase in the apparent curvature, appearing more spiral like, culminating in the closed loop structures of sections cut parallel to the FIA (000° and 180°). Structures observed in sections cut very close to the axis of curvature (e.g. the 010°, 020° and 350° sections of Fig. 12) exhibit almost 180° of apparent rotation from the centre to the margin of the porphyroblast. A comparison of sections made through the trails of the schematic model and the original model of Huddlestone-Holmes and Ketcham (in press) is presented in Fig. 12. The sections through the schematic model clearly reflect the geometry represented by the central quartz inclusions of the original model but the schematic model has the advantage that it is unaffected by the paucity of inclusions, particularly opaques/ilmenite.

3.3. The cut effect

All sections pass through the centre of the porphyroblast in Fig. 11. However, it is unlikely that any particular porphyroblast will be perfectly bisected by a thin section. Consequently, the inclusion trails observed usually vary from central cuts as shown for a set of radial thin sections in Fig. 13 (the numbers in parenthesis are those section orientations that can be obtained simply by flipping the original section over; 210° is equivalent to 030° viewed from the opposite direction). Significantly, the flip in asymmetry occurs very close to 0° regardless of whether the sections utilised pass through the centre or closer to the edge of the porphyroblast for one phase of porphyroblast growth. That is, the asymmetry method for determination of the axis of curvature is unaffected by cut effects. However, the doubly curving, non-cylindrical nature of the inclusion

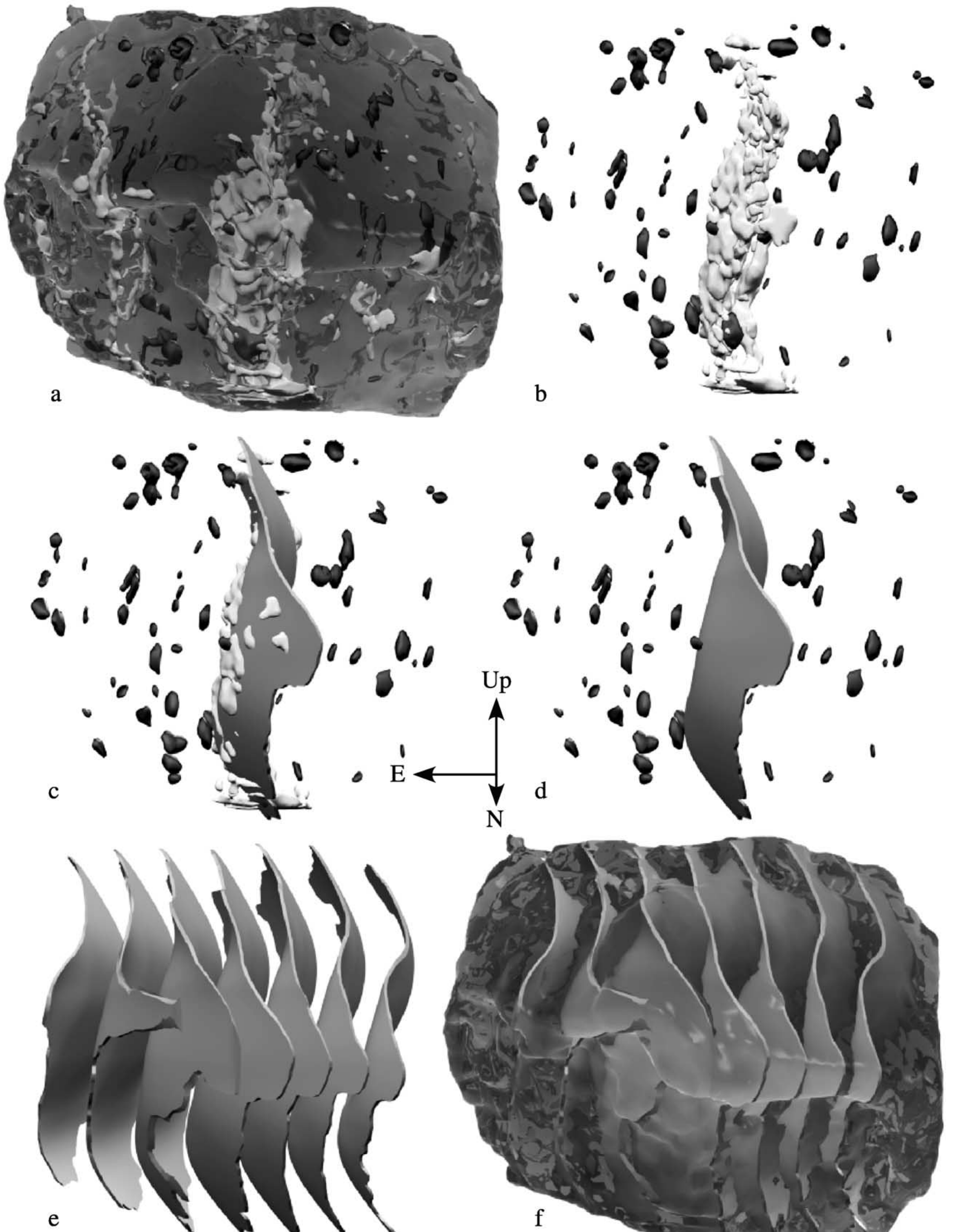

Fig. 10. (a) The 3-D inclusion trail geometry, produced from the high-resolution X-ray CT by Huddlestone-Holmes and Ketcham (in press) on a sample of Cram Hill Formation from south-eastern Vermont (sample V209 in Bell and Hickey, 1997). (b) Shows garnet and crack-fill material stripped away to reveal the central quartz inclusion trail (light coloured) along with higher attenuation opaques (ilmenite) inclusions. (c) 3-D inclusion surface drawn to pass through the

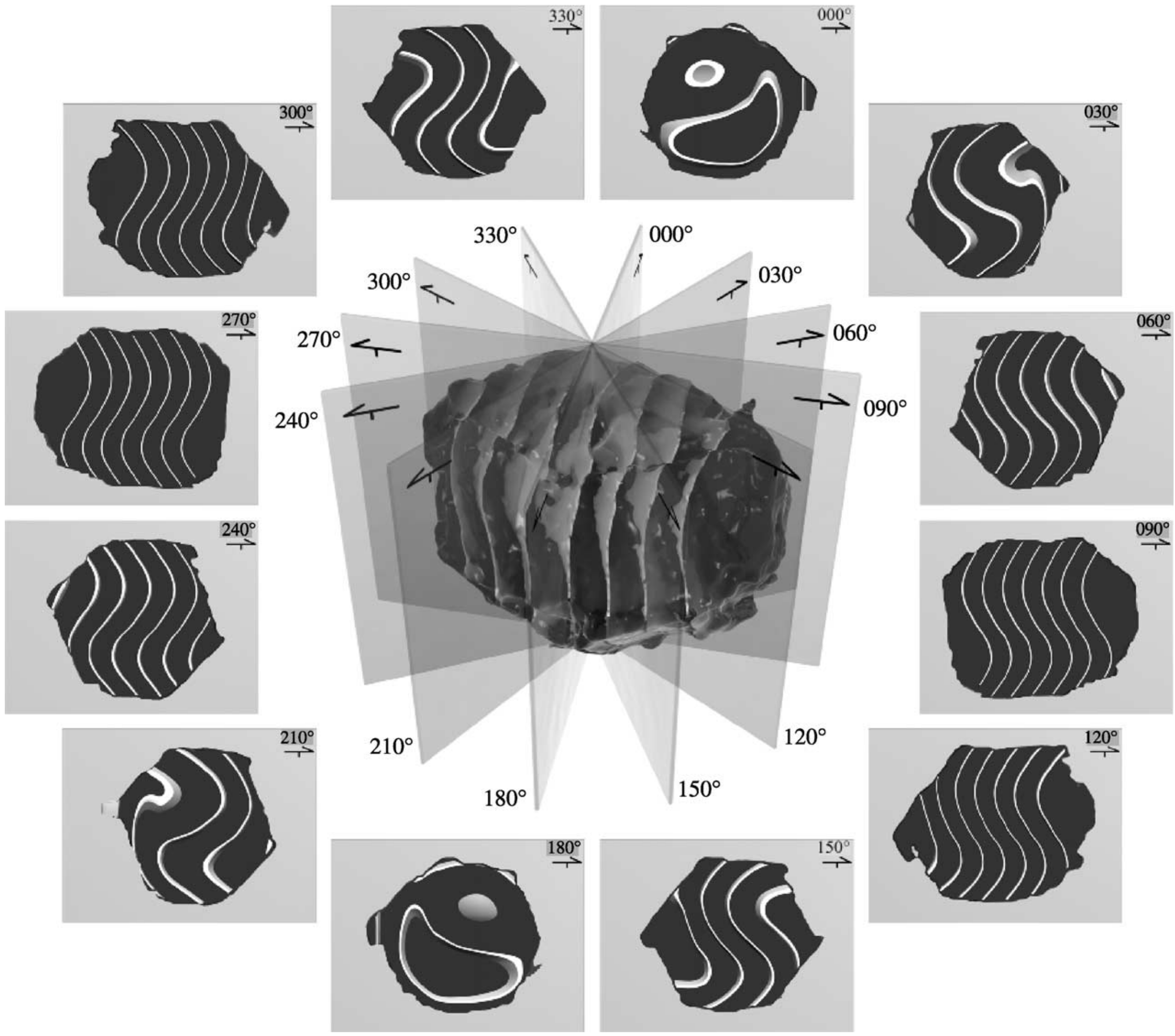

Fig. 11. Shows the inclusion trail geometries encountered in a set of radial sections made through the centre of the 3-D porphyroblast constructed in Fig. 10. In reality, we need only cut sections at 0, 30, 60, 90, 120 and 150° to get this information. Sections cut perpendicular to the FIA (090° and 270°) display the least apparent curvature of the trails. These sections, passing through the centre of the porphyroblast and cut perpendicular to the FIA can be considered true profiles of the inclusion trails.

trails results in a significant decrease in the apparent curvature of the inclusion trails from the centre to the outer margin of the porphyroblast. This is especially apparent in sections cut nearly orthogonal to the FIA (e.g. at 090°). While this can potentially make determination of asymmetry difficult, these effects can be overcome by examining a large enough population of porphyroblasts.

Another aspect to cut effects is the orientation of a section relative to the FIA. Structures observed in sections cut within 30° of the axis of curvature (Fig. 11 and the 010°, 020° and 350° sections of Fig. 12) exhibit almost 180° of apparent rotation from the centre to the margin of the porphyroblast and would be called spiral inclusion trails as opposed to sigmoidal if viewed in isolation through cutting just one or two thin sections from this sample. Different sets of FIAs can show a large range of trends relative to the matrix foliation (e.g. Ham and Bell, 2004). Therefore, thin sections cut perpendicular to the matrix foliation and perpendicular or parallel to a lineation, may cut through a porphyroblast where the FIA lies at 30° or less to the section plane. Such thin sections may show perfect spiral shaped inclusion trails in porphyroblasts where the actual geometry is a sigmoid (e.g. Fig. 11) and would be interpreted by many

centre of the quartz inclusions. (d) The dark ilmenite inclusions are parallel to the central surface drawn with the quartz inclusions removed. (e) Additional inclusion surfaces were made by extrapolation of the central trail, using the ilmenite inclusions as a guide and adjusting to create a satisfactory fit. (f) Shows garnet, as established from the original X-ray CT, resulting in the final model.

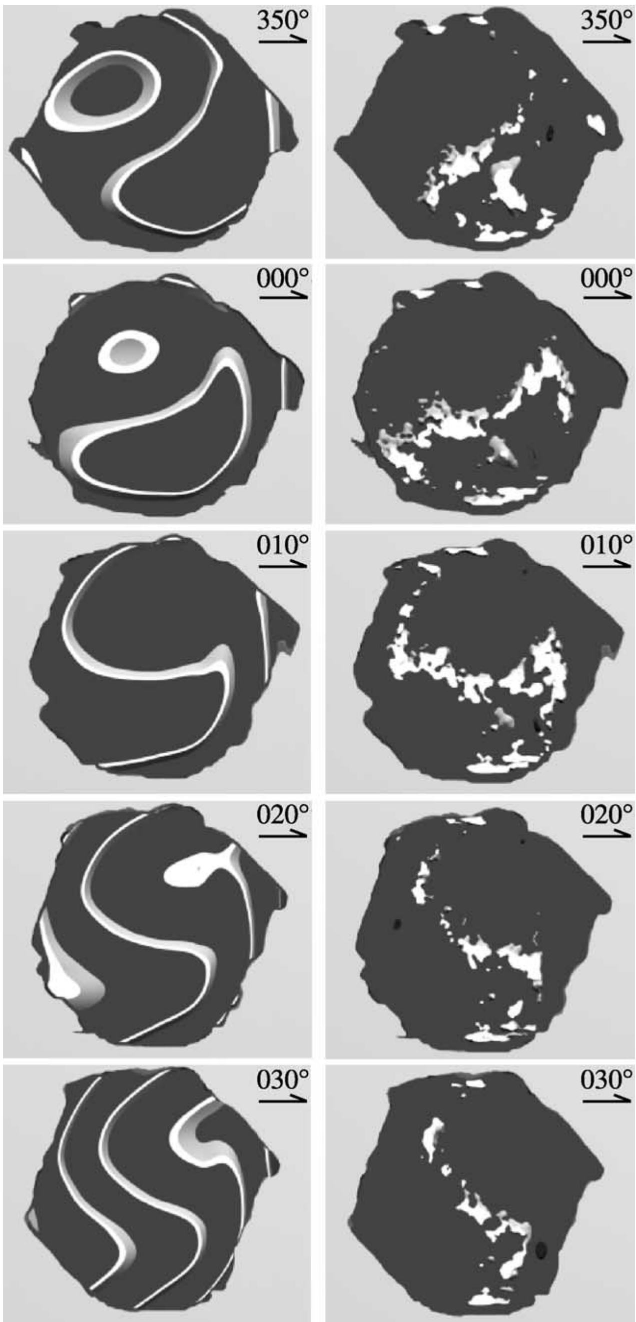

Fig. 12. The trend of the FIA can be further constrained by cutting additional sections close to 000°. Sections made through the schematic inclusion trails are compared with sections made through the original model of Huddlestone-Holmes and Ketcham (in press).

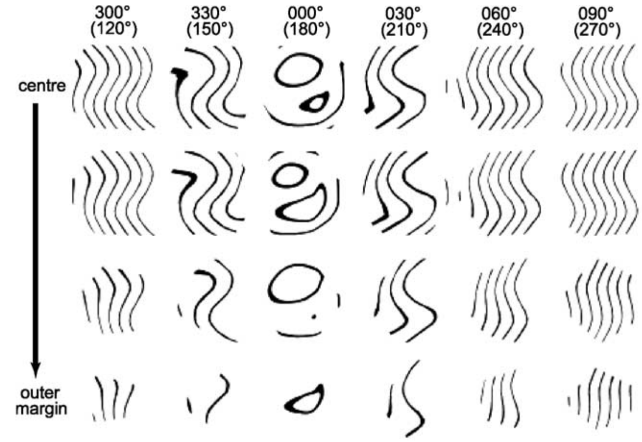

Fig. 13. Shows the range of potential inclusion trail patterns made by taking sections through the schematic model porphyroblast at different orientations and at various distances from the centre. It is statistically unlikely that a particular porphyroblast will be perfectly bisected by a thin section. The inclusion trails observed are more commonly variations on these perfect delineations, as illustrated here.

today as a product of intense local shear zone development (e.g. Williams and Jiang, 1999).

3.4. Variation in FIA trend through the model

Fig. 14a shows three horizontal cuts through the inclusion trail geometry. The variation in the orientation of the intersection of the inclusion trails with the horizontal cut that passes through the porphyroblast centre potentially defines the maximum variation in trend of a FIA that could be recorded by the growth of a single porphyroblast that grew in this event. The intersection of this foliation with the horizontal cut varies through a maximum of 60°. Huddlestone-Holmes and Ketcham (unpublished data) measured the FIAs separately in 58 porphyroblasts using X-ray CT on five cylinders cored from different portions of this sample and found a maximum variation of 30° around the mean FIA trend giving a total variation of 60°. Therefore, the question to be resolved is how much of this variation predated or was synchronous with porphyroblast growth. This is particularly pertinent with this sample because, as mentioned above, it contains evidence of a foliation inflection through the vertical that strongly suggests the foliation either initially had a sub-horizontal orientation (Fig. 14b(i)) or was a reactivated oblique moderately east dipping foliation sub-parallel to compositional layering (Fig. 14b(ii)) or was a pre-existing crenulation about a steep axial plane (Fig. 14b(iii)). This foliation in Fig. 14b(i) was initially rotated by a deformation with a sub-vertical axial plane to the steep east dip or started in this orientation prior to the deformation with the sub-horizontal axial plane that accompanied porphyroblast growth. It was then overprinted by the crenulation with the sub-horizontal axial plane that accompanied porphyroblast growth. If the porphyroblast did not overgrow the centre of a partially decrenulated pre-existing hinge (Fig. 14c(i)), but instead was centred above that as shown in Fig. 14c(ii), then the resulting foliation through the centre of the porphyroblast would look like Fig. 14a(ii) with the actual geometry that should have been preserved in the porphyroblast centre looking like that in Fig. 14a(i). Therefore, we conclude that the bulk of the

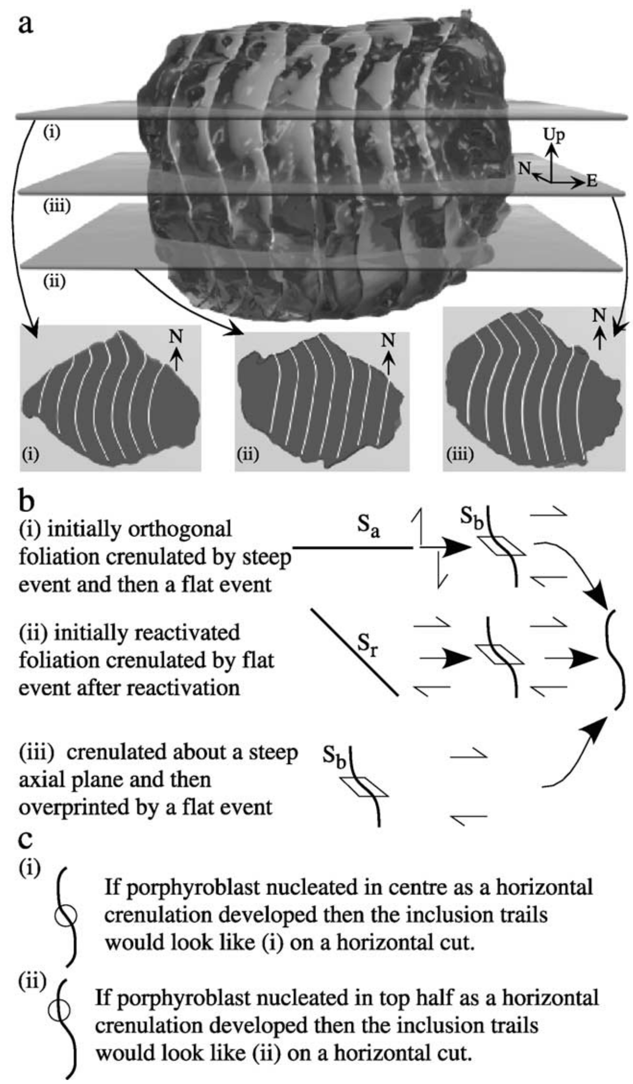

Fig. 14. (a) Shows the inclusion trail geometry in three different horizontal cuts through the porphyroblast. (b) The inflection through the vertical shown in (a) can be explained by overprinting during a deformation that develops a sub-horizontal axial plane shown in a vertical cross-section through (i) a foliation that was initially flat lying but which had been overprinted by an earlier steep event, (ii) a foliation that was reactivated and dipping right, or (iii) a pre-existing crenulation. (c) Shows (i) a porphyroblast nucleating in the centre of inflection described in (b) and (ii) a porphyroblast nucleating in the upper part of the same inflection.

variation occurred prior to development of the sub-horizontal foliation in this sample.

4. Discussion

4.1. The early growth of porphyroblasts relative to deformation

Porphyroblast growth during regional metamorphism commences very early during a deformation event (Bell et al., 2003) and ceases once a differentiated crenulation cleavage begins to form in the immediate vicinity (Fig. 15; Bell and Hayward, 1991). Nucleation of a porphyroblastic phase for the first time at a particular site requires irregular partitioning of the deformation into progressive shearing and shortening components on the scale of a porphyroblast (e.g. Fig. 15a), which generally involves relatively coaxial strain to enhance microfracture along pre-existing foliations (e.g. Bell et al., 2004). This means that the first phase of porphyroblast growth generally preserves simple trails that commonly have a very similar orientation across a thin section (Ramsay, 1962), fold or region (Fyson, 1980; Aerden, 2004). However, deformation may locally commence and be distributed very homogeneously on a scale much larger than a porphyroblast. For example, if reactivation of the pre-existing foliation is possible or becomes possible, then the foliation can rotate without crenulations developing at the scale of a porphyroblast (e.g. Bell et al., 2003). If this occurs, porphyroblasts will not nucleate unless the deformation begins to partition into progressive shearing and shortening components at the scale of a porphyroblast. Consequently, the foliation preserved as inclusion trails within such porphyroblasts could vary significantly from its orientation prior to the commencement of that deformation event. However, it is significant that in many examples this is not the case.

Foliations that have been folded several times before porphyroblast growth begins should show a large range of variation in orientation when preserved as inclusion trails. It is intriguing how uncommon this appears to be at the scale of several outcrops (Steinhardt, 1989; Aerden, 1995), shear

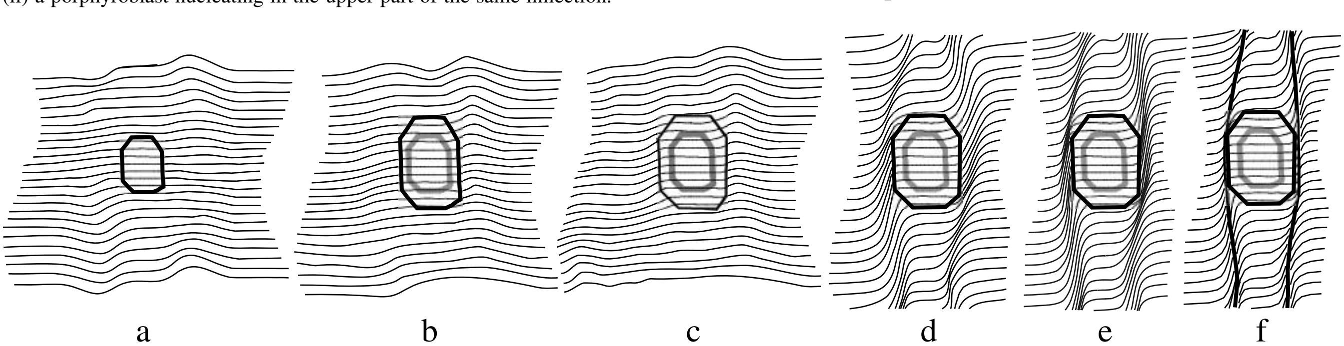

Fig. 15. Shows how porphyroblast growth that has commenced very early during a deformation event ((a)–(c)) ceases once a differentiated crenulation cleavage begins to form in the immediate vicinity ((d)–(f)). Also shows how nucleation of a porphyroblastic phase for the first time at a particular site requires partitioning of the deformation into progressive shearing and shortening components on the scale of a porphyroblast through that location.

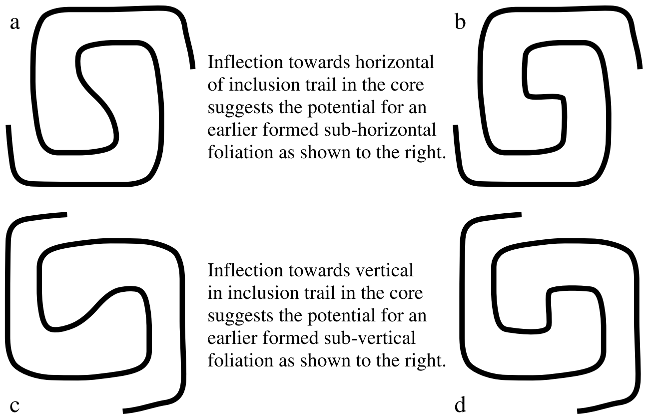

Fig. 16. Skeletal diagrams of vertical cross-sections through spiral-shaped inclusion trails in porphyroblasts. Curvature towards horizontal of the central inclusion trail in (a) suggests the presence of an earlier formed sub-horizontal foliation as shown in (b). Curvature towards vertical of the central inclusion trail in (c) suggests the presence of an earlier formed sub-vertical foliation as shown in (d).

zone (Jung et al., 1999), or region (Fyson, 1980). Possible reasons for this are:

1. Such variation is less interesting than consistency and has not been recorded; consequently, it is less well represented in the literature.
2. Foliations lying parallel to bedding are crenulated at a coarser scale than recently developed axial planar ones causing porphyroblasts to preferentially nucleate in the latter.

A significant factor that would promote the situation described in point 2 is that compositional layering always will reactivate if the geometry is appropriate and this reduces the number of sites available for porphyroblast growth (Bell et al., 2003).

4.2. Porphyroblast nucleation and initial growth

As a result of the early commencement of porphyroblast growth relative to deformation in the vicinity, the most common inclusion trail geometry preserved is one of straight inclusion trails that are slightly curved at the porphyroblast edges (Fig. 15c). Porphyroblast growth ceases once inclusion trail curvature becomes significant because the progressive shearing causing foliation curvature also causes a differentiated crenulation cleavage to begin to develop. The dissolution and solution transfer associated with this process stops further porphyroblast growth (Fig. 15d–f; Bell and Hayward, 1991). Consequently, porphyroblasts will generally not nucleate over a foliation lying at a low angle to that which is newly developing as such foliations will reactivate antithetically as shown in Fig. 1 (e.g. Bell et al., 2003) or be reused synthetically (e.g. Davis and Forde, 1994). The next most common inclusion trail geometry is one of sigmoidal inclusion trails that are slightly more curved at the porphyroblast edges than towards the core. Such trails commonly result from the overprint of a pre-existing crenulation hinge by a younger event as shown in Fig. 14b(iii). Their development is very similar to that just described except that relics of an early crenulation are present providing more curvature of the inclusion trails.

4.3. Significance of foliation curvature towards the vertical or horizontal

Multiple thin sectioning of samples commonly reveals, in some porphyroblasts, inflections towards the vertical or horizontal for the earliest observable portion of the inclusion trail as shown in Fig. 16. These inflections have significance if inclusion trails result from the development of successive sub-vertical and sub-horizontal foliations as first argued by Bell and Johnson (1989). They can form in one of three ways.

1. They reflect the remains of an older crenulation that predates porphyroblast growth as shown in Fig. 14b(iii).
2. They reflect the remains of a reactivated foliation that lies oblique to the horizontal or vertical (Fig. 14b(ii)).
3. They result from relatively coaxial deformation occurring early during the deformation that occurred prior to the first phase of porphyroblast growth (Fig. 15a–c; Bell and Bruce, unpublished data).

If they result from nucleation on an older crenulation, then one would expect that X-ray CT scans of 3-D inclusion trail geometries from many porphyroblasts in the same sample, would reveal such geometries in a lot of them. This could also apply if the foliation was the remains of an

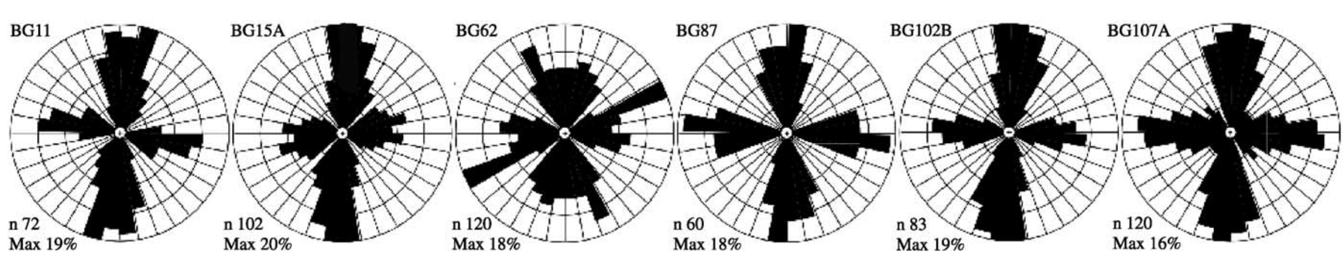

Fig. 17. Equal area rose diagrams showing the pitch of truncational discontinuities preserved as inclusion trails measured from between 8 and 12 vertical thin sections with different strikes per sample (from Gavin, 2004).

oblique reactivated one. Indeed this is the situation recorded by Huddlestone-Holmes and Ketcham (unpublished data). If, however, they formed by early coaxial deformation one would expect that the variation in geometry from porphyroblast to porphyroblast would be very large (e.g. Bell and Bruce, unpublished data). If such changes occurred at a much larger scale than a porphyroblast then no porphyroblast would tend to nucleate. However, if repartitioning of the deformation occurred at a finer scale through the outcrop, any porphyroblasts that nucleated would overgrow the previously rotated foliation and perhaps have a similar geometry to that described for points 1 and 2 above. At a larger scale this might not be the case and the inclusion trail geometry could vary significantly from porphyroblast to porphyroblast.

4.4. Curvature of the intersection or inflexion axis within a porphyroblast

When a porphyroblast first nucleates the FIA could show considerable curvature in 3-D (Fig. 10) causing a change in trend in a horizontal plane in Fig. 14a(i)–(iii) and plunge in a vertical plane in Fig. 14b. This variation can be recorded using X-ray CT methods within individual porphyroblasts as shown in Fig. 10. However, the method of measurement used to record the FIA and described by Hayward (1990) records the FIA for a sample and not for an individual porphyroblast. The effects of such primary variation within a porphyroblast are eliminated.

4.5. Apparent spiral shaped inclusion trails due to section orientation

The 3-D geometry of inclusion trails in the garnet porphyroblast revealed by X-ray CT shows that some section orientations in space contain a spiral shaped inclusion trail geometry even though the inclusion trails are sigmoidal in 3-D (e.g. the 030° and 150° sections in Fig. 11). This possibility will be recognized by anyone who works extensively with multiple thin sections around the compass but will not be known by most metamorphic and structural geologists because they have not done this type of work. Consequently, where thin sections are cut either randomly or relative to the matrix microstructures, the porphyroblasts can contain spiral shaped inclusion trails that may even appear to be continuous with the matrix foliation (Cihan, 2004), when in fact only sigmoidal ones are present in 3-D. This could dramatically influence interpretation of the structural history of the region, depending on whether one interpreted that the inclusion trails had formed by porphyroblast rotation or non-rotation. Wherever spiral shaped inclusion trails are seen in thin section showing a maximum of 180° of curvature, extra thin sections in other orientations should be cut to check whether true spirals or just sigmoidal trails are present.

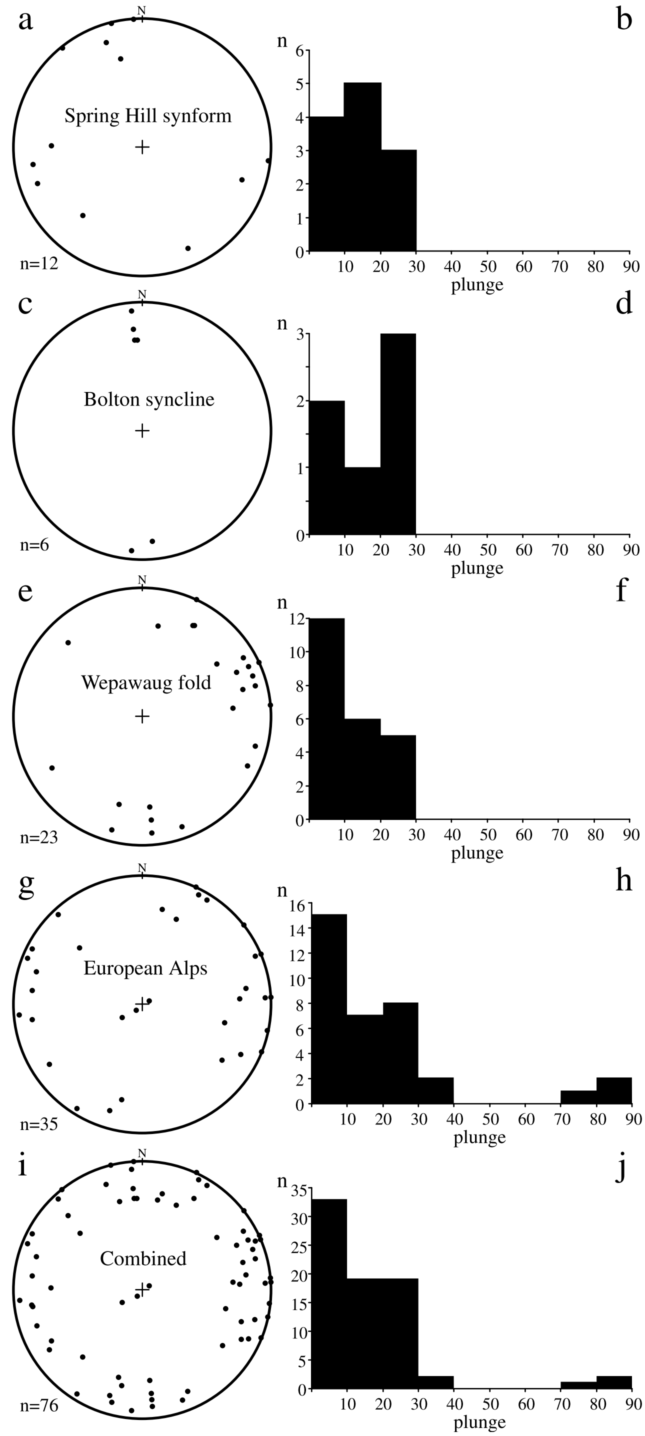

Fig. 18. Stereonets of FIA plunges and histograms of angle of plunge data from (a) and (b) the Spring Hill syncline (Bell and Hickey, 1997), (c) and (d) the Bolton syncline (Hickey and Bell, 1999), (e) and (f) the Wepawaug fold (Bell and Newman, unpublished data), (g) and (h) the European Alps (Bell and Wang, 1999) and (i) and (j) these four regions all combined into one plot. The plunges are pre-dominantly sub-horizontal ranging up to 30°. The three steep plunges recorded in the Alps all occur in samples where the porphyroblasts grew for the first time during the development of a sub-vertical foliation.

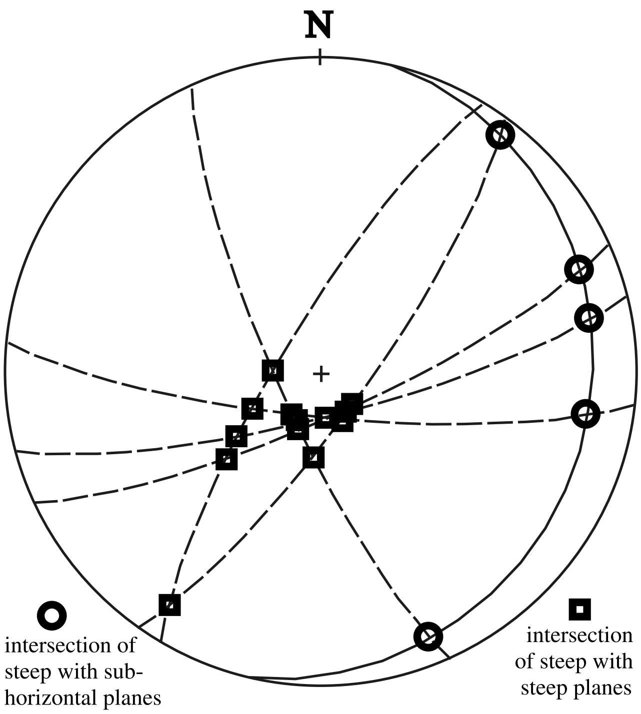

Fig. 19. Stereonet showing how the intersection of a sub-horizontal plane with any other steeply dipping plane produces a gentle plunge (circles). It also shows how the intersections of steeply dipping planes have mainly steep plunges. They only range to gentle plunges when the intersecting steeply dipping planes are very close in strike, and mainly have opposite dips.

4.6. Geometry of foliation development against a porphyroblast

Once a porphyroblast has formed it provides a rigid or competent object against which the shearing component of the deformation in the matrix tends to nucleate soon after the commencement of deformation. The large amount of quantitative data available on the orientation of foliations forming after an initial stage of porphyroblast growth suggests that they form predominantly sub-vertically or sub-horizontally (Fig. 17, modified from Gavin (2004); see also fig. 10 in Hayward, 1992). This is confirmed by the shallow plunges of FIAs in the terrains where these have been measured (Fig. 18 from data in fig. 9d of Bell and Hickey (1997); table 1 of Bell and Wang (1999); fig. 9 of Hickey and Bell (1999); and Bell and Newman, unpublished data). FIAs resulting from successive steep foliations would have plunges ranging from mainly very steep to locally very gentle (Fig. 19), which is not what is observed where porphyroblasts have grown for a second or subsequent time. The only way to achieve plunges less than 30° during every phase of porphyroblast growth after the first is for the FIAs to result from the intersection of successively preserved sub-vertical and sub-horizontal foliations. Such sub-horizontal plunges are independent of whether a sub-horizontal foliation overprints a sub-vertical foliation or a sub-vertical foliation overprints a sub-horizontal foliation.

4.7. The FIA method versus the cut effect

The FIA method uses the asymmetry of inclusion trails in all porphyroblasts present in a thin section. Therefore, it uses all cuts through a porphyroblast from the core to the rim, in at least eight different orientations around the compass. Conceptually, all slices through one period of growth of the porphyroblast should preserve the asymmetry and the FIA method should be independent of any cut effect, but it is clearly important to test this. Fig. 13 shows that this is the case. Therefore, the FIA method provides an excellent method for measuring foliation inflection/intersection axes preserved within the porphyroblasts within a sample that is independent of any cut effect on the inclusion trail geometry through a porphyroblast.

4.8. Consistency of FIA trends

Where FIAs have been measured regionally they maintain remarkably consistent successions of trends for large distances (e.g. Aerden, 2004; Bell et al., 2004). In a range of locations, individual FIAs result from successions of up to seven foliations intersecting in the one axis requiring that directions of relative bulk shortening remain constant for significant periods of time. Bell and Welch (2002) suggest that these periods are around 10–30 million years in length. Layer A in sample TC1365i contains garnet porphyroblasts preserving evidence for five foliations plus a crenulation axial plane in the matrix that intersect in the one axis at 350°. Variation from this trend only occurs in samples where there is one phase of growth that occurred during the development of a horizontal foliation. Such samples can be readily eliminated from a regional analysis if anomalies relative to multiple FIA samples are recorded.

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