J. metamorphic Geol., 1993, **11**, 621–634

Unravelling the spirals: a serial thin-section study and three-dimensional computer-aided reconstruction of spiral-shaped inclusion trails in garnet porphyroblasts

S. E. JOHNSON
School of Earth Sciences, Macquarie University, Sydney, New South Wales, 2109, Australia

ABSTRACT Seventy-seven spatially orientated, serial thin sections cut from a single rock reveal changes in the geometry of spiral-shaped inclusion trails (SSITs) in garnet porphyroblasts. The observed SSITs are doubly curved, non-cylindrical surfaces, with total inclusion-trail curvature decreasing systematically from the cores to the rims of porphyroblasts. The three-dimensional geometry of the SSITs, reconstructed with the aid of computer graphics, shows that the orientations of spiral axes defined by the SSITs are not related in any expected nor predictable way to the main foliation in the matrix. This suggests continued deformation after or during the latest stages of porphyroblast growth, which has important implications for the use of SSITs as shear-sense indicators. Whether the formation of SSITs involves significant porphyroblast rotation with respect to a geographically fixed reference frame cannot be determined from the available data.

Key words: computer graphics; garnet porphyroblasts; serial thin sections; spiral-shaped inclusion trails; three-dimensional reconstruction.

INTRODUCTION

This paper presents a serial thin-section study and a three-dimensional (3-D) computer-aided reconstruction of spiral-shaped inclusion trails (SSITs) in garnet porphyroblasts. The principal aim of this study is to provide an understanding of the 3-D geometry of SSITs. Results are compared with three previous studies of the 3-D geometry of SSITs, which relied on theoretical (Powell & Treagus, 1967, 1970) or mechanical (Rosenfeld, 1970; Schoneveld, 1979) models to generate a 3-D picture of SSITs. In contrast, the 3-D images in this study are generated by applying computer graphics to inclusion-trail data collected from serial thin-sectioning of natural garnet porphyroblasts with SSITs. The theoretical (Powell & Treagus, 1967, 1970) and mechanical (Rosenfeld, 1970; Schoneveld, 1979) models are found to agree reasonably well with the geometries described in this study, suggesting that assumptions made in these models concerning porphyroblast growth are valid, at least where SSITs are smoothly curving.

Porphyroblasts with SSITs occur in many orogenic belts (e.g. Spry, 1963; Rosenfeld, 1968, 1970; de Wit, 1976; Schoneveld, 1977, 1979; Powell & Vernon, 1979; Bell & Brothers, 1985; Brunel, 1986; Meneilly & Storey, 1986; Gibson, 1989; Holm & Selverstone, 1990; Johnson, 1990; Hayward, 1992; Passchier *et al.*, 1992). Even though several models (e.g. de Wit, 1976; Schoneveld, 1977, 1979; Bell & Johnson, 1989; Johnson 1993) have been advanced to explain SSITs since they were first described by Flett (1912, pp. 111, 178), much controversy still surrounds their mode of formation. The controversy centres around whether formation of SSITs requires porphyroblast rotation relative to a geographically fixed reference frame (see Johnson, 1993, for review). The microstructural details provided in this paper may be useful to researchers attempting to settle this controversy.

SAMPLE CHOICE AND THIN-SECTIONING TECHNIQUE

The sample analysed in this study was chosen because the garnet porphyroblasts consistently contain SSITs and are large enough to obtain 6–10 serial thin sections per porphyroblast. The sample was collected from garnet schists in the Main Central Thrust Zone north-east of Pokhara, in the Nepal Himalaya. Samples with smaller porphyroblasts could potentially be studied by photographing serially ground and polished rock surfaces, which would avoid the inherent material loss involved with making thin sections. However, each polished surface is destroyed to produce the next polished surface. In contrast, serial thin sections allow continual comparison, appraisal and interpretation of microstructures.

To maximize the usefulness of serial thin sections made for the purpose of studying SSITs, the orientations of the sections must be known, relative to the orientation of 'spiral axes' within the porphyroblasts. In the present study, the orientation of spiral axes was determined by a method similar to that described by Hayward (1990) and

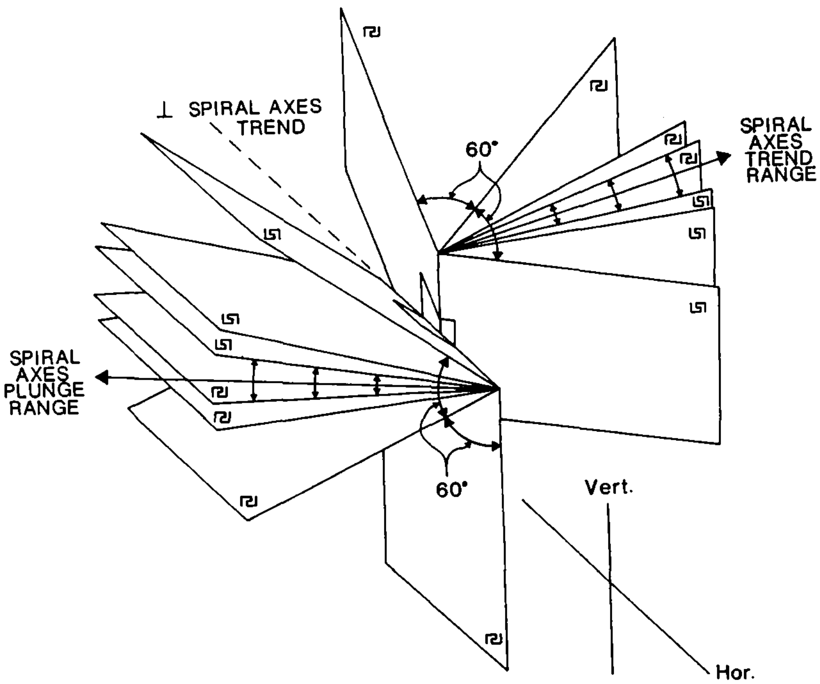


Fig. 1. Sketch showing the technique used to find the orientation of spiral axes. See text for details.

shown in Fig. 1. Three vertical thin sections were first cut at 60° to one another. When observed from the same direction (clockwise or anticlockwise), a change in the spiral asymmetry was seen to occur between two of the sections, indicating that the spiral axes lay between these two section orientations. Further thin sections were cut between these two until a suitably tight spiral-axes trend range was determined.

In order to determine the 3-D orientation of spiral axes, it is also necessary to determine a plunge range. To accomplish this, three thin sections were made at 60° to one another, through the horizontal, with their long axes parallel to the previously determined trend range. As in the trend-range determination above, a change in the spiral asymmetry was observed between two of the sections, indicating that the spiral axes lay between these two section orientations. More thin sections were cut between these two until a suitably tight spiral-axes plunge range was determined. Thus, spiral-axes trend and plunge ranges were determined, which equates to finding the approximate orientation of a line in three dimensions.

Changes in spiral asymmetries observed during the above-described process were remarkably consistent, indicating that: (1) spiral axes in this rock appear to be consistently orientated from porphyroblast to porphyroblast, and (2) relative rotation (between matrix foliation and porphyroblast) occurred about only one axis during porphyroblast growth. Further studies of different rocks are required to determine how common these observations may be (cf. Rosenfeld, 1968, 1970; Hayward, 1990, 1992; fig. 17 in Bell & Hayward, 1991).

After the orientation of spiral axes was determined using the above technique, 77 vertical serial thin sections were cut with various strikes to obtain views ranging from subperpendicular, to subparallel, to the trend of spiral axes. These thin sections were cut from several thin-section blocks, which were removed from the hand sample in a known orientation relative to the spiral axes. Lines were marked at 1-mm intervals on the sides of the thin-section blocks, as shown in Fig. 2. After each section was cut from a block, the block was prepared for the next section, and the position of the prepared surface relative to the marked 1-mm intervals was noted. In this way, sections were generally spaced at approximately 1.25-mm intervals, although some were spaced as little as 1 mm or as much as 1.5 mm apart.

Three representative sets of serial thin sections, which show the internal morphology of porphyroblasts with SSITs, are shown in Figs 3–5. These serial sets are

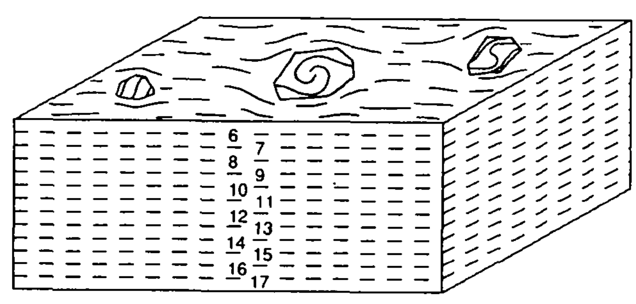


Fig. 2. Sketch of a thin-section block showing how the distances between serial thin sections in any individual serial set were controlled. Dashed lines down the side of the block are 1 mm apart, and the numbers associated with each dashed line denote 1-mm spacings. In this case, 5 mm has already been removed from the block.

orientated subperpendicular, subparallel and oblique to the trend of spiral axes, respectively.

3-D COMPUTER-AIDED RECONSTRUCTION OF SSITs

Three types of computer-aided reconstructions were employed.

(1) The photomicrographs in Figs 3–5 were scanned at 300 DPI resolution using an Apple® scanner. These scanned images were imported into the program Adobe Photoshop™ for the purpose of enhancing grey scales. The enhanced images were imported into the program Aldus Freehand®, and skewed. The skewed images were stacked at convenient, equal spacings, which provided 3-D views of entire serial thin-section sets (Fig. 6). Ideally, computer graphics would be used to connect the scanned photomicrographs into actual 3-D images of the porphyroblasts and inclusions in their entirety, rather than combining these photomicrographs into stacked cross-sections. However, because of the difficulty in correlating individual inclusion surfaces and other features from one serial thin section to the next, actual 3-D reconstruction is beyond the capabilities of standard, available computer software. The same problem was noted over a decade ago by Schoneveld (1979).

(2) Tracings of central inclusion curves (the trail of inclusions passing through the centre of a porphyroblast) were made from the photomicrographs in Fig. 3 (Fig. 7) and scanned at 150 DPI resolution using an Apple scanner. The scanned curves were imported into the program Mathematica (Wolfram Research Inc., USA), where they were redefined as functions with a fitting routine. These functions were then connected with a separate set of functions to form a 3-D surface corresponding to the central inclusion surface within the porphyroblast in Fig. 3 (Fig. 8). Details of the Mathematica manipulations and the Mathematica code for connecting lines in 3-D are presented elsewhere (Johnson & Moore, 1993).

(3) The shape of a garnet porphyroblast was assumed to be a sphere. The program Mathematica was used to split the sphere by perpendicular cuts into two hemispheres, and to generate exploded views of these hemispheres. Inclusion patterns seen in sections subparallel and subperpendicular to spiral axes were generalized and drawn on the components of the exploded hemispheres (Fig. 9), providing views of how inclusion patterns seen in different sections are connected in three dimensions.

RESULTS

Several important observations were made from Figs 3–9.

(1) Total inclusion-trail curvature (from cores to rims of porphyroblasts) decreases regularly in successive serial sections from the centres of porphyroblasts to their margins. This regular change in inclusion-trail geometry demonstrates that the SSITs have non-cylindrical shapes (Figs 3 & 7–9). Closed loops in sections subparallel to the spiral axes (Fig. 4) are products of non-cylindrical SSITs (Figs 8 & 9).

(2) Although inclusion trails and external foliation surfaces were commonly found to be continuous in sections subperpendicular to the spiral axes (e.g. Fig. 3), suggesting little deformation subsequent to porphyroblast growth, the spiral axes do not lie in the plane of the external foliation. This is presented in Fig. 10, which shows the orientation of the main foliation, as measured in the field, and the orientation of the spiral axes as determined by the method shown in Fig. 1. Obliquity between the main foliation and spiral axes was also verified in sections subparallel to the spiral axes (Fig. 4), where the orientations of spiral axes (solid line in Fig. 4d) and external foliation can be seen together.

(3) In sections cut subparallel to the spiral axes, the angle at which included foliation surfaces intersect the thin section varies markedly, but systematically (Figs 8 & 9). This leads to variations in the shape and orientation of inclusion grains (Figs 4 & 5). In the regions of closed loops, where included foliation surfaces intersect the thin section at a very low angle (Fig. 9), elongate inclusions define a mineral elongation lineation (Fig. 4). This lineation is consistently orientated subperpendicular to the spiral axes, as might be expected.

DISCUSSION

Comparison with previous 3-D studies of SSITs

Three previous studies of the 3-D shape of SSITs have been published (Powell & Treagus, 1967, 1970; Rosenfeld, 1970; Schoneveld, 1979). Powell & Treagus (1967, 1970) presented a theoretical model in which it was assumed that a porphyroblast is spherical and rotates (relative to the matrix fabric) a constant amount for a constant increase in volume.

Rosenfeld (1970) built a mechanical model that shows the 3-D geometry of a central inclusion surface by connecting a set of concentric rings by a common axis ('rotation' axis). Implicit in this model is the assumption that a garnet porphyroblast is spherical and rotates (relative to geographically fixed coordinates) a constant amount for a constant linear increase in its radius.

Schoneveld (1979) built a mechanical model from strings, Plasticine and brass rings, in which it was assumed that a garnet porphyroblast is spherical and rotates (relative to geographically fixed coordinates) a constant amount for a constant linear increase in its radius. To define his model porphyroblast, Schoneveld (1979) constructed 55 serial sections, varying the rotation angles

Fig. 3. (overleaf) Set of eight serial thin sections through a single garnet porphyroblast with spiral-shaped inclusion trails showing approximately 200° of total inclusion-trail curvature. Sections are vertical and strike subperpendicular to the trend of spiral axes. Plane-polarized light; long axes of all photomicrographs subvertical, 17 mm.

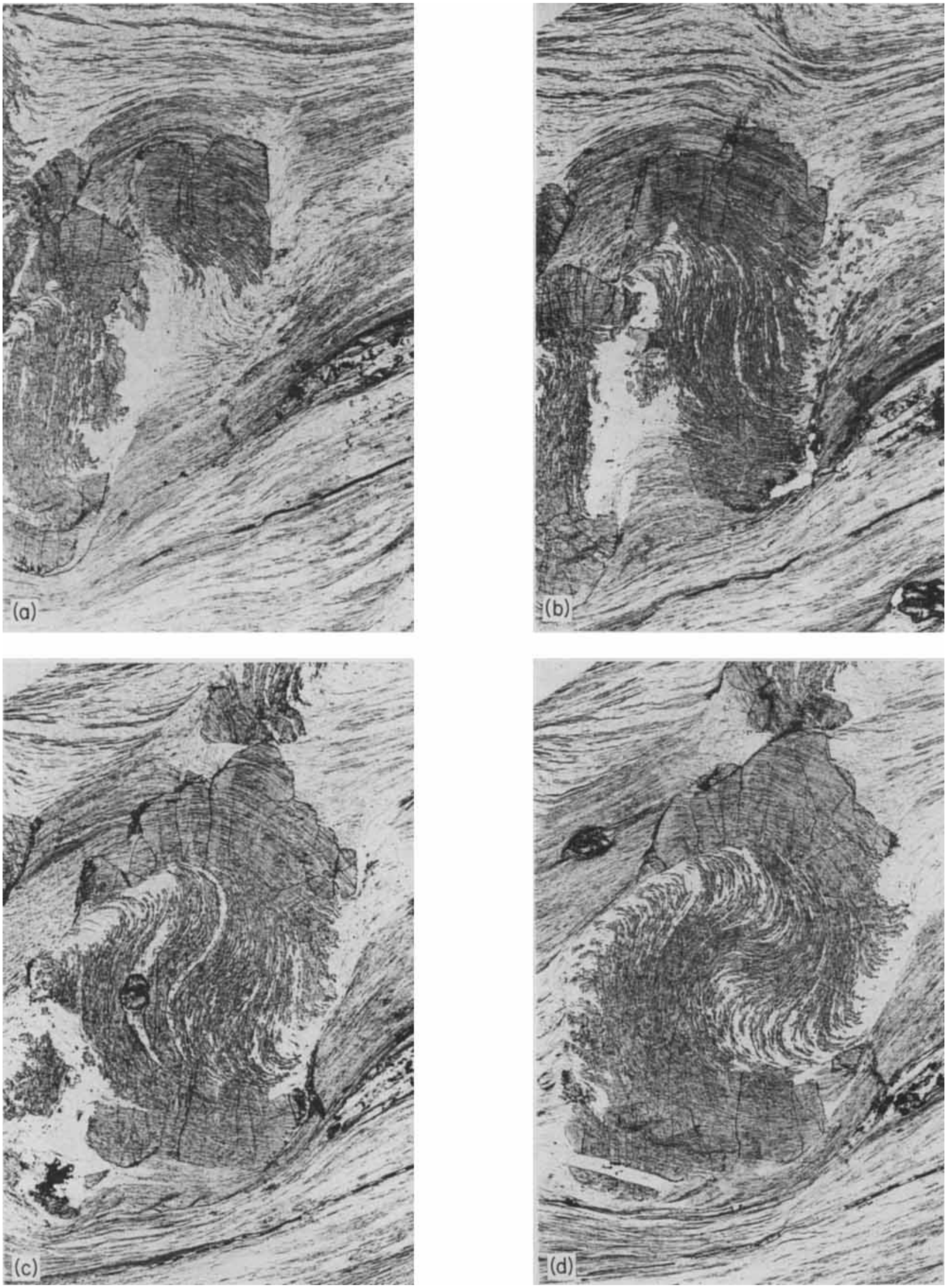


Fig. 3.

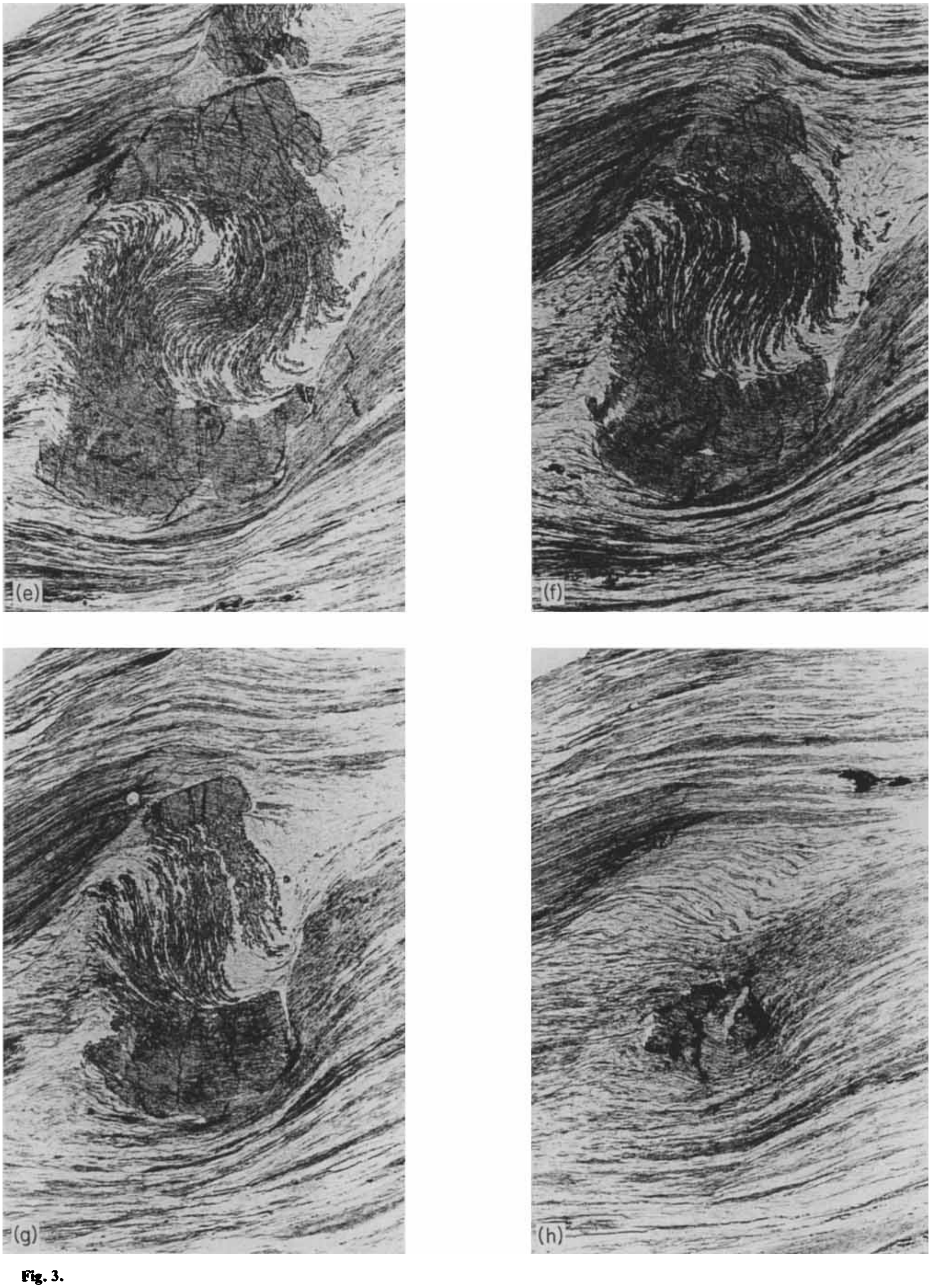


Fig. 3.

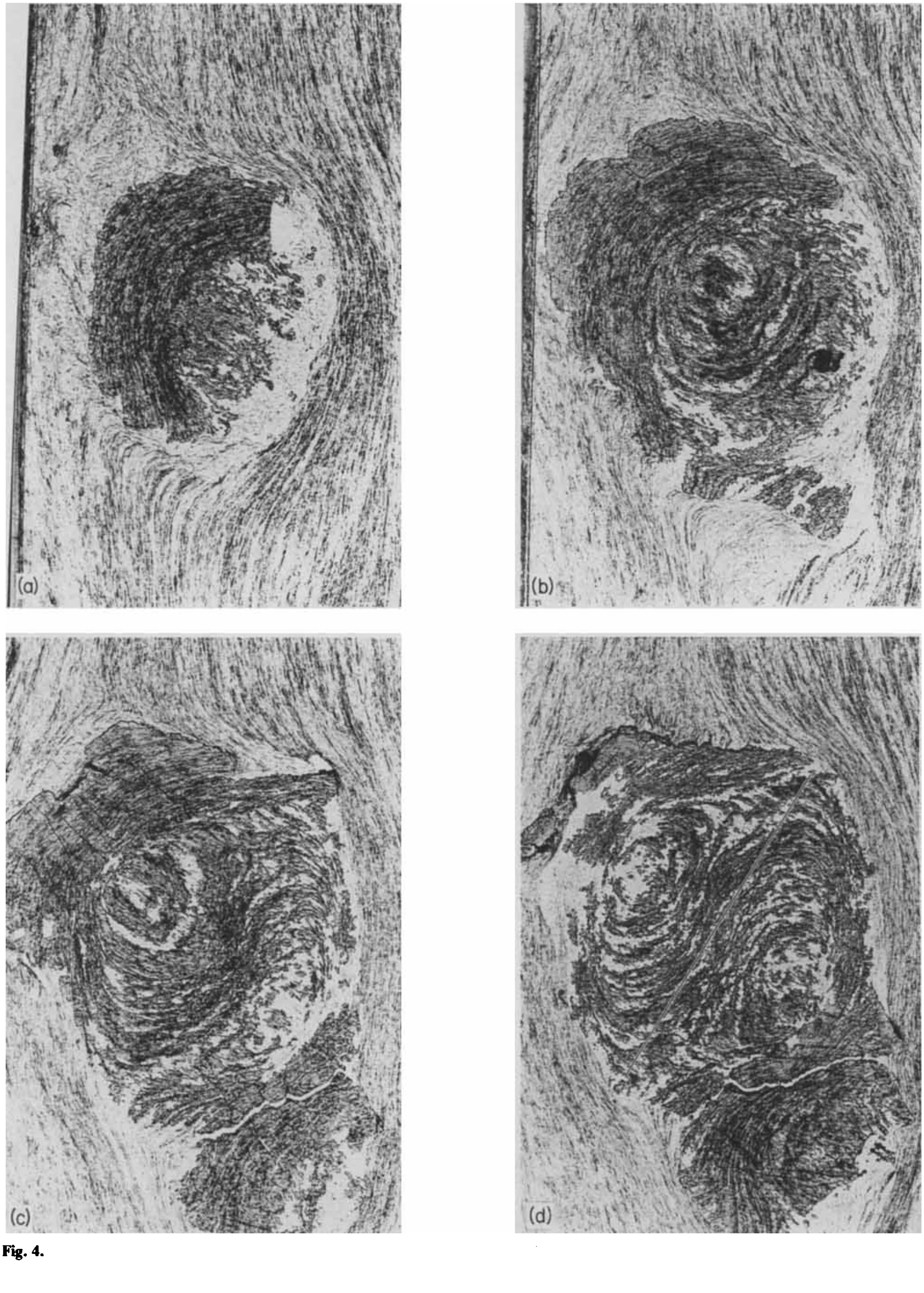


Fig. 4.

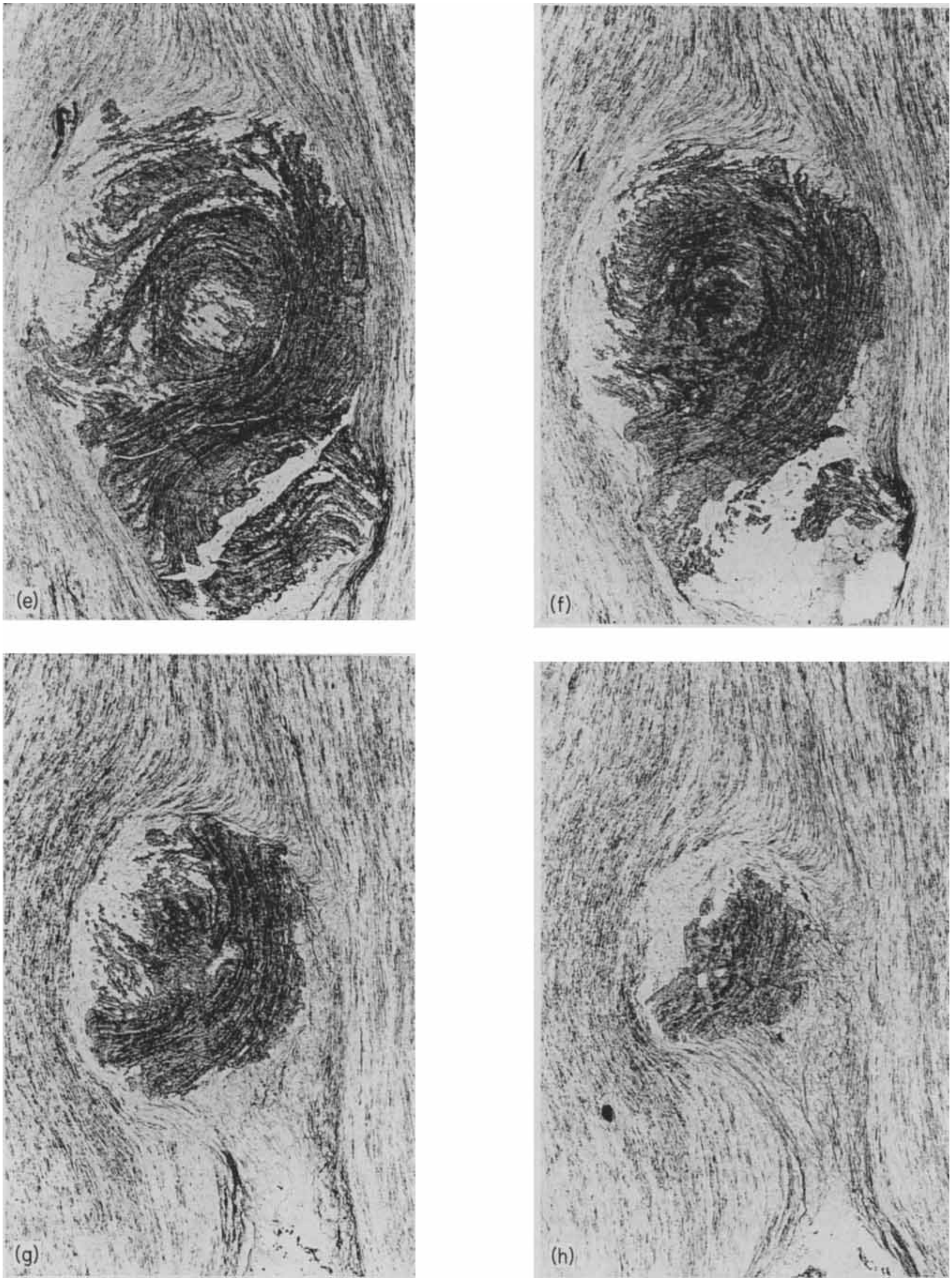


Fig. 4.

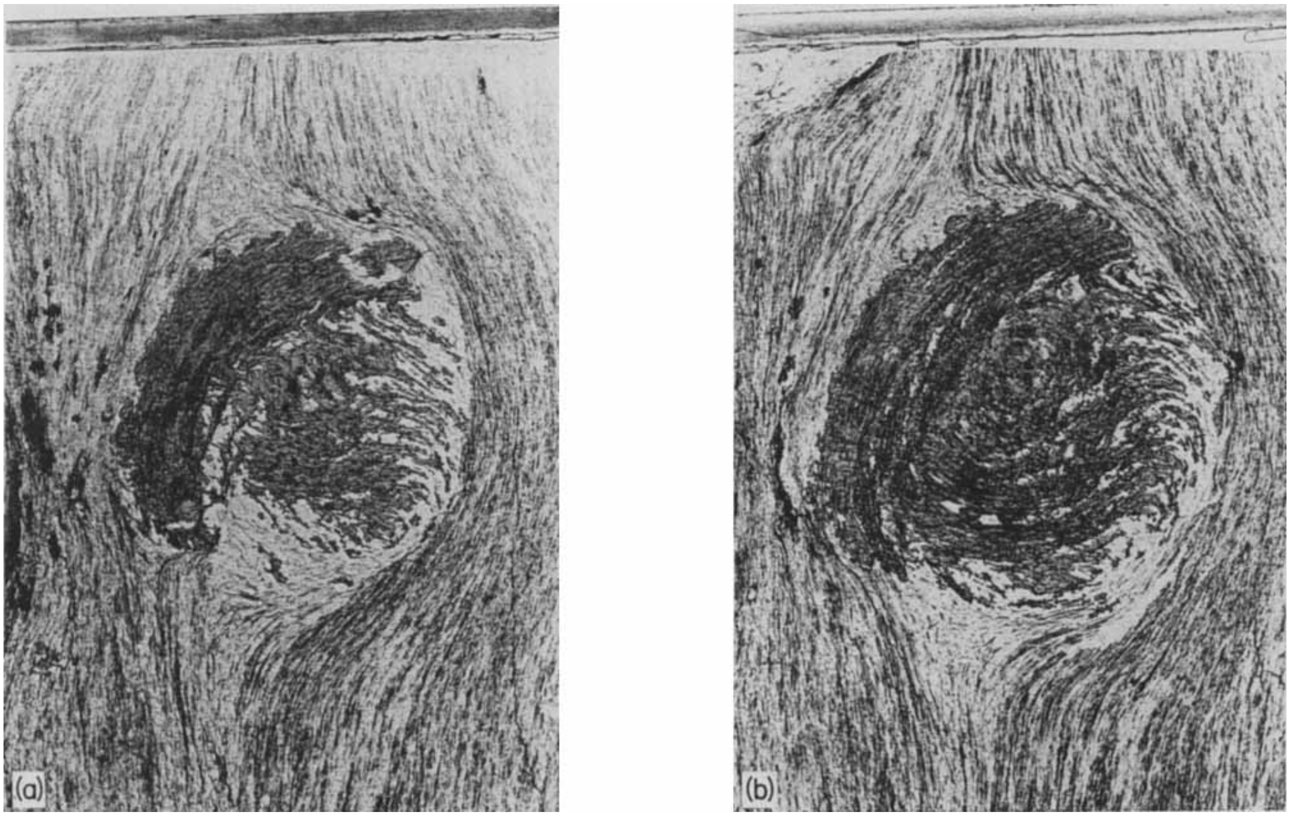


Fig. 5. Set of six serial thin sections through a single garnet porphyroblast with spiral-shaped inclusion trails. Sections are vertical and strike oblique to the trend of spiral axes by approximately 15°. Note that the geometry is spiral shaped even though the section lies only 15° from the spiral axes. Comparison with Figs 3 & 4 leads to recognition that this is indeed an oblique cut: the geometry is somewhat spiral shaped, but a mineral elongation lineation can still be seen in the regions of (nearly) closed loops. Plane-polarized light; long axes of all photomicrographs subhorizontal, 19 mm. Continued on p. 629.

from 0° at the margins to 405° in the median (central) section. All sections were stored in a computer, and a program written by Westbroek *et al.* (1976) was used to produce 3-D stereo pairs of a non-central inclusion surface.

The geometries produced by Powell & Treagus (1967, 1970), Rosenfeld (1970) and Schoneveld (1979) are remarkably similar to one another and to the geometry shown in Fig. 8, which was reconstructed from a natural garnet porphyroblast with very smoothly curving SSITs (Fig. 3). This similarity suggests that the general assumptions made by these authors regarding porphyroblast growth characteristics are reasonable in the situation in which SSITs are smoothly curving. In particular, Fig. 8 supports the assumption that porphyroblasts with SSITs grow from a single nucleus, and that the centre of nucleation corresponds to the region of the central included foliation surface where its direction of curvature changes (inflection point). The ideal models presented by the above authors could, with minor modifications to the assumptions concerning porphyroblast growth behaviour (e.g. varying the relative rates of porphyroblast growth and rotation), also account for porphyroblasts containing SSITs with complex curvature and discontinuities (Johnson, 1993).

Formation of SSITs

Johnson (1993) reviewed the issue of how SSITs form, and showed that the two models presented by Schoneveld (1977, 1979) and Bell & Johnson (1989) are capable, with minor modifications, of explaining most or all of the microstructural features commonly found in association with SSITs. The principal difference between these two models is that Schoneveld (1977, 1979) assumed that SSIT formation involves porphyroblast rotation relative to a geographically fixed reference frame, whereas Bell & Johnson (1989) assumed no such porphyroblast rotation,

Fig. 4. (see pp 626 and 627) Set of eight serial thin sections through a single garnet porphyroblast with spiral-shaped inclusion trails. Sections are vertical and strike subparallel to the trend of spiral axes. The solid line in (d) is subparallel to the spiral axis. Note that the spiral axis is significantly oblique to the main foliation surrounding the porphyroblast. Note also the mineral elongation lineation in the regions of closed loops. Plane-polarized light; long axes of all photomicrographs subhorizontal, 17 mm.

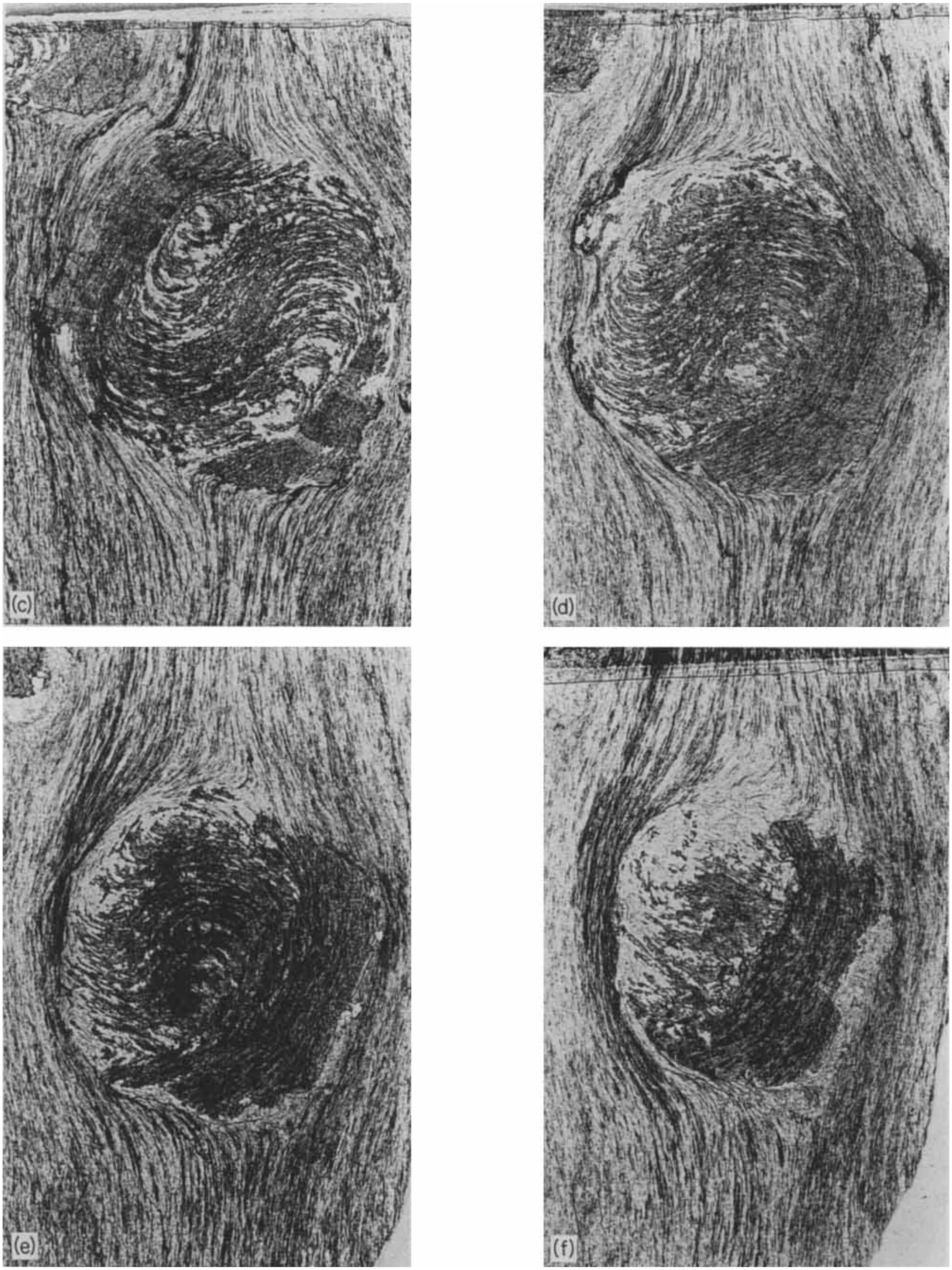


Fig. 5.

Fig. 6.

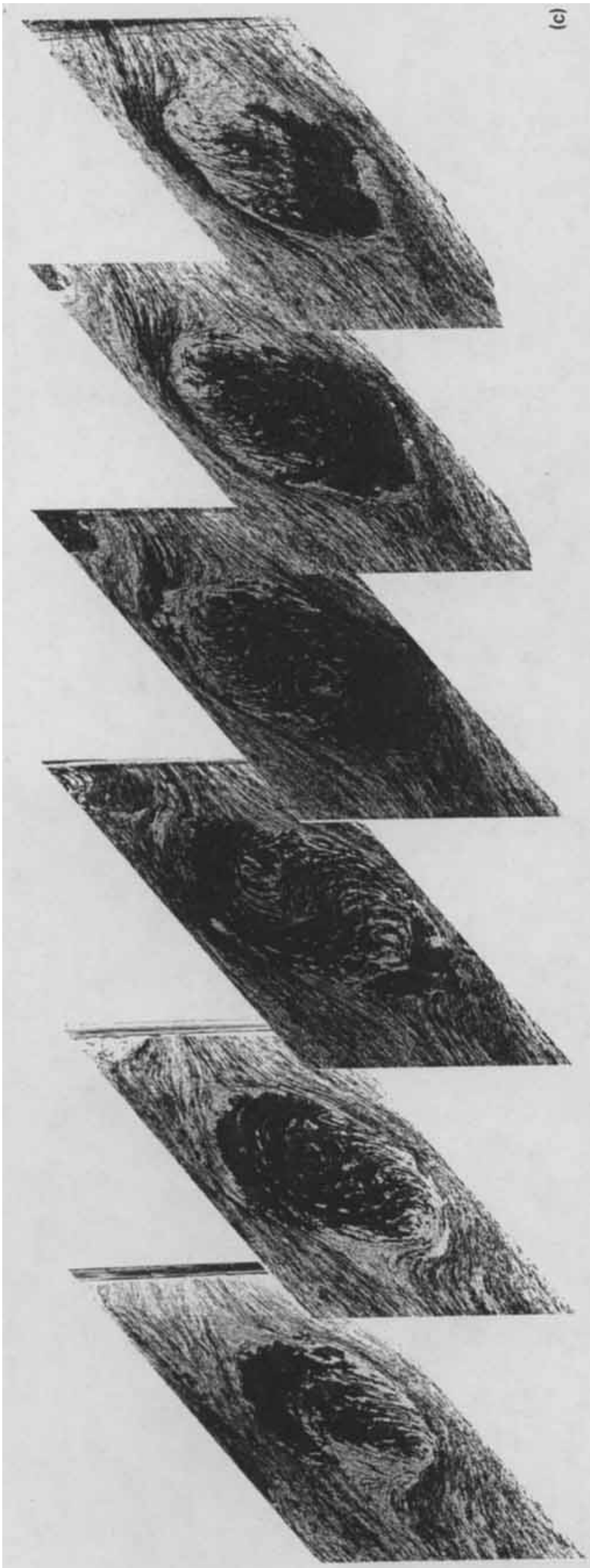


Fig. 6. Computer-generated images of the porphyroblasts shown in Figs 3–5. (a) Stacked cross-sections through the porphyroblast shown in Fig. 3. Sections are vertical and strike subperpendicular to the trend of spiral axes. Long axes of all sections subvertical, 17 mm. (b) Stacked cross-sections through the porphyroblast shown in Fig. 4. Sections are vertical and strike subparallel to the trend of spiral axes. Long axes of all sections subhorizontal, 17 mm. (c) Stacked cross-sections through the porphyroblast shown in Fig. 5. Sections are vertical and strike oblique to the trend of spiral axes by approximately 15°. Long axes of all sections subhorizontal, 19 mm.

arguing that SSIT formation involves only matrix-foliation rotation relative to a geographically fixed reference frame. Although both Schoneveld and Bell & Johnson relied on careful microstructural observations and theoretical considerations, neither study used serial thin sections to gain a better understanding of SSITs. The present study provides information about the 3-D shape of SSITs, but does not allow conclusive determination of how they form.

SSITs as shear-sense indicators

Because they record a consistent direction of relative rotation between the matrix foliation and porphyroblast, SSITs should provide an unambiguous indicator of the sense of shear during their formation. However, because it is still unclear whether SSITs are a product of porphyroblast rotation relative to a geographically fixed reference frame (Johnson, 1993), the sense of shear (with respect to this fixed reference frame) associated with their formation is also unclear. Even if it were clear how SSITs form, it must be unequivocally demonstrated that the SSITs are contemporaneous with the movement being investigated before they could be reliably used as shear-sense indicators. Johnson (1993) argued that this would be very difficult to demonstrate. The present study supports this argument.

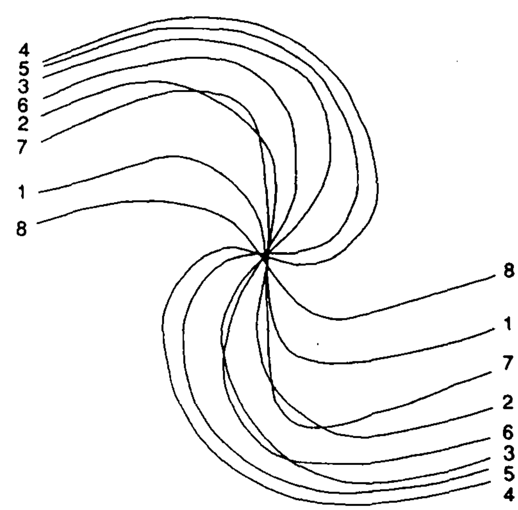


Fig. 7. Central inclusion curves traced from the photomicrographs in Fig. 3. Numbers indicate the position within the porphyroblast: 1 corresponds to the first serial thin section and 8 the last serial thin section in the set.

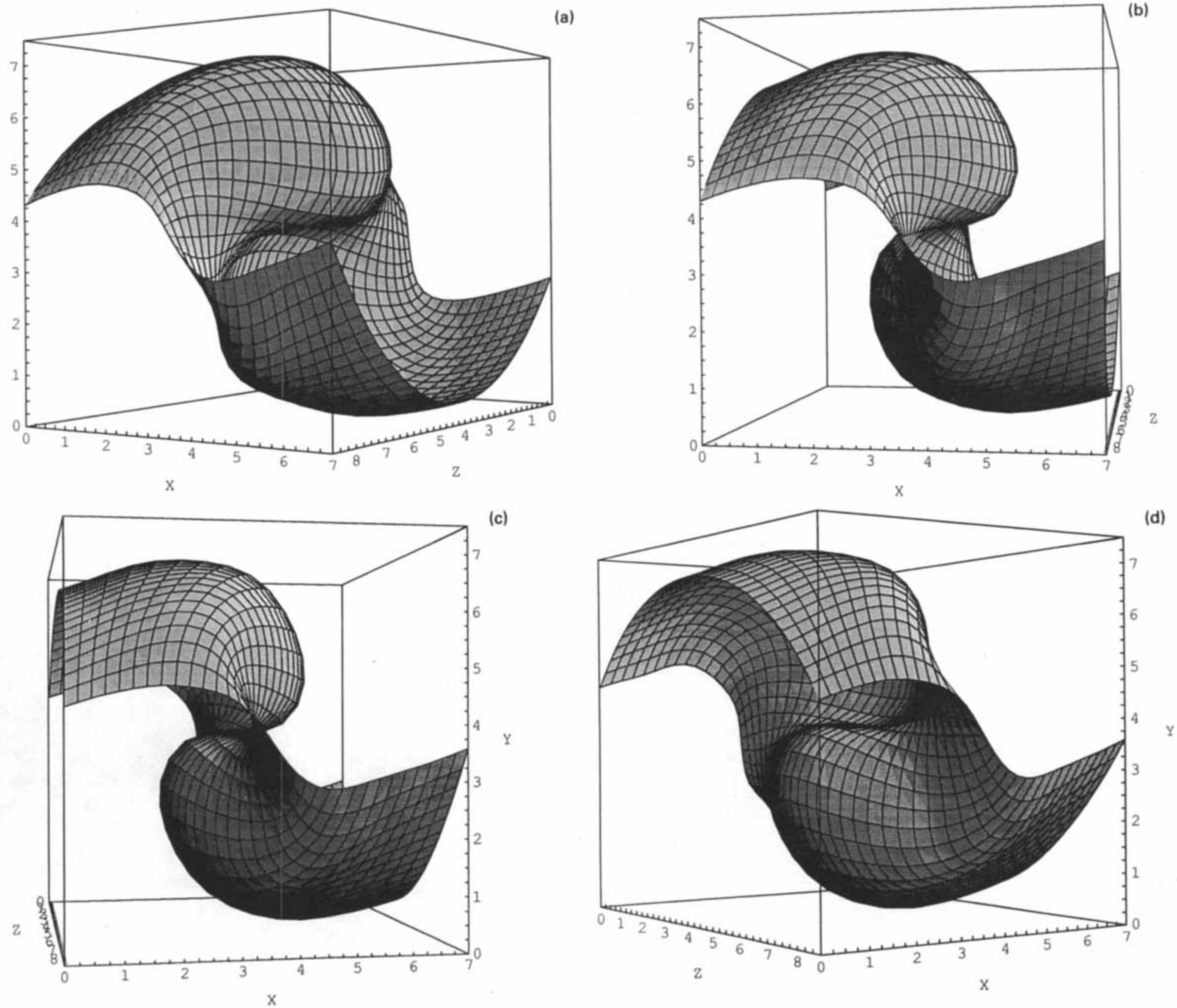
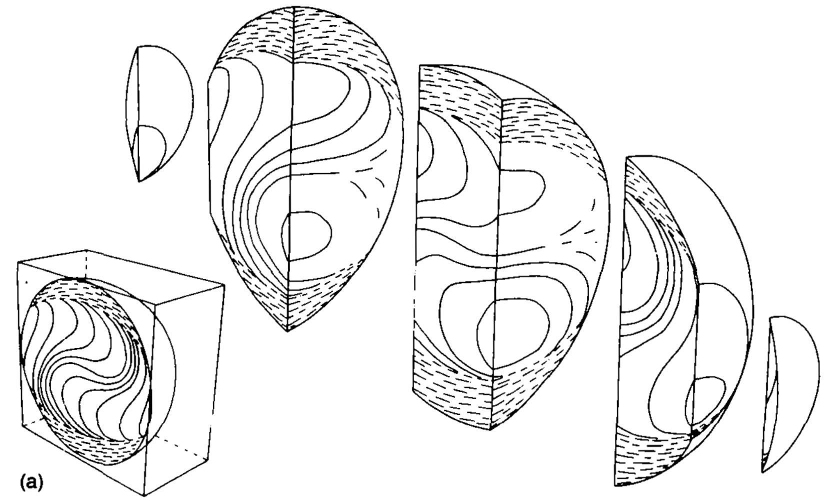


Fig. 8. Three-dimensional representations of the central inclusion surface in the porphyroblast shown in Fig. 3. The surface is shown from different viewpoints, through a progressive rotation, to illustrate more clearly the details of its shape. Numbers along the margins indicate true dimensions (mm).



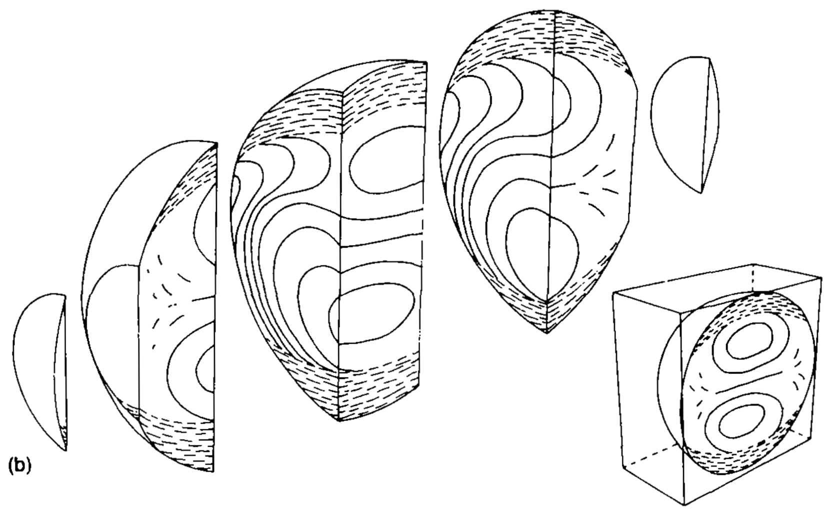


Fig. 9. Three-dimensional representations of spiral-shaped inclusion trails. A garnet porphyroblast is approximated as a sphere, which is split in two directions, forming two hemispheres. Exploded views of these hemispheres provide three-dimensional relationships between views seen subparallel and subperpendicular to the spiral axis. (a) The sphere is split by cutting perpendicular (inset hemisphere in rectangular box), and exploded by cuts parallel, to the spiral axis. (b) The sphere is split by cutting parallel (inset hemisphere in rectangular box), and exploded by cuts perpendicular, to the spiral axis.

Figures 4d & 10 show that the spiral axes do not lie in the plane of the foliation, which is a prerequisite for contemporaneity between the SSITs and latest movement on the foliation. This indicates that: (1) further deformation occurred after or during the latest stages of SSIT development; and (2) the movement direction has changed. The extent of post- or late syn-SSIT deformation and the change in movement direction cannot be determined from the microstructures observed in this study. Thus, the SSITs in these porphyroblasts may not be reliable indicators of the shear sense on the main foliation during the most recent deformation(s) of these rocks.

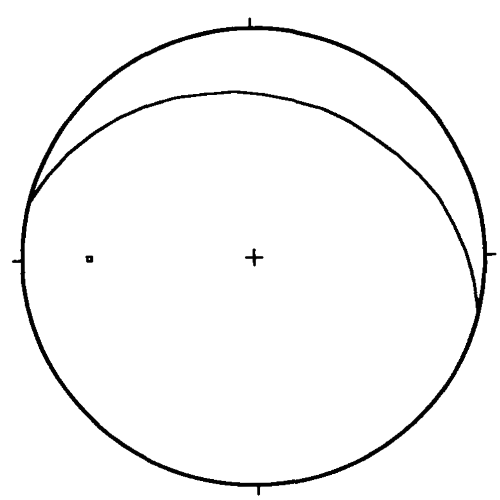


Fig. 10. Stereonet demonstrating that spiral axes do not lie in the main foliation. The main foliation, as measured in the field and shown as a great circle, dips 30° to azimuth 15°. Applying the method in Fig. 1 to the chosen sample gave an approximate spiral-axes orientation plunging 30° to azimuth 270°, which is shown as a square.

The continuity between inclusion trails and external foliation at some porphyroblast margins (Fig. 3) may provide a compelling reason for using these porphyroblasts as shear-sense indicators, even though the spiral axes do not lie in the main foliation. However, this continuity can coincide with marked changes in the direction of movement on the main foliation if strain is not strongly partitioned against the porphyroblast margins. If strain is strongly partitioned against these margins, continuity is likely to be broken.

ACKNOWLEDGEMENTS

I gratefully acknowledge support for this project by the Rothmans Foundation and Australian Research Council. Some of the serial thin sections for this study were made at the Geology Department, James Cook University, during tenure of a Rothmans Foundation Research Fellowship. Professor R. M. Carter and the Geology Department are thanked for providing me with comfortable academic surroundings and excellent facilities. R. Moore of the School of MPCE at Macquarie University is thanked for introducing me to the program Mathematica, and helping to generate the 3-D images in Fig. 8. R. H. Vernon and R. H. Flood are thanked for constructive comments on an early draft of this manuscript. Reviews by W. Means and M. L. Williams were helpful and inspiring.

REFERENCES

Bell, T. H. & Brothers, R. N., 1985. Development of P–T prograde and P-retrograde/T-prograde isogradic surfaces during blueschist to eclogite regional metamorphism in New Caledonia as indicated by progressively developed porphyroblast microstructures. *Journal of Metamorphic Geology*, **3**, 59–78.

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

Brunel, M., 1986. Ductile thrusting in the Himalayas: shear sense criteria and stretching lineations. *Tectonophysics*, **5**, 247–265.

Flett, J. S., 1912. *The Geology of Ben Wyvis, Carn Chuinneag, Inchbae and the Surrounding Country, Including Garve, Evanton, Alness and Kincardine (explanation of sheet 93).* Memoirs of the Geological Survey of Scotland.

Gibson, R. L., 1989. The relationship between deformation and metamorphism in the Canigou Massif, Pyrenees: a case study. *Geologie en Mijnbouw*, **68**, 345–356.

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 classic spiral garnet porphyroblasts of southeast Vermont: evidence for non-rotation. *Journal of Metamorphic Geology*, **10**, 567–587.

Holm, K. H. & Selverstone, J., 1990. Rapid growth and strain rates inferred from synkinematic garnets, Penokean orogeny, Minnesota. *Geology*, **18**, 166–169.

Johnson, S. E., 1990. Deformation history of the Otago schists, New Zealand, from progressively developed porphyroblast-matrix microstructures: uplift–collapse orogenesis and its implications. *Journal of Structural Geology*, **12**, 727–746.

Johnson, S. E., 1993. Testing models for the development of spiral-shaped inclusion trails in garnet porphyroblasts: to rotate or not to rotate, that is the question. *Journal of Metamorphic Geology*, **11**, 635–659.

Johnson, S. E. & Moore, R., 1993. Reconstruction of three-dimensional surfaces from serially collected lines using the program Mathematica: example reconstruction and code. *Computers & Geosciences*, in press.

Meneilly, A. W. & Storey, B. C., 1986. Ductile thrusting within subduction complex rocks on Signy Island, South Orkney Islands. *Journal of Structural Geology*, **8**, 457–472.

Passchier, C. W., Trouw, R. A. J., Zwart, H. J. & Vissers, R. L. M., 1992. Porphyroblast rotation: *eppur si muove*? *Journal of Metamorphic Geology*, **10**, 283–294.

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.

Powell, D. & Treagus, J. E., 1967. On the geometry of S-shaped inclusion trails in garnet porphyroblasts. *Mineralogical Magazine*, **36**, 453–456.

Powell, D. & Treagus, J. E., 1970. Rotational fabrics in metamorphic minerals. *Mineralogical Magazine*, **37**, 801–814.

Rosenfeld, J. L., 1968. Garnet rotations due to the major Palaeozoic deformations in Southeast Vermont. In: *Studies of Appalachian Geology* (ed. Zen, E-an, *et al.*), pp. 185–202. Wiley Interscience, New York.

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

Schoneveld, C., 1977. A study of some typical inclusion patterns in strongly paracrystalline rotated garnets. *Tectonophysics*, **39**, 453–471.

Schoneveld, C., 1979. The geometry and the significance of inclusion patterns in syntectonic porphyroblasts. *Published PhD Thesis, University of Leiden.*

Spry, A., 1963. The origin and significance of snowball structure in garnet. *Journal of Petrology*, **4**, 211–222.

Westbroek, P., Hesper, B. & Neijndorff, F., 1976. Three-dimensional stereographic representation of serial sections. *Journal of Geology*, **84**, 725–730.

de Wit, M. J., 1976. Metamorphic textures and deformation: a new mechanism for the development of syntectonic porphyroblasts and its implications for determining timing relationships in metamorphic rocks. *Geological Journal*, **11**, 71–100.

Received 12 August 1992; revision accepted 4 November 1992.