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Rotational fabrics in metamorphic minerals

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SUMMARY. A model has been constructed that establishes the geometry of inclusion fabrics to be expected in near-spherical crystals that grow continuously while either the crystals rotate in a static matrix or a matrix fabric rotates about them. Garnets in certain metamorphic rocks contain inclusion fabrics whose geometry is very similar to that of the model. Such syntectonic, snowball, or rotational garnets, as they have previously been termed, can be studied in three dimensions. A method is outlined whereby the rotation axes for individual crystals viewed in thick sections can be located in certain planes of cut. The significance of the geometry of included rotational fabrics is discussed in relation to previous work and to possible mechanisms of rotation.

THE recognition of syntectonic crystal growth in metamorphic rocks (as opposed to stress- or strain-induced crystallization or recrystallization) has largely been achieved by the interpretation of S and Ƨ inclusion patterns in porphyroblasts as patterns developed during the growth of crystals while they were rotating and only partially digesting adjacent matrix minerals (Schmidt, 1918; Becke, 1924; Mügge, 1930; Harker, 1932; Rast, 1958; Zwart, 1960; Spry, 1963). This interpretation in its more general aspects is not here questioned but it is shown that earlier assumptions of the geometry of the inclusion fabrics are probably incorrect and previous attempts to locate rotation axes (McLachlan, 1953; Peacey, 1961; Spry, 1963 and 1969; Cox, 1969) and to measure angles of rotation (Flett, 1912; Harker, 1932; Spry, 1969; Cox, 1969) are likely to be inaccurate.

It is demonstrated that a thorough understanding of the three-dimensional geometry of inclusion fabrics is necessary before measurement of rotation axes and angles of rotation and discussion of possible mechanisms of rotation can be undertaken.

The conclusions drawn in the present paper largely result from consideration of a model syntectonic crystal that has been constructed and was briefly described in an earlier preliminary note (Powell and Treagus, 1967).

The model is based upon consideration of the growth of a near-spherical crystal in a foliated matrix so that flat, co-planar elements of this matrix are preserved as inclusions within the growing crystal. It is assumed that the matrix fabric rotates around the growing crystal at a constant velocity. The crystal is also assumed, for the purposes of construction, to grow by the addition of equal volume increments of material over its entire external surface. Thus Z 1, 2, etc. (fig. 1*a*) represent successive stages in the growth of the crystal.

With every unit increment of material to the crystal it is envisaged that the planar elements of the matrix fabric rotate through 10°; the growing crystal, however, remains stationary. As growth proceeds the planar matrix elements are partially preserved within the crystal by a process of selective digestion and inclusion. At all times continuity between the planar fabric of the matrix and that included in the crystal is maintained.

The main elements of the model construction can be demonstrated diagrammatically (fig. 1). In fig. 1*a* a median section through the model crystal is shown to contain a proposed axis of rotation, *R*.

At an early growth stage when no rotation has occurred the included and matrix fabrics are continuous, flat, and undisturbed (fig. 1 *b*, *c*, and *d*). With rotation of the matrix fabric it can be seen (fig. 1*e*) that the presence of the growing crystal affects the attitude of this fabric, and a shadow zone is produced about the crystal. It is possible to gain an understanding of the origin and effects of this shadow zone by the study of the progressive growth and rotation indicated in serial sections through the model (1–12, fig. 1*a*). At an early growth stage (Zone 1, fig. 1*f*) the included fabric preserves its original attitude with respect to the matrix, however with the growth of Zone 2 the matrix fabric has been rotated around the crystal by 10°. Away from the crystal the fabric will have rotated the full 10° but where the matrix fabric passes into the crystal its attitude will be a compromise between the former and the original attitude, which is preserved within the crystal's inner zone (fig. 1*f*). The resultant shadow zone intensifies with every increment of rotation and becomes preserved within the crystal. Its degree of development, however, varies in directions parallel to the rotation axis (fig. 1*e*) being greatest within a median plane cut through the crystal normal to *R* (fig. 1*f*). It gradually diminishes in successive parallel serial sections away from this median plane (fig. 1*g*) until at the points of emergence of *R* from the crystal the attitude of the included fabric is the same as that of the matrix (fig. 1*h*).

The three dimensional pattern of the included material resulting from the foregoing construction is a group of doubly curved non-cylindrical surfaces (Powell and Treagus, 1967, fig. 1, this paper fig. 7). The pattern arising from a consideration of the rotation of a crystal in a static matrix would be very similar to that described.

A study of sections cut at different angles through the complete model reveals considerable but systematic variation in the patterns resulting from the intersection of the inclusion planes with the plane of the section. An account of these variations has been presented elsewhere (Powell and Treagus, 1967, fig. 2) but of particular significance are S, Ƨ, ᗡ D, Ɔ C, and I I-shaped patterns. Sections cut normal or nearly normal to *R* and some cut oblique to *R* with the orientations indicated in fig. 7 give S or Ƨ patterns depending on the sense of rotation. Sections cut so that they contain *R* can give ᗡ D, Ɔ C, or I I patterns (fig. 2 of Powell and Treagus, 1967), and the recognition of such patterns is the only precise method of locating the position of *R* in two-dimensional sections. It is not possible to locate *R* in sections that exhibit S or Ƨ patterns unless the attitudes of the inclusion planes are known.

The complex attitudes of the inclusion planes can be visualized by means of stereographic plots. Figs. 2 and 3 illustrate the non-cylindrical nature of the inclusion planes and indicate the variety of plots that can be obtained for sections cut at different angles through the model. In sections cut normal to *R* (fig. 2*c*) the rotation axis forms a unique axis of symmetry to the plots and as a symmetry axis it is recognizable even

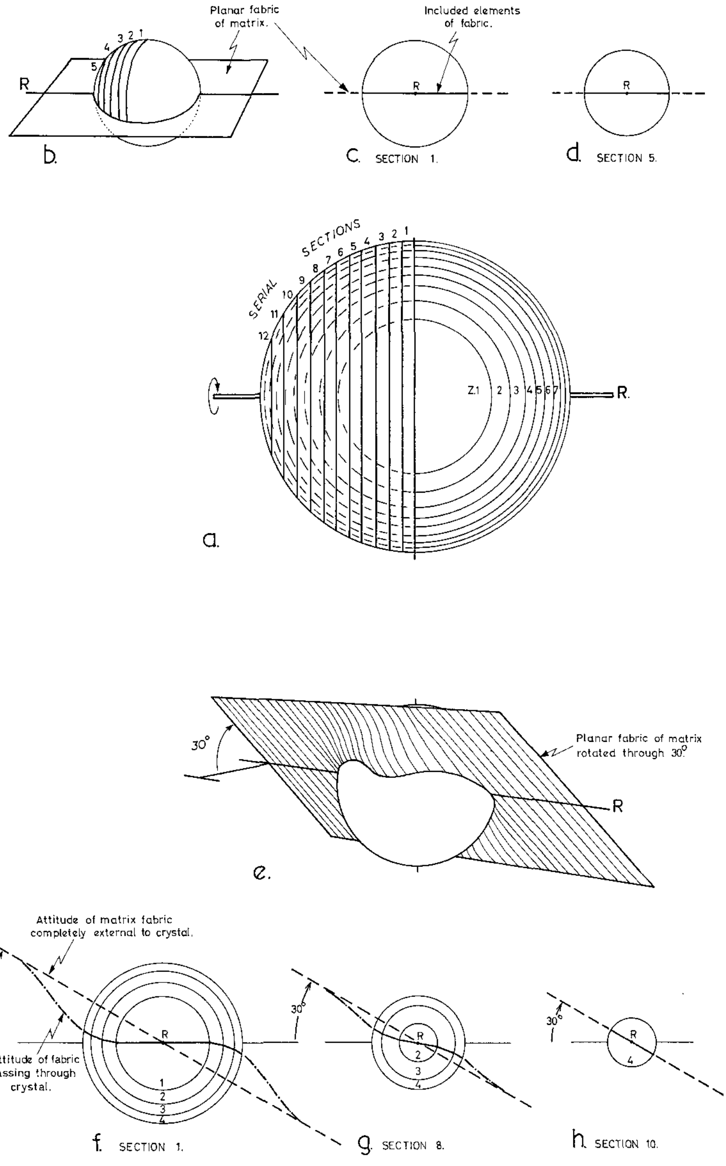


FIG. 1. *a*, Median section through a sphere containing a supposed rotation axis *R*. Z 1–9 represent successive growth zones. Serial sections 1–12 can be cut through such a sphere in planes normal to *R* and will contain different growth zones. *b*, Sphere just before end of growth giving Z 1; no rotation has occurred. The sphere is cut by sections 1–5. *c*, Plan view of serial section 1 indicating the attitude of the matrix and the included fabric. *d*, As *c* but section 5. *e*, Sphere at end of growth of Z 4; the planar fabric of the matrix has rotated through 30° about *R*; the sphere has not rotated. Note the deflection of the matrix fabric close to the sphere. *f*, Plan view of section 1 at growth stage shown in *e*. Note the change in attitude of the included fabric with increments of growth Z 1–4. *g*, As *f* but section 8. Z 1 is not cut by this section. *h*, As *f* but section 10. Only Z 4 is cut by this section so that the included fabric shows the full 30° of rotation and is coplanar with the matrix fabric away from the sphere (see *f*).

with a change in section along *R*. No such simple relationship exists between the rotation axis and the loci of poles to inclusion planes in plots derived from either non-median inclusion planes or sections cut at other angles through the model (figs. 2 *d*, *e*, and 3).

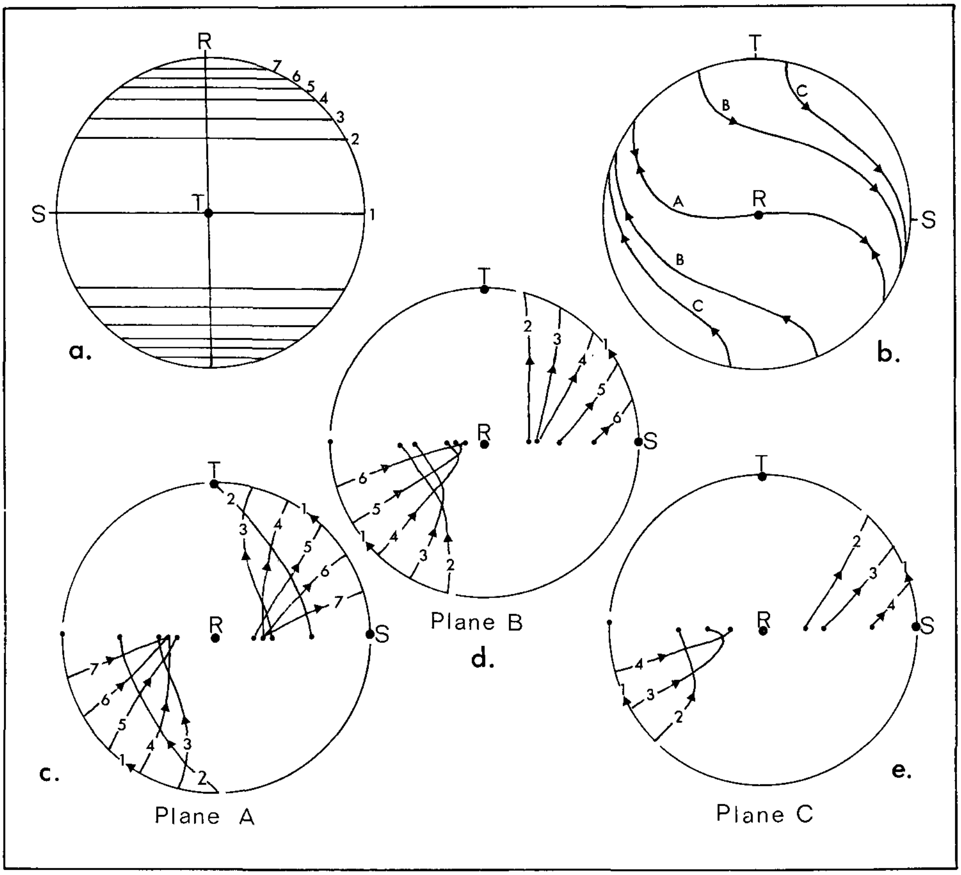


FIG. 2. Attitudes of inclusion planes in sections cut normal to the rotation axis. *a*, Position of cuts perpendicular to *R* and tangent to incremental growth zones. *b*, Traces of five inclusion planes on the *S–T* plane (section 1). *c*, *d*, and *e*, Stereographic projections (lower hemisphere Wulff) illustrating the loci of poles to planes A, B, and C of *b* above in serial sections 1–7 of *a* above. The diagrams may be inverted to derive the loci of poles to the inclusion planes encountered in the six cuts through the lower half of fig. 2*a*.

Inclusion fabrics in some metamorphic crystals. Syntectonic garnet crystals in metamorphic rocks from Scotland and Norway have been studied in thick sections by the methods outlined in Powell (1966). In addition serial sections of several individual crystals have been made. These studies have enabled a three-dimensional understanding of the geometry of the inclusion fabrics to be obtained and demonstrate the fundamental validity of the model.

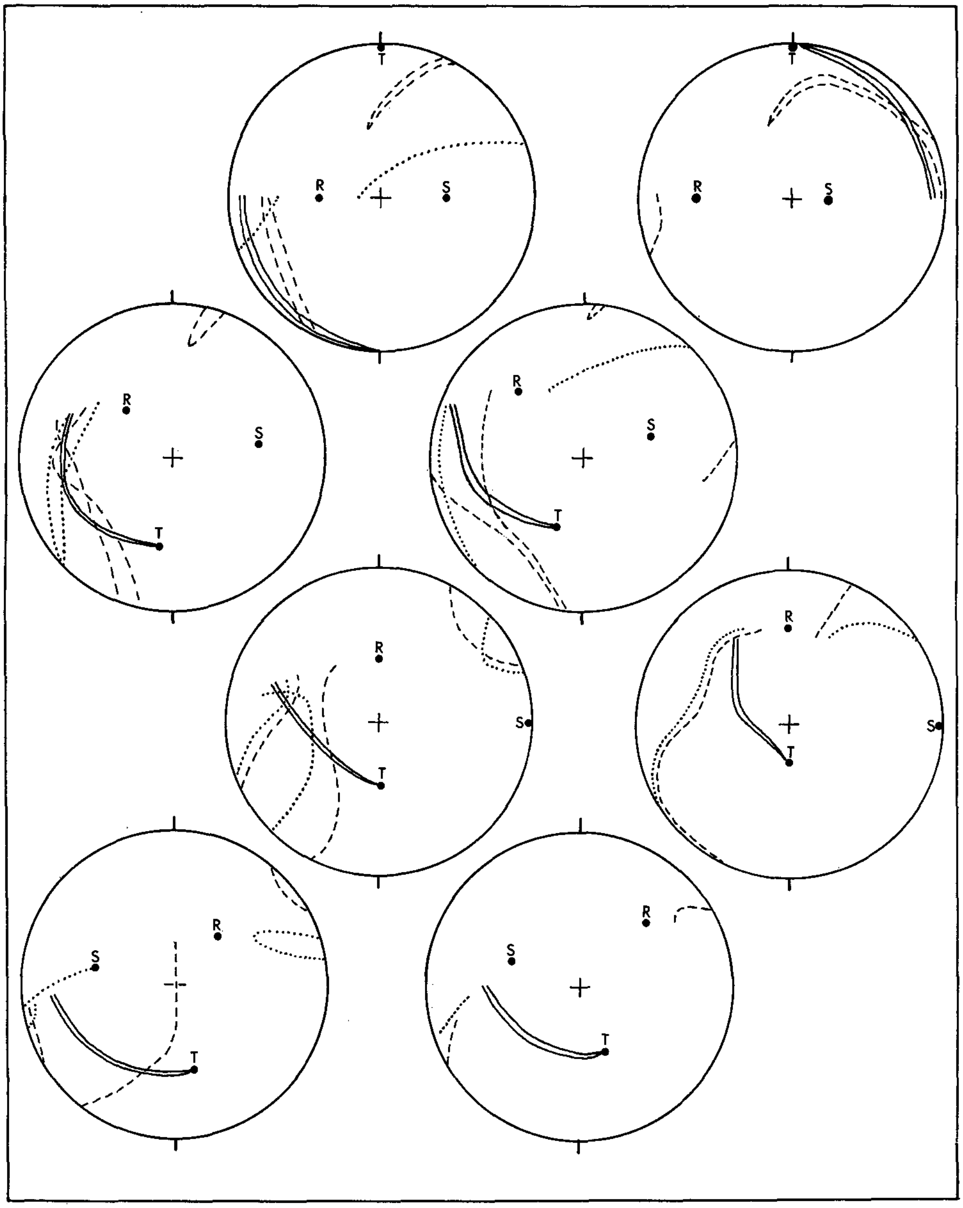


FIG. 3. Stereographic projections of the loci of poles to inclusion planes A, B, and C of fig. 2 in various sections oblique to R. The attitudes of the different sections are given by the location of the reference axes R, S, and T (fig. 2a). Full lines, plane A; broken lines, plane B; dotted lines, plane C. The apparent symmetrical relationship between the reference axes and the loci of poles is a function of the assumed 90° of rotation of the model and has no general significance. It should be noted that the plot shown in fig. 2c would not be confused with plots illustrated here.

Serial sections of a garnet porphyroblast from Norwegian schists (fig. 4*a*) demonstrate a gradual change in the shape of the inclusion trails through the crystal. Such changes are predicted by the model and are comparable with those illustrated in fig. 1. It would appear that the sections are cut almost normal to the rotation axis. Similarly sections cut through different crystals within a single thin section (fig. 4*b*) suggest that the variations in the shape of the inclusion trails are directly connected with the size of the sections through the crystals and thus can be interpreted as being equivalent to serial sections. The systematic change in the shape of the Ƨ pattern can again be compared with that of the model in serial sections cut normal or nearly normal to *R*.

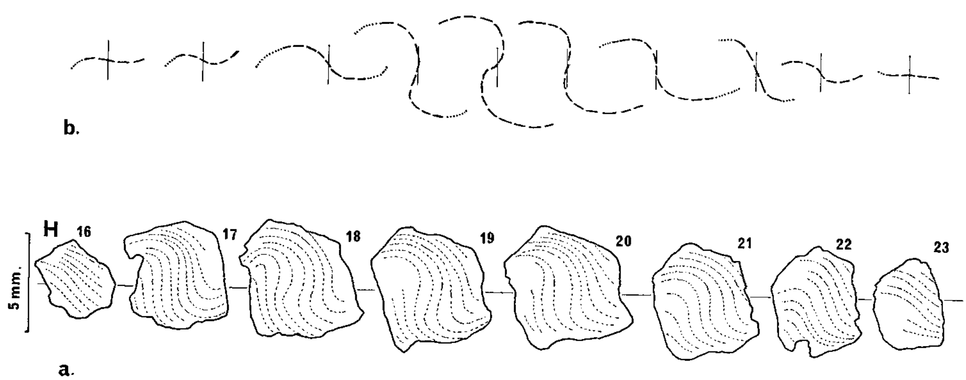
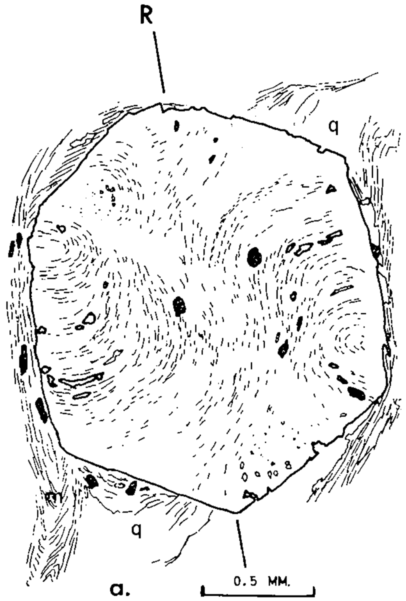


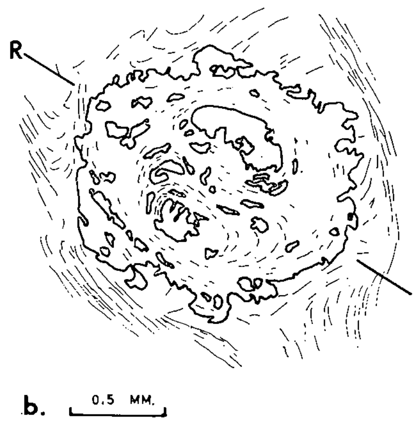
FIG. 4. *a*, Serial sections through a rotational garnet porphyroblast. Sections 16–23 are cut from the same crystal and have been arranged so that they are in order of cut; each slice is shown with its original orientation relative to its neighbours. Slices 20 and 21 are analysed in fig. 6. *b*, Traces of median inclusion planes from 10 garnet crystals in one thin section. The vertical line in each indicates a constant reference direction in the rock. The diameter of the crystals containing the trails is indicated by the spacing of the end points to the trails and it is significant that a decrease in diameter is associated with a decrease in curvature.

The garnet crystals illustrated in fig. 5 *a* and *b* are from rocks that show in other sections S inclusion patterns within the crystals. The Ɔ C and ᗡ D patterns are comparable with those predicted by the model (Powell and Treagus, 1967, fig. 2). Such patterns are rarely seen in natural crystals because, as the model predicts, they can only occur within a very limited number of sections.

Further indications of the model's validity in interpreting natural syntectonic crystals are gained by measurement of the attitudes of inclusion planes within thick sections of crystals. Fig. 6 *d* and *g* illustrate the opposing directions of plunge of two halves of Ƨ inclusion planes in garnet crystals; similar attitudes are seen in the model in sections cut normal or nearly normal to *R*; they reflect the essentially non-cylindroidal form of the inclusion planes.

The location of the rotation axis in syntectonic crystals is evidently important. Its location in thin sections can only be achieved by the recognition of Ɔ C, ᗡ D, C Ɔ, or I I inclusion patterns (fig. 5 *a* and *b*) when it will lie within the plane of the section. It will not necessarily lie normal to sections that exhibit S or Ƨ patterns (fig. 7).





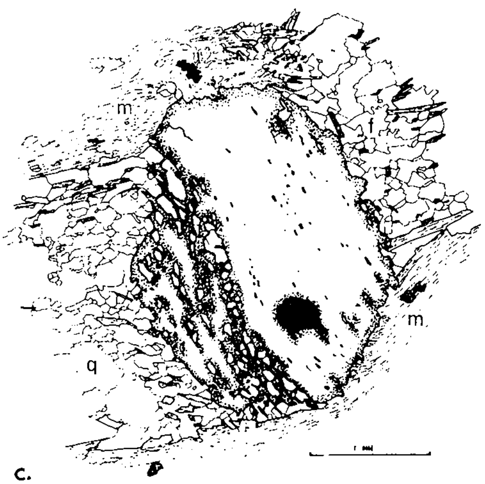


FIG. 5. *a*, Thin section of a garnet porphyroblast from the Dalradian of Glen Shee illustrating the Ↄ C pattern. *R* denotes the rotation axis, which is here contained by the plane of the section. *b*, Thin section drawn from Cox 1969 illustrating the ᗡ D pattern predicted by the model. *c*, Thin section of a garnet crystal in Moine pelite from Skye indicating the continuity of matrix and inclusion fabric. Where the mica felt seen to the south-east of the diagram has been overgrown by garnet only relics of ore and occasionally quartz remain. The junction between the micaceous layer and quartz-rich layer seen to the north-west is clearly preserved within the garnet.

In thick sections not only can *R* be similarly located but also in certain sections exhibiting S and Ƨ patterns it can be established by measurement of the attitudes of inclusion planes according to the following procedure:

The attitude of the median inclusion plane is measured at a number of points including the centre of the S and these data are plotted on a stereographic projection as poles to planes (fig. 6 *a* and *b*).

The pole to the plane representing the centre of the S is rotated to the primitive and each other pole is rotated in a like manner. If the loci of the poles lie on two

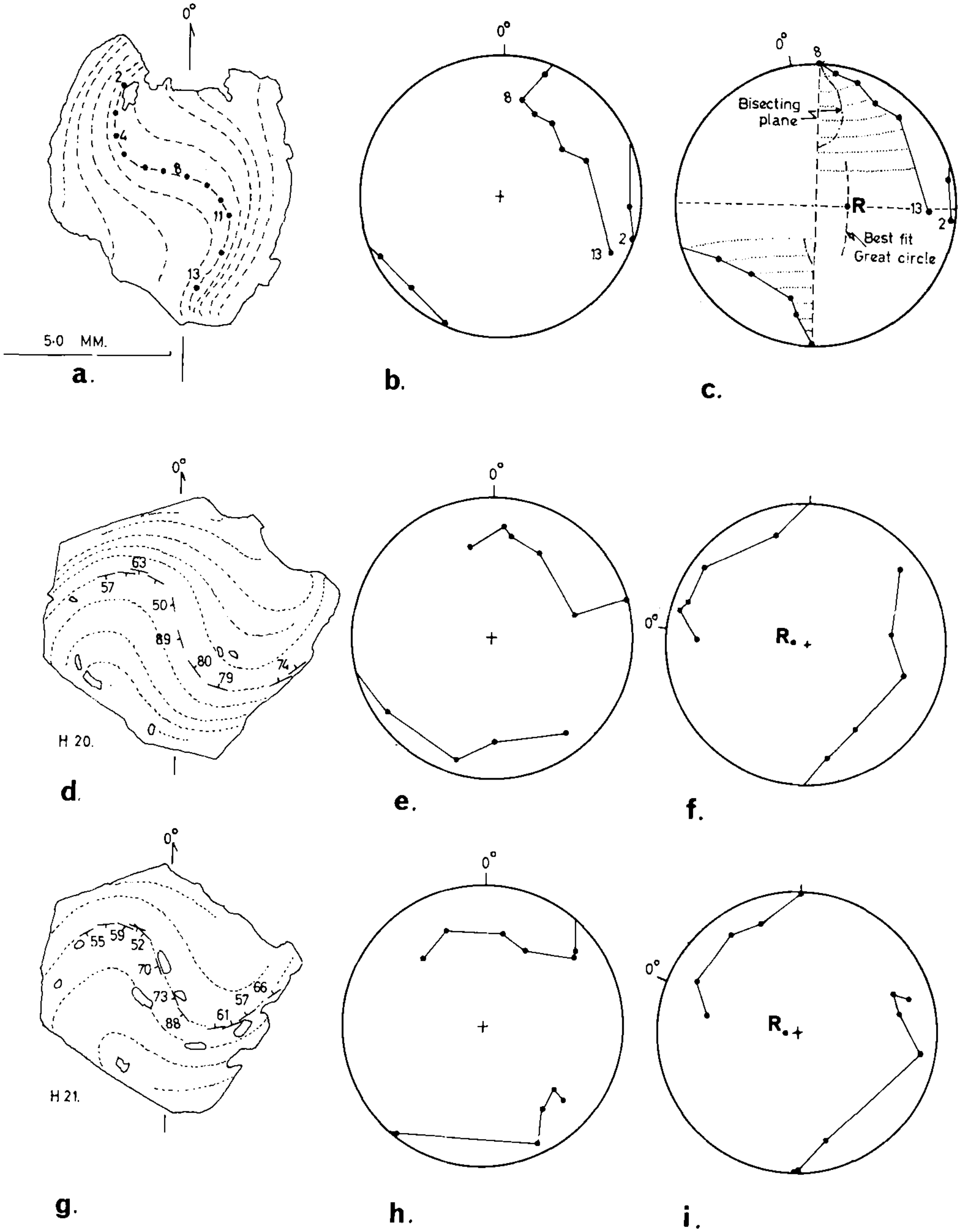


FIG. 6. *a*, Thick section of a garnet from Norwegian Schist. Points 2–13 are sites of measurement of the attitude of the median inclusion plane. *b*, Stereographic projection (lower hemisphere, Lambert) of poles to planes measured in *a*. *c*, Rotation of mid tangent of median inclusion trail (pole to 8) to vertical and establishment of symmetry locating *R*. *d*, *e*, and *f*, Thick section of garnet from Norwegian Pelite treated in a similar manner to *a*, *b*, *c* above. *g*, *h*, and *i*, Thick section of the same crystal as illustrated in *d* above treated as in *a*, *b*, *c* above. The sections illustrated in *d* and *g* are those seen in fig. 4*a* (H20 and H21). *R* has almost exactly the same orientation in both sections.

separate trends corresponding to the two halves of the S the plot is comparable with that given for the model in fig. 2*c* and *R* must lie close to the vertical. If the plot has affinities with those illustrated in fig. 3 then it would appear impossible to establish the position of *R*.

Since the plot in fig. 6*c* suggests that *R* is near vertical, *R* can be fairly closely located since it will be the unique axis of symmetry to the plot. *R* lies at the intersection of the plane representing the middle of the inclusion trail and the plane bisecting the plot.

The attitude of *R* in the section can then be determined by reversing the rotations given above.

The application of this method is unfortunately restricted since thick sections are required to allow measurement and only sections cut at high angles to *R* can be used.

It appears that the model serves to explain the geometry of inclusion planes within some garnet porphyroblasts. If it (or variations therefrom) is of more general application (e.g. Rosenfeld, 1968) then it follows that earlier statements as to the spatial location of rotation axes based upon thin section studies are probably incorrect and the statement that 'The inclusion structure can be considered as basically a cylindroidal surface' (Spry, 1969) is misleading.

Angles of rotation. Several authors have sought to measure angles of rotation for syntectonic crystals by comparing in thin sections the trends of inclusion planes constituting an S or Ƨ pattern, within the inner and outer parts of crystals, e.g. Spry (1969) cites angles of 50–60°. The present analysis indicates the types and order of errors that are likely to accrue from estimates that are dependent solely upon two-dimensional appraisal. For example, fig. 7 indicates the possible variations in apparent angles of rotation resulting from changes in the angle of cut through a model which has suffered an actual rotation of 90°. Angles of rotation ranging from almost 0° to over 140° could be read from individual thin sections with these attitudes. Figs. 4 and 8 illustrate a further range of variations due to the 'cut effect' in natural crystals.

For these reasons earlier claims for the recognition of angles of rotation of greater than 90° must be viewed with caution (Spry, 1969; Cox, 1969).

Care has also to be exercised in the interpretation of crystals whose inclusions show little or no curvature in thin sections and those whose inclusions in places show no preferred shape orientation. Inclusion patterns of the former type, which, because the inclusion trails are straight, are often interpreted as being the result of static crystal growth, may arise in syntectonic crystals from certain cuts containing the rotation axis (Powell and Treagus, 1967) or from cuts near to the outer surface of the crystal (figs 4 and 7). A further consequence of the complex three-dimensional shape of the inclusion planes in syntectonic crystals is that the inclusion planes will show a marked variation in dip relative to the plane of cut. Thus if individual inclusions are arranged so that their largest diameters lie within the inclusion planes, then because of the change in the attitude of the inclusion planes relative to the plane of section, inclusions in some areas of the crystal will exhibit marked shape orientation (steeply dipping inclusion planes) whereas others will show none (low-dipping inclusion planes).

Similarly patches or zones of inclusions will exhibit apparent changes of grain size and density (figs. 5 *a* and *b*).

Calculations of angles of rotation are best made from stereographic plots of median inclusion planes in sections cut through the centres of crystals at high angles to *R*. The angle between the pole to the outermost part of the inclusion plane and the pole to its middle will still, however, be an apparent angle of rotation in excess of the true angle (Spry, 1969, p. 255).

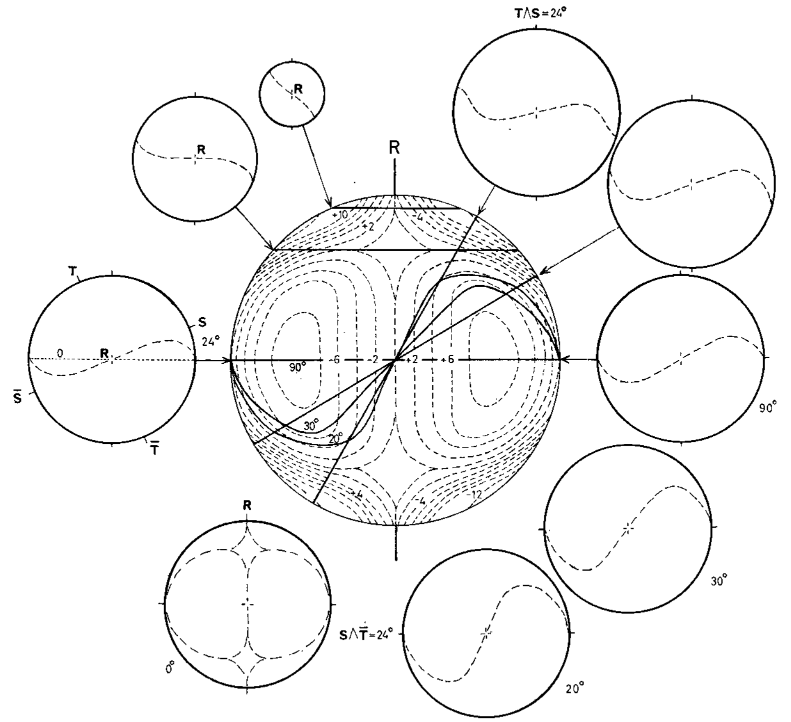


FIG. 7. Contour map of the median inclusion plane to a model which has suffered 90° of rotation illustrating the variation in curvature of the plane in different sections.

Recognition of real angles of rotation is pertinent to considerations of the mechanisms of rotation. Schmidt, Mügge, Spry, and Cox and others have put forward the view that the crystals rotate during growth within a rock suffering laminar movements parallel to its foliation: a mechanism involving essentially simple shear deformation within the rock matrix. Ramsay (1962), however, has suggested that the growing crystals can be regarded as stationary objects in a rock matrix whose layering rotates by homogeneous irrotational strain. The former hypothesis will allow angles of rotation in excess of 90° whereas the latter can only give rise to angles of less than 90°.

Mechanisms of growth and rotation. It is clear in many examples that the included fabric of syntectonic crystals is a relic of a pre-existing rock structure (texture) since compositional banding is often preserved and can be traced from the matrix into the crystal without break (fig. 5c). The inclusion of material from different parts of the adjacent matrix as suggested by Spry (1963) seems therefore unlikely and the mechanism

FIG. 8. Thin section of Dalradian Schist from Glen Shee illustrating the change in curvature of the inclusion trails in garnets due to the cut effect. Note the common sense of curvature of the inclusion trails, the indication of preferred crystallographic orientation of the garnets and the possible association between the formation of the rotational inclusion fabrics and the development of the crenulation folds and the strong secondary schistosity.

of rotation advocated by Mügge (1930) and reiterated by Cox (1969) appears improbable. Garnets appear to grow in metamorphic rocks by fingering along grain boundaries in quartz/feldspar-rich areas and by in-place rearrangements of lattice structure in micaceous areas. Such mechanisms are reflected by the common occurrence of straight crystallographic boundaries to garnet where it is overgrowing mica felts and irregular boundaries in areas rich in non-micaceous minerals (fig. 5c).

If such a mechanism of growth is accepted it follows that the development of rotational fabrics must be either by rotation of the matrix fabric around a static but growing crystal or by the 'keying' of a microfold to a growing crystal and the subsequent rotation of both the crystal and the matrix fabric.

The authors' findings show that the geometry of the inclusion patterns resulting from each of the two mechanisms would be the same in as much as doubly curved non-cylindrical surfaces would be produced. Consequently discussion of mechanisms of rotation can be limited to consideration of angles of rotation and the behaviour of rock materials during deformation.

In the material studied from Eocambrian rocks of Norway and Scotland it is commonly found that the sense of curvature of the inclusion trails within garnets showing S or Ƨ patterns is the same from crystal to crystal throughout a hand specimen (fig. 8). Further, the garnets often exhibit preferred crystallographic orientation such that rhombdodecahedral faces are parallel from crystal to crystal. It also appears that where sections through individual crystals are near median sections there is a parallelism of the innermost parts of the inclusion trails between crystals, suggesting that the preferred crystallographic orientation arises by the nucleation of garnet with preferred lattice orientation (Powell, 1966). The garnets exhibiting these features are associated with crenulation (strain slip) folds and cleavage (fig. 8) and it seems that the development of the rotational inclusion patterns may be associated with the formation of such folds.

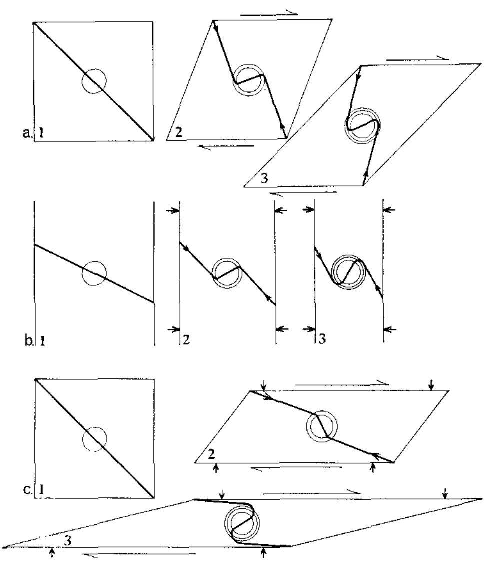


FIG. 9. Mechanisms of rotation. *a*, Simple shear inducing buckling. *b*, Buckling in an oblique stress field. *c*, Buckling during rotational homogeneous strain. In each case the diagonal thick line represents a rock layer of relatively low ductility which responds to stress by buckling. The length of the layer remains constant throughout the deformation. The arrows on the layers represent directions of resolved compressive stress while those outside each diagram indicate the orientations of external stress systems. The circles show the progressive growth of an incompressible crystal. 1, 2, and 3 represent successive stages in the deformation. Rotation of both the layering and the crystal occurs in each case.

Other material from Moinian schists of Skye (fig. 5*c*) demonstrates the presence in garnet porphyroblasts of angles of rotation greater than 90°. Individual garnet crystals here 'key' microfolds of the schistosity, in such a way that *R* of the crystal is continuous with a fold hinge in the adjacent matrix. The folds extend for only a short distance away from the garnet crystals into the matrix, which is otherwise not folded. Clearly the development of the folds is directly related to the presence of the garnets.

It is perhaps possible to consider the development of rotational fabrics in crystals in relation to the formation of microfolds 'keyed' to growing crystals. In metamorphic rocks undergoing deformation folding can take place as a result of instabilities set up during the differential shortening of rock layers of varying ductilities. Where the rocks contain growing incompressible crystals it seems reasonable to assume that such crystals will key sites of increased instability and thus generate microfolds. The continued development of the folds together with growth of the crystals would give rise to rotational inclusion fabrics (fig. 9 *a*, *b*, and *c*).

Such a mechanism and others must, however, be viewed in relation to the bulk strain of the rocks undergoing deformation. Mechanisms of rotation involving homogeneous irrotational strain can produce a symmetrical system of folds of a matrix fabric around static crystals provided the crystals are spherical or very nearly so. Any marked departure in shape from a sphere would cause rotation of the crystal (Gay, 1968) and would result in complex fold patterns adjacent to and within the crystals. A more systematic fold (rotational) pattern could, however, result if the early growth shapes of the crystals had a preferred orientation; for example, if the 'young' crystals had grown preferentially along the layering. Such a mechanism will not, however, account for angles of rotation of greater than 90°.

Deformation by rotational homogeneous strain can give rise to rotational fabrics in a similar way as does irrotational strain, but rotation of both the matrix fabric and the growing crystal would occur; angles of rotation over 90° are possible (fig. 9*c*).

To account for the observed angles of rotation of greater than 90° it appears necessary to regard the matrix layering as active during deformation and to combine rotation by buckling of the layering with rotation of the growing crystal. This can be achieved by inducing buckling either by bulk simple shear (fig. 9*a*) or by bulk rotational strain accompanied by flattening (fig. 9*c*), or by the buckling of layers in an oblique stress field (fig. 9*b*).

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