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Development of early composite cleavage in pelites from West Donegal

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Abstract—In the Portnoo–Rosbeg area of west Donegal the main penetrative cleavage, S_2, generally dips to the south with F_2 folds facing up to the north. In places the S_2 cleavage is cut by a gently SW-dipping crenulation cleavage (S_3) verging and facing south on the long limbs of F_2 folds.

A series of structural domains have been mapped in which the relationship of S_2 and S_3 changes from cross-cutting at a large angle (Rosbeg domain) to the development of a composite $S_{2/3}$ cleavage (Portnoo domain). The relationship between the two phases and the composite cleavage was investigated by mapping out cleavages (megascopic scale), detailed mesoscopic field observations and on a microscopic scale using textural relationships to widespread post D_2–pre D_3 garnet porphyroblasts.

In addition to demonstrating the composite nature of the cleavage, the examples of D_2/D_3 interference and the rotation of, and drag patterns around, the garnet porphyroblasts allow discussion of the kinematics of D_3. D_3 appears to have involved either bulk pure shear or north-directed bulk simple shear, or any intermediate type of deformation history, and was promoted by southerly directed active slip parallel to S_2.

INTRODUCTION

THE STRUCTURE of the Dalradian rocks of Donegal has received relatively little attention in comparison with the Dalradian of the southwest Highlands of Scotland and of Connemara (see Johnson *et al.* 1979 for a review). A regional synthesis of the early work in Donegal is given by Pitcher & Berger (1972) and more recently Hutton (1977a,b, 1979) has described the structures in northwest Donegal. A regional study of the Gweebarra Bay area in western Donegal has revealed extensive polyphase deformation (Fig. 1) with three of the phases predating the emplacement of the Ardara Granite (Meneilly 1982). The present paper seeks to describe and explain the textural relationships between these early phases.

The Portnoo–Rosbeg area lies to the northwest of the Ardara Granite (Fig. 2) and is situated within an incomplete succession of the Falcarragh Limestone overlain by the Upper Falcarragh Pelite. Harris & Pitcher (1975) have correlated the Falcarragh Limestone of the Creeslough Succession with the Lismore Limestone of the Appin Group in Argyllshire, Scotland. The Upper Falcarragh Pelite Formation crops out over most of the area concerned and affords a suitable lithology for the development of early cleavages and metamorphic recrystallization. It is a generally homogeneous, banded semipelite with a few calcareous or psammitic horizons. Although some beds display cross lamination or grading, large thicknesses of strata contain no clear evidence of younging.

The area can be divided into three structural domains (Fig. 2) based on the different geometry of the interference of the two early penetrative deformation phases and bedding. These two phases, D_2 and D_3, produced the main early schistosities in the area. Each of the three domains is characterized by a particular geometrical relationship between bedding and the S_2 and S_3 cleavages, although within each broad domain narrower zones of different geometry occur.

DESCRIPTION OF THE EARLY DEFORMATION IN THE PORTNOO–ROSBEG AREA

The Rosbeg domain

This structural domain occurs in the south and west of the Portnoo–Rosbeg area between Dawros Head and the western aureole of the Ardara Granite (Fig. 2).

The first cleavage seen in the field in pelitic rocks is a penetrative schistosity, S_2. In thin sections of pelites from F_2 fold hinges S_2 is commonly a penetrative parallel alignment of elongate grains of muscovite, quartz, feldspar and ore (0.1–0.4 mm long). S_2 is occasionally seen to crenulate an earlier fabric preserved as minute muscovite laths and grains of opaque material around microfolds. Thus, the slaty appearance of S_2 may be due to the transposition of an earlier tectonic fabric (S_1) and this conclusion is supported by a good correlation of D_2 in west Donegal with D_2 in northwest Donegal (Hutton 1977b, 1979, Meneilly 1982). No major or minor F_1 folds have been recognized and hence the facing of S_1 could not be determined.

S_2 is axial planar to open or close F_2 folds. S_2 and F_2 axial planes have a gentle to steep dip to the S, SW or SE and β_2, the intersection of S_2 and bedding, plunges gently to the W, SW or SE (Figs. 3a and 4a). F_2 folds face upward and, hence, generally to the north. Second-order F_2 folds with short limbs, 2–20 m long, are the

DEFORMATION EVENT		METAMORPHIC EVENT	
D_1	S_1 RARELY PRESERVED. NO MAJOR OR MINOR F_1 FOLDS. FACING OF S_1 UNKNOWN.		
D_2	S_2 CLEAVAGE DIPPING SOUTH. NORTH FACING MAJOR F_2 FOLDS.	MS_2	RECRYSTALLIZATION OF QUARTZ, MUSCOVITE AND ORE.
		MP_2	STATIC GROWTH OF GARNET PORPHYROBLASTS (SOME EARLY D_3 GROWTH).
D_3	CRENULATION CLEAVAGE VERGING SOUTH ON S_2.	MS_3	PRESSURE SOLUTION AND REDISTRIBUTION OF QUARTZ.
		MP_3	STATIC GROWTH OF FELDSPAR PORPHYROBLASTS.
D_4	S OR SE DIPPING S_4 CRENULATION CLEAVAGE. N OR NW FACING MAJOR F_4 FOLDS. SYN-KINEMATIC INTRUSION OF ARDARA GRANITE.	MS_4	PRESSURE SOLUTION AND REDISTRIBUTION OF QUARTZ. (GROWTH OF ANDALUSITE, STAUROLITE AND GARNET IN THERMAL AUREOLE OF ARDARA GRANITE IS LATE MP_3 TO EARLY MP_4).
		MP_4	GROWTH OF CHLORITE PORPHYROBLASTS.
D_5	UPRIGHT OR SOUTH DIPPING CRENULATION CLEAVAGE. NORTH FACING MAJOR F_5 FOLDS.	EARLY MS_5	
D_6	NE-SW TRENDING UPRIGHT CRENULATION. NO MAJOR F_6 FOLDS.		NOTE: RETROGRESSION OF MP_2 GARNETS IS PRE-D_4.
LATE DEFORMATION	MINOR CRENULATIONS, SHEAR ZONES AND KINKBANDS.		

Fig. 1. Chronology of deformation and metamorphism in the Portnoo–Rosbeg area.

most common mesoscopic structure in the Rosbeg domain.

The first crenulation cleavage recognizable in the field, S_3, dips gently SW (Figs. 3b and 4b). S_3 faces and verges south on the long limbs of F_2 folds but commonly has opposing vergence and facing on the opposite limbs of first-order F_2 folds (Figs. 5a & b).

S_3 is a crenulation cleavage generally associated with considerable metamorphic segregation that produced quartz-rich and mica-rich domains or microlithons. S_2 muscovite flakes are bent in the hinge zones of S_3 crenulations. There is some recrystallization of muscovite resulting in polygonized interlocking grains but otherwise D_3 is not associated with growth of new metamorphic minerals.

Large (2–3 mm) porphyroblasts of wholly or partially chloritized garnet preserve straight inclusion trails (S_i) of opaque minerals and quartz grains which are continuous with the S_2 cleavage outside (S_e). S_3 crenulates S_e with differentiation into quartz-rich hinge zones and mica-rich limbs but S_i is undeformed (Fig. 6a). S_3 commonly forms augen around the garnet porphyroblasts with quartz-rich pressure shadows developed. These relations suggest that the garnets are post-S_2 and pre-S_3, that is MP_2 (metamorphism post-D_2).

The Lefrin Hill domain

This domain occurs in two main areas, around Lefrin Hill and to the southeast of Kiltooris Lough (Fig. 2). It is characterized by its position in the hinge zones of major F_2 folds and by the absence of an S_3 crenulation cleavage.

S_2 dips gently S or SW and β_2 plunges W, SW or E (Figs. 3c and 4a). North-verging major F_2 folds face up to the north.

S_2 in thin section is similar to that in the Rosbeg domain, that is a penetrative parallel alignment of elongate grains of quartz, muscovite and ore. Chloritized MP_2 garnets are common, and in thin sections from the Lefrin Hill domain the S_2 schistosity forms augen around the garnets with quartz-rich pressure shadows developed (Figs. 6b & c). The garnets have straight inclusion trails which lie at a high angle to and are sometimes discontinuous with S_2 outside. Commonly they are elongate and the inclusion trails everywhere lie parallel to their long axes (Figs. 6b & c). The origin of these features can be explained by looking at the relationships between garnets and S_2 across the gradational boundary between the Rosbeg and Lefrin Hill domains.

As the Lefrin Hill domain is approached, S_2 becomes gently S dipping while S_3 remains gently SW dipping. Thus, the angle between S_2 and S_3 becomes more acute and S_3 changes from a symmetric crenulation of S_2 to an asymmetric crenulation (Fig. 8b). Within zones of asymmetric S_3 crenulations, MP_2 garnet porphyroblasts are rotated relative to S_2 with the same sense of rotation of their straight S_2 inclusion trails as S_2 in the S_3 microfolds (Fig. 7a). The rotation of the garnet relative to the external S_2 schistosity and the accompanying formation of pressure shadows are considered to be the result of the D_3 deformation which formed the asymmetric crenulations. When S_2 and S_3 become subparallel, S_3 no longer crenulates S_2, but the MP_2 garnet porphyroblasts continue to be rotated relative to S_2 (Fig. 8b). D_3 in this situation stretches and intensifies rather than crenulating S_2 and the only evidence for D_3 strain is the relative rotation of the MP_2 garnets and the wrapping of S_2 around them. The schistosity is therefore a composite $S_{2/3}$ fabric.

In the Lefrin Hill domain, S_4 (Fig. 1) is therefore the first crenulation cleavage recognized in the field. S_4 and later cleavages crenulate the composite $S_{2/3}$ schistosity.

In alternating psammites and pelites in the transition zone between the Rosbeg domain and the Lefrin Hill domain gently dipping S_2 in the pelite is uncrenulated while the steeper S_2 in the psammite bands is crenulated

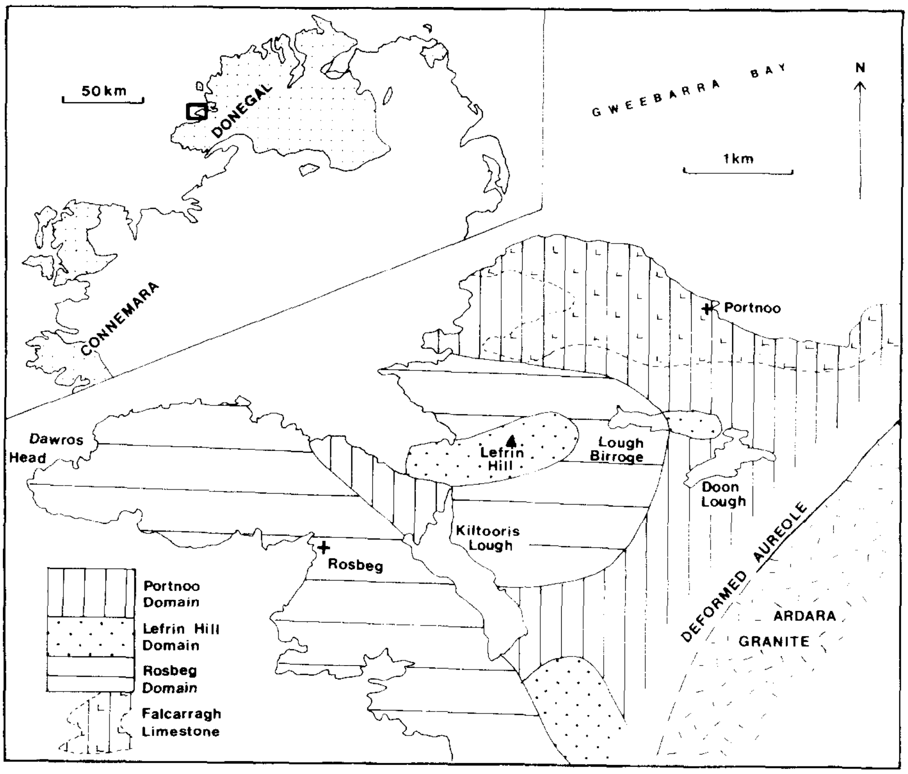

Fig. 2. Structural domains in the Upper Falcarragh Pelite of the Portnoo–Rosbeg area. Inset: location of area. Dalradian rocks stippled.

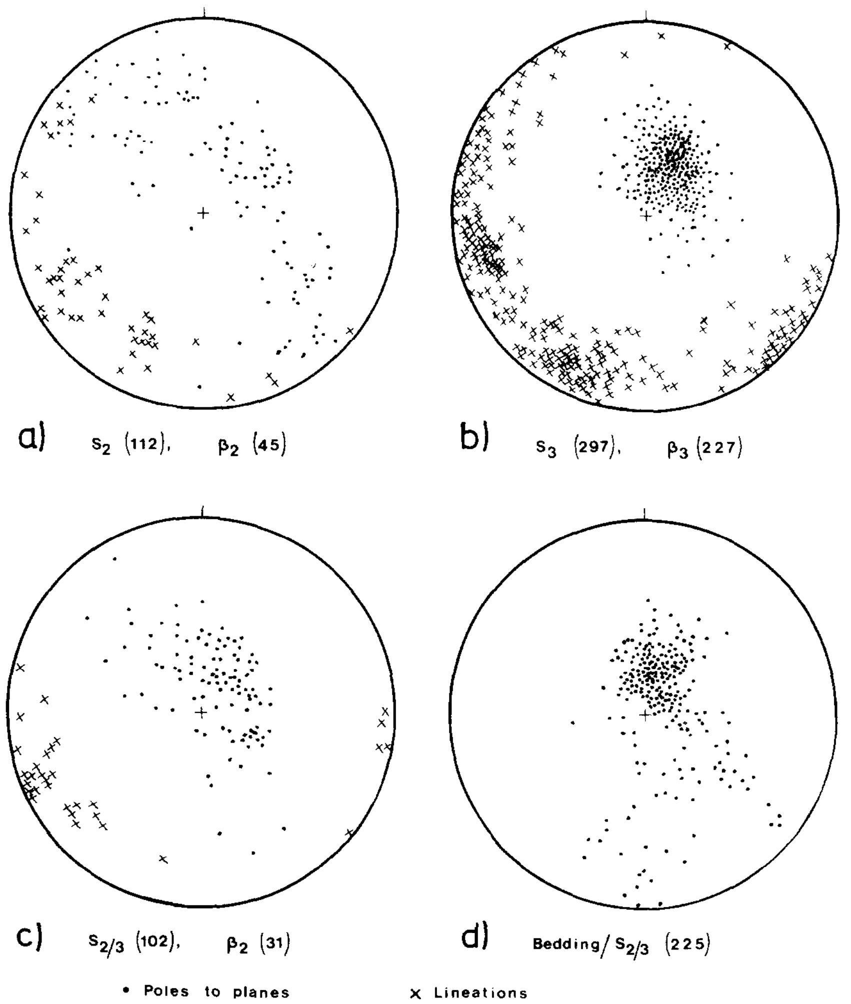

Fig. 3. Equal-area stereograms of cleavages and related lineations. (a) and (b) Rosbeg domain. (c) Lefrin Hill domain. (d) Portnoo domain.

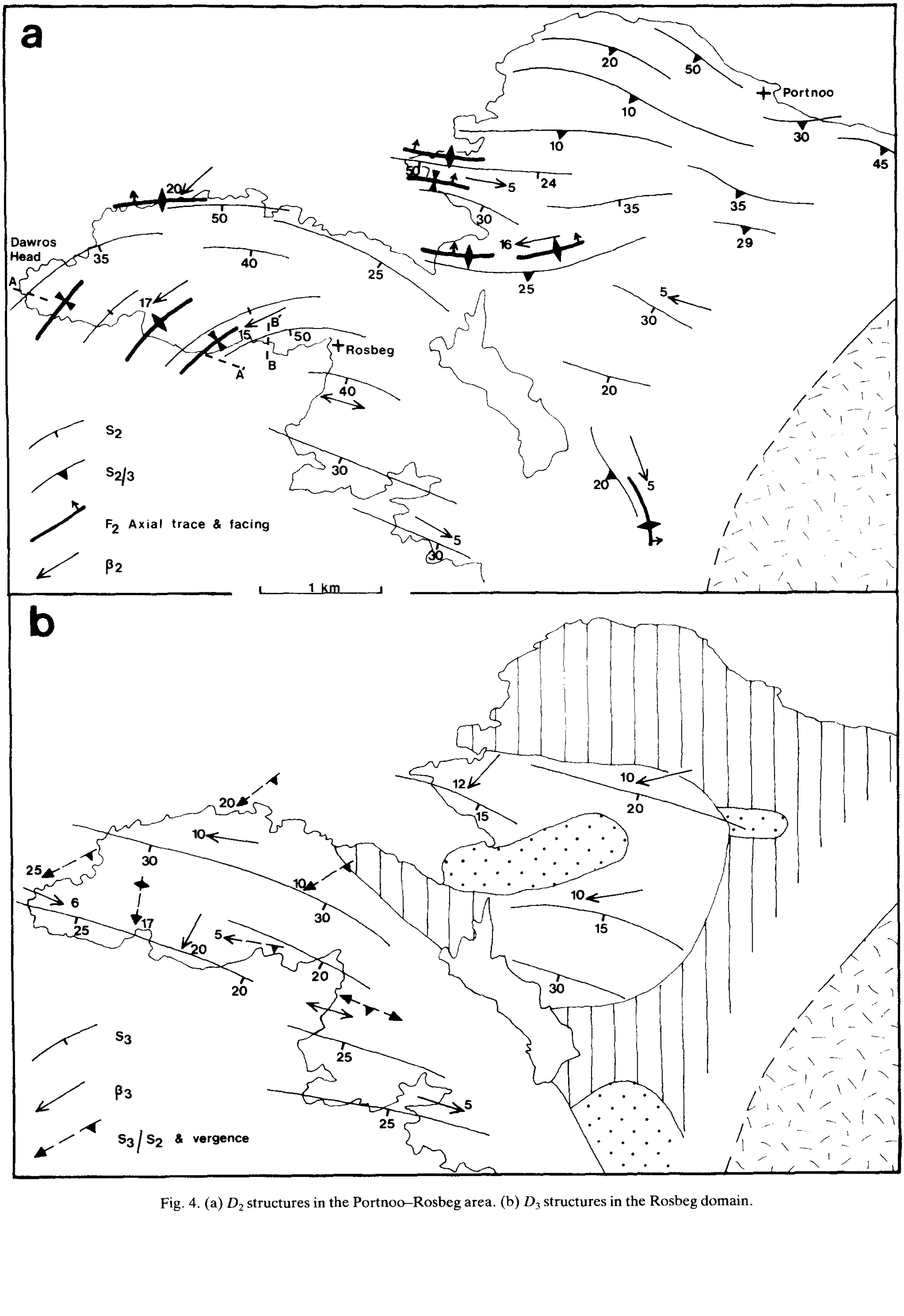

Fig. 4. (a) D_2 structures in the Portnoo–Rosbeg area. (b) D_3 structures in the Rosbeg domain.

by S_3 (Fig. 7b). It is interpreted that S_2 originally refracted through the different lithologies, being steeper in the psammites than in the pelites on the long limbs of F_2 folds. The steep S_2 in the psammites was therefore crenulated, while S_2 in the pelites was extended during D_3 deformation. This example is a mesoscopic equivalent to the larger-scale change in the geometrical relationship between S_2 and S_3 from the Rosbeg to the Lefrin Hill domains. The structural relationships seen in the Rosbeg domain are preserved in the psammite bands, with both S_2 and S_3 cleavages being developed. These pass into a composite $S_{2/3}$ cleavage in the pelites. Thus, the relationship between S_2 and S_3 and the development of composite $S_{2/3}$ cleavage has been deduced both by mapping of cleavages from one domain to another and by detailed observations from lithology to lithology.

The Portnoo domain

This structural domain occurs in the north of the Portnoo–Rosbeg area (Fig. 2). It is characterized throughout by a composite $S_{2/3}$ schistosity, subparallel to bedding and generally dipping gently south (Fig. 3d) and only rarely axial planar to minor F_2 folds verging and facing to the north. Later deformation structures, particularly those of D_4, become more strongly developed and fold this strong bedding/$S_{2/3}$ fabric. S_2 is wrapped around MP_2 garnets by D_3 deformation as in the Lefrin Hill domain. S_2 is only seen as inclusion trails in MP_2 garnet porphyroblasts. Thus, the textural relationship of the garnets could be interpreted as $MS_{2/3}$, that is syntectonic with respect to the composite $S_{2/3}$ cleavage. S_3 as a crenulation cleavage is absent from the Portnoo domain.

Summary of early deformation and metamorphism in the Portnoo–Rosbeg area

The geometry of the first two penetrative deformation phases D_2 and D_3 in the Portnoo–Rosbeg area is summarized in Fig. 8(a). The following relationships of bedding, S_2 and S_3 occur on traversing from south to north.

(i) S_3 has a gentle dip to the south throughout the area.

(ii) S_2 gradually changes from subvertical or steeply south dipping in the south to gently south dipping in the north. Thus, S_3 cuts S_2 at progressively smaller angles until it becomes subparallel to it in the Lefrin Hill and Portnoo domains.

(iii) S_2 cuts the sheet dip of bedding at progressively smaller angles. Nearly neutral-vergent major F_2 folds in the south pass into north-verging folds and finally S_2 becomes subparallel to bedding.

These changes combine to produce three structural domains. In the south (Rosbeg domain), S_3 verges south on the steep S_2 and cuts across F_2 folds. As S_2 becomes more gently dipping and parallel to S_3 one enters the Lefrin Hill domain. Here a composite $S_{2/3}$ cleavage is in the hinge of major F_2 folds. In the Portnoo domain, the composite $S_{2/3}$ cleavage lies parallel to bedding and later folds are more common. The D_3 rotation of MP_2 garnets allows the composite nature of the schistosity in the Lefrin Hill and Portnoo domains to be recognized (Fig. 8b).

KINEMATICS OF D_2 DEFORMATION

In the preceding section, it was shown that in the Lefrin Hill and Portnoo domains D_3 deformation does

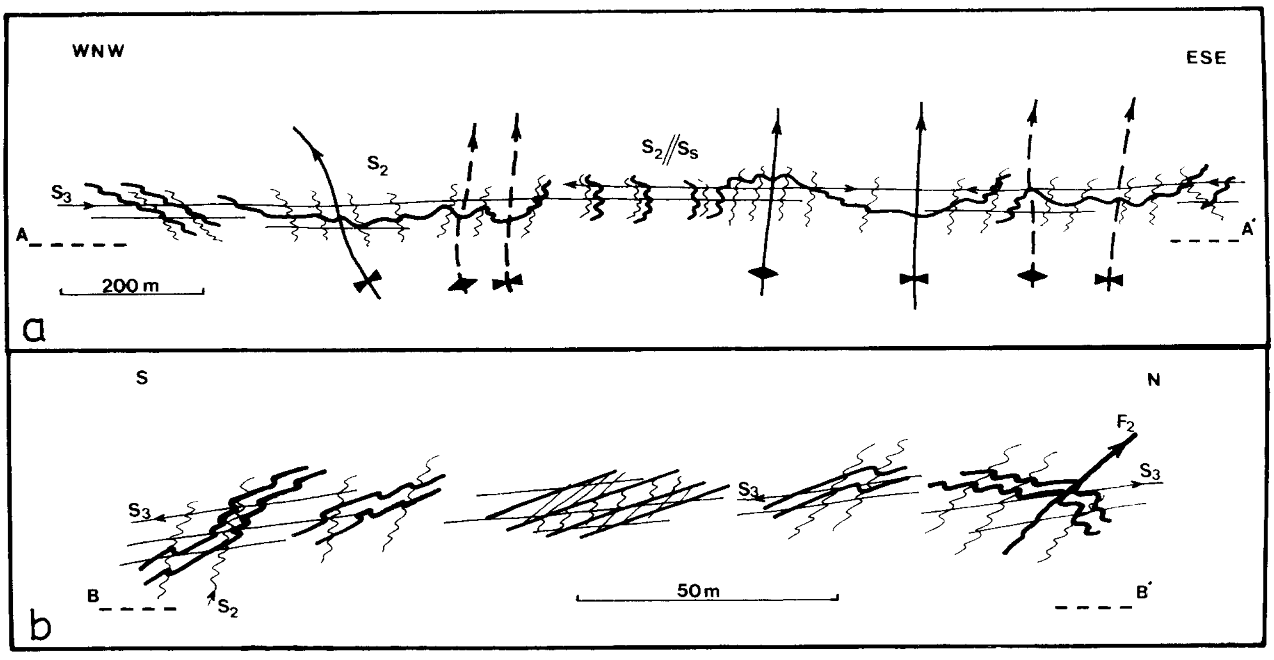

Fig. 5. (a) Structural cross-section of the coast southeast of Dawros Head. Facing directions of F_2 folds and S_3 are indicated by arrows. (b) Cross-section 750 m west of Rosbeg showing change in facing of S_3 across an F_2 fold. For lines of sections see Fig. 4(a).

not crenulate but extends S_2, producing a composite $S_{2/3}$ fabric. It was seen that D_3 is characterized by wrapping of S_2 around MP_2 garnet porphyroblasts and, if S_3 is at a moderate or small angle to S_2, rotation of the MP_2 garnets relative to S_2. In this section field and microstructural observations are used to determine a kinematic model for the D_3 deformation.

In the Rosbeg domain, S_3, which is at a high angle to S_2, is ubiquitously developed with little apparent change in the intensity of S_3. This suggests a relatively homogeneous development of D_3 strains within the Rosbeg domain. S_3 dips gently SW and hence, assuming that cleavage records the approximate orientation of the XY plane of the strain ellipsoid (see Williams 1976 for discussion), Z is steep. Quartz veins subnormal to S_3 are buckle folded and suggest a shortening of 60%: seven veins were measured for which the mean shortening, L_1/L_0, was 0.39 ($\pm$0.07) that is 54–68% (using 95% confidence limits). Thus, $1 + e_3 \approx 0.4$. Without a knowledge of the type of strain, and recognizing the possibility of volume reduction during pressure solution, the other principal strains cannot be estimated uniquely. For flattening ($K = 0$) and no volume change;

$$1 + e_1 = (1 + e_3)^{-1/2} \approx 1.6.$$

For plane strain ($K = 1$) and no volume change;

$$1 + e_1 = (1 + e_3)^{-1} \approx 2.5.$$

These values would be reduced for volume loss. Thus, the maximum strain ratios are probably less than 6 or for simple shear $\gamma < 2$. The above discussion gives some idea of the degree of finite strain allowable in any kinematic model rather than being a quantitative estimate of the strain.

The finite D_3 strain could be achieved by various types of deformation. To determine the kinematics of deformation, simplified models are examined and tested against structural observations, both in a quantitative and qualitative manner.

The gently south-dipping S_3 cleavage could result from a number of different types of deformation history, three of which are illustrated in Fig. 9:

(i) northerly directed simple shear;
(ii) southerly directed simple shear;
(iii) pure shear or flattening normal to S_3.

Combinations of the three situations above could also produce the observed state of strain. In the following discussion the three models outlined in Fig. 9 will be examined. They are considered to represent 'end members' in the spectrum of possible deformations. It is by combining features of these models that a final kinematic model is constructed.

Response of S_2 *to* D_3 *strain in banded lithologies*

In banded psammites and pelites where S_3 lies subparallel to bedding, S_2 within psammite bands is steep, whilst in pelite bands it is inclined gently south (Fig. 10a). The rotation of pre-D_3 garnet porphyroblasts (see below) implies that S_2 was originally at a high angle to layering in the examples illustrated in Fig. 10(a). In the following discussion it is assumed that psammite is less ductile and will record less strain than pelite.

A variety of bulk strain states could produce the observed geometry. A bulk south-directed simple shear is incompatible with less ductile psammite as it requires the psammite illustrated in Fig. 10(a) to record more shear strain than the pelite.

(i) Bulk pure shear will result in greater shortening in the pelite bands and hence greater apparent rotation of S_2 relative to bedding (Fig. 10b).

(ii) Northerly directed bulk simple shear will rotate S_2 in the pelite more than in the psammite (Fig. 10c).

(iii) Any combination of pure shear and northerly directed simple shear could produce the observed geometry in Fig. 10(a).

Apparent rotations of MP_2 *garnets*

Where S_3 verges south on S_2, MP_2 garnet porphyroblasts contain straight inclusion trails (S_i) of S_2 which show a consistent southerly sense of vergence relative to the external S_2 fabric (S_e). This ubiquitous relationship is illustrated in Figs. 6(d) and 11.

Apparent rotation of porphyroblasts can result from either coaxial or non-coaxial deformation history. For pure shear a rigid porphyroblast will not rotate, but the surrounding fabric rotates with deformation producing apparent rotation (ω) which cannot exceed 90°. In rotational strain, such as progressive simple shear, the rigid porphyroblast produces strain perturbations in a matrix which leads to solid body rotation (Ramsay 1969, p. 52, Schwerdtner 1979).

Three simple kinematic models are examined.

(i) *Northerly directed simple shear (Fig. 12a).* If S_2 was originally at a high angle to the shear direction (i.e. $45° < \alpha < 135°$) the porphyroblast initially rotates less rapidly than S_2 (Ghosh 1975, Dixon 1976). S_e rotates according to $\cot \alpha' = \cot \alpha + \gamma$, and S_i rotates according to $\theta - \theta' = \gamma/2$ (Jeffrey 1923). The maximum apparent rotation, $\omega = \theta' - \alpha'$, is generally small (Fig. 12d). For a shear strain of $\gamma \approx 2$, ω does not exceed *c.* 40°. The observed rotations are much greater, typically 80°, hence northerly directed simple shear alone is not compatible with the observed rotations.

(ii) *Shear parallel to* S_2 *(Fig. 12b).* This model utilizes S_2 planes as shear planes. Southerly directed simple shear will rotate the porphyroblast according to $\omega = \gamma/2$ with no rotation of the S_2 planes, producing southerly vergence of S_i relative to S_e. The observed rotations of 80° could be produced by a shear strain of $\gamma \approx 2.8$.

(iii) *Pure shear normal to* S_3 *(Fig. 12c).* In this case the porphyroblast does not rotate and S_e is rotated towards the S_3 plane according to $\tan \alpha' = R_s \tan \alpha$, where R_s is the strain ratio. Very high strains would be necessary to produce the observed apparent rotations. For example if S_i is at 80° to S_3 and S_e at 10°, that is $\alpha = 80°$, $\alpha' = 10°$, then

$$R_s = \frac{\tan 80°}{\tan 10°} \approx 32.$$

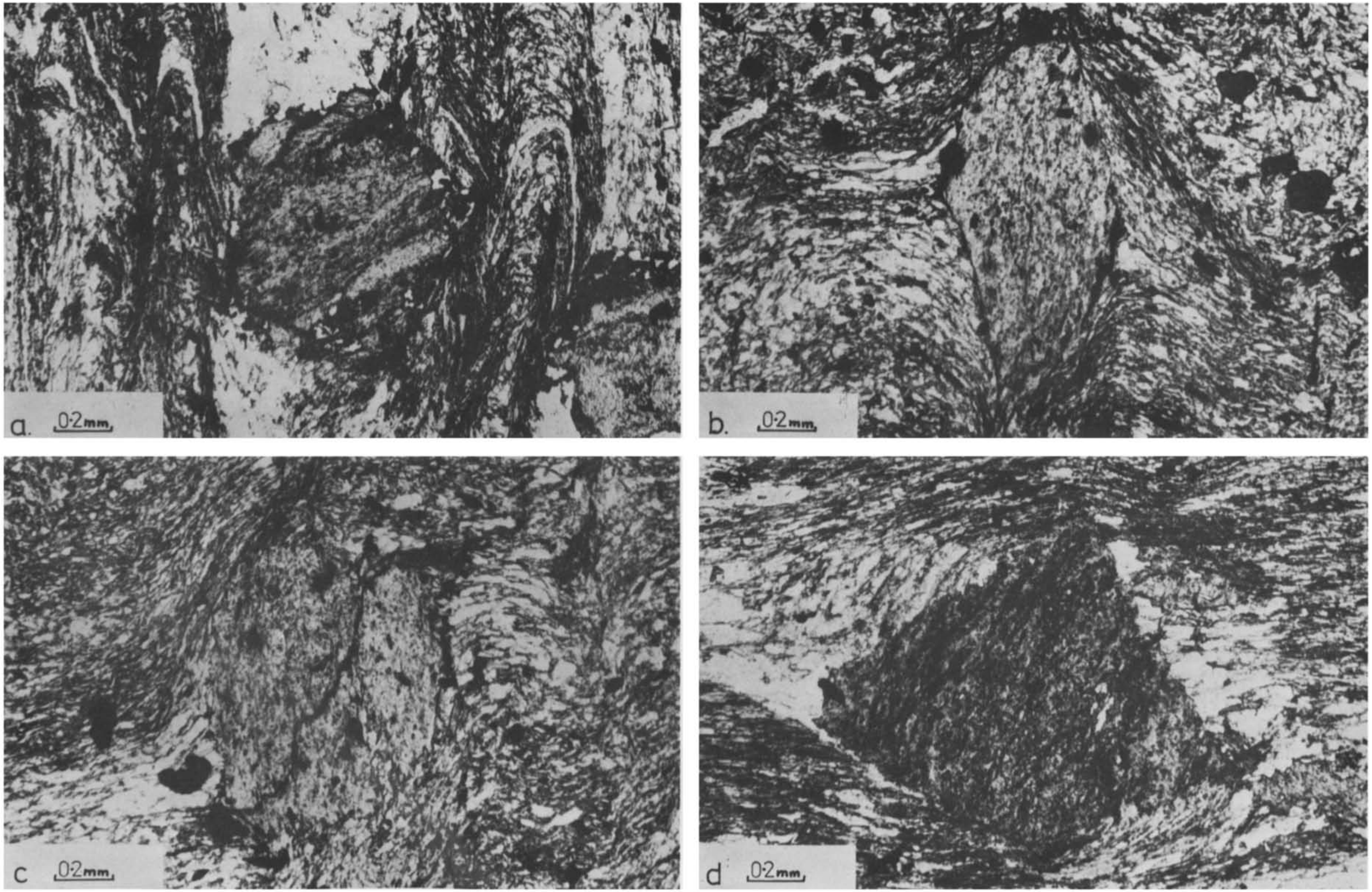

Fig. 6. Photomicrographs of MP_2 garnet porphyroblasts. (a) Garnet from the Rosbeg domain containing straight inclusion trails of S_2 and wrapped by an S_3 crenulation cleavage. (b) Composite $S_{2/3}$ cleavage wrapping around chloritized garnet from the Lefrin Hill domain. (c) Composite $S_{2/3}$ cleavage continuous with the straight S_2 inclusion trails in garnet; from same thin section as (b). (d) Drag pattern of S_2 around garnet from the Rosbeg domain which has been rotated during D_3.

This illustrates the high strain necessary to produce large rotations by pure shear and these rotations can never exceed 90°. A few porphyroblasts with $\omega > 90°$ confirm the inapplicability of the pure shear model and hence the necessity for some progressive rotational strain during D_3.

Thus, the apparent rotation of MP_2 garnet porphyroblasts could have resulted from any combination of the above three models but a significant component of southerly directed simple shear parallel to S_2 is required to produce the observed large rotations of S_i.

Drag patterns around MP$_2$ *garnet porphyroblasts*

Ghosh (1975) has examined the deformed patterns (drag patterns) of planar structures around rigid spherical bodies and used them to determine the initial angle between pre-existing foliation and the direction of simple shear. Four types of drag pattern produced by shear parallel to pre-existing foliation and at angles of 45, 90 and 135° to it are shown in Figs. 13(a)–(d), based on Ghosh's work.

The garnet–S_2 relationships from the Rosbeg domain (Fig. 11) conform to the situation in which the foliation was initially parallel to the direction of simple shear (Fig. 13a). The drag pattern is asymmetric, but with the same sense of drag of the foliation all round the margin of the rigid body relative to that distant from the margin. In this case S_e is dragged in an anticlockwise direction at the edge of the rigid body. A superficially similar geometry arises if shear takes place at 90° to the initial orientation of S_e (Fig. 13c). However in this case the sense of drag of the foliation changes around the rigid body and has both clockwise and anticlockwise drag of S_e at the contact.

Ghosh also examined the drag patterns produced by pure shear (Fig. 13e). He showed that for initial foliation at angles of less than 90° to the principal axis of compression the sense of drag of the foliation lines will be the

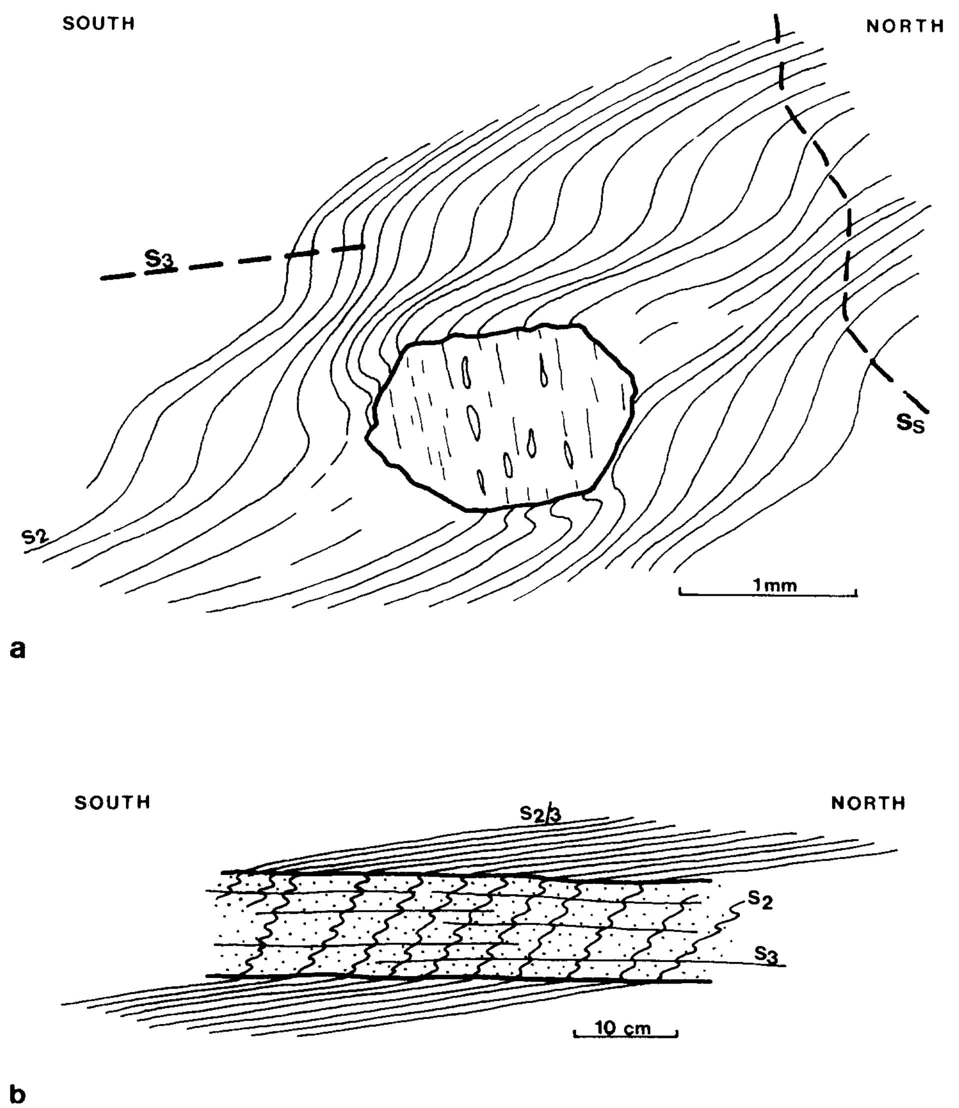

Fig. 7. (a) Asymmetric S_3 crenulations and D_3 pressure shadows around MP_2 garnet. (b) S_2–S_3 relationships in psammite (stippled) and pelite from west of Rosbeg.

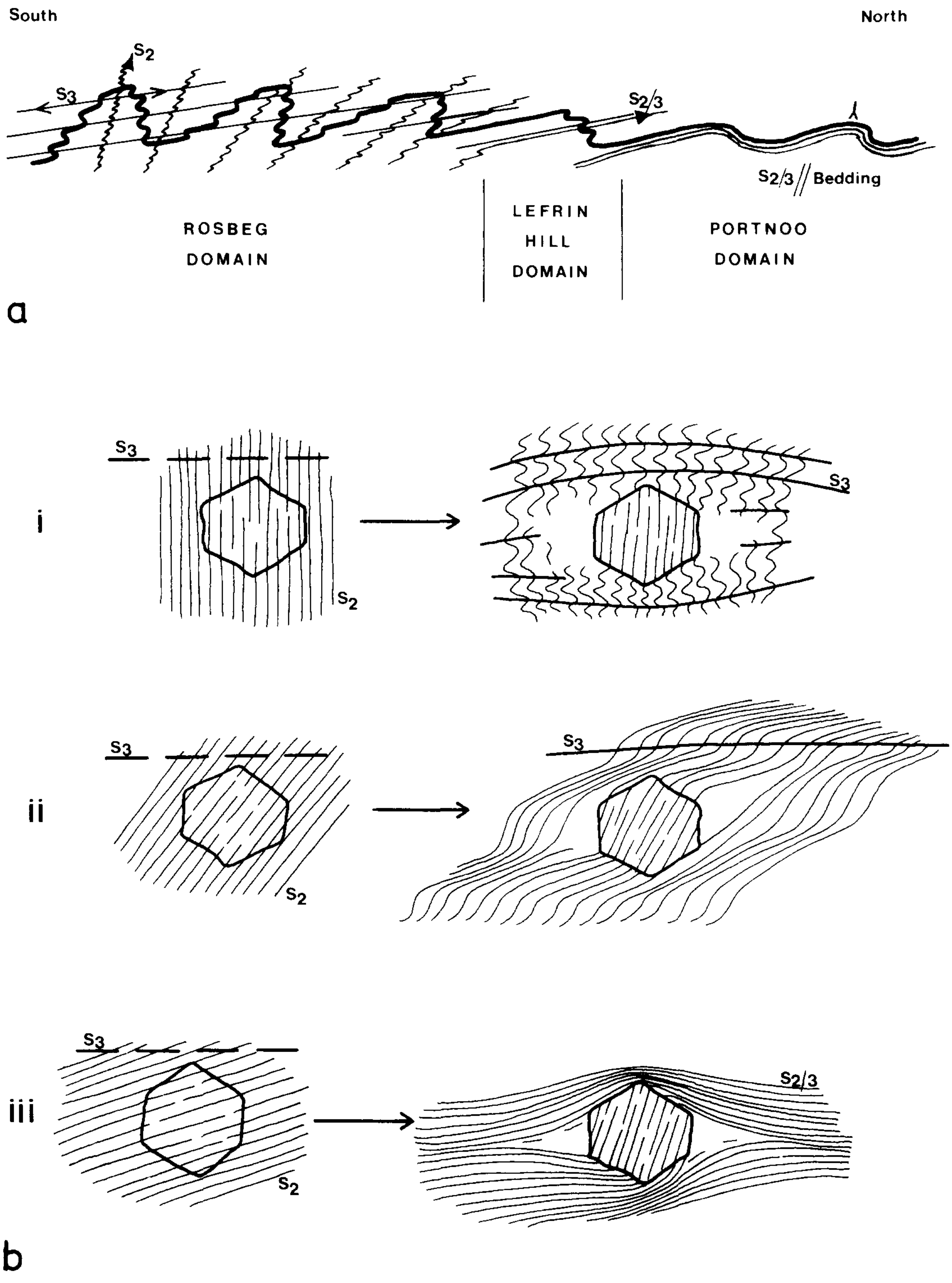

Fig. 8. (a) Schematic summary of the structural changes in the Portnoo–Rosbeg area. (b) Progressive development of the composite $S_{2/3}$ cleavage: (i) Rosbeg domain, (ii) Transition between the Rosbeg and Lefrin Hill domains and (iii) Lefrin Hill domain.

same all around the rigid body. The drag pattern for pure shear is almost identical to that for simple shear parallel to the foliation (cf. Figs. 13a & e).

Thus, the drag patterns around the MP_2 garnets suggest either southerly directed simple shear parallel to S_2, or pure shear normal to S_3 or a combination of both.

Kinematic model for D$_3$ *in the Rosbeg domain*

The field and mesoscopic evidence is best explained by either bulk pure shear or northerly directly bulk simple shear, or any intermediate type of deformation history. However, where S_2 dips moderately or gently south, garnet porphyroblasts indicate southerly directed active slip on S_2. Where S_2 is at a high angle to S_3 it is simply crenulated and there is no evidence for a consistent sense of active slip on S_2.

Southerly slip on S_2 is not incompatible with bulk pure shear or northerly directed bulk simple shear. Compression at an angle to S_2 during pure shear may be expected to initiate active shear on S_2 planes (Fig. 14a). Thus slip, accompanied by rotation of S_2 planes, can produce a strain approximating to pure shear. This is analogous to the operation of a single slip system in crystals undergoing compression (see discussion in Hobbs *et al.* 1976, pp. 122–125). If S_2 is at a large angle to the bulk shear direction, northerly directed bulk simple shear will produce southerly shear along S_2 (Fig. 14b) (see Ghosh 1966, p. 179 and Fig. 11).

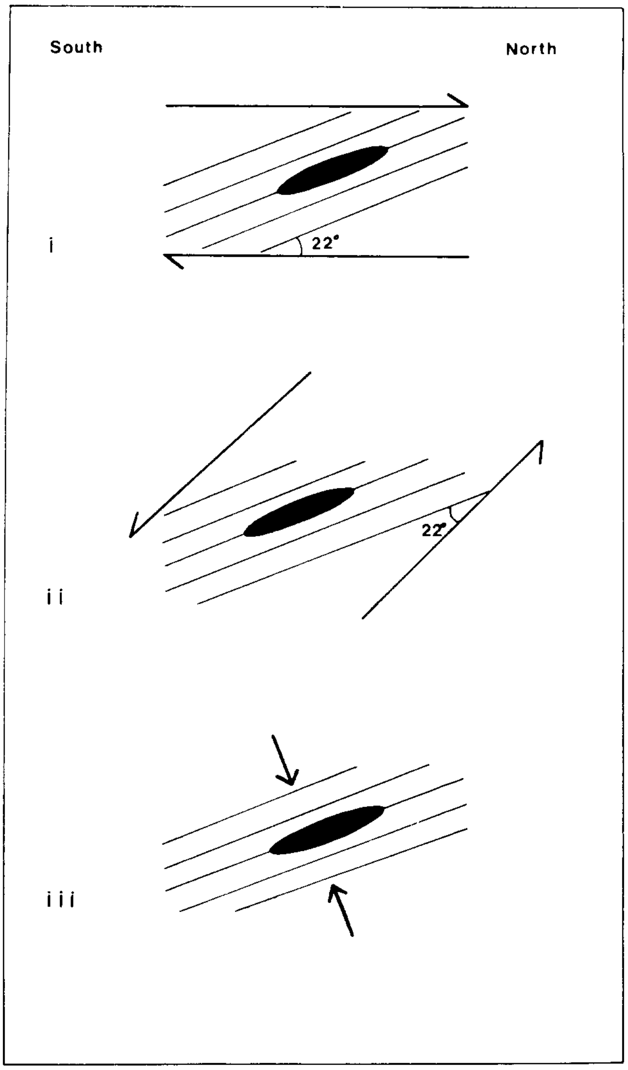

Fig. 9. Three ways of producing a gently south-dipping S_3 cleavage (a strain ratio of 6.0 has been used for illustration only).

Extension to other domains: S$_3$ *as an extensional crenulation cleavage*

S_3, when traced into the Lefrin Hill and Portnoo domains, cross-cuts S_2 at progressively smaller angles until it is subparallel to it, forming a composite $S_{2/3}$ cleavage. Porphyroblast rotation is generally largest (*c*. 90°) in the transition between the Rosbeg and the other two domains, where S_2 and S_3 were originally at a moderate angle to each other. In this situation S_2 is in an optimum orientation for slip during D_3. Where S_2 and S_3 become subparallel porphyroblast rotation is rarely observed, and S_2 may have been simply extended during D_3 with no slip parallel to S_2.

Platt (1979) distinguishes the normal type of crenulation cleavage, where the crenulated foliation lies initially in the shortening field, from what he terms 'extensional crenulation cleavage' where both the finite and incremental extension axes are at a small angle to the older foliation throughout the development of the new cleav-

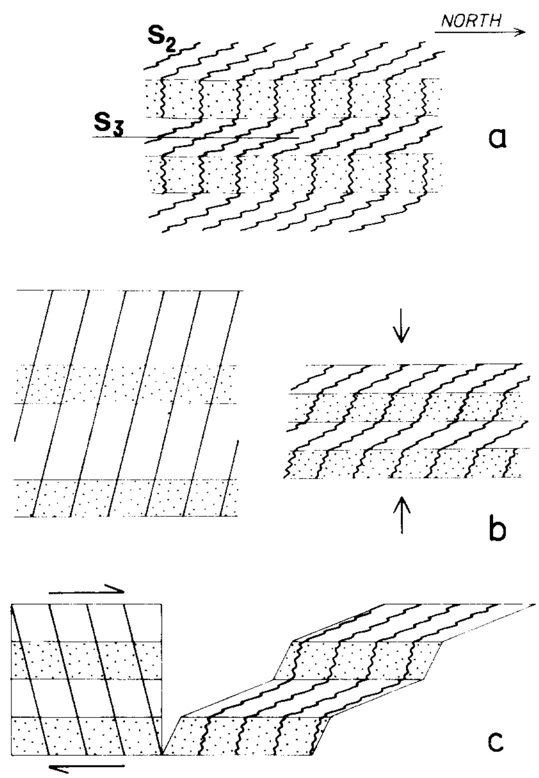

Fig. 10. (a) S_2 and S_3 in banded lithologies (psammite stippled). (b) Geometry similar to that in (a) produced by an inhomogenous bulk pure shear. In the example shown the bulk strain ratio is 4 with no change in area; the strain ratio is *c*. 7.1 in the pelite and *c*. 1.8 in the psammite. (c) Geometry similar to that in (a) produced by an inhomogenous bulk simple shear. In this example the bulk shear strain is 1.5, the shear strain is 2.5 in the pelite and 0.5 in the psammite.

age. S_3 in the transition zone between the Rosbeg domain and the Lefrin Hill or Portnoo domain is, therefore, an extensional crenulation cleavage as defined by Platt (1979).

COMPOSITE CLEAVAGE IN THE DALRADIAN AND MOINE

(For the sake of clarity the structural episodes $\boldsymbol{D_n}$, $\boldsymbol{F_n}$, $\boldsymbol{S_n}$ of other workers are in bold type.)

Pitcher & Berger (1972, pp. 66–68 and figs. 3.7 and 3.8) described porphyroblasts of garnet, plagioclase and ilmenite which preserve straight, curved or rare microfolded inclusion trails of their $\boldsymbol{S_1}$ cleavage. They considered the curved or microfolded $\boldsymbol{S_1}$ trails to be preexisting $\boldsymbol{S_2}$ crenulations of $\boldsymbol{S_1}$ over which the $\boldsymbol{MP_2}$ porphyroblasts grew. The $\boldsymbol{S_2}$ crenulation cleavage then formed augen around the porphyroblasts and intensified during $\boldsymbol{D_3}$ deformation producing a composite $\boldsymbol{S_{2/3}}$ crenulation cleavage. They illustrated this sequence of events in their fig. 3.8 which is reproduced in Fig. 15. Although they recognized separate $\boldsymbol{S_2}$ and $\boldsymbol{S_3}$ surfaces cross-cutting at a low angle in a few places, Pitcher & Berger (1972) did not describe the situation where the two cleavages

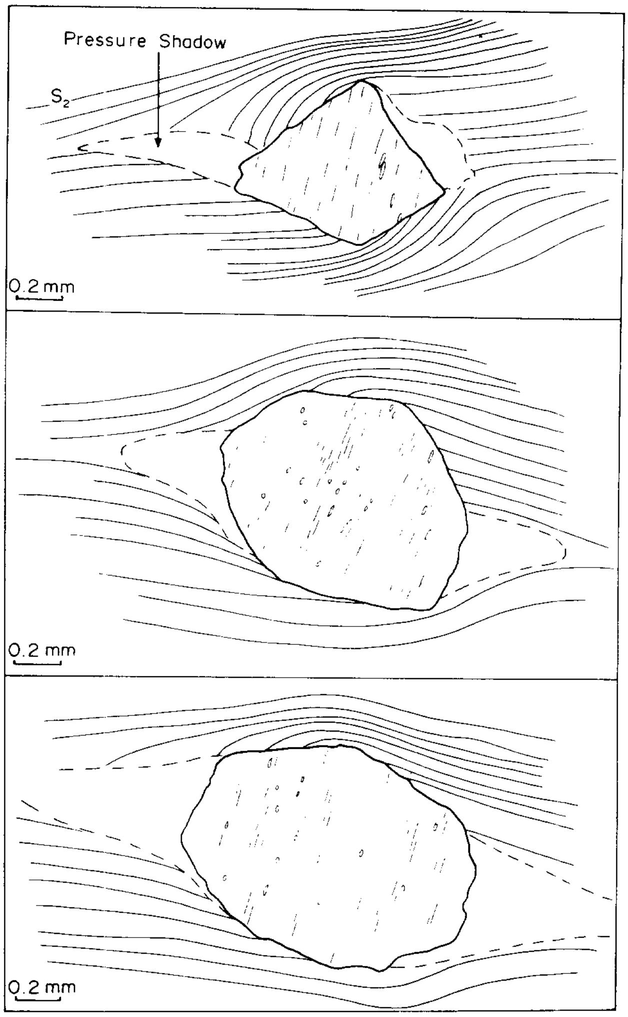

Fig. 11. Garnet–S_2 relationships in the Rosbeg domain traced from thin sections.

can be seen in relation to the porphyroblasts. Hutton (1977a, 1979) interpreted the feldspar porphyroblasts in northwest Donegal as $\boldsymbol{MS_2}$ rather than $\boldsymbol{MP_2}$. He considered that the porphyroblasts grew over early-formed $\boldsymbol{S_2}$ crenulations which were subsequently intensified and wrapped around the porphyroblasts during a continuous, progressive $\boldsymbol{D_2}$ deformation phase.

It is concluded that the composite $S_{2/3}$ cleavage of Pitcher & Berger (1972) is not a correlative of the composite $S_{2/3}$ in the Lefrin Hill and Portnoo domains. The textural features described by Pitcher & Berger are open to alternative interpretation (Hutton 1977a), while the composite nature of $S_{2/3}$ in west Donegal can be clearly demonstrated.

The preservation of an early cleavage only as relicts within the hinge zones of later crenulations, or in porphyroblasts, has been described from many areas in the Dalradian. For example, in Connemara (Badley 1976, Yardley 1976) and north Mayo (Max 1973) $\boldsymbol{S_1}$ (parallel to bedding) is only recognized occasionally in F_2 fold hinges. This probably results from the intense crenulation and transposition of S_1 by S_2 but on F_2 fold limbs it is possible that S_2 is a composite $\boldsymbol{S_{1/2}}$ fabric.

In the Kinlochleven area of the southwest Highlands of Scotland, Treagus (1974) showed that the main structures resulted from the interference of his $\boldsymbol{D_1}$ and $\boldsymbol{D_3}$ deformation phases. He considered his $\boldsymbol{S_2}$ of only local importance and described it as an intense crenulation cleavage cutting $\boldsymbol{S_1}$ at a low angle. There is a similarity in geometry between the $\boldsymbol{S_1}$–$\boldsymbol{S_2}$ interference described by Treagus from Kinlochleven and the S_2–S_3 interference in the Portnoo–Rosbeg area, although no direct correlation of events is proposed. In the Portnoo–Rosbeg area S_3 crenulation cleavage is only locally developed as a separate surface (Rosbeg domain). But it can be demonstrated that where the separate S_2 crenulation cleavage is absent, D_3 strains are still present and extend S_2 forming a composite $S_{2/3}$ fabric. It is suggested that in the Kinlochleven area $\boldsymbol{D_2}$ strains which result in the locally developed $\boldsymbol{S_2}$ crenulation may be of more widespread occurrence and may have extended $\boldsymbol{S_1}$ to produce a composite $\boldsymbol{S_{1/2}}$ fabric as in the Portnoo–Rosbeg area.

Another example of composite cleavage comes from the Tummel steep belt in the Central Scottish Highlands, from where Bradbury *et al.* (1979) described the transposition of successive planar fabrics into subparallelism with one another to form a composite S_1–S_3 foliation.

Thomas (1980, fig. 5) illustrated how his $\boldsymbol{S_2}$ cleavage is superimposed on $\boldsymbol{S_1}$ in the Moine rocks of the Strathtummel–Glen Errochty district, central highlands of Scotland. He indicates a zone on Craig Nan Caiscan where S_1 is parallel to S_2. Thomas (1980) also described a zone where his S_3 is parallel to S_1 and S_2 forming a composite schistosity.

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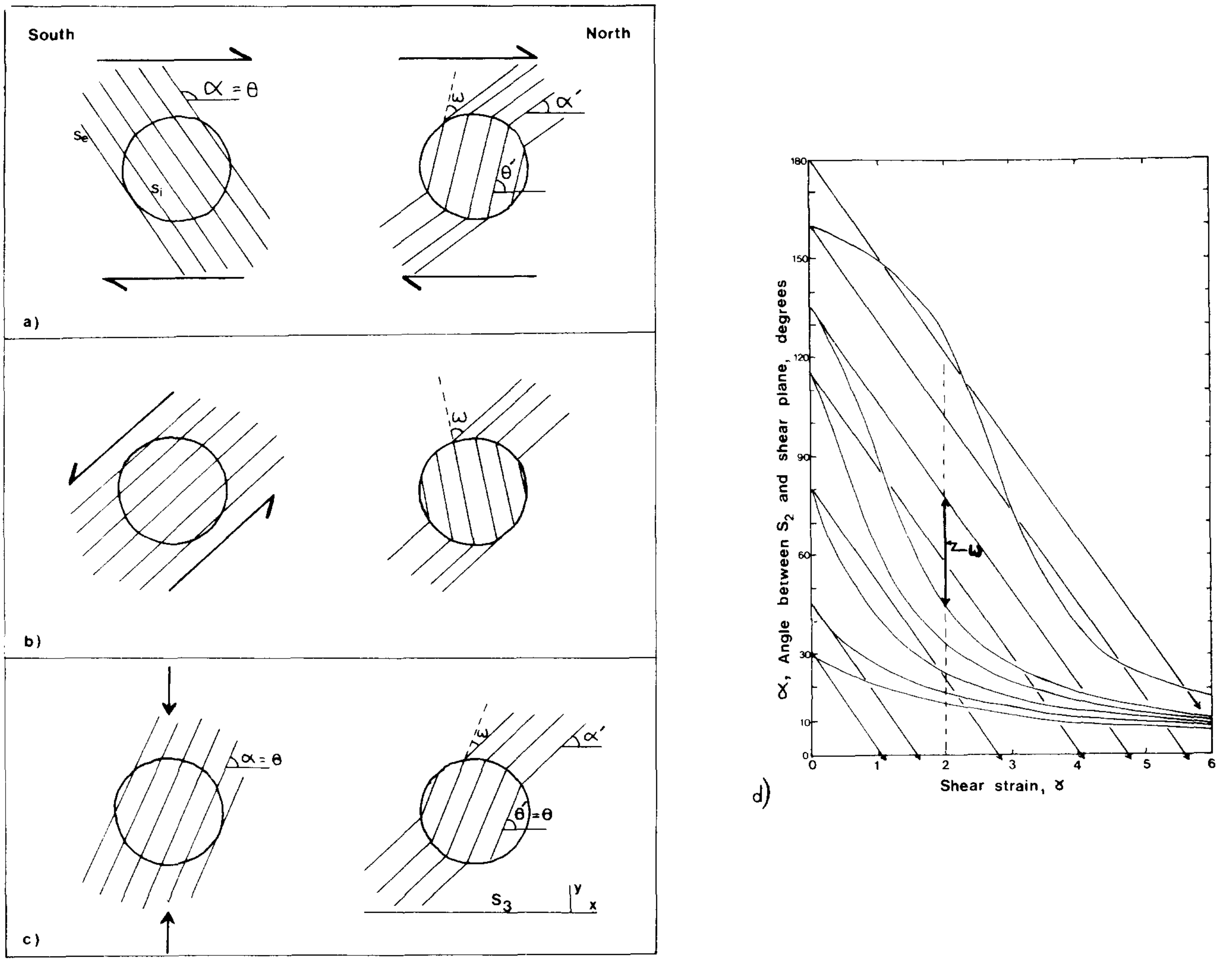

Fig. 12. Three possible origins of the observed apparent rotation of MP_2 garnets. (a) Northerly-directed simple shear. (b) Simple shear parallel to S_2. (c) Pure shear normal to S_3. α, α', angles between S_e and the simple shear direction or the direction of maximum elongation during pure shear, before and after deformation, respectively. θ, θ', angles between S_i and the simple shear direction or the direction of maximum elongation during pure shear, before and after deformation, respectively. ω, apparent rotation of S_i relative to S_e. (d) Graph of change in angle between shear planes and S_i (straight lines) or S_e (curved lines) during simple shear. In the example shown S_e and S_i initially make an angle of 135° with the shear planes. After a shear strain $\gamma = 2$, S_e makes an angle of 45° and S_i an angle of 77° with the shear planes. The apparent rotation, ω, is therefore 32° (after Dixon 1976, fig. 2).

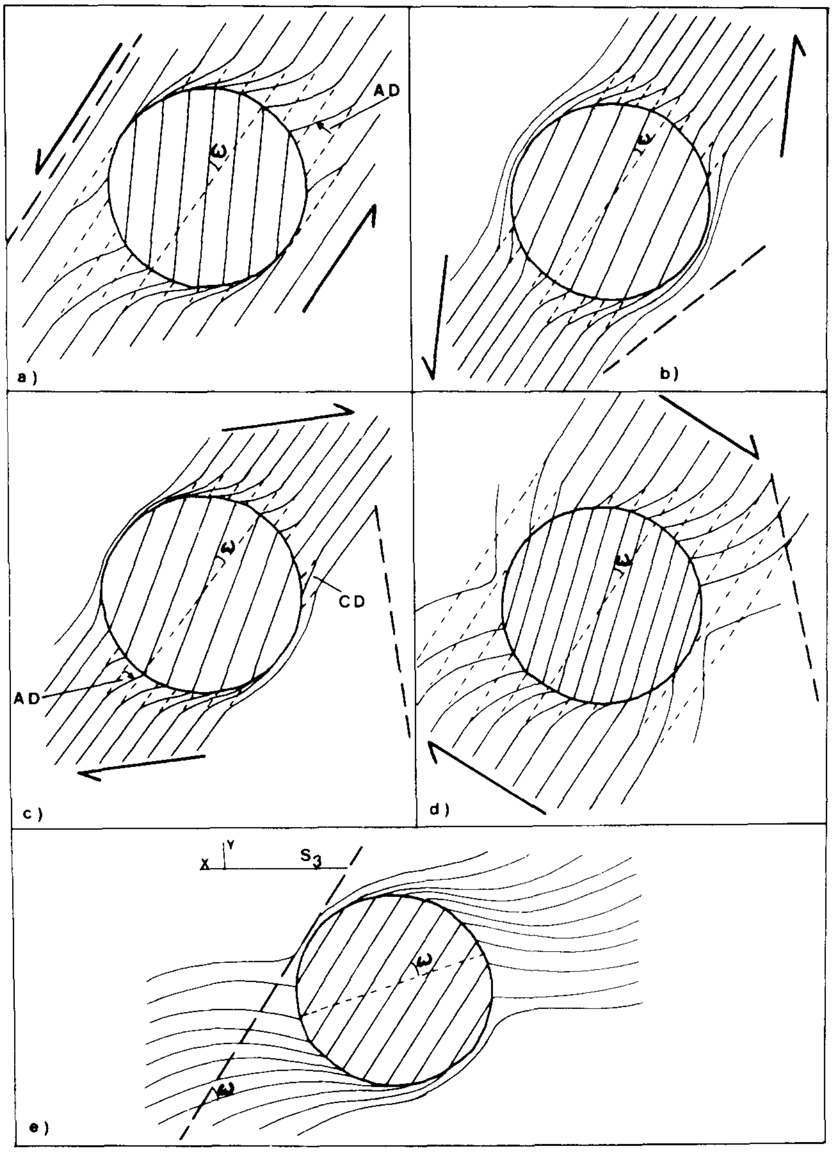

Fig. 13. Drag patterns of passive markers around a rigid spherical body (after Ghosh 1975). Marker lines initially (a) parallel, (b) at 45°, (c) at 90° and (d) at 135° to shear direction during simple shear ($\gamma = 1$). In (e) the marker lines were initially at 30° to the axis of compression during pure shear ($\lambda_y^{1/2} = 0.5$). AD, anticlockwise drag; CD, clockwise drag; ω, angle of apparent rotation. Initial orientation of marker lines indicated by heavy dashed line.

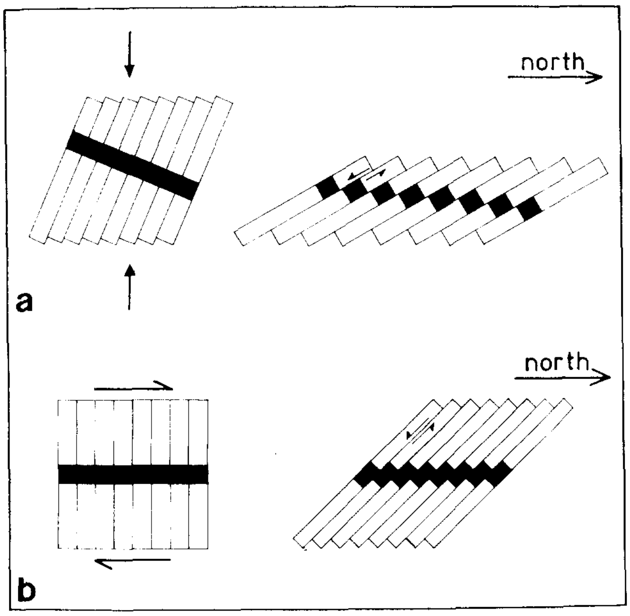

Fig. 14. (a) Southerly slip on S_2 planes produced by pure shear. (b) Southerly slip on S_2 produced by northerly directed bulk simple shear.

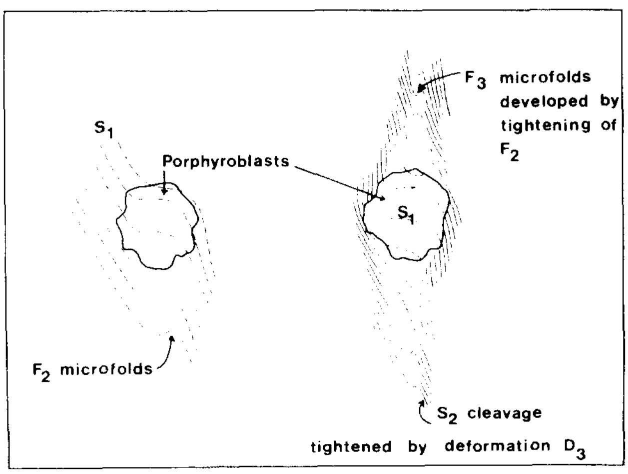

Fig. 15. Development of a composite $S_{2/3}$ cleavage in north Donegal (after Pitcher & Berger 1972, fig. 3.8).

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