Kinematic and tectonic significance of microstructures and crystallographic fabrics within quartz mylonites from the Assynt and Eriboll regions of the Moine thrust zone, NW Scotland

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Kinematic and tectonic significance of microstructures and crystallographic fabrics within quartz mylonites from the Assynt and Eriboll regions of the Moine thrust zone, NW Scotland

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ABSTRACT: Using a combination of optical microscopy and X-ray texture goniometry, an integrated microstructural and crystallographic fabric study has been made of quartz mylonites from thrust sheets located beneath, but immediately adjacent to, the Moine thrust in the Assynt and Eriboll regions of NW Scotland. A correlation is established between shape fabric symmetry and pattern of crystallographic preferred orientation, a particularly clear relationship being observed between shape fabric variation and quartz ***a***-axis fabrics.

Coaxial strain paths dominate the internal parts of the thrust sheets and are indicated by quartz ***c***- and ***a***-axis fabrics which are symmetrical with respect to foliation and lineation. Non-coaxial strain paths are indicated within the more intensely deformed quartzites located near the boundaries of the sheets by asymmetrical ***c***- and ***a***-axis fabrics. These kinematic interpretations are supported by microstructural studies. At the Stack of Glencoul in the northern part of the Assynt region, the transition zone between these kinematic (strain path) domains is located at approximately 20 cm beneath the Moine thrust and is marked by a progression from symmetrical cross-girdle ***c***-axis fabrics (30 cm beneath the thrust), through asymmetrical cross-girdle ***c***-axis fabrics to asymmetrical single girdle ***c***-axis fabrics (0·5 cm beneath the thrust).

Tectonic models (incorporating processes such as extensional flow, gravity spreading and tectonic loading) which may account for the presence of strain path domains within the thrust sheets are considered, and their compatibility with local thrust sheet geometries assessed.

KEY WORDS: extensional flow, foliation, gravity spreading, lineation, shear bands, strain path, texture goniometry, vorticity.

In recent years a considerable effort has been made to develop techniques for the quantitative analysis of the amount, mechanisms and distribution of finite strain within geological structures (e.g. Ramsay 1967, Ramsay & Huber 1983). Microstructures and crystallographic fabrics of naturally deformed rocks have proved particularly useful in assessing the kinematics of deformation events (Lister & Williams 1979, 1983; Schmid 1982; Bouchez *et al.* 1983; Simpson & Schmid 1983). The integration of such small-scale studies into regional deformation studies has helped characterise the types of strain path involved and constrain both movement directions (e.g. Behrmann & Platt 1982) and tectonic models (e.g. Behrmann 1982; Law *et al.* 1984; Miller *et al.* 1985; Platt & Behrmann 1986). One of the first such integrated studies was reported by Christie (1956, 1960, 1963) in a series of classic papers describing the microstructures and optically measured ***c***-axis fabrics of quartz mylonites from the Assynt region of the Moine thrust zone.

In this paper the mylonites from three localities in the Assynt region (Fig. 1) are re-examined in the light of recent advances in the understanding of the processes of microstructural and crystallographic fabric development. Previously unpublished fabric data from mylonites occupying a similar structural position beneath the Moine thrust in the Eriboll region of the thrust zone (Fig. 1) will also be briefly described. The aims of this study are:

1. To establish the strain paths (deformation histories) indicated by microstructures and ***c***-axis fabrics within quartz mylonites adjacent to the Moine thrust in the Assynt region.
2. To compare the suggested deformation histories (kinematics) of the northern Moine thrust zone mylonites at Eriboll (Law *et al.* 1984) with those at Assynt, some 30–50 km further S.
3. To assess the additional kinematic information on the fabric evolution which is contained in the preferred orientation of quartz ***a***-axes within these mylonites.

The data described in this paper were first presented in poster form at the Tectonic Studies Group 14th Annual General Meeting held at Glasgow University on 18–21 December 1983.

1. Moine thrust zone

Along the Moine thrust zone intensely deformed late Proterozoic sediments (Moine assemblage) were thrust, during the Caledonian orogeny, over a foreland sequence consisting of the Lewisian complex (mainly late Archaean gneisses) overlain by late Proterozoic Torridonian sandstones and Cambro–Ordovician shelf sediments (for stratigraphic details see McClay & Coward 1981).

The Moine thrust zone consists of a series of thrusts (Peach *et al.* 1907) of which the Moine thrust (*sensu stricto*) is considered to be the oldest (Elliott & Johnson 1980). The Moine thrust is structurally the highest thrust and crops out furthest to the E (Fig. 1). The lower and successively younger thrusts crop out successively westward each carrying a sheet of rocks which is named after the thrust on which it moved. The general transport direction is to the WNW subparallel to the trend of the elongation direction in the more highly deformed rocks. Along the length of the thrust zone, a considerable variation in local thrust sheet geometry is observed (Peach *et al.* 1907). A series of balanced cross-sections illustrating this variation in structural geometry within the northern part of the Moine thrust zone is presented by Elliott and Johnson (1980) and Butler (1984a, b).

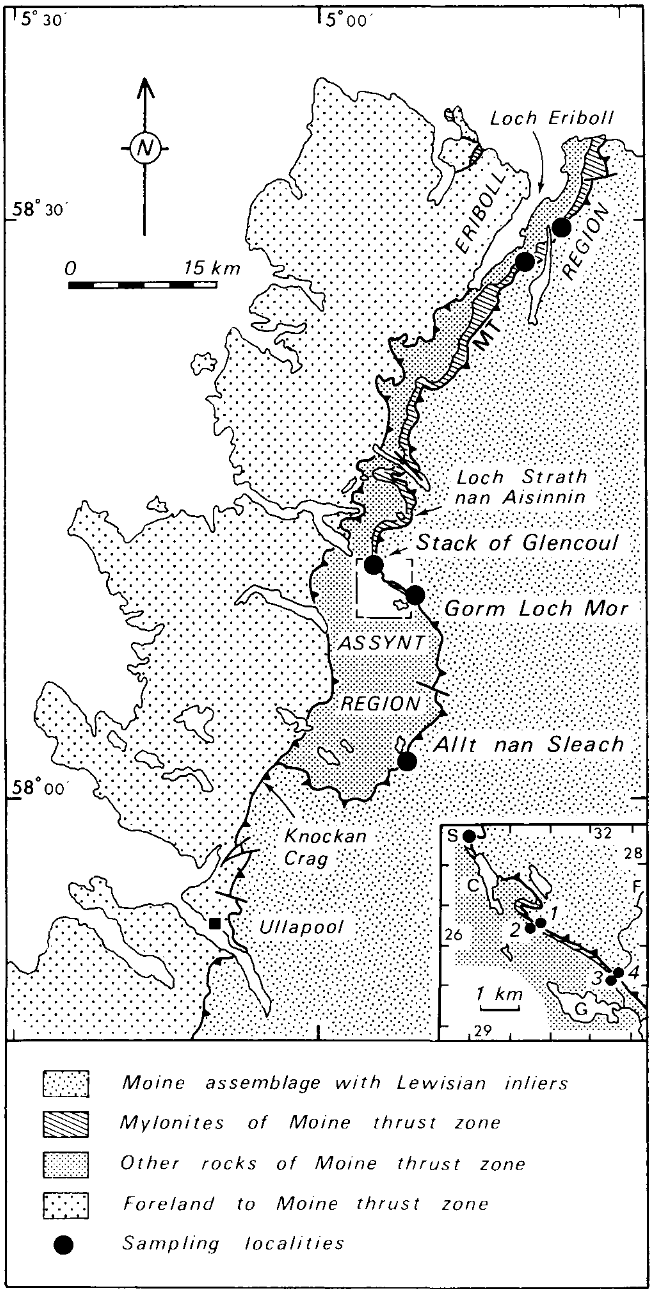

Figure 1 Simplified geological map of the northern part of the Moine thrust zone, NW Scotland, showing locations of the main sampling localities; MT Moine thrust. Inset: detailed map of the Gorm Loch Mor area showing position of sampling localities (specimens GM1–GM4) in relation to Gorm Loch Mor (G), the Fionn Allt stream (F), Loch nan Caorach (C) and the Stack of Glencoul (S); National Grid coordinates indicated.

Deformation styles and intensities vary across the Moine thrust from sharp fault breaks associated with lower thrusts in the W, to thick mylonite zones in the E. These mylonites lie immediately beneath the Moine outcrop (Fig. 1) and are locally derived from most members of the foreland succession including the Lewisian complex, Torridonian sandstone and the Cambro–Ordovician sediments (Peach *et al.* 1907). The quartz mylonites described in this paper are principally derived from the Basal Quartzite and overlying Pipe Rock of the Cambrian succession. Formation of these mylonites is associated with greenschist facies metamorphism in both the Assynt (Christie 1963; Johnson *et al.* 1985) and Eriboll (Soper & Barber 1982) regions.

2. Techniques of quartz petrofabric analysis

Petrofabric analysis of quartz ***c***-axis preferred orientation was carried out on one thin section from each specimen collected using an optical microscope and universal stage, a minimum of 600 ***c***-axes being measured in each thin section. The ***c***-axis data are displayed on equal area, lower hemisphere stereographic projections whose plane of projection contains the specimen lineation and pole to foliation; in all these stereographic projections the foliation is vertical and lineation within the foliation horizontal. In geographical terms all these stereograms are viewed towards the NNE, the lineation being represented as a horizontal structure; ***c***-axis plots were contoured using a modified version of the computer program developed by Starkey (1970).

Pole figures for first and second order prisms (*m* & *a*) and combined rhombs (*r* & *z*) were measured at ETH, Zurich with an automatic X-ray texture goniometer (Seiffert Scintag) operating in combined reflection and transmission modes (Siddans 1976). Pole figures obtained using X-ray texture goniometry are displayed using the same orientation convention as that previously described for the optically derived ***c***-axis fabrics.

Quartz ***c***-axes cannot be measured directly with the X-ray texture goniometer, but must be calculated, through the Orientation Distribution Function (ODF), from other pole figures obtained by X-ray texture goniometry (Schmid *et al.* 1981). The calculated ***c***-axis fabrics of representative specimens are included in this paper and are compared with their optically derived ***c***-axis fabrics.

It should be noted that for the optically determined ***c***-axis fabrics, intensities are proportional to the number of quartz grains measured. In contrast, for pole figures obtained by X-ray texture goniometry, the recorded intensities, corrected for defocusing and background, will be proportional to the volume fraction of minerals which diffract into the counter at any particular setting of the Eularian cradle. No information related to individual grains can be obtained by X-ray texture goniometry.

3. Mylonites from the Stack of Glencoul, Assynt

A suite of specimens has been collected from the mylonitic quartzites which lie beneath similarly deformed Moine rocks within the northwestern crags of the Stack of Glencoul (Figs 2, 3a) in northern Assynt (Fig. 1). These $S > L$ and $L - S$ tectonites, which were first described by Callaway (1884), are considered to be derived from Cambrian quartzites and contain at one horizon (Fig. 2, specimen SG8) intensely deformed Cambrian Pipe Rock (Fig. 3c). In addition, specimens of less highly deformed Cambrian quartzite (specimens SG14, 15) were collected from outcrops located immediately beneath the sampled crags of quartz mylonite.

The tectonic junction taken to represent the Moine thrust (*sensu stricto*) at the Stack of Glencoul has been the subject of some controversy. The foliation parallel ductile contact (Fig. 3a, b) between the mylonitic Cambrian quartzite and similarly deformed overlying Moine metasediments (and ?Lewisian rocks) has been regarded by C. T. Clough (in Peach *et al.* 1907, p. 503), Christie (1956; 1963, p. 363; 1965), Weathers *et al.* (1979) and Coward (1983) as marking the position of the Moine thrust. However, Johnson (1965) considered the Moine thrust (*sensu stricto*) to be a late brittle feature, thus creating the necessity to place the thrust at the base of the mylonitic Cambrian quartzites (Johnson 1967) in the unexposed ground between these strongly developed tectonites and the underlying, relatively weakly deformed, Cambrian quartzites (Johnson, in Macgregor & Phemister 1972, p. 63). This structural position has been followed by McLeish (1971), Wilkinson *et al.* (1975) and Elliott and Johnson (1980). In the present paper the former (and historically earlier) definition of the Moine thrust at the Stack of Glencoul will be adopted (Fig. 2).

Beneath the Moine thrust at the Stack of Glencoul green phyllosilicate-rich horizons have been observed within the quartz mylonites (Figs 2 & 3d). These phyllosilicate horizons, which are aligned parallel to the mylonitic foliation in the surrounding quartzites, range in thickness from 1 to 75 cm and, in general, become thinner and more numerous as the Moine thrust is approached. Shear bands (extensional crenulation cleavage of Platt & Vissers 1980) dipping towards the WNW (specimen SG5, Fig. 2) are concentrated within these horizons. Three possible interpretations of these phyllosilicate rich horizons may be suggested:

1. They may reflect original sedimentary layering within the quartzites, but such lithological variations are not observed within the undeformed Cambrian quartzites of the foreland.
2. They may be highly deformed sills. In thin section (specimens SG2, 5) they are seen to contain equant grains of sericitised plagioclase feldspar with phyllosilicate beards aligned parallel to the foliation: similar microstructures have been recorded within deformed sills located close to the Moine thrust in southern Assynt (Section 5), but are not observed within the Moine rocks immediately overlying the Moine thrust at the Stack of Glencoul.
3. These phyllosilicate horizons which, as pointed out by Christie (1963, p. 362) are, at least in hand specimen, lithologically similar to the overlying Moine rocks, may indicate that the Moine thrust has been breached in this area, resulting in the local interleaving of Moine rocks and mylonitic Cambrian quartzite. Along the upper surface of one of these thin (20 cm) horizons the overlying quartzite (specimen SG12, Fig. 2) is brecciated. No such brittle deformation, however, appears to be associated with any of the other quartzite:phyllosilicate horizon contacts.

3.1. Mylonites more than 40 m beneath Moine thrust

The least deformed specimen (SG15) of Cambrian quartzite was collected from approximately 70 m beneath the thrust. In *XZ* thin sections individual detrital quartz grains (Fig. 4a) are slightly flattened (average aspect ratio 2:1) and display

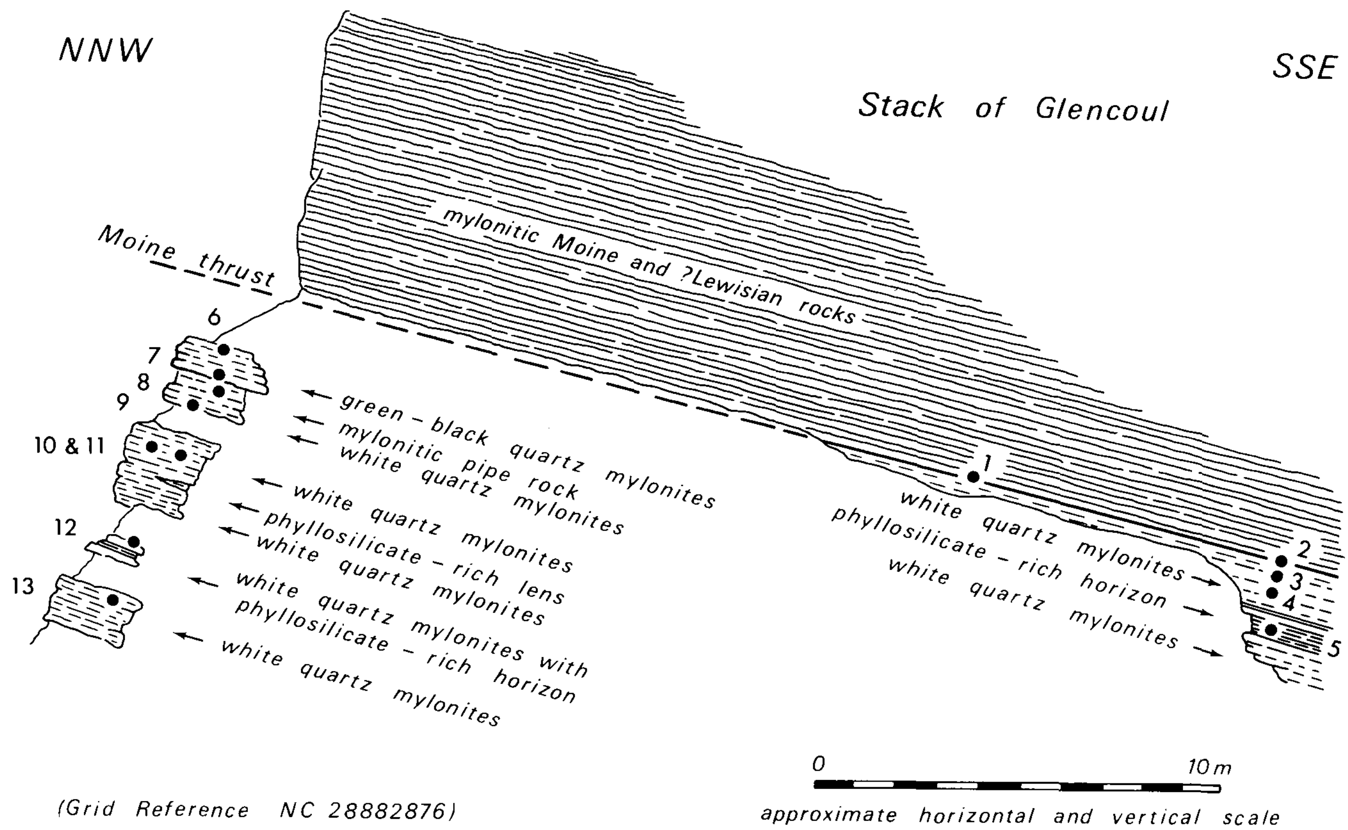

Figure 2 Diagrammatic illustration of sampling locations (specimens SG1–SG13) within mylonitic Cambrian quartzites exposed in the NW crags of the Stack of Glencoul.

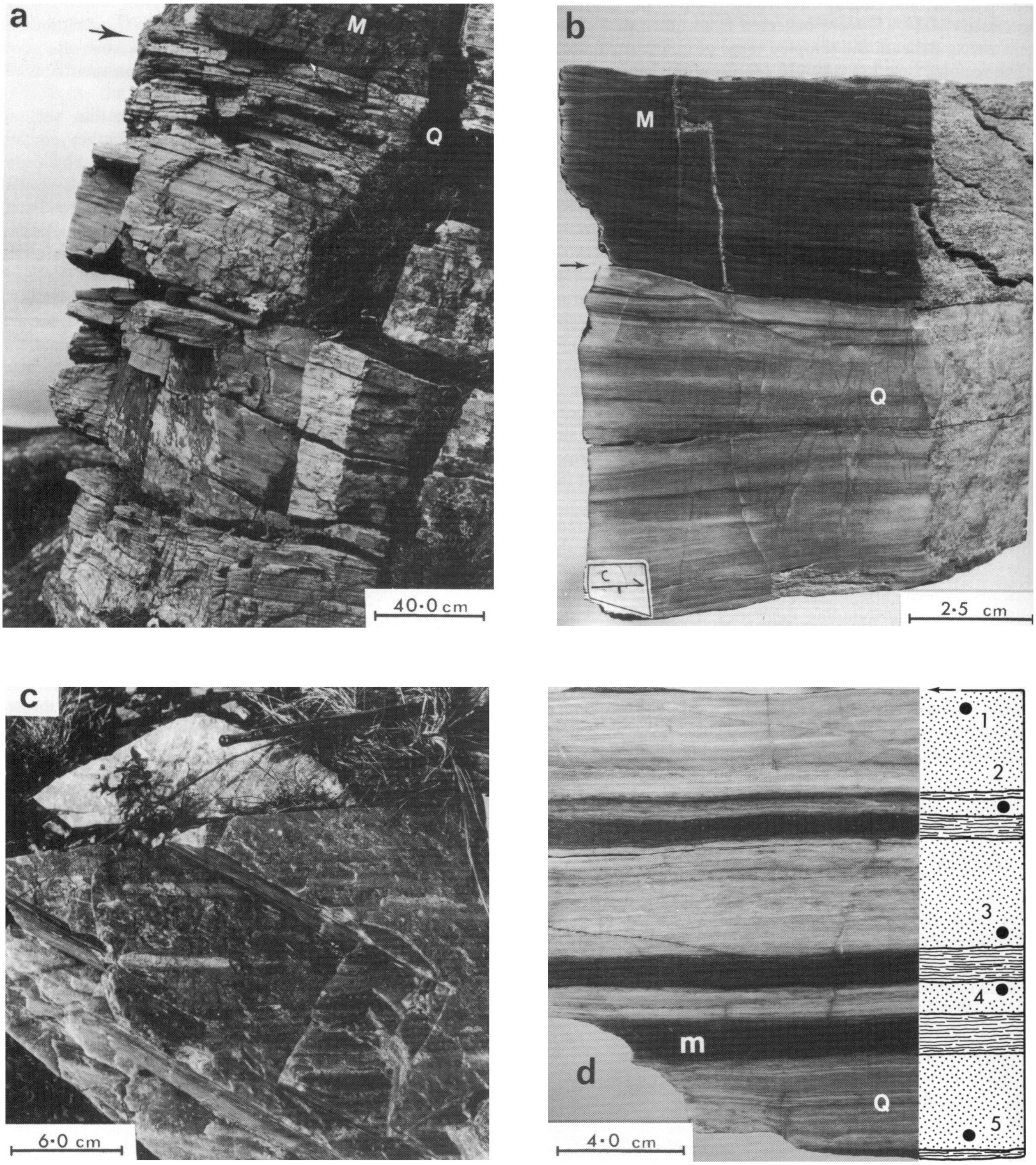

Figure 3 Mylonitic Cambrian quartzites and phyllosilicate-rich Moine rocks at the Stack of Glencoul; all exposures viewed towards the NNE.

(a) Mylonitic Cambrian quartzite (Q) underlying similarly deformed Moine rocks (M); arrow marks position of the Moine thrust; specimen SG2 was collected immediately to the left of quartzite labelled Q.

(b) Contact between Moine rocks (M) and mylonitic Cambrian quartzite (Q) marking position of the Moine thrust (arrowed); polished surface cut perpendicular to foliation and parallel to lineation; note ESE dipping listric extensional fault which off-sets mylonitic foliation in the quartzites (specimen SG1).

(c) Mylonitic Cambrian Pipe rock showing highly elongate pipes (light coloured) aligned on foliation planes (specimen SG8).

(d) Alternating layers of mylonitic Cambrian quartzite (Q) and green phyllosilicate rich horizons (m); polished surface cut perpendicular to foliation and parallel to mineral elongation lineation; upper surface (arrowed) marks position of Moine thrust; positions of the five individual regions of this specimen (SG2) selected for petrofabric analysis are indicated.

undulose extinction, deformation bands and sub-basal deformation lamellae. Recrystallisation of quartz is of a very minor nature, being confined to a few deformation band boundaries and detrital grain margins. The detrital quartz grains have a more flattened appearance (Fig. 4b) at 40 m beneath the thrust (specimen SG14) with typical aspect ratios of 4:1. Recrystallisation of quartz is slightly more pronounced in this structural position, accounting for up to 10% of the total rock volume.

Both these weakly foliated and lineated quartzites display (1) diffuse cross-girdle ***c***-axis fabrics which are approximately symmetrical with respect to foliation and lineation (Fig. 5), and (2) globular detrital quartz grains whose ***c***-axes are aligned subparallel to the foliation pole (Fig. 4a) and around which more flattened grains anastomose.

3.2. Mylonites 9·6–0·3 m beneath Moine thrust

Due to lack of exposure on the northwestern side of the Stack of Glencoul a sampling gap exists between the relatively weakly deformed quartzites such as specimen SG14 and the intensely deformed quartzites (Fig. 2) located at less than 9·6 m beneath the Moine thrust. Within these strongly developed $S > L$ and $L - S$ tectonites, mylonitic foliation dips at approximately 20° to the ESE, the grain shape lineation lying within the foliation plunging down dip towards the ESE.

Mylonitic foliation is defined in thin section by a preferred alignment of flattened relict detrital quartz grains. In XZ sections these flattened grains display variable aspect ratios both within individual thin sections (Fig. 4c), and from one specimen to another. No convincing systematic increase in degree of quartz grain flattening, when traced towards the Moine thrust, has been detected within those quartz mylonites collected at between 9·6 m and 0·3 m beneath the thrust. Ribbon-like quartz grains are observed in all these specimens, typically displaying aspect ratios of between 50:1 and 100:1, with long dimensions commonly measuring 2–3 mm in XZ sections. Other quartz grains display less extreme aspect ratios (Fig. 4d, e). Globular quartz grains whose ***c***-axes are aligned at a low angle to the foliation pole (Fig. 5) and around which more flattened grains may anastomose, have been observed (Fig. 4d, e, f) within all these mylonites (cf. Riekels & Baker 1977, p. 12). In some cases these globular grains appear to be original detrital grains, while in other cases it would seem that they are the product of recrystallisation and grain boundary migration within elongate quartz grains of different original crystallographic orientation.

The volume fraction of quartz recrystallisation within these mylonites varies from 40%–75%. The recrystallised grain size appears to remain fairly constant at approximately 10 μm–15 μm within these specimens. No systematic increase in degree of recrystallisation with distance beneath the Moine thrust has been detected.

Mylonites collected at distances of between 9·6 m and 0·3 m beneath the Moine thrust (Fig. 2) are characterised by cross-girdle quartz ***c***-axis fabrics which are symmetrical (in terms of both skeletal outline and intensity distribution) with respect to foliation and lineation (Figs 5, 6, 7). These Type I (Lister 1977) cross-girdle fabrics, which have been measured on relict deformed detrital grains, consist of an elliptical girdle symmetrically disposed about the inferred Z direction (opening angle 25°–35° in XZ, approximately 30°–35° in YZ) and connected through Y. A high degree of ***c***-axis preferred orientation is detected within all of these $S > L$ and $L - S$ tectonites. Corresponding quartz ***a***-axis fabrics from these tectonites are characterised by two maxima aligned within the inferred XZ plane and equally inclined at 20° to the lineation (Fig. 6). These maxima may either be of equal intensity (specimens SG6, 7, 8) or unequal intensity (specimens SG10, 11, 13). The ***a***-axis maxima are connected by a broad, weakly populated band of ***a***-axes which define a small-circle girdle distribution of large opening angle centred about the pole to mylonitic foliation (Z).

3.3. Mylonites less than 0·15 m beneath Moine thrust

At distances of less than 0·15 m beneath the Moine thrust, quartz recrystallisation is more advanced (60%–100%) than at greater distances beneath the thrust, with relict grains only locally being preserved in specimen SG2. At the contact (Fig. 3d) between the mylonitic quartzites and the overlying Moine rocks (specimen SG1) the quartzite is totally recrystallised to an approximately 10 μm grain size. Mylonitic foliation within the quartzite is defined, in XZ thin sections, by a preferred alignment of highly elongate domains of recrystallised quartz grains of similar crystallographic orientation (Fig. 4g). These domains, which commonly display aspect ratios of 80:1 and long dimensions of up to 5 mm, are thought to be relict deformed detrital grains. The foliation, as seen in thin section, appears to be parallel (±2°) to both the quartzite—Moine contact (i.e. the Moine thrust) and the foliation in the overlying phyllosilicate-rich Moine rocks. At this locality the Moine thrust dips at 20° towards 110°, the grain shape lineation within the foliation plunging at 18° towards 118° in both the quartzite and Moine rocks.

In specimens SG1 and SG2, elongate dynamically recrystallised quartz grains display, in XZ thin sections, a preferred alignment (S_B) which is oblique to the mylonitic foliation (S_A); in all cases S_B dips more steeply to the ESE than S_A (Fig. 4h). Tectonites containing such microstructures have been classified by Lister and Snoke (1984) as Type II $S - C$ mylonites. These microstructures have not been observed within the less intensely deformed and recrystallised quartzites located at greater distances beneath the thrust.

Within the quartzite layers of specimen SG2 (Fig. 3d), quartz ***c***-axes from specimen areas located at distances of between 14·5 cm and 1·0 cm beneath the Moine thrust define cross-girdle fabrics which are asymmetrical (both in terms of skeletal outline and intensity distribution) with respect to mylonitic foliation (S_A) and lineation (Figs 5, 7). At 0·5 cm beneath the thrust, quartz ***c***-axes from the totally recrystallised Cambrian quartzite of specimen SG1 define an approximate single girdle distribution (Figs 5, 7) which contains the inferred Y-axis of the finite strain ellipsoid and is oblique to mylonitic foliation (S_A) and lineation. The corresponding quartz ***a***-axis fabric from this specimen consists of a single ***a***-axis maximum oriented within the inferred XZ plane and inclined at 25° to the lineation (Fig. 6). This ***a***-axis point maximum occupies the pole position to the single girdle of ***c***-axes detected by optical microscopy.

Using the criteria reviewed by Simpson and Schmid (1983), both microstructures and crystallographic fabrics within specimens SG1 and SG2 are consistent with non-coaxial deformation associated with WNW directed overthrusting (sinistral shear sense in all figures).

Within specimen SG1, however, the contact between Moine rocks and underlying quartz mylonites is displaced, with dextral shear sense, along a small ESE dipping listric extensional fault (Fig. 3b). In thin section, this structure is marked by a zone of intense quartz recrystallisation (grain size less than 5 μm) which overprints and displaces both the

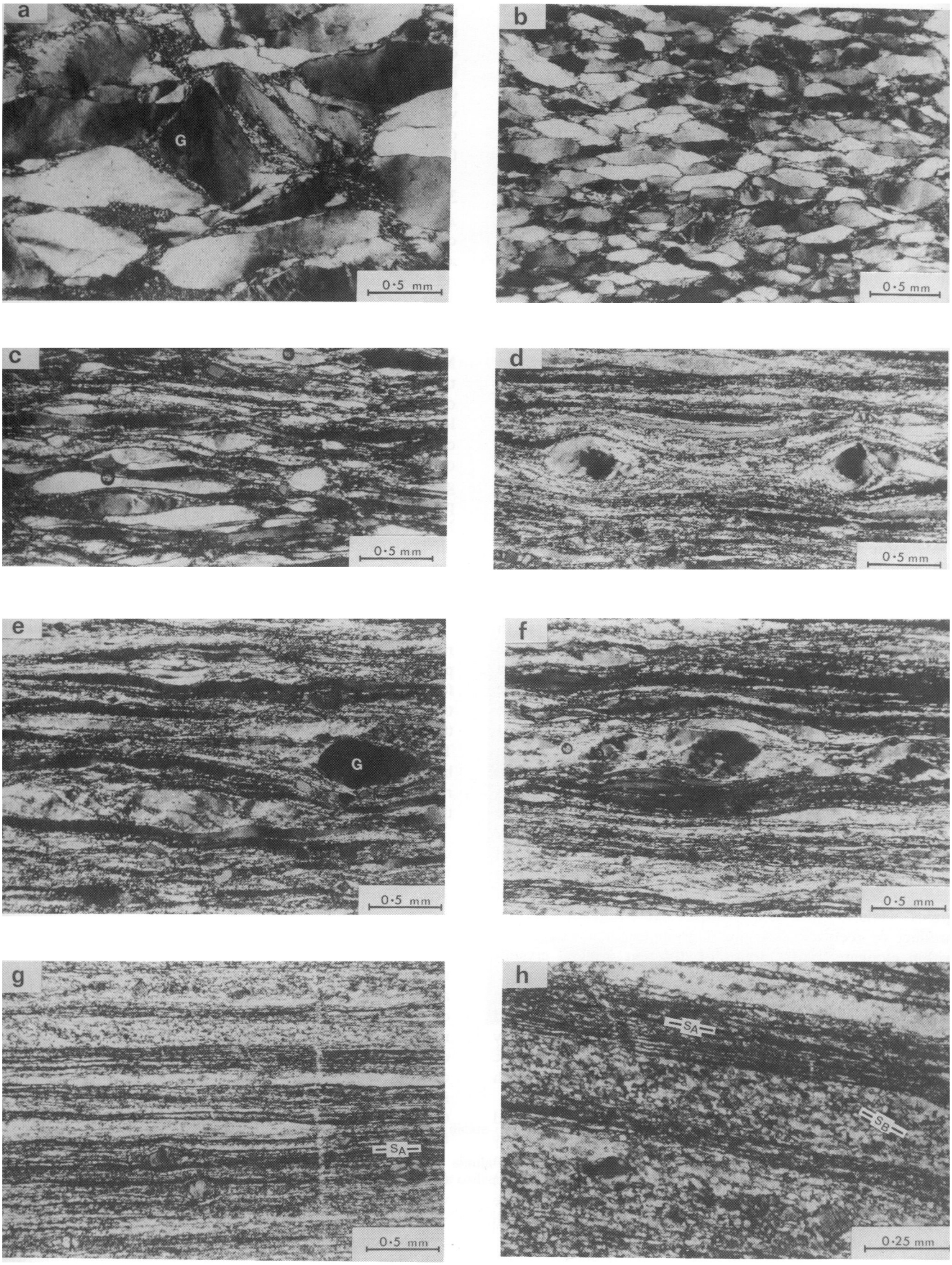

Figure 4 Photomicrographs (viewed towards the NNE) of mylonitic Cambrian quartzites at the Stack of Glencoul; thin sections cut perpendicular to mylonitic foliation and parallel to lineation.

(a) Weakly deformed quartzite; note quartz augen (G) with deformation bands (specimen SG15).

(b) Moderately deformed quartzite; foliation defined by preferred alignment of flattened detrital quartz grains (specimen SG14).

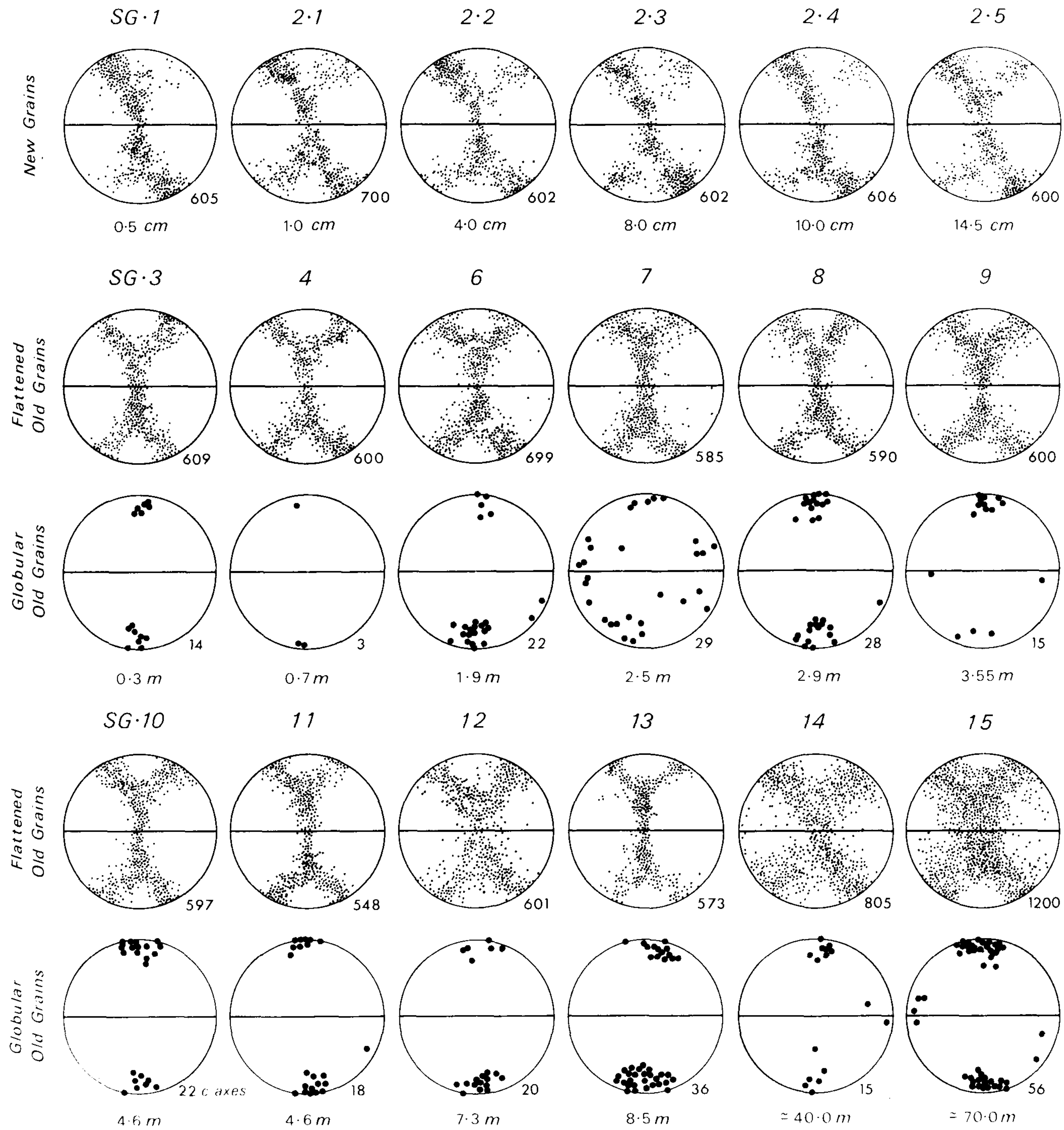

Figure 5 Quartz *c*-axis fabrics (viewed towards the NNE) from mylonitic Cambrian quartzites at the Stack of Glencoul; distance of individual specimens beneath the Moine thrust indicated; see Figure 2 for specimen locations and Figure 6 for details of orientation convention.

(c) Variably flattened relict detrital quartz grains (specimen SG7).
(d) Highly deformed quartzite; note ribbon grains and large globular quartz grains (specimen SG13).
(e) Variable deformed quartz grain morphology; widespread development of ribbon grains and recrystallisation at ribbon grain margins; globular quartz grains (G) also present (specimen SG10).
(f) New (syntectonic) globular quartz grains within an elongate relict quartz grain of different crystallographic orientation (specimen SG4).
(g) Highly elongate relict quartz grains defined by domains of recrystallised quartz grains of similar crystallographic orientation; the preferred alignment of these domains defines the mylonitic foliation (S_A) observed in hand specimen (specimen SG1).
(h) Preferred alignment (S_B) of elongate, dynamically recrystallised quartz grains which dips more steeply to the ESE than mylonitic foliation (S_A); sinistral shear is indicated by petrofabric analysis of this specimen (SG1).

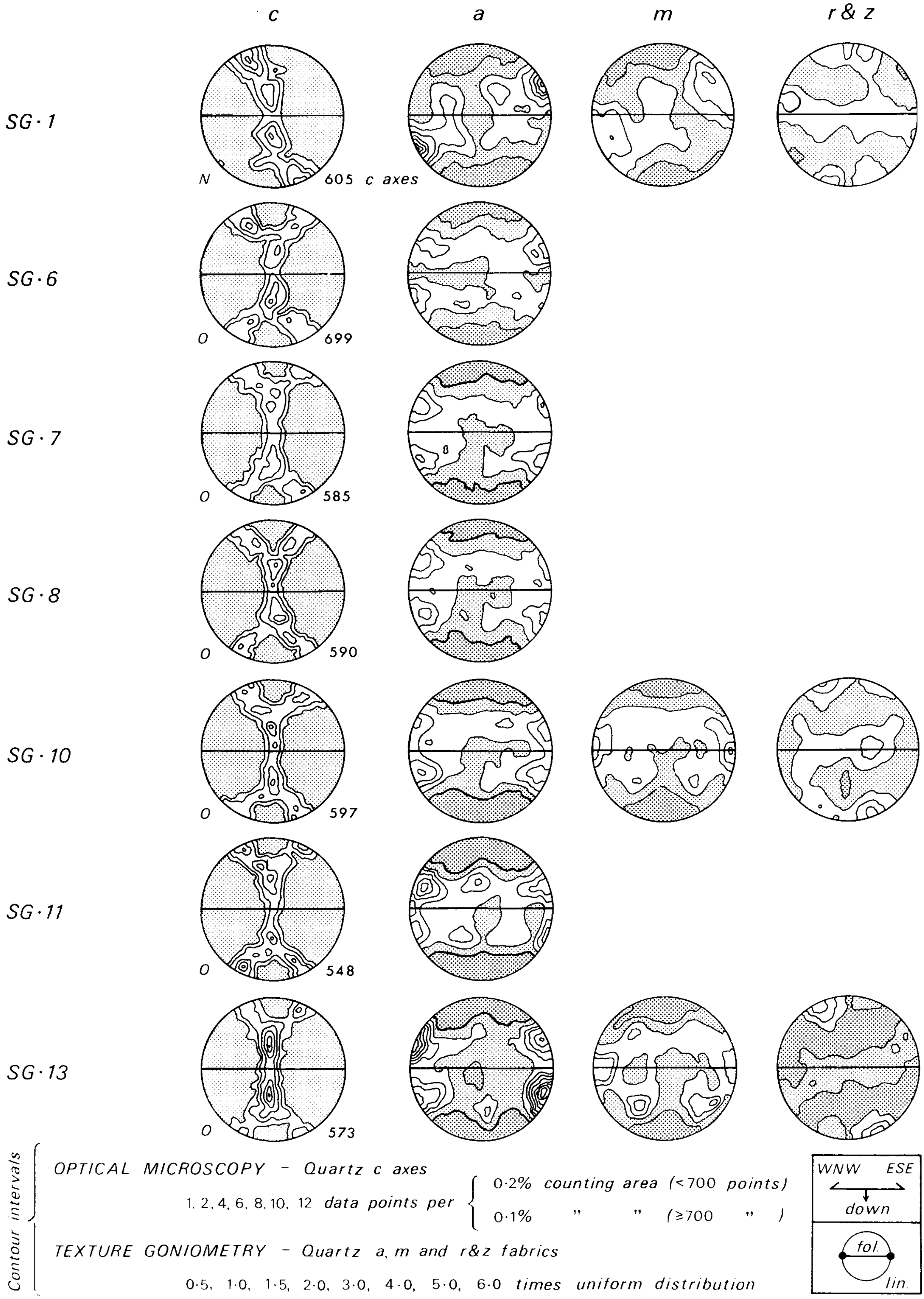

Figure 6 Comparison of quartz fabrics obtained by optical and X-ray texture goniometry methods within quartz mylonites from the Stack of Glencoul; optical microscopy–*c*-axis free areas stippled, O old grains, N new (recrystallised) grains; X-ray texture goniometry–less than 0·5 and 0·5–1·0 times uniform density, heavy and light stipple respectively; all lower hemisphere equal area projections viewed towards the NNE.

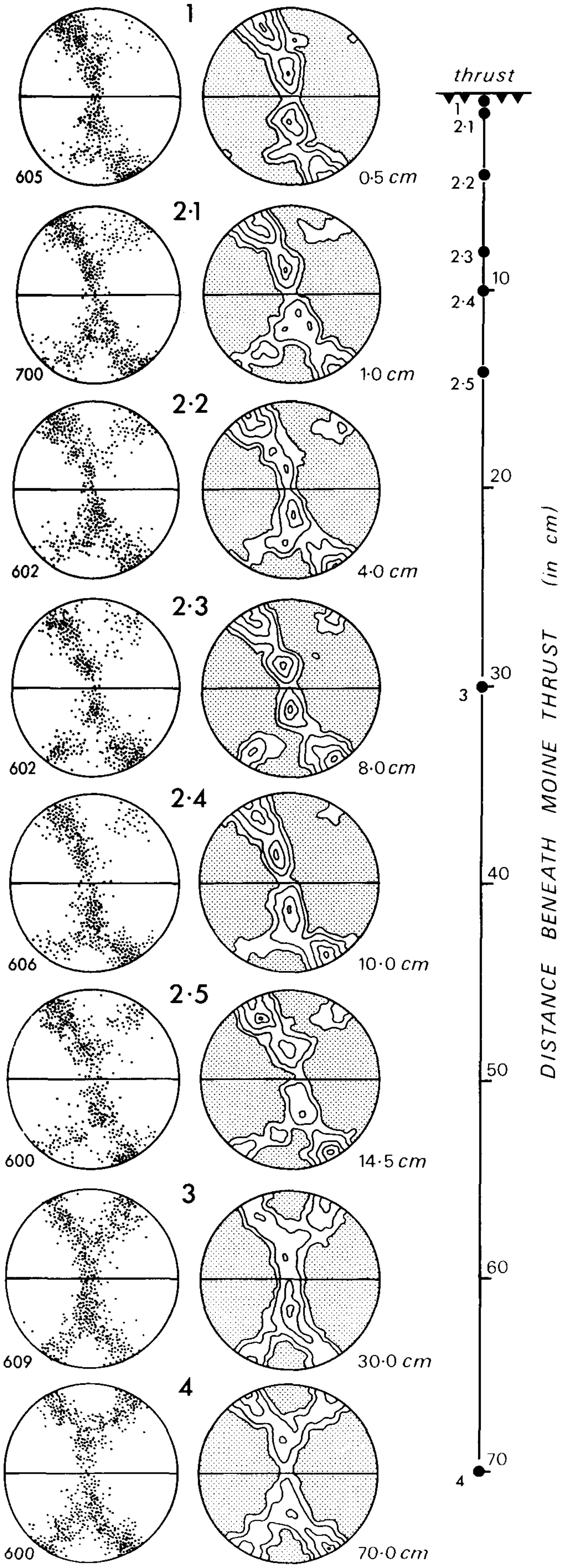

Figure 7 Transition in quartz **c**-axis fabrics (viewed towards the NNE) from single girdle fabrics (specimen SG1), through asymmetrical cross-girdle fabrics (the five areas measured in specimen SG2) to symmetrical cross-girdle fabrics (specimens SG3, SG4) with increasing distance beneath the Moine thrust at the Stack of Glencoul; see Figures 2 and 3d for specimen locations; explanation of contour intervals is given in Figure 6.

mylonitic foliation (S_A) and oblique grain shape alignment (S_B) within the surrounding quartzite. A dextral shear sense is indicated by quartz **c**-axis preferred orientation within this zone. The opposite shear sense, it will be recalled, is indicated by both microstructures (Fig. 4h) and crystallographic fabrics (Figs 5, 6, 7) within the quartzite to the left of this zone (Fig. 3b). This anomalous structure may be interpreted (S. Schmid, pers. comm. 1984) as indicating the superimposition of a localised flattening domain whose western boundary is marked by the listric extensional fault in Figure 3b.

3.4. Correlation with previous microstructural studies

A fairly constant recrystallised quartz grain size of approximately 10–15 μm is observed within these quartz mylonites located both at, and also beneath, the Moine thrust. Identical observations have been made at the Stack of Glencoul by Weathers *et al.* (1979), who also document a progressive increase in both finite strain magnitude and degree of recrystallisation within the quartz mylonites as the Moine thrust is approached from below. Although the results of the present paper are in broad agreement with these observations, no systematic increase in either degree of flattening of detrital quartz grains or degree of quartz recrystallisation has been observed within those mylonites situated at distances of between 9·6 m and 0·3 m beneath the thrust.

Weathers *et al.* (1979) further record a constant dislocation density within this sequence of mylonites, which, they suggest, may indicate that palaeo-stress is independent of distance from the Moine thrust. These authors suggest that the combined observations of increasing finite strain towards the thrust and constant inferred palaeo-stress, which is independent of distance beneath the thrust, must indicate that strain rates increased towards the thrust surfaces. They further suggest that this increase in strain rate towards the thrust surface may have been driven by strain or shear heating. Although a plausible explanation of these observations, it seems equally likely, however, to the authors of the present paper that the observations by Weathers *et al.* (1979) of increasing finite strain towards the Moine thrust may simply indicate that deformation has occurred over a longer time period near the thrust surface. Similarly, the significance of a constant dislocation density at the Stack of Glencoul is also open to question. In a recent study of quartz mylonites from the Assynt region (including the Stack of Glencoul), Ord and Christie (1984) have proposed that observed dislocation densities were produced during a late annealing recovery event which post dates the main penetrative deformation.

3.5. Correlation with previous crystallographic fabric studies

Cross-girdle quartz **c**-axis fabrics which are symmetrical with respect to foliation and lineation have previously been described from the Assynt region by Christie (1963, figs 22, 23). At the Stack of Glencoul, Christie (1956, 1963) has measured the **c**-axis preferred orientation of large relict quartz grains (Riekels & Baker 1977, p. 8) within three specimens (his specimens E23, 66, 62), all of which yield symmetrical cross-girdle fabrics. Unfortunately, as the exact locations of these specimens are not given, it is impossible to draw direct comparisons between the results of Christie's fabric studies and the results published in this paper. However, it is noted that Christie's specimen 62 is composed of highly deformed Cambrian Pipe Rock in which the pipes '. . . lie with perfect alignment on the plane of foliation . . .'

(Christie 1963, p. 400). This description fits exactly that of specimen SG8 (Fig. 3c) and it may well be that the two specimens have been taken from the same outcrop.

Previous X-ray texture goniometry work on the Stack of Glencoul quartz mylonites has been reported by Riekels and Baker (1977) and Baker and Riekels (1977). In these companion papers, Riekels and Baker attempted to make a complete textural analysis of quartz crystallographic preferred orientation within specimen 62 of Christie (1956, 1963) using the ODF obtained from X-ray pole figure data. For specimen 62, Riekels and Baker (1977, fig. 2) detected two ***a***-axis maxima of unequal intensity aligned within the inferred XZ plane, the dominant maximum plunging to the WNW and being inclined at a lower angle to the lineation (10° according to their figure) than the weakly populated maximum (20°). From study of the ODF for specimen 62, Riekels and Baker (1977, p. 8) have emphasised the difference between their asymmetrical ***c***-axis fabric, which was calculated from the ODF, and the symmetrical cross-girdle ***c***-axis fabric obtained by Christie (1956, 1963) from the same specimen using optical methods. They attribute this discrepancy to the difficulty of measuring ***c***-axes of very small quartz grains (which may form the asymmetrical element of a fabric pattern) with the optical microscope.

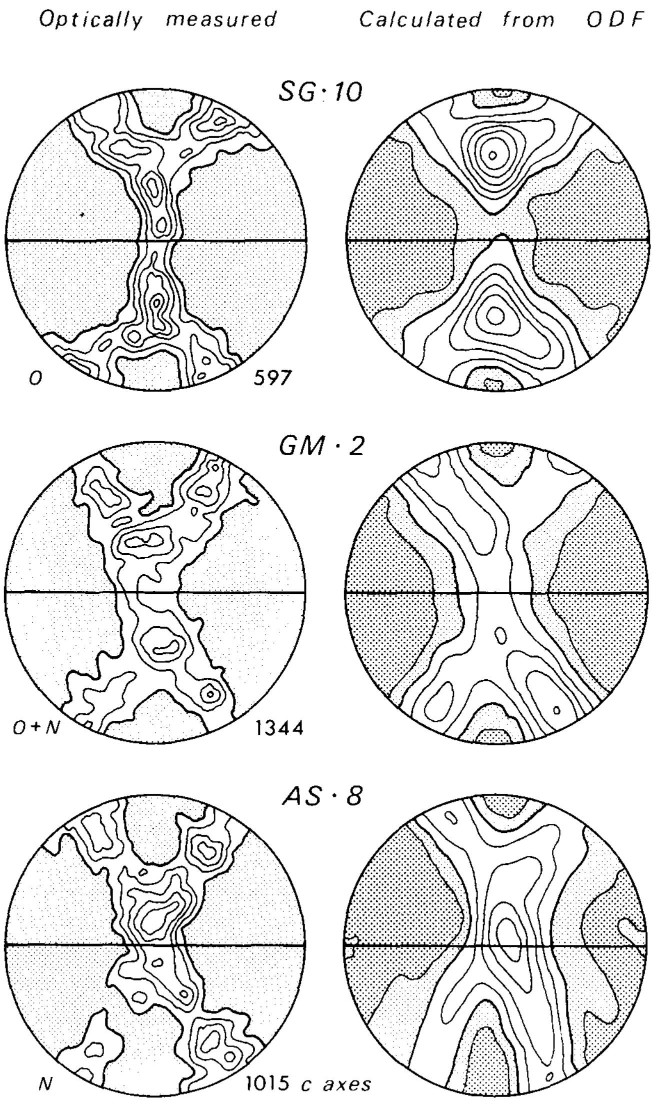

Figure 8 Comparison of optically measured and calculated quartz ***c***-axis fabrics of three specimens (SG10, GM2 and AS8) from the Stack of Glencoul, Gorm Loch Mor and Allt nan Sleach areas respectively. Contour intervals of optically measured fabrics—1, 2, 3, 4, 5 and 6 data points per counting area: contour intervals of calculated fabrics 0·5, 1·0, 2·0, 2·5, 3·0, 3·5 and 4·0 times uniform distribution; for further details see Figure 6. All lower hemisphere, equal area projections viewed towards the NNE.

Orientation Distribution Functions of selected quartz mylonites from the Stack of Glencoul and other areas within the Moine thrust zone are, at present, being calculated at ETH, Zurich, and will form the subject of a separate paper. Preliminary results indicate that there is no significant difference in skeletal symmetry between calculated and optically measured ***c***-axis fabrics, although some differences in density distribution are detected (Fig. 8). Specimen SG10 (approximately 50% quartz recrystallisation) from the Stack of Glencoul has yielded measured and calculated ***c***-axis fabrics which are almost perfectly symmetrical (both in terms of skeletal outline and intensity distribution) with respect to foliation and lineation (Fig. 8).

4. Mylonites from the Gorm Loch Mor area, Assynt

Within this region of variable exposure, located immediately to the S of the Stack of Glencoul (Fig. 1) mylonitic quartzites (and ?Torridonian) dip eastwards beneath similarly deformed Moine metasediments. The actual contact between the mylonitic Cambrian quartzites and Moine rocks (i.e. the Moine thrust) is only exposed due E of Loch nan Caorach (Christie 1963, p. 362) within this area, although its position can usually be placed to within several metres on the ground. Four specimens (all $L-S$ tectonites) will be described from this area; their locations are shown in Figure 1 and a summary of their microstructures and crystallographic fabrics is presented in Table 1.

Specimen GM1. This specimen of mylonitic Cambrian Pipe Rock was collected at a distance of approximately 20 m beneath the Moine thrust. The long axes of deformed pipes (originally worm burrows orientated perpendicular to bedding) in this specimen are almost perfectly aligned within the bedding parallel mylonitic foliation (S_A). Pinch and swell structures are occasionally displayed by the pipes on XZ sections of this $L-S$ tectonite. Exposed on the foliation planes (XY) the pipes display either highly elongate rectangular outlines or elliptical outlines (aspect ratios of 7:1) whose long axes are aligned parallel to the mineral elongation lineation (X). The elliptical outlines are caused by the intersection of foliation with those pipes which display pinch and swell structures. The pipes, which are composed of equant-elongate recrystallised quartz grains, are enclosed in a matrix of phyllosilicates (20% of total rock composition) and variably flattened detrital quartz grains whose preferred alignment defines the mylonitic foliation (S_A) seen in hand specimen (Fig. 9a). Quartz ***c***-axes from these flattened grains define a broad cross-girdle fabric, while the ***c***-axes of globular quartz grains are aligned either close to the lineation or pole to foliation (Fig. 10). The corresponding ***a***-axis fabric consists of two maxima aligned within the inferred XZ plane at 30° to the lineation, which are partially linked by a diffuse small-circle girdle of ***a***-axes centred about the lineation (Fig. 11).

Specimen GM2. This quartz mylonite was collected at approximately the same distance beneath the Moine thrust as specimen GM1. Within this specimen large (1–3 mm long) relict quartz grains are aligned parallel to the mylonitic foliation (S_A). These relict quartz grains are, in XZ sections, usually highly elongate (aspect ratios commonly 10:1) and may be interpreted as either extremely flattened large detrital grains or as deformed vein material. Locally within these elongate grains, syntectonic recrystallisation and grain boundary migration appear to have led to the formation of new grains which possess less extreme aspect ratios and different crystallographic orientations. Some of these syntectonic grains are globular in outline (Fig. 9b) and have their ***c***-axes aligned at low angles to the S_A foliation pole (Fig. 10). Typical microstructures observed outside the elongate relict quartz domains are shown in Figure 9c.

Diffuse cross-girdle ***c***-axis fabrics which are slightly asymmetrical (in terms of skeletal outline) with respect to foliation (S_A) and lineation are obtained from measurement of both relict (old) and recrystallised (new) quartz grains (Fig. 10). This pattern and sense of fabric asymmetry is also displayed in the more clearly defined ***c***-axis fabric calculated from the ODF for specimen GM2 (Fig. 8). The corresponding ***a***-axis fabric consists of two maxima, of unequal intensity, symmetrically inclined at 27° to the lineation within the inferred *XZ* plane, and connected by diffuse small-circle girdles of ***a***-axes which are centred about the foliation pole (*Z*) and lineation (Fig. 11).

Specimen GM3. This weakly-deformed Cambrian quartzite was collected from the E bank of the Fionn Allt at a distance of approximately 40 m beneath the Moine thrust (Fig. 1). The weakly-developed foliation is defined by a preferred alignment of variably flattened relict detrital quartz grains set in a matrix of recrystallised quartz (Fig. 9d, e). Recrystallised quartz grains are predominantly elongate (average aspect ratio 4:1); their long axes are typically aligned subparallel to the specimen foliation. Quartz ***c***-axes from the detrital grains define a cross-girdle fabric (Fig. 10) which appears to be symmetrical with respect to foliation and lineation; ***c***-axes from globular detrital quartz grains are either aligned close to the foliation pole, or at a larger angle to the lineation.

Specimen GM4. This grey-green, intensely foliated and lineated quartz mylonite was collected from the E bank of the Fionn Allt at a distance of 150 m to the N of specimen GM3 (Fig. 1). Lithologically the specimen is unlike any of the other mylonitic Cambrian quartzites encountered in this study and could possibly be of either Moine or Torridonian derivation. Christie (1963, fig. 4) has mapped the rocks at this locality as 'Primary Mylonitic Rocks' overlying the Moine thrust. The rock is a totally recrystallised quartzite (Fig. 9f) containing subordinate feldspar and phyllosilicates (20% of total rock composition) aligned parallel to the

Table 1 Locations, microstructural details and summaries of crystallographic fabrics for specimens collected from the Gorm Loch Mor area.

Specimen	GM·1	GM·2	GM·3	GM·4
Grid Ref.	NC 307265	NC 305264	NC 32652490	NC 32602510
Shape Fabric	L - S	L - S	L - S	L - S
Lithology	mylonitic Cambrian Pipe rock	mylonitic Cambrian Quartzite	yellow, weakly foliated and lineated, Cambrian Quartzite	quartz mylonite of either Moine or Torridonian derivation
Microstructure	globular - flattened relict quartz grains in phyllosilicate - rich matrix	globular - ribbon - like relict quartz grains in recryst. quartz matrix	globular - ribbon - like relict quartz grains in recryst. quartz matrix	recryst. quartz grains in phyllosilicate matrix
Foliations	S_A	S_A & S_B	S_A	S_A
Recrystallisation of quartz, degree and grain size	very little recryst. in matrix, within pipes 100% to 27 μm	approx. 75 - 80% recryst. to 22 μm grain size	approx. 60% recryst. to 20 - 40 μm grain size	100% recryst. to 32 μm grain size
c axis fabric	broad, symmetrical Type I (Lister 1977) cross-girdle	asymmetrical, Type I, cross-girdle	symmetrical, Type I, cross-girdle	symmetrical cross-girdle intermediate between Types I and II
a axis fabric	two maxima in XZ plane at 30° to lineation	two maxima in XZ plane at 27° to lineation		two maxima in approx. XZ plane at 30° to lin., third near fol. pole
Strike and dip of foliation	030°/ 20° E	040° / 10° E	150°/ 24° E	030°/ 30° E
Plunge of lineation	20° towards 120°	10° towards 130°	15° towards 100°	10° towards 085°

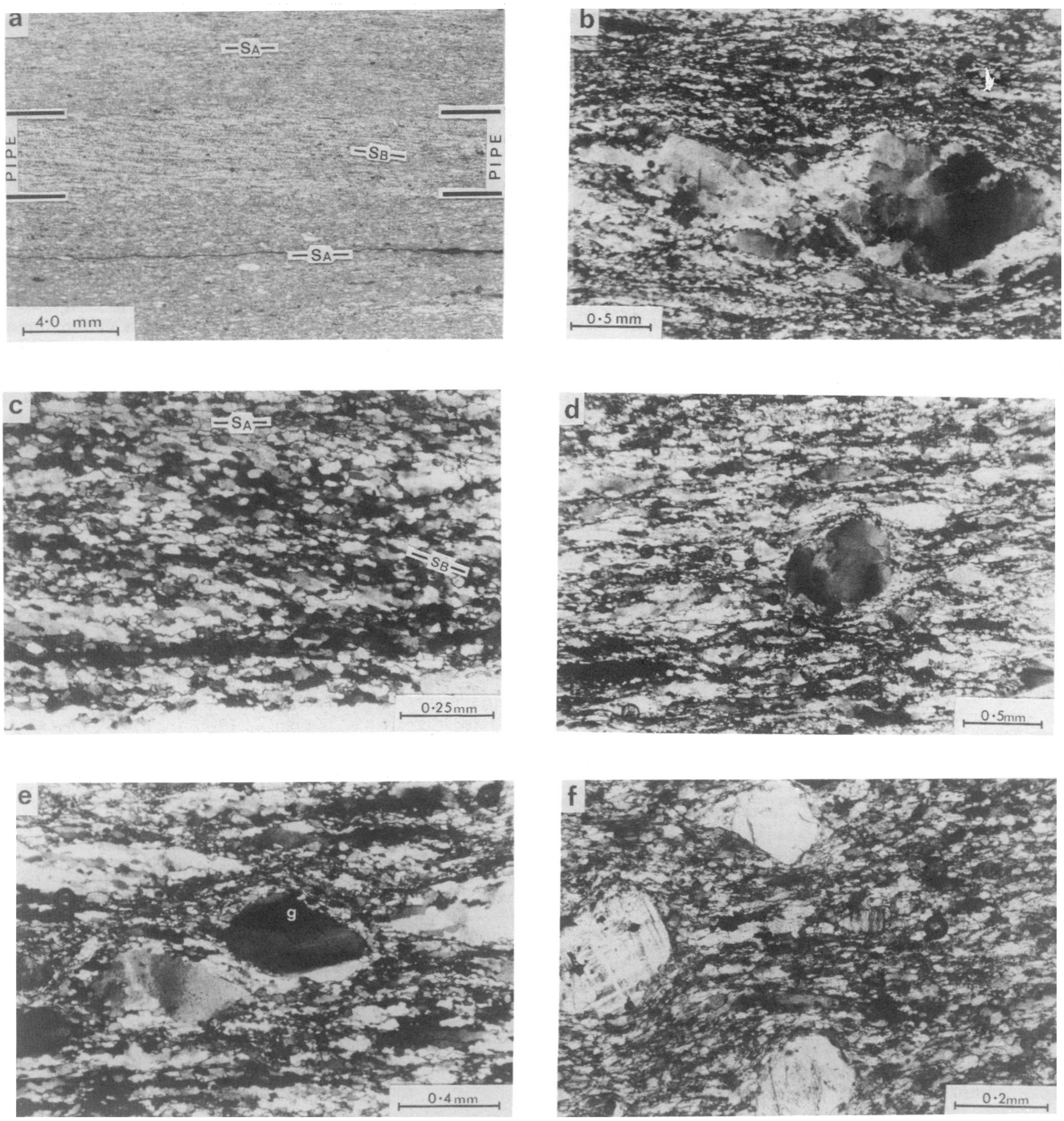

Figure 9 Photomicrographs (viewed towards the NNE) of mylonitic quartzites from the Gorm Loch Mor area; thin sections cut perpendicular to mylonitic foliation and parallel to lineation; see Figure 1 for specimen locations.

(a) Mylonitic Cambrian Pipe Rock (specimen GM1); elongate recrystallised quartz grains within pipe display a preferred alignment (S_B) which dips 10° more steeply to the ESE than the mylonitic foliation (S_A) parallel pipe boundaries.
(b) Large new (recrystallised) globular quartz grains within an elongate relict quartz grain (possibly a deformed vein) of different crystallographic orientation (specimen GM2); note deformation band boundaries aligned perpendicular to mylonitic foliation in this globular quartz grain.
(c) Preferred alignment (S_B) of elongate, dynamically recrystallised quartz grains which dip more steeply to the ESE than mylonitic foliation (S_A) defined by phyllosilicates and boundaries of elongate relict quartz grains. Sinistral shear is indicated by petrofabric analysis of this specimen (GM2).
(d) Variably flattened quartz grains (specimen GM3); note globular quartz grain in centre of micrograph.
(e) Globular quartz grain (g) displaying deformation bands aligned parallel to mylonitic foliation defined by preferred alignment of more flattened relict quartz grains (specimen GM3); **c**-axes in this globular quartz grain are aligned sub-parallel to the grain shape lineation observed in hand specimen.
(f) Large undeformed plagioclase feldspar grains within phyllosilicate rich quartz mylonite (specimen GM4).

macroscopic foliation. Recrystallised quartz grains vary in outline from equant to slightly elongate (aspect ratio 2:1) the long axes of the more elongate grains being aligned parallel to the foliation.

Quartz ***c***-and ***a***-axis fabrics from these recrystallised grains are shown in Figures 10 and 11, and are summarised in Table 1. Christie (1963, pp. 398, 400) has described a 'primary mylonite' (his specimen F6) from the Fionn Allt stream section, whose microstructures seem very similar to that of specimen GM4; the location of the two specimens appears to be coincident. Christie (1963, fig. 23) found that the ***c***-axis fabric of specimen F6 consisted of a cross-girdle fabric intersecting in the specimen '*a*' direction (inferred *Y* axis) to produce a ***c***-axis maximum in this direction. Thus the ***c***-axis fabrics of specimens GM4 and F6 are very similar.

It is interesting to note that the first ODF of a naturally deformed quartzite was made by Baker and Wenk (1972) on Christie's specimen F6. In their X-ray texture goniometry study of this specimen, Baker and Wenk (1972, fig. 5) detected three ***a***-axis maxima in almost identical orientations to those described for specimen GM4 (Fig. 11).

5. Mylonites from the Allt nan Sleach section, Assynt

Along the banks of this small tributary of the River Oykell in southern Assynt (Fig. 1) are located some of the most extensive outcrops of mylonitic quartzites within the Assynt region. Unfortunately, due to the thick deposits of glacial material in this area, these outcrops cannot be traced for any great distance laterally, and any geological map of the area must, therefore, be of a conjectural nature.

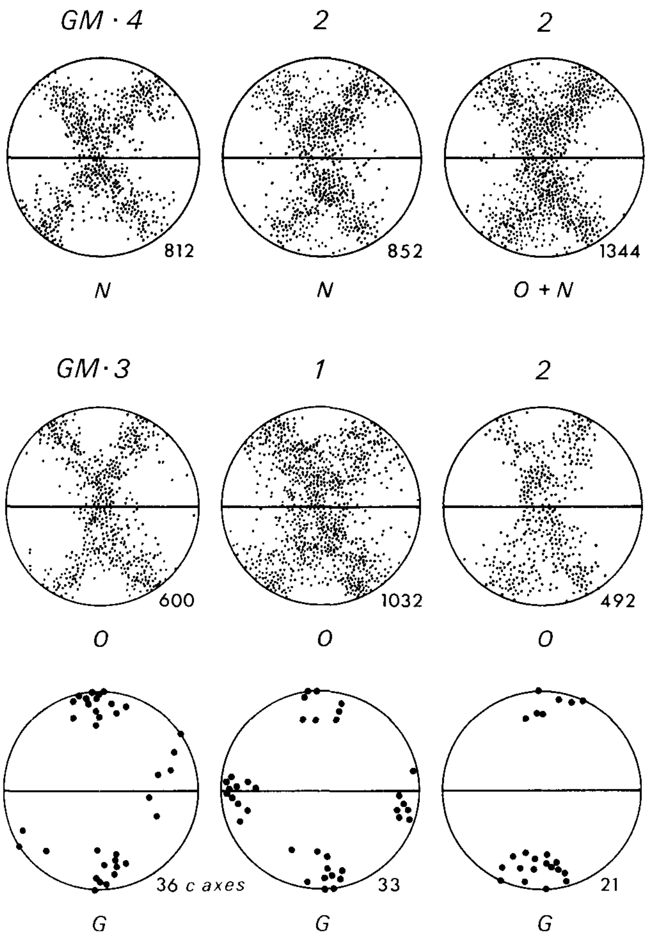

Figure 10 Quartz ***c***-axis fabrics (viewed towards the NNE) from the Gorm Loch Mor area; N new (recrystallised) grains, O old grains; see Figures 1 and 6 for location and orientation convention details respectively.

Two major sheets of mylonitic quartzite, separated by a series of Moine rocks, are exposed in this stream section (Fig. 12). Lithologically these mylonite sheets are identical, being composed of fairly pure quartzite with only locally 5–10% phyllosilicate. The structurally lower, more westerly outcropping mylonite sheet (approximately 57 m thick) dips at 2°–25° to the ENE and is considered to have been derived from Cambrian quartzites. Peach *et al.* (1907, p. 609) have recorded sheared Cambrian Pipe Rock within this mylonite sheet; no such structures were found during the present study. The lithologically identical, more easterly outcropping sheet of quartz mylonite (exposed thickness approximately 22 m) dips at 25°–45° to the ENE and was considered by the Geological Survey (Assynt 1 inch Special Sheet) to be composed of '*Quartz Schists*' belonging to the '*Eastern Schists*' (Moine assemblage). This interpretation was questioned by Christie (1963, p. 369) who, on the basis of similarity of lithology and structure, suggested that both sheets of quartz mylonite were derived from Cambrian quartzite. No other such quartzites have been recorded in the Moine metasediments and therefore Christie's interpretation will be followed in this paper. Within both mylonite sheets the quartzites are intensely foliated and lineated, varying in hand specimen from $L-S$ to $L>S$ tectonites; the grain shape lineation in both sheets plunges to the E (Fig. 12).

The lower sheet of quartz mylonites rests upon (and is presumably thrust over) stratigraphically younger dolomitic limestones of Cambrian age (Fig. 12). The dolomite exhibits a weak horizontal foliation and E trending grain shape lineation. Within the dolomite a thin (0·5 m thick) concordant sheet of intensely foliated and lineated quartzite has been noted.

Lying between the lower and upper quartz mylonite sheets are a series of pelitic-psammitic Moine rocks of mylonitic appearance. The contact between the lower quartz mylonites and the overlying Moine mylonites is exposed in the stream section (specimen AS7, Figs 12, 13a) and has been taken by all previous workers as indicating the position of the Moine thrust. Foliation within the quartzites and overlying Moine rocks is observed (both in hand specimen and thin section) to be parallel to this contact (Figs 13b, 14a); no evidence of brittle deformation has been found along this contact. For approximately 0·5 m above the Moine thrust, the pelitic Moine mylonites have the appearance of *curly schists* (terminology after Sibson *et al.* 1981) and in thin section (Fig. 14a) exhibit widespread shear band development which is oblique to, and deforms the penetrative foliation. The sense of obliquity between foliation and shear bands is consistent with westward directed overthrusting of the Moine rocks.

The upper, more easterly outcropping, sheet of quartz mylonites is separated from the underlying Moine rocks by a thin (0·5–1·0 m) sill of feldspar porphyry (Fig. 12). This porphyry sill cross-cuts the mylonitic foliation in the overlying quartzite (Fig. 13c) but is itself deformed, exhibiting a spaced foliation defined by quartz and phyllosilicate overgrowths on feldspar phenocrysts (Fig. 14f). The upper sheet of quartz mylonites is overlain by mylonitic and then flaggy Moine rocks of similar lithology to those situated beneath the sheet; the contact between these quartzites and the overlying Moine rocks is not exposed, but can be placed to within 0·5 m.

If both the lower and upper quartz mylonite sheets have been derived from Cambrian quartzite, then the Moine thrust may be either breached or folded in this area, the two sheets originally forming one tectonic unit.

5.1. Quartz mylonite microstructures

Within these intensely recrystallised $L-S$ and $L>S$ tectonites, foliation is defined by a parallel alignment of phyllosilicates (less than 5% of total rock composition) and highly elongate domains of recrystallised quartz grains of similar crystallographic orientation which may represent original intensely deformed detrital grains. Only near the centre of the quartz mylonite sheets (specimens AS4, 9) have some of these original grains escaped recrystallisation (Fig. 13d) and display more variable aspect ratios.

Recrystallised quartz grain size varies both with structural position within the mylonite sheets and also with domainal (thin section scale) variation in phyllosilicate content. Recrystallised quartz grain size was always observed to be inversely proportional to the phyllosilicate content of these domains. Within the lower quartz mylonite sheet, recrystallised quartz grain size in phyllosilicate-poor quartzites was found to vary from 26 μm at the upper (specimen AS7) and lower (specimen AS11) margins of the sheet, to approximately 42 μm (specimen AS9) close to the centre of the sheet. This systematic spatial variation in grain size has not been detected within the generally coarser phyllosilicate-poor quartzites of the upper mylonite sheet, where recrystallised quartz grain size ranges from approximately 62 μm (specimen AS2) to 55 μm (specimen AS4).

In XZ thin sections, recrystallised quartz grains vary in outline from equant to elongate with aspect ratios commonly of between 2:1 and 4:1. These elongate grains display a preferred alignment (S_B) which dips more steeply to the E than the mylonitic foliation (Fig. 14c). A considerable domainal variation in degree of obliquity between mylonitic foliation (S_A) and S_B was commonly observed within individual thin sections.

5.2. Quartz crystallographic fabrics

The structural distribution of sampling localities within the quartz mylonites and adjacent Moine rocks is shown in Figure 12. Calculated distances of specimens either above (Moine rocks) or below (quartz mylonites) the Moine thrust are indicated in Figure 15.

Quartz **c**-axes from the foliation (S_A) parallel quartz-rich domain in specimen AS1, a mylonitic Moine rock situated approximately 1·5 m above the Moine thrust, define a broad single girdle fabric (Fig. 15) which is oblique to foliation and lineation, but contains the inferred Y-axis. Within the underlying $L-S$ and $L>S$ tectonites of the upper quartz mylonite sheet (specimens AS2–5), quartz **c**-axes define either single or cross-girdle fabrics (Fig. 15). These cross-girdle fabrics, which are asymmetrical with respect to foliation (S_A) and lineation in terms of density distribution, are compared in Figure 16 with their corresponding **a**-axis fabrics. For specimen AS2, two **a**-axis maxima of unequal intensity, orientated within the inferred XZ plane and symmetrically inclined at 30° to the lineation, were detected. Specimens AS3 and AS4 are characterised by a planar distribution of three **a**-axis maxima of unequal intensity, the dominant maximum in both specimens being orientated

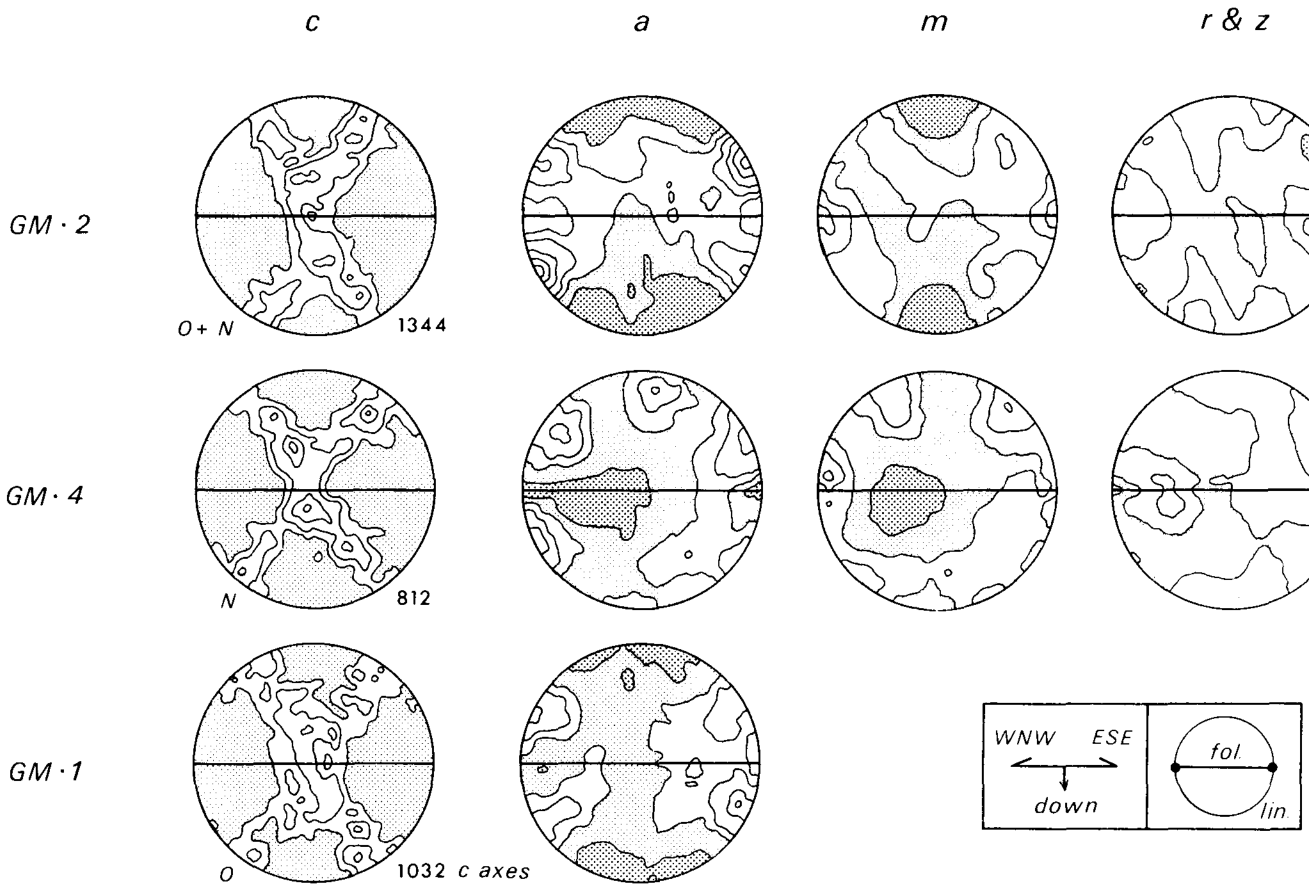

Figure 11 Comparison of quartz fabrics (viewed towards the NNE) obtained by optical and X-ray texture goniometry methods within quartz mylonites from the Gorm Loch Mor area; for location details and explanation of contour intervals see Figures 1 and 6 respectively.

within the inferred XZ plane at a moderate angle (15° in specimen AS3, 25° in specimen AS4) to the lineation.

Quartz ***c***-axis fabrics from the lower sheet of quartz mylonites and adjacent Moine rocks (specimen AS6) all define preferred orientations (Fig. 15) which are intermediate between Type I and Type II (Lister 1977) cross-girdle fabrics. Some variation in both skeletal outline and intensity distribution is observed in these fabrics. The ***c***-axis fabric of specimen AS10 is fairly symmetrical (both in terms of skeletal outline and intensity distribution) with respect to foliation (S_A) and lineation. Other specimens, such as AS6, AS7, AS8 and AS9, yield ***c***-axis fabrics which, although symmetrical with respect to foliation (S_A) and lineation in terms of skeletal outline, are asymmetrical in terms of density distribution. In contrast, the ***c***-axis fabric of specimen AS11 (collected 2 m above the thrust contact of the quartz mylonites with the underlying dolomitic limestones) is strongly asymmetrical with respect to foliation and lineation both in terms of skeletal outline and intensity distribution. A similar asymmetrical fabric has been detected (specimen AS12) within the quartz mylonite sheet lying within the dolomitic limestones (Fig. 12).

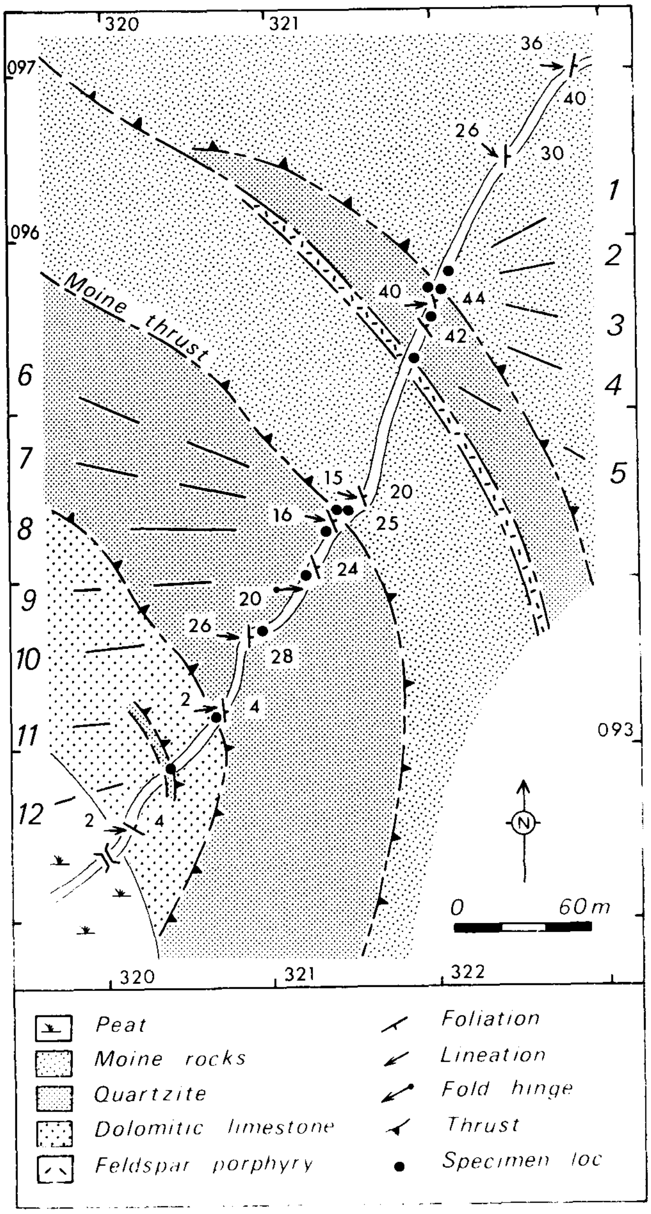

Figure 12 Geological map of the Allt nan Sleach stream section (see Fig. 1 for location) showing individual sampling locations (specimens AS1–12); National Grid coordinates indicated.

Quartz ***a***-axis fabrics from the lower sheet of quartz mylonites are shown in Figure 16. Specimens such as AS8, AS9 and AS10 each yield two ***a***-axis maxima aligned within the inferred XZ plane, the more intense maximum always plunging more steeply to the WNW than the lineation. However, while the ***a***-axis maxima in specimens AS9 and AS10 are symmetrically inclined at 25°–30° to the lineation, specimen AS8 is characterised by an asymmetrical distribution of maxima within the inferred XZ plane, the dominant and weaker maxima being inclined at 20° and 30° to the lineation respectively. These maxima are partially

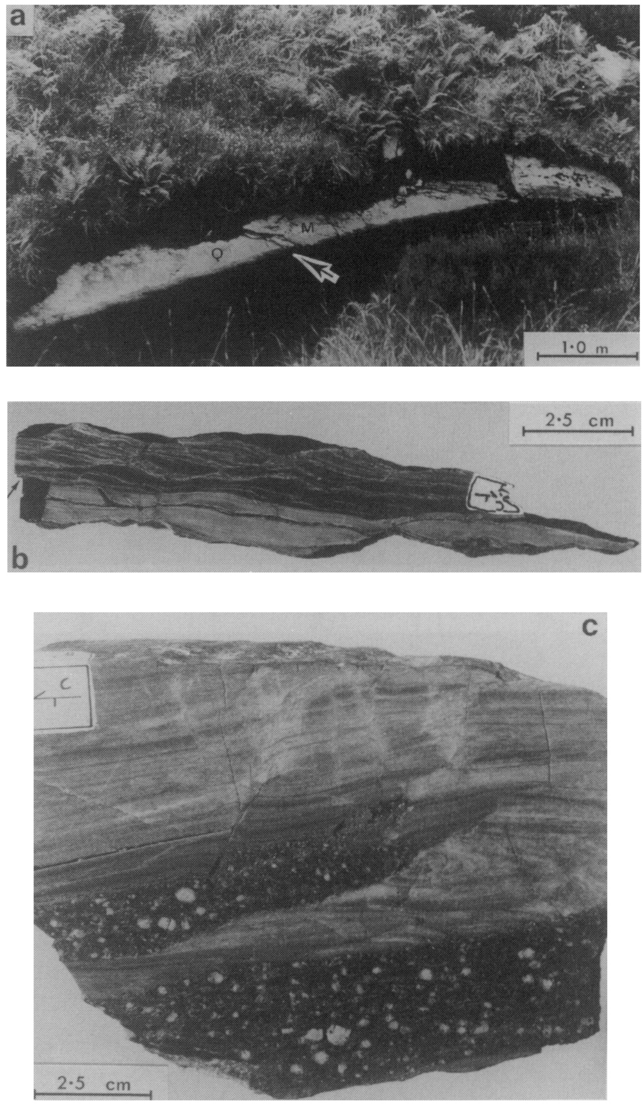

Figure 13 Allt nan Sleach stream section
(a) Exposure of the Moine thrust (at arrow tip) viewed towards the NW. Mylonitic Moine rocks (M) overlie similarly deformed Cambrian quartzites (Q); specimen AS7 collected from the contact (arrowed) between these lithologies; specimen AS8 collected from mylonitic quartzites located 1·5 m to the left of arrow; specimen AS6 collected from mylonitic Moine rocks on extreme right of photograph.
(b) Polished surface (viewed towards the NNE) of specimen AS7 cut perpendicular to mylonitic foliation and parallel to lineation; mylonitic Moine rocks (dark) overlie similarly deformed Cambrian quartzite (light), the contact between these two lithologies being taken to mark the position of the Moine thrust; note shear bands (dipping towards the WNW) within the phyllosilicate-rich Moine rocks.
(c) Polished surface (viewed towards the NNE) of specimen AS5 cut perpendicular to mylonitic foliation and parallel to lineation; sills of feldspar porphyry cross-cut mylonitic foliation in adjacent Cambrian quartzites.

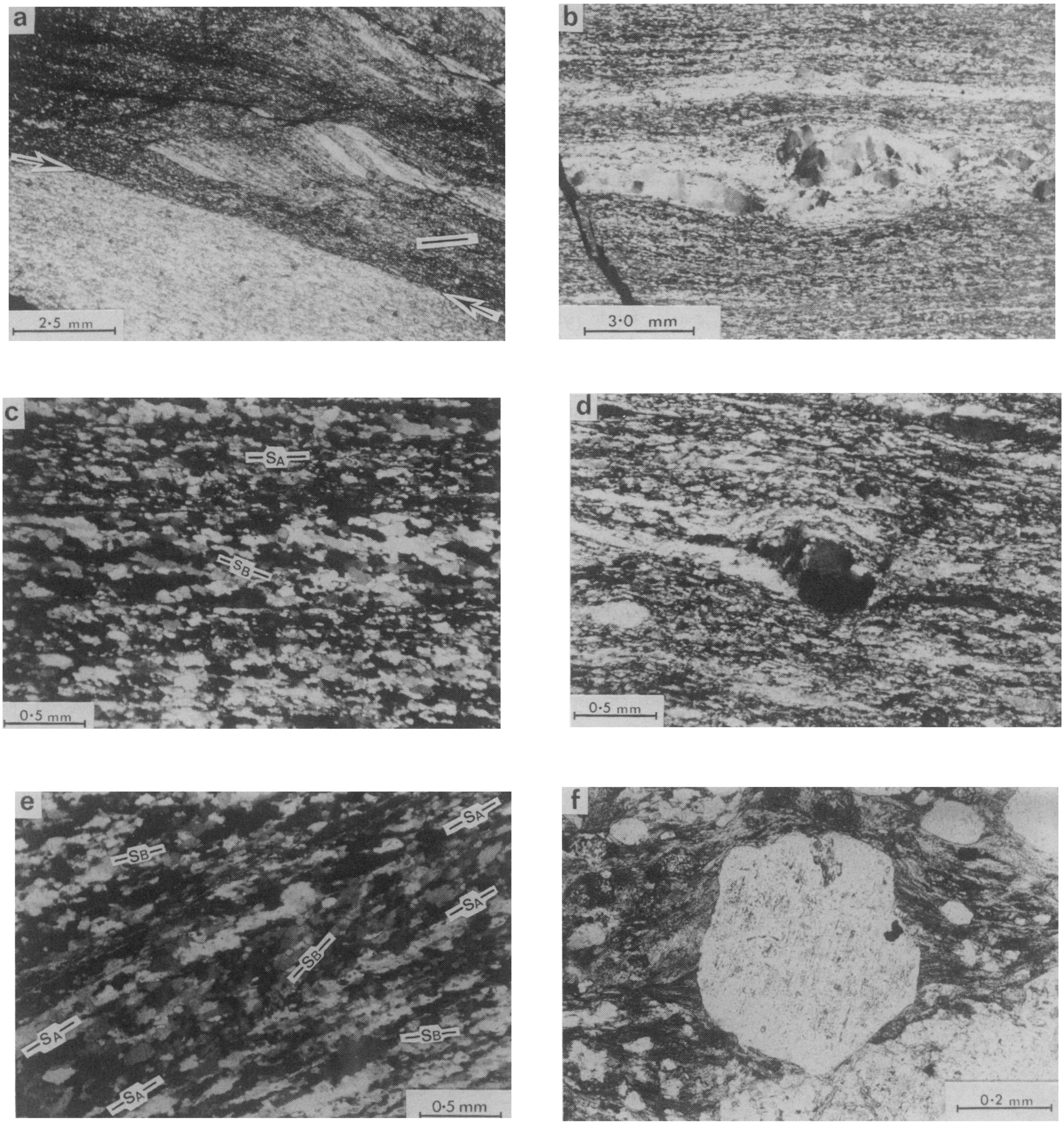

Figure 14 Photomicrographs (viewed towards the NNE) of specimens from the Allt nan Sleach stream section; thin sections cut perpendicular to mylonitic foliation and parallel to lineation.

(a) Phyllosilicate rich Moine rocks (dark) overlying mylonitic Cambrian quartzites (light) within specimen AS7; contact (arrowed) between Moine rocks and Cambrian quartzite is taken to represent position of Moine thrust; note shear bands (orientation indicated by bar) within Moine rocks.

(b) Mylonitic, intensely recrystallised Cambrian quartzite (specimen AS2). Note large, elongate domains of relatively unrecrystallised quartz; within these domains (which may be interpreted as deformed veins) large syntectonic globular quartz grains are observed.

(c) Preferred alignment (S_B) of elongate, dynamically recrystallised quartz grains dipping more steeply to the ESE than the mylonitic foliation (S_A) defined by phyllosilicates and boundaries of elongate relict quartz grains (specimen AS2).

(d) Relict (globular) quartz grain within recrystallised quartz mylonite (specimen AS9).

(e) Domainal variation in sense of obliquity between S_B and spaced mylonitic foliation (S_A); **c**-axis fabrics within these domains are illustrated in Figure 17 (specimen AS2).

(f) Quartz and phyllosilicate beards on plagioclase phenocrysts within deformed porphyry sill (specimen AS5); although these porphyry sills cross-cut the mylonitic foliation of the adjacent Cambrian quartzites, the quartz and phyllosilicate beards within the sills are aligned parallel to this mylonitic foliation.

connected by diffuse small circle girdles of ***a***-axes centred about the lineation. In contrast to these two maxima fabrics, specimen AS11 yields a single ***a***-axis maximum approximately aligned within the inferred *XZ* plane, inclined at 25° to the lineation, and which plunges more steeply to the WNW than the lineation.

The ***c***-axis fabrics of two quartzites from the Allt nan Sleach section have previously been described by Christie (1963, fig. 23). Both quartzites (his specimens E15 from the upper mylonite sheet, and E14 for the lower mylonite sheet) yielded fairly symmetrical cross-girdle fabrics which intersected in the inferred *Y* direction. In contrast, all ***c***-and ***a***-axis fabrics from the Allt nan Sleach mylonites reported in the present paper are, with the possible exception of specimen AS10, asymmetrical with respect to foliation and lineation. Using the criteria reviewed by Simpson and Schmid (1983), the sense of ***c***-and ***a***-axis fabric asymmetry is consistent with non-coaxial deformation associated with WNW directed overthrusting. This interpretation is strongly supported by the observed sense of obliquity between mylonitic foliation (S_A) and preferred alignment (S_B) of elongate dynamically recrystallised quartz grains within these tectonites (Figs 14c, 15).

Only one possible exception to this generally inferred shear sense has been found within the Allt nan Sleach mylonites. In specimen AS2, it was noted that a single elongate (0·4 mm × 10 mm) relict quartz grain (defined by recrystallised grains of similar crystallographic orientation) was composed of elongate new quartz grains whose preferred alignment was oblique to S_A, but with the opposite sense of obliquity to that noted within the rest of the thin section (Fig. 14e). Quartz ***c***-axes within this anomalous domain define a markedly different fabric pattern to that observed outside the domain (Fig. 17). It is uncertain if this small domain is reflecting a local reversal in shear sense (Garcia–Celma 1982) or the crystallographic influence of an anomalously oriented relict grain.

6. Mylonites of the Upper Arnaboll thrust sheet, Eriboll

This thrust sheet is located beneath, but immediately adjacent to, the Moine thrust at Loch Eriboll (Fig. 1). The microstructures and ***c***-axis fabrics of the mylonitic Cambrian quartzites within this thrust sheet (together with specimen location details) have previously been described by Law *et al.* (1984). In Figure 18 some of these optically determined ***c***-axis fabrics are compared with previously unpublished fabric data obtained by *X*-ray texture goniometry on the same specimens.

Within the upper and central levels of the thrust sheet (at some distance from both the underlying Upper Arnaboll thrust and the overlying Moine thrust), $L-S$ tectonites

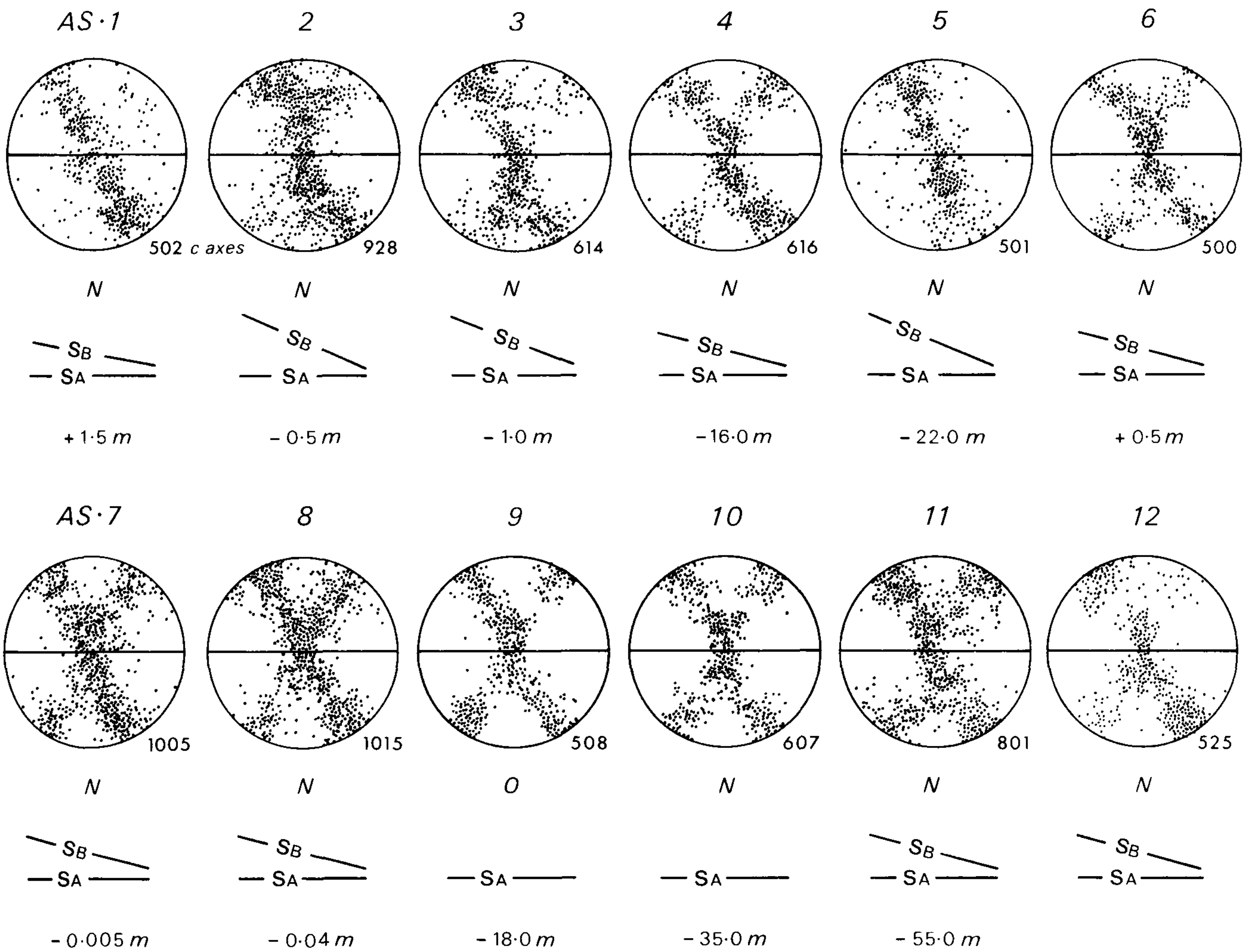

Figure 15 Quartz ***c***-axis fabrics (viewed towards the NNE) from the Allt nan Sleach section; geometrical relationships between mylonitic foliation (S_A) and preferred alignment (S_B) of elongate, dynamically recrystallised quartz grains indicated; distances of Moine rocks above (+) the Moine thrust and Cambrian quartzites beneath (−) the Moine thrust, are also indicated; for specimen locations see Figure 12.

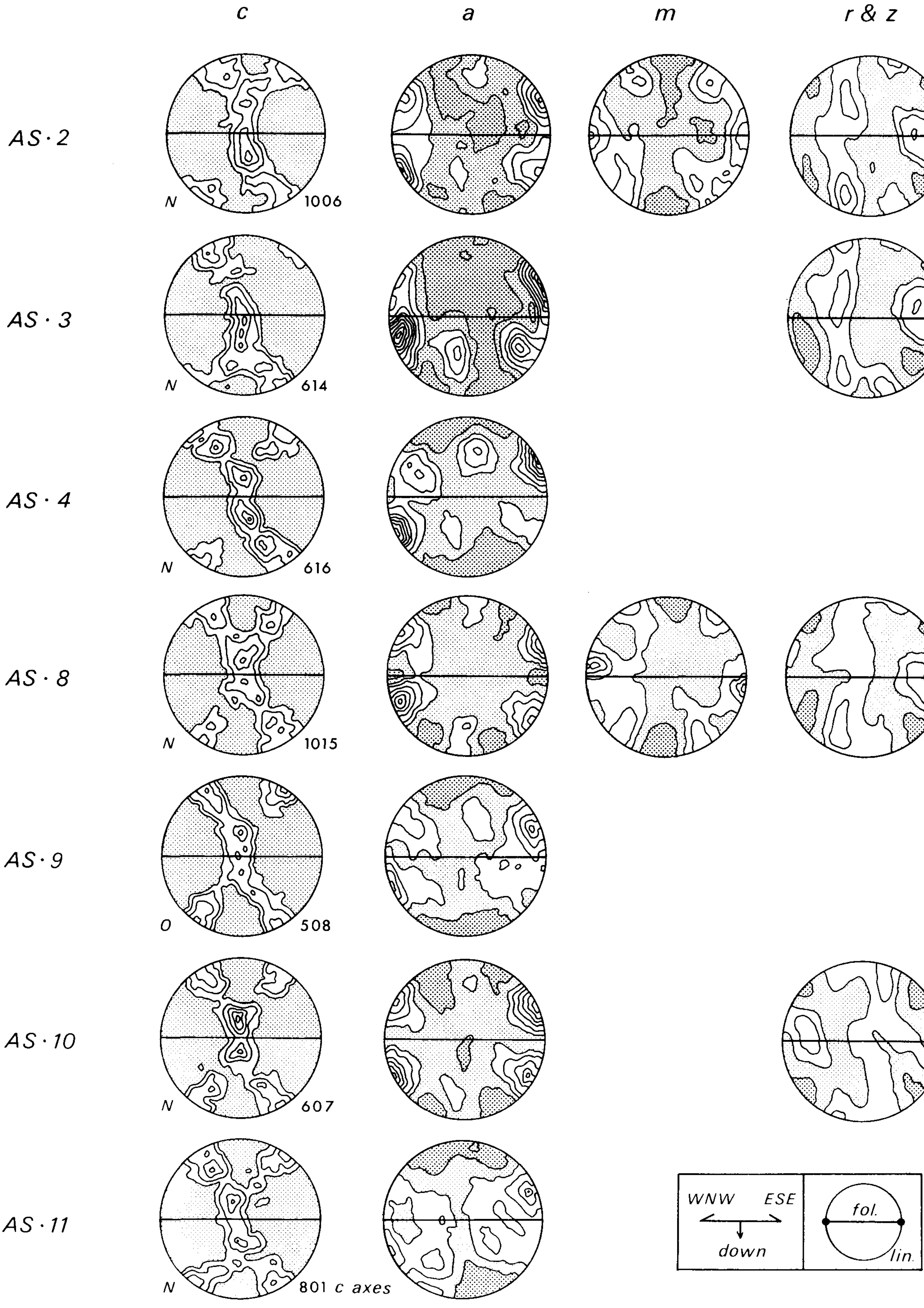

Figure 16 Comparison of quartz fabrics (viewed towards the NNE) obtained by optical and X-ray texture goniometry methods within quartz mylonites from the Allt nan Sleach section; N new (recrystallised) grains, O old grains; for explanation of contour intervals see Figure 6.

yield symmetrical Type I (Lister 1977) cross-girdle ***c***-axis fabrics. Corresponding ***a***-axis fabrics are characterised by two maxima aligned within the inferred *XZ* plane and symmetrically inclined at 25°–30° to the lineation.

Within the lower levels of the thrust sheet (close to the Upper Arnaboll thrust) highly recrystallised $L-S$ tectonites yield asymmetrical, approximately single girdle ***c***-axis fabrics. Corresponding quartz ***a***-axis fabrics are displayed in Figure 18. Specimens E41498 and E41510 are characterised by a single ***a***-axis maximum orientated within the inferred *XZ* plane, inclined at 25°–30° to the lineation, and accompanied by geometrically necessary sub-maxima; this single ***a***-axis maximum occupies the pole position to the dominant ***c***-axis single girdle distribution obtained by universal stage work. In specimen E41497, quartz ***a***-axes are confined to the inferred *XZ* plane in which they form two low-density maxima. In contrast, specimen E41475 yields a broad, diffuse ***a***-axis containing the inferred *Y*-axis, and which is oblique to foliation and lineation.

7. Correlation between shape fabric and crystallographic fabrics

Within the Assynt region, the mylonitic Cambrian quartzites range from $S>L$ through $L-S$ to $L>S$ tectonites. Theoretical studies (e.g. Bouchez 1978; Lister *et al.* 1978; Lister & Hobbs 1980; Schmid & Casey, in press) suggest that this variation in shape fabric should be reflected in the corresponding quartz ***c***-and ***a***-axis fabrics of these tectonites (Fig. 19). Quantitative strain analysis is, unfortunately, impossible within these tectonites due to extensive ribbon grain development and recrystallisation.

Mylonites at the Stack of Glencoul range from $S>L$ to $L-S$ tectonites and, at distances of greater than 30 cm beneath the Moine thrust, are characterised by symmetrical approximate Type I (Lister 1977) cross-girdle ***c***-axis fabrics optically measured on relict quartz grains (Fig. 5). These cross-girdle fabrics may be interpreted as indicating approximate plane strain ($k=1$) deformation conditions (Fig. 19). However, a study by Schmid and Casey (in press) of one of these mylonites (specimen SG10) in which foliation is more obviously developed than lineation, suggests that the grain shape fabric is oblate. The ***c***-axis fabric calculated from the ODF from this specimen (Fig. 8) is transitional between a Type I cross-girdle and a small circle girdle fabric centred about the foliation pole, suggesting (Fig. 19) a deformation intermediate between that of flattening ($k=0$) and plane strain ($k=1$). Further supporting evidence for a component of oblate strain within at least some of these mylonites from the Stack of Glencoul is provided by study of their corresponding ***a***-axis fabrics (cf. Figs 6, 19). These ***a***-axis fabrics are composed of two maxima symmetrically inclined to the lineation within the inferred *XZ* plane and partially connected by a diffuse small circle girdle of large opening angle centred about the pole to foliation. A similar correlation between shape fabric and quartz ***a***-axis fabrics is detected within two of the mylonite specimens (E41514, E41474) from the Eriboll region (Fig. 18).

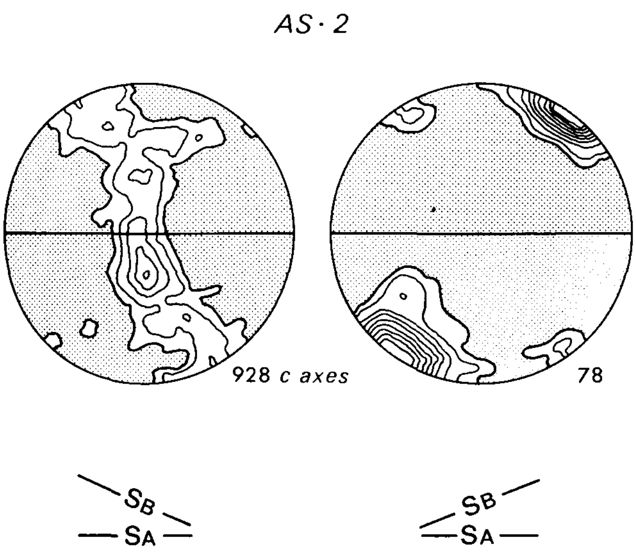

Figure 17 Domainal quartz *c*-axis fabrics (viewed towards the NNE) in specimen AS2; note correlation between domains with opposite senses of obliquity between S_A and S_B and *c*-axis fabrics; contour intervals 1, 2, 3, ... 7, 8 and 9 data points per counting area; for further details see Figure 6.

Theoretical studies suggest that $L-S$ tectonites formed under exact plane strain ($k=1$) conditions should be characterised by two ***a***-axis maxima aligned within the *XZ* plane at a low angle to the lineation (Fig. 19). Only one specimen (AS10), an $L-S$ tectonite from the Allt nan Sleach section, displays an ***a***-axis fabric (Fig. 16) which is in exact correspondence with this theoretical prediction. Optically measured ***c***-axes from this specimen define a Type I (Lister 1977) cross-girdle fabric.

The majority of mylonites from the Gorm Loch Mor area (Fig. 11) and the Allt nan Sleach section (Fig. 16) are characterised by ***a***-axis fabrics consisting of two dominant maxima aligned within the inferred *XZ* plane, which are connected by partial small circle girdles of ***a***-axes centred about the lineation. In agreement with theoretical predictions (Fig. 19), the small circle girdle element of these ***a***-axis fabrics, which is centred about the lineation, is most strongly developed in those mylonites in which lineation is more obviously developed than foliation ($L>S$ tectonites). Optically measured ***c***-axes within these tectonites define patterns which are intermediate between Type I and Type II (Lister 1977) cross-girdle fabrics. In contrast, a well defined Type II cross-girdle ***c***-axis fabric, displaying a dominant *Y*-axis maximum, has been calculated from the ODF of one of these tectonites (specimen AS8) from the Allt nan Sleach section (Fig. 8).

Two possible interpretations of the Type I and Type II cross-girdle fabrics described in this paper may be proposed:

1. Lister and Dornsiepen (1982) have suggested that both Type I and Type II cross-girdle fabrics are indicative of approximately plane strain ($k=1$) deformation, the transition from Type I to Type II fabrics being promoted by the increasing importance of prism slip in relation to other slip systems.
2. Alternatively, while Type I cross-girdle fabrics may be indicative of approximate plane strain deformation, Type II cross-girdle fabrics may reflect deformation within the constrictional field ($k>1$) of the deformation plot (Schmid & Casey, in press).

These alternative interpretations may be tested by detailed study of Orientation Distribution Functions from the tectonites under consideration. Grains with their ***c***-axes parallel to *Y* are in a special situation with regard to approximately coaxial plane strain ($k=1$) deformation, as conjugate shear (duplex slip) can simultaneously operate on two first order prisms within the same crystal. These grains would be expected to display a hexagonal distribution of other crystal directions about the ***c***-axis (hexagonal character in ODF). In contrast, duplex slip on the first order prisms is not suitable for accommodating constric-

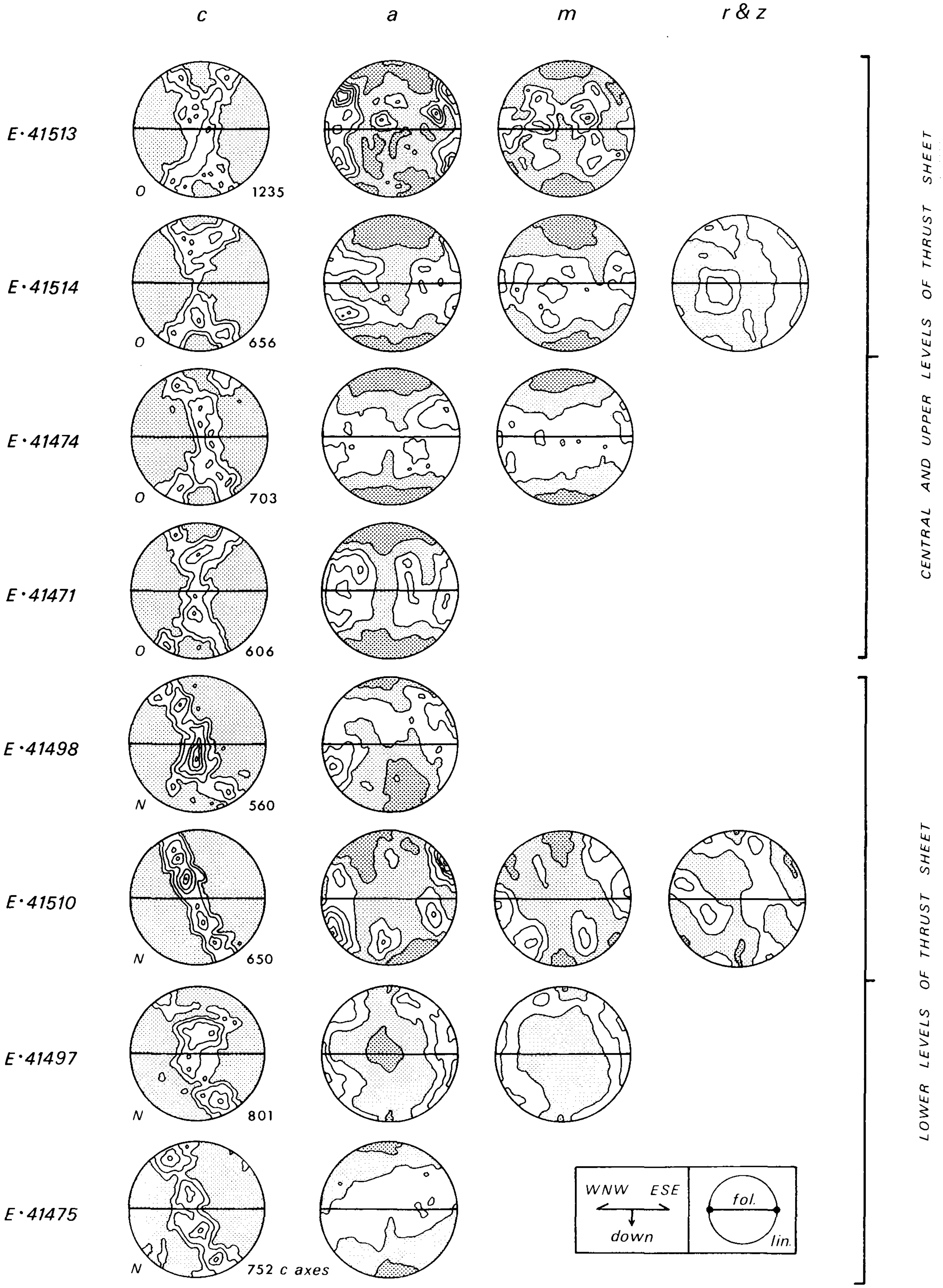

Figure 18 Comparison of quartz fabrics (viewed towards the NNE) obtained by optical and X-ray texture goniometry methods within quartz mylonites from the Upper Arnaboll thrust sheet at Loch Eriboll; N new (recrystallised) grains, O old grains; for explanation of contour intervals and orientation convention see Figure 6.

tional ($k > 1$) deformation, and consequently slip on the negative rhombs will predominate (Schmid & Casey, in press), resulting in a trigonal distribution of other crystal directions about the **c**-axis (trigonal character in ODF).

Detailed study of the ODF for specimen AS8 indicates that grains with their **c**-axes aligned parallel to the Y direction are characterised by a strong trigonal distribution of other crystal directions about the **c**-axis. It is therefore suggested that the Type II calculated cross-girdle **c**-axis fabric displayed by this $L > S$ tectonite (Fig. 8) is indicative of constrictional deformation. In contrast, the ODF for specimen GM2 from the Gorm Loch Mor area indicates that grains with their **c**-axes aligned parallel to the Y direction are characterised by a hexagonal distribution of other crystal directions about the **c**-axis. The Type I calculated cross-girdle fabric from this $L - S$ tectonite (Fig. 8) is therefore interpreted as indicating approximate plane strain deformation conditions.

To summarise, both grain shape fabrics and crystallographic fabrics indicate an important component of flattening strain within the Stack of Glencoul mylonites. In the Allt nan Sleach mylonites, however, a component of cylindrical flow (Bouchez 1978) within the constrictional regime is indicated by these deformation features. In addition, while approximate plane strain conditions (in some specimens slightly into the constrictional field) are indicated within the Gorm Loch Mor mylonites, more variable strain symmetries are detected (Law *et al.* 1984) within the Eriboll mylonites.

8. Kinematic interpretation of microstructures

Three microstructural features encountered in this study (globular 'hard orientation' quartz grains, shear bands and oblique grain shape fabrics) are considered to provide important information on the kinematics of deformation.

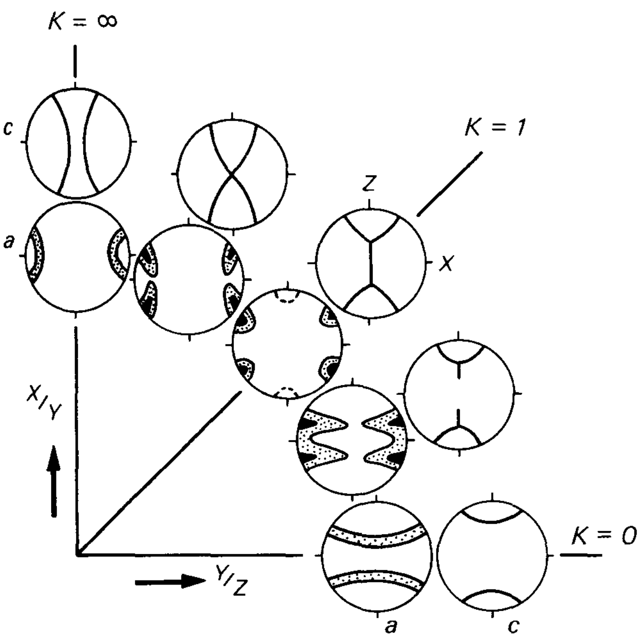

Figure 19 Theoretical relationships (for coaxial deformation) between strain symmetry (expressed by Flin Plot) and quartz **c**- and **a**-axis fabrics; **c**-axis fabrics represented by fabric skeletons, **a**-axis fabrics represented by contours; in all stereograms foliation (XY) is vertical and trends from right–left, lineation (X) within foliation is horizontal; adapted from Schmid and Casey (in press).

8.1. Globular quartz grains

Globular detrital quartz grains whose **c**-axes are aligned subparallel to the principal finite shortening direction (Z) and around which more flattened quartz grains anastomose, have been observed within quartz mylonites located at distances of greater than 30 cm beneath the Moine thrust at the Stack of Glencoul (Fig. 5), and within specimens GM2 (Fig. 10) and AS9 (Fig. 14d) from the Gorm Loch Mor and Allt nan Sleach areas respectively. The presence of similar globular grains within mylonites from the upper and central levels of the Upper Arnaboll thrust sheet at Eriboll has been taken by Law *et al.* (1984) to indicate the preservation of a coaxial deformation history (Fig. 20a).

Much rarer, low strain quartz grains whose **c**-axes are aligned at low angles to the lineation have been observed within quartz mylonites from the Stack of Glencoul (Fig. 5) and Gorm Loch Mor (Fig. 10) areas. Deformation bands within these grains are aligned subparallel to the mylonitic foliation (Fig. 9e). During coaxial deformation these grains would have low resolved shear stresses on their basal slip planes.

In using these globular grains as indicators of a coaxial strain path, care must be taken, however, to ensure that the globular grain morphology pre-dates deformation. This is because recrystallisation and grain growth during the late stages of a non-coaxial deformation may produce some grains whose crystal lattices are unfavourably oriented for slip during the last few remaining increments of deformation. These grains may then remain undeformed while more favourably orientated grains deform around them into an anastomosing pattern.

Clear examples of these syntectonic globular quartz grains have been observed within specimen GM2 (Fig. 9b) and AS2 (Fig. 14b) from the Gorm Loch Mor and Allt nan Sleach areas respectively. Both are Type II $S - C$ mylonites (Fig. 20c) in which a consistent sense of non-coaxial deformation is indicated by microstructures and crystallographic fabrics. Rare, less clearly defined examples of these syntectonic globular grains have also been observed (Fig. 4d, f) within some of the quartz mylonites from the Stack of Glencoul. In these mylonites, however, it will later be argued that the preservation of a coaxial deformation history is indicated by symmetrical quartz **c**-and **a**-axis fabrics.

8.2. Shear bands

Single sets of shear bands have been observed within: (1) mylonitic Moine rocks lying above the Moine thrust at the Stack of Glencoul, (2) some of the phyllosilicate-rich horizons (e.g. specimen SG5, Fig. 2) within the mylonitic Cambrian quartzites lying beneath the thrust at this locality, and (3) mylonitic Moine rocks and Cambrian quartzites located close to the Moine thrust in the Allt nan Sleach section (Figs 13b, 14a). In all observed cases the sense of obliquity (Platt & Vissers 1980; White *et al.* 1980) between these shear bands and mylonitic foliation is consistent with non-coaxial (approximately simple shear) deformation associated with WNW-directed overthrusting. Similarly orientated single sets of shear bands (Fig. 20b) were found by Law *et al.* (1984) to characterise mylonites located close to the base of the Upper Arnaboll thrust sheet in the Eriboll region. In contrast, the presence of conjugate, mutually interfering shear bands (Fig. 20b) within the central and upper levels of this thrust sheet was taken by Law *et al.* (1984) to indicate a coaxial (pure shear) strain path for this structural position. Conjugate shear bands have not been observed within the mylonites from the Assynt region.

8.3. Oblique grain shape fabrics

Within the mylonitic quartzites (specimens SG1, SG2) located close to the Moine thrust at the Stack of Glencoul elongate, dynamically recrystallised, quartz grains display in XZ thin sections (Fig. 4h) a preferred alignment (S_B) which is oblique to the mylonitic foliation (S_A). A constant sense of obliquity between S_A and S_B is observed, with S_B always dipping more steeply to the ESE than S_A. Similar microstructures and geometrical relationships have been observed within specimen GM2 from the Gorm Loch Mor area (Fig. 9c), all the quartz mylonites located close to the base of the Upper Arnaboll thrust sheet at Loch Eriboll (Law *et al.* 1984) and, with the exception of specimens AS9 and AS10, all the mylonitic Moine rocks and Cambrian quartzites of the Allt nan Sleach section (Fig. 15). All are either $L-S$ or $L>S$ tectonites. Law *et al.* (1984) have previously argued that, within the Eriboll mylonites, these microstructures are indicative of non-coaxial (approximately simple shear) strain paths associated with WNW-directed overthrusting (Fig. 20c). This kinematic interpretation may now be extended to those mylonites from the Assynt region which contain such microstructures.

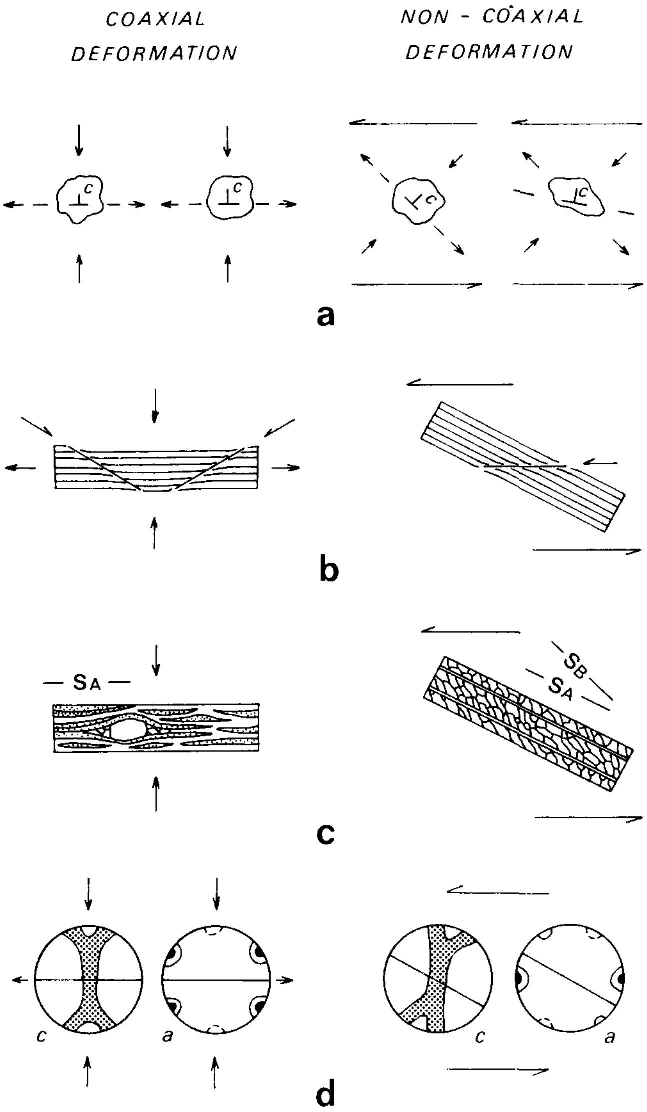

Figure 20 Microstructural and crystallographic fabric criteria used to distinguish between coaxial and non-coaxial strain paths (after Law *et al.* 1984).
(a) Globular quartz grains whose ***c***-axes are aligned close to the foliation pole (Z); in coaxial deformation these grains will have low resolved shear stresses on their basal and prism slip planes throughout the deformation history; in non-coaxial deformation, the lattices of these grains will rotate relative to the kinematic framework, and the resolved shear stresses on their potential slip planes will vary, allowing plastic deformation.
(b) Shear bands; in coaxial (pure shear) deformation, conjugate sets of shear bands which are symmetrically orientated relative to the foliation may develop; in non-coaxial (simple shear) deformation, only one set of shear bands is developed.
(c) In ductile shear zones, a consistent sense of obliquity is commonly observed between mylonitic foliation (S_A) and preferred alignment of elongate, dynamically recrystallised quartz grains (S_B). Tectonites containing these microstructures are considered to have been formed during non-coaxial deformation, and have been classified by Lister and Snoke (1984) as Type II $S-C$ mylonites. In contrast, coaxial deformation histories may be indicated by tectonites containing globular (hard orientation) quartz grains around which ribbon quartz grains anastomose.
(d) Coaxial deformation is indicated by quartz ***c***- and ***a***-axis fabrics which are symmetrical with respect to foliation (vertical planes in stereograms) and lineation (horizontal structure within foliation on stereograms); non-coaxial deformation is indicated by asymmetrical ***c***- and ***a***-axis fabrics.

9. Kinematic interpretation of quartz crystallographic fabrics

Within the mylonites located beneath the Moine thrust at the Stack of Glencoul, a clear relationship has been established between the pattern of quartz ***c***- and ***a***-axis preferred orientation and proximity to the thrust surface (Figs 5, 6, 7). At distances of less than approximately 20 cm beneath the thrust, ***c***- and ***a***-axis fabrics are asymmetrical with respect to foliation and lineation. In contrast, mylonites located at greater distances beneath the thrust yield ***c***- and ***a***-axis fabrics which are symmetrical with respect to foliation and lineation.

A similar correlation between fabric symmetry and proximity to thrust surfaces has been detected within the Upper Arnaboll thrust sheet at Loch Eriboll, symmetrical ***c***- and ***a***-axis fabrics being observed within the internal parts of the thrust sheet, while asymmetrical ***c***- and ***a***-axis fabrics are observed near the base of the thrust sheet (Fig. 18). Both at the Stack of Glencoul and Loch Eriboll, the most intense strains are always observed in those tectonites which exhibit asymmetrical fabrics.

Three possible kinematic interpretations of this spatial variation in crystallographic fabric symmetry are discussed in Sections 9.1, 9.2, and 9.3.

9.1. Strain path partitioning

The simplest kinematic interpretation of the observed spatial variation in fabric symmetry is that symmetrical fabrics within the thrust sheets indicate coaxial strain paths, while asymmetrical fabrics located near the margins of the thrust sheets are indicative of non-coaxial (approximately simple shear) strain paths associated with WNW-directed overthrusting. In this interpretation, the observed gradual transition from symmetrical to asymmetrical ***c***-axis fabrics at the Stack of Glencoul (Fig. 7) would be taken to indicate the contemporaneous development of a vorticity gradient within these mylonites, ranging from strongly non-coaxial flow near the Moine thrust to essentially coaxial flow at distances of greater than 20 cm beneath the thrust.

This interpretation of fabric symmetry is in accord with the previously proposed kinematic interpretation of microstructures within these mylonites (Fig. 20), and is supported by the fabric simulation studies of Lister and Hobbs (1980). These computer simulation studies predict that the skeletal outline of quartz ***c***-axis fabrics will remain constant with respect to the kinematic framework with increasing finite strain as long as the strain path and slip system activities remain constant.

9.2. Increasing strain in simple shear

Several recent studies of natural and experimentally produced crystallographic fabrics have indicated that, with increasing finite strain along a constant strain path, the skeletal outline of **c**-axis fabrics does not (in contradiction to the findings of Lister & Hobbs 1980) remain constant with respect to the kinematic framework. For example, a transition from symmetrical cross-girdle to asymmetrical single girdle **c**-axis fabrics with increasing heterogeneous shear strain of quartz veins has been recorded by Garcia-Celma (1983, p. 78) within the Cap de Creus mylonites of NE Spain. A similar transition from double to single point maxima has been observed by Bouchez and Duval (1982) with increasing shear strain in ice subjected to experimental simple shear deformation. By analogy with these studies, it may be proposed that a progressive transition from symmetrical to asymmetrical quartz **c**- and **a**-axis fabrics could be produced with increasing strain during simple shear deformation (Fig. 21). This fabric transition (which would involve an increase in strain partitioning at the grain scale) may be assisted (Schmid & Casey, in press) by grains in unfavourable orientations for continued intracrystalline slip being partially removed, by grain boundary migration of more favourably orientated grains, and partially reorientated by selective recrystallisation.

This proposal is compatible with the observation in the Stack of Glencoul and Eriboll mylonites that while symmetrical **c**- and **a**-axis fabrics are recorded in the relatively low strain tectonites, asymmetrical fabrics are recorded in the more intensely deformed and recrystallised rocks. If those mylonites which display symmetric fabrics have formed in predominantly simple shear deformation, then all should be $L-S$ tectonites. It has previously been demonstrated (see Section 7) that mylonites with associated symmetric crystallographic fabrics at the Stack of Glencoul are predominantly $S>L$ tectonites displaying **a**-axis fabrics indicative of deformation within the flattening field of the strain plot (Fig. 19). Similarly within the Eriboll region, mylonites with symmetric fabrics have been demonstrated by Law *et al.* (1984) to exhibit a considerable variation in strain symmetry, ranging from S tectonites (oblate strains

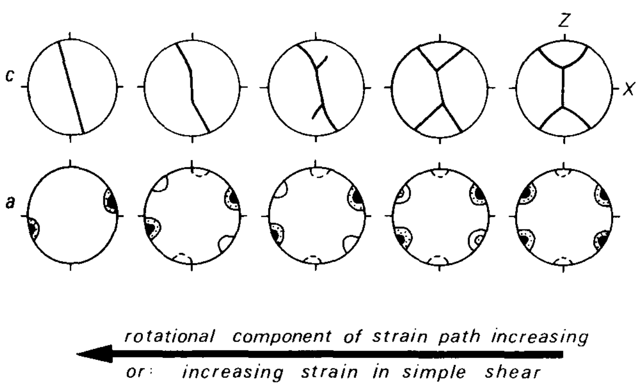

Figure 21 Two possible kinematic interpretations of quartz **c**- and **a**-axis fabrics produced by plane strain ($k=1$) deformation (sinistral shear sense indicated); **c**-axis fabrics represented by fabric skeletons, **a**-axis fabrics represented by contours; in all stereograms foliation (XY) is vertical and trends from right–left, lineation (X) lying within foliation is horizontal; adapted from Schmid and Casey (in press).

with associated small circle **c**-axis girdles centred about the foliation pole) to $L-S$ tectonites with cross-girdle **c**-axis fabrics.

Thus it seems unlikely that the simple shear fabric transition model is applicable to the Stack of Glencoul and Eriboll mylonites.

9.3. Fabric overprinting

It may be argued that the observed symmetrical relationship between crystallographic fabrics and foliation and lineation is due to a late coaxial overprint on an earlier fabric produced during non-coaxial deformation. For example, Christie (1963, p. 405) has interpreted quartz **c**-axis fabrics from the Stack of Glencoul, which are symmetrical with respect to foliation and lineation, as indicating a late (post-thrusting) coaxial flattening superimposed upon originally asymmetrical fabrics produced by shearing deformation. This interpretation involving late coaxial overprinting requires that symmetric fabrics will be observed within the most highly deformed quartzites. Once again it is emphasised that both at the Stack of Glencoul and at Eriboll, symmetrical **c**- and **a**-axis fabrics are only observed within those quartzites exhibiting relatively low finite strain magnitudes, asymmetrical fabrics being recorded within the more highly deformed quartzites. These observations at the Stack of Glencoul argue strongly against Christie's interpretation of symmetric fabrics in the Assynt region of the Moine thrust zone as indicating a late period of coaxial flattening which took place after the shearing deformation.

At the Stack of Glencoul (Fig. 7) formation of the asymmetrical fabrics near the Moine thrust (non-coaxial deformation associated with WNW-directed overthrusting) must either be contemporaneous with, or later than, formation of the symmetrical fabrics (coaxial deformation) at greater distances from the thrust. If these symmetrical and asymmetrical fabrics are contemporaneous, then strain path partitioning must (as originally suggested in Section 9.1) have accompanied deformation. This strain path partitioning interpretation of spatial variation in crystallographic fabric symmetry has previously been shown by Law *et al.* (1984) to be applicable to the Eriboll mylonites.

Quartz **c**- and **a**-axis fabrics from the Allt nan Sleach section are predominantly asymmetrical with respect to foliation and lineation (Fig. 16); their sense of asymmetry is also consistent with WNW-directed thrusting. Although no strain markers are preserved within these strongly recrystallised $L-S$ and $L>S$ tectonites, intuitively it would seem that they have undergone far higher strains than 'within thrust sheet' mylonites from the Stack of Glencoul and Eriboll areas. In relation to these mylonites, the asymmetrical fabrics from the Allt nan Sleach mylonites could reflect either a greater degree of non-coaxiality associated with their entire deformation history, or a more advanced overprinting of coaxial by non-coaxial deformation.

10. Kinematic interpretation of dominant maximum in quartz *a*-axis fabrics

Bouchez (1978) and Bouchez *et al.* (1979) have proposed that in simple shear deformation of a quartzite, the dominant crystallographic slip direction ($\langle a \rangle$) will tend to become aligned parallel to the direction of bulk simple shear deformation. Thus for simple shear deformation, the dominant **a**-axis maximum would be interpreted as indicating the shear direction, and with increasing strain

(Ramsay & Graham 1970) one would expect the lineation lying within the foliation to be progressively rotated into alignment with this shear direction parallel ***a***-axis maximum (Boullier & Quenardel 1981, fig. 5).

If, as previously suggested, the quartzites located near the margins of the thrust sheets in the Assynt and Eriboll regions have been subjected to predominantly simple shear deformation and associated high shear strains, then the dominant ***a***-axis maximum in these tectonites should be aligned within the XZ plane at a very low angle to the lineation. However, X-ray texture goniometry indicates that these tectonites are characterised by a dominant ***a***-axis maximum which, although aligned within the inferred XZ plane, is inclined at 35°–25° to the lineation, indicating (for simple shear deformation) shear strains of 0·728–1·678 (Ramsay & Graham 1970) corresponding to shortening estimates perpendicular to the foliation of 30–53% (Ramsay 1980).

These shear strain estimates are extremely low for their structural position. Consider, for example, specimen SG1, a sample across the Cambrian quartzite–Moine contact (i.e. the Moine thrust) at the Stack of Glencoul. The mylonitic foliation in this specimen is parallel to the quartzite–Moine contact (Fig. 3b) and could be interpreted as indicating shear strains close to infinity. However, texture goniometry of a quartzite area located 0·5 cm beneath the contact in this specimen yields a single ***a***-axis maximum aligned within the inferred XZ plane, but inclined at 25° to the lineation (Fig. 6). According to the model of Boullier and Quenardel (1981), one would expect the ***a***-axis maximum in this specimen to be coincident in orientation with the lineation. Three possible interpretations of the ***a***-axis fabric for specimen SG1 are discussed below.

10.1. Complex strain path

The crystallographic fabric could be the product of a complex strain path. Theoretical studies (Sanderson 1982; Knipe 1985) suggest that complex strain paths may be produced by the motion of thrust sheets over ramps during thrusting. No evidence, however, has been found for such structures in the study areas and it is uncertain if, in general, such ramp–flat geometries would develop during ductile deformation.

10.2. Duplex slip

During simple shear deformation, the dominant ***a***-axis maximum may not have developed parallel to the shear direction. For example, intracrystalline deformation may have been dominated by the simultaneous operation of $\langle a \rangle$ slip on conjugate slip planes (duplex slip). However, although this process offers a potential explanation (using negative rhomb slip systems, see Section 7) for the double ***a***-axis maxima detected within the Allt nan Sleach mylonites (Fig. 16), it cannot explain the single ***a***-axis maximum detected in specimen SG1 (Fig. 6).

10.3. Degree of non-coaxiality

Perhaps it is unrealistic to think in terms of strict simple shear deformation. Many authors (e.g. Elliott 1972; Means *et al.* 1980; Pfiffner & Ramsay 1982; Lister & Williams 1983) have pointed out that on theoretical grounds there exists a complete spectrum of deformation paths of differing non-coaxiality (vorticity). This variation in the degree of non-coaxiality will clearly be reflected in the crystallographic fabrics produced by deformation. For example, if the vorticity of deformation was somewhere between pure shear and simple shear in these mylonites, this might have a profound effect upon the development of associated fabrics (Fig. 21).

In conclusion, therefore, it is probably more realistic to interpret the symmetry of crystallographic fabrics in terms of the degree of non-coaxiality (Behrmann 1982; Platt & Behrmann 1986) rather than in terms of strict coaxial or non-coaxial deformation.

11. Tectonic models

Two kinematic domains may be recognised within mylonites lying beneath the Moine thrust at the Stack of Glencoul and, also, within the Upper Arnaboll thrust sheet at Loch Eriboll; a domain of approximately coaxial deformation within the internal parts of the thrust sheets, and a domain of non-coaxial (approximately simple shear) deformation located near the thrust surfaces bounding the thrust sheets. In both areas no convincing difference in trend of lineations has been observed within the quartzites from these two domains and the intermediate principal axes of the finite strain ellipsoid (Y) inferred from the c-axis skeletal outlines are coincident. At the Stack of Glencoul it may, in addition, be demonstrated that mylonitic foliation within these two domains is parallel to the overlying Moine thrust.

Law *et al.* (1984) have previously argued that within the Upper Arnaboll thrust sheet these two kinematic domains were operating simultaneously during thrusting. A similar interpretation involving strain path partitioning may be proposed for the Stack of Glencoul mylonites, with non-coaxial deformation (involving a component of simple shear) close to the Moine thrust being accompanied by essentially coaxial deformation at greater distances beneath the thrust. Note, however, that this interpretation does not exclude the possibility that the domain of non-coaxial deformation may have been active for longer (cf. Section 3.4). Thus, for example, the gradual transition from symmetrical to asymmetrical ***c***-axis fabrics at the Stack of Glencoul (Fig. 7) may be interpreted as indicating either (1) the contemporaneous development of a vorticity gradient within these mylonites (see Section 9.1), or (2) the relative movement of material within the domain of coaxial flow into the domain of non-coaxial flow. Possible geological causes for the movement of material across strain path domain boundaries are discussed by Law *et al.* (1984, p. 495). On the basis of crystallographic fabric studies, similar examples of strain path (vorticity) partitioning have recently been recognised both within thrust sheets from the Betic Cordilleras of SE Spain (Behrmann 1982; Platt & Behrmann 1986) and also associated with the Northern Snake Range decollement of the eastern Basin and Range Province of Nevada (Miller *et al.* 1985).

Three tectonic models have been proposed by Law *et al.* (1984) to explain the distribution of kinematic domains within the Upper Arnaboll thrust sheet at Eriboll. One of these models involves the deformation of bedded quartzites being carried over a ramp. In detail, deformation of the quartzites in this model may involve shearing along discontinuities such as bedding, accompanied by coaxial thinning and extension of the quartzites between the discontinuities. No direct field evidence to support this ramp-related model has been found in the Stack of Glencoul area, although it is possible that coaxial thinning of the quartzites at this locality may have been accompanied by shearing within those interlayered phyllosilicate-rich horizons which contain single sets of shear bands (see Section 3).

The other two models proposed by Law *et al.* (1984) for the Upper Arnaboll thrust sheet involve important gravitational components. In one model the domains of coaxial and non-coaxial deformation are associated with the emplacement of a frontal culmination. Loading of material beneath the culmination may generate coaxial thinning of the lower level thrust sheet and simultaneous extrusion accompanied by shearing. In the alternative model, involving a gravitational component, it is proposed that extensional flow (plane strain with maximum extension parallel to the transport direction) involving coaxial deformation was produced by gravity spreading (Elliott 1976) from a thickened Caledonian mass to the E of the present day outcrop of the Moine thrust zone. This coaxial deformation would be accompanied by shearing (non-coaxial deformation) along the base of the extensional flow regime.

Possible field evidence for extensional flow associated with mylonite formation at the Stack of Glencoul has been described by Coward (1982, 1983). Within the mylonitic Cambrian Pipe Rock at this locality, Coward (1982, p. 252) has noted that pipes show elliptical outlines (aspect ratios 5:1) on bedding surfaces, the long axes of these elliptical outlines being parallel to the transport direction. Assuming no shortening of the thrust zone normal to the transport direction, these axial ratios indicate considerable thinning and layer parallel elongation of the quartzites, and have been interpreted by Coward (1983, p. 797) as providing evidence for extensional flow within these mylonites. It has previously been demonstrated (see Section 7) that mylonites within the domain of inferred coaxial flow at the Stack of Glencoul are characterised by deformation features indicative of flattening ($k < 1$) strains. Thus deformation within these tectonites appears to have, at least slightly, departed from strict extensional ($k = 1$) flow.

Some 5 km to the N of the Stack of Glencoul, immediately to the NW of Loch Strath nan Aisinnin (Fig. 1) considerable bulk vertical shortening may be demonstrated within mylonitic Cambrian Pipe Rock which is preserved within a series of imbricate slices whose floor thrust branches onto, and forms a linked fault system with, the underlying Glencoul thrust (Butler 1984a, b). Within the Pipe Rock of this area, pipes are highly flattened and aligned parallel to an intense mineral lineation which plunges towards 110° (Butler 1984b). In one section through the mylonites in this areas immediately to the N of Loch Strath nan Aisinnin, C. T. Clough (in Peach *et al.* 1907, p. 499) has estimated a total thickness of just 13 m for the Cambrian quartzite. This stratigraphic thickness for these mylonitic quartzites, when compared with their known stratigraphic thickness in the undeformed foreland sequence, suggests a bulk vertical shortening of 82% (Butler 1984b). Clearly this intense stratigraphic thinning cannot be associated with bedding parallel shearing. Field relationships dictate (Butler 1984b, p. 178) that these extensional strains are synchronous with, or immediately post-date, the emplacement of the overlying Moine sheet. Butler (1984b) has suggested that the Cambrian quartzites in the footwall to the Moine thrust may have extended parallel to the transport direction as the *c.* 10 km thick Moine sheet climbed onto the Cambro-Ordovician shelf; this field data supports the tectonic loading model proposed by Law *et al.* (1984) for the Eriboll mylonites located immediately beneath the Moine thrust.

Gravitational spreading has been invoked by Coward (1983, 1984) and Butler and Coward (1984) as the main driving force for early deformation within the northern part of the Moine thrust zone. This suggestion is based on the general observation that deformation within the area usually involves thrusts which cut up section from basement to cover in the transport direction, but also involves localised extensional flow and thinning of the thrust sheets.

Thus there is considerable possible agreement between the tectonic models proposed on the basis of large scale studies of thrust sheet geometries in northern Assynt and tectonic models proposed on the basis of both microstructural and crystallographic fabric studies at the Stack of Glencoul in northern Assynt and further N at Loch Eriboll. Extensional flow (*sensu lato*), possibly associated with either gravity spreading or tectonic loading, is considered to be a tectonic process of at least local importance within this part of the Moine thrust zone. Due to the general paucity of exposure, it has proved impossible to make any objective geometrical test of whether these tectonic models may be applied to the mylonites of southern Assynt. No convincing evidence for extensional flow has been found within the Allt nan Sleach mylonites of southern Assynt.

12. Conclusions

The integration of microstructural and crystallographic fabric studies of quartz mylonites from the Assynt and Eriboll regions of the Moine thrust zone leads to the following conclusions.

1. A correlation is established between shape fabric symmetry and pattern of crystallographic preferred orientation. Quartz ***a***-axis fabrics obtained from X-ray texture goniometry are, in general, found to be more sensitive to variation in shape fabric symmetry than optically measured ***c***-axis fabrics.
2. At the Stack of Glencoul in northern Assynt, two kinematic domains are recognised. At distances of greater than 30 cm beneath the Moine thrust, essentially coaxial deformation is indicated by quartz ***c***- and ***a***-axis fabrics which are symmetrical with respect to foliation and lineation. Closer to the thrust, non-coaxial deformation is indicated by asymmetrical ***c***- and ***a***-axis fabrics; the sense of crystallographic asymmetry in these more highly deformed and recrystallised quartzites is consistent with WNW-directed overthrusting. This kinematic interpretation is supported by microstructural studies of these $S > L$ and $L - S$ tectonites. Formation of the asymmetrical fabrics (non-coaxial deformation) near the thrust surface must either be contemporaneous with, or later than, formation of the symmetrical fabrics (essentially coaxial deformation) at greater distances beneath the thrust. A similar, although less clearly defined, correlation between fabric symmetry and proximity to thrust surfaces has been detected within the Upper Arnaboll thrust sheet at Loch Eriboll (Law *et al.* (1984)).
3. In contrast, no such correlation between fabric symmetry and proximity to thrust surfaces has been found within the Allt nan Sleach mylonites of southern Assynt. Non-coaxial flow associated with WNW-directed overthrusting is indicated by both microstructures and crystallographic fabrics within these intensely deformed and recrystallised $L - S$ and $L > S$ tectonites.
4. Quartz ***a***-axis fabrics from the Assynt mylonites indicate that it is probably more realistic to interpret the symmetry of crystallographic fabrics in terms of the degree of non-coaxiality (vorticity) rather than in terms of strict coaxial or non-coaxial deformation.
5. Extensional flow, possibly associated with either tectonic loading or gravity spreading, has been suggested by

Butler and Coward (1984) to have been a tectonic process of at least local importance within the northern Assynt region of the Moine thrust zone. The identification of kinematic (strain path) domains within mylonites from the Stack of Glencoul provides additional support for these models, which were based on larger-scale studies of thrust sheet geometries. These models also offer an explanation for the presence of similar kinematic domains within the Upper Arnaboll thrust sheet located further N at Loch Eriboll (Law *et al.* 1984).

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