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Relationships between marginal thrusting and movement on major, internal shear zones in the Northern Highland Caledonides, Scotland

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Abstract—The development of the syn-metamorphic Sgurr Beag slide zone, a major ductile shear zone of initially low dip, caused at least 50 km north-western thrust displacement of part of the internal metamorphic complex of the Northern Highland Caledonides of Scotland. Initiation of the zone, and movements upon it, were earlier than formation of the marginal Moine Thrust zone. Movement on the zone followed but overlapped the peak Caledonian metamorphism and the mid to high amphibolite facies mineral assemblages, fabrics and structures produced during the development of the slide zone and those surviving from earlier events, were reworked under greenschist facies conditions during mylonitization associated with initiation of the Moine Thrust zone. Displacements on the slide zone and thrust movements were separated by emplacement of a regional suite of pegmatites and a considerable change of metamorphic grade. Thus, they may not constitute members of a progressive sequence of Caledonian thrusts formed over a short time interval. Rather, preliminary isotopic data may imply an interval of *c*. 25 Ma between movement on the slide zone and final, ductile translation along the Moine Thrust zone.

INTRODUCTION

THE DISCOVERY, in the Northern Highlands of Scotland, of major ductile shear zones (slides), (Tanner 1971, Tanner *et al.* 1970, Rathbone & Harris 1979, Powell *et al.* 1981), which appear to be deep crustal analogues of thrust zones, is leading to a reappraisal of the structure and evolution of the Orthotectonic Caledonides of Northern Britain. In particular, the possible role of crustal overthrusting is being evaluated (Soper & Barber 1982, Coward 1983, Powell & Phillips in press). An assumption common to most of these recent discussions is that thrusting, marginal to the orthotectonic zone, and internal 'sliding', are both Caledonian in age and broadly coeval, forming a sequence of foreland propagating thrusts.

It is against this background that the relationships between the development of the Moine Thrust zone at the northwestern boundary of the metamorphic Caledonides in Northern Britain (Fig. 1), and the Sgurr Beag slide zone, a regionally developed ductile shear zone lying within Proterozoic Moine rocks of the Caledonide metamorphic complex of the Northern Highlands (Fig. 1), are herein examined.

The relationships between the relative timing of movements in the Moine Thrust zone and the structural/metamorphic events of the Northern Highland metamorphic complex has been a subject of controversy since the initial mapping by the British Geological Survey in the late nineteenth century. Bailey (1935) argued that the thrust zone and the Moine rocks of the metamorphic complex shared the same deformation history and that all tectono-metamorphic events were Caledonian in age. On the other hand, Read (1934) argued that development of the Moine Thrust zone was entirely younger than the regional metamorphism of the Moine schists.

A four phase sequence of deformation was proposed for both zones (Johnson 1957, 1960, Christie 1963, Barber 1965, Soper & Wilkinson 1975), but more recent work has suggested a more complex deformation history for the Moine schists (Tobisch *et al.* 1970, Powell 1974, Barber & May 1976). The earliest deformation (mylonitization) within the thrust zone, affects fossiliferous Cambro-Ordovician shelf sediments (Soper 1971) and is thus younger than Arenig (Llanvirn?—Higgins 1967, i.e. *c.* 478 Ma) but older than 430 Ma, the age of intrusion of the Loch Borolan syenite (van Breemen *et al.* 1979b). Recent isotopic studies of Moine schists and associated rocks in the metamorphic complex, reflect the effects not only of Caledonian tectonic and metamorphic activity between *c.* 460 and 400 Ma (post-intrusion of the Carn Chuinneag granite at *c.* 555 Ma; Pigeon & Johnson 1974), but also Precambrian orogenic events (van Breemen *et al.* 1978, 1979a, Brewer *et al.* 1979, Powell & Phillips in press).

The broad coincidence at *c.* 450 Ma, of early movements in the thrust zone and the D_1 and D_2 deformation phases, displacement on slide zones, and peak metamorphism in the Moine schists, has been postulated (Soper & Barber 1982). Indeed, isotopic evidence (Brewer *et al.* 1979) and similarities in the geometry of the thrust and slide zones at depths inferred from seismic reflection profiles (Smythe *et al.* 1982, Brewer & Smythe 1984), imply a Caledonian age for movement on the slide zones but, as yet, the precise age of their initiation is not known.

The present work provides evidence that mylonitization within the thrust zone effected reworking, at low grades of metamorphism, of metamorphic Moine schists that had previously suffered extensive translation along the Sgurr Beag slide under amphibolite facies metamorphic conditions. Thrust and slide movements, at least in the Fannich–Ullapool area (Fig. 1), where the Moine thrust and Sgurr Beag slide zone approach to within 2 km

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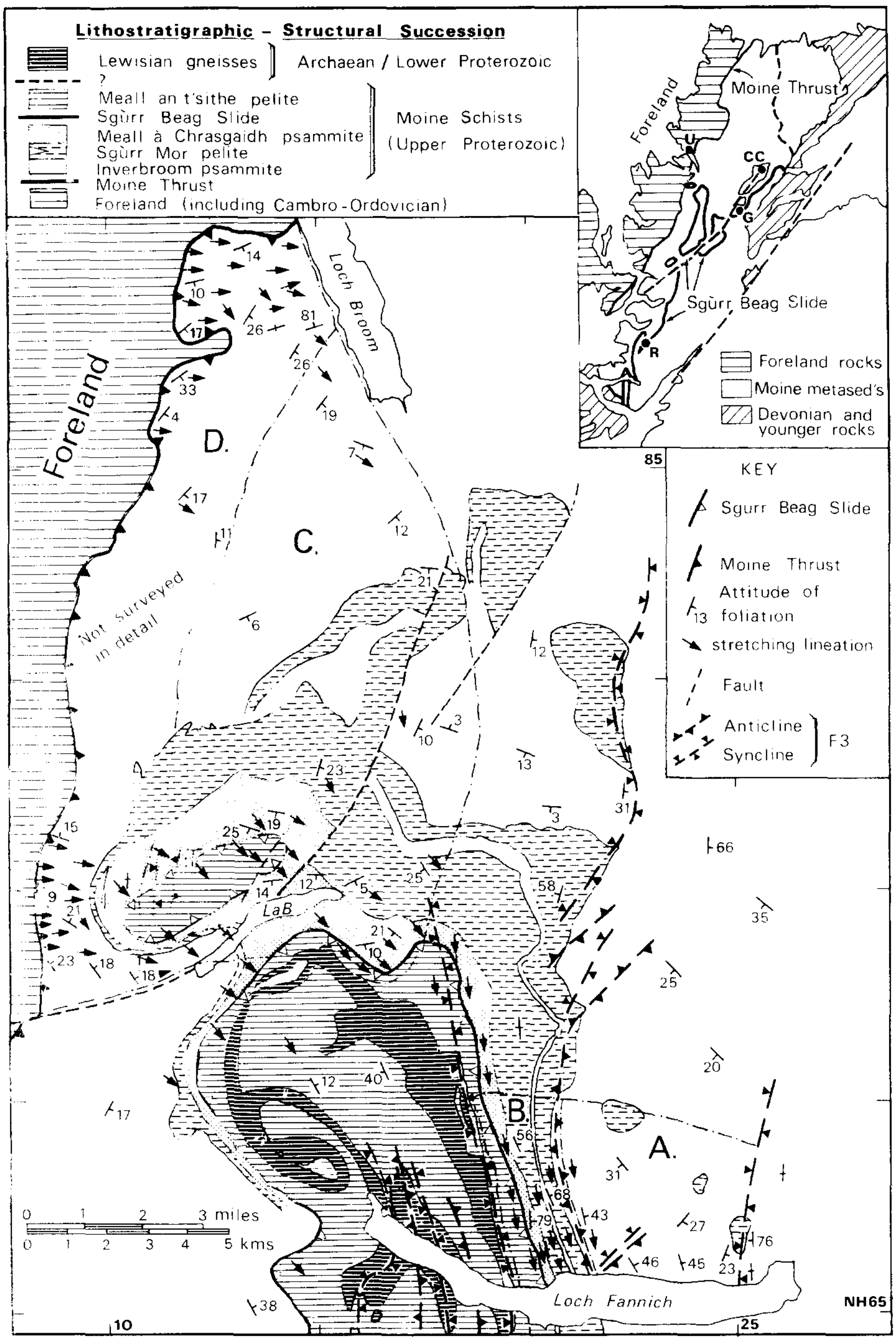


Fig. 1. Location and geological map of the Ullapool–Fannich area. CC, Carn Chuinneag; G, Garve; LB, Loch Broom; LaB, Loch a Bhraoin; LF, Loch Fannich; R, Ranochan; U, Ullapool; (A) to (D), sub-areas referred to in text. The boundary between sub-areas C and D corresponds to the upper limit of mylonitic rocks in the Moine Thrust zone. Based on mapping by Kelley, and Sutton & Watson (1954).

of each other, are separated by a regional phase of pegmatite emplacement and a change from mid-high amphibolite facies to greenschist facies conditions.

THE SGURR BEAG SLIDE

Several tectonic slides have been described from Moine rocks in the Northern Highlands of Scotland (Tanner *et al.* 1970, Powell 1974, Rathbone & Harris 1979, Soper & Barber 1982). The best documented example, the Sgurr Beag slide zone (Tanner 1971) has the most extensive outcrop, being traceable over 150 km from the area around Carn Chuinneag in the north, to Ardnamurchan in the south (Fig. 1). The slide represents a major zone of tectonic translation within which slices of Archaean to Lower Proterozoic basement have been emplaced into the Moine cover. It separates high-grade migmatitic pelites and psammites of the Glenfinnan division of the Moine schists, from lower-grade metasediments of the Morar division (Johnstone *et al.* 1969).

Over much of its outcrop the slide zone is deformed by later major folds, but itself has reworked structures and

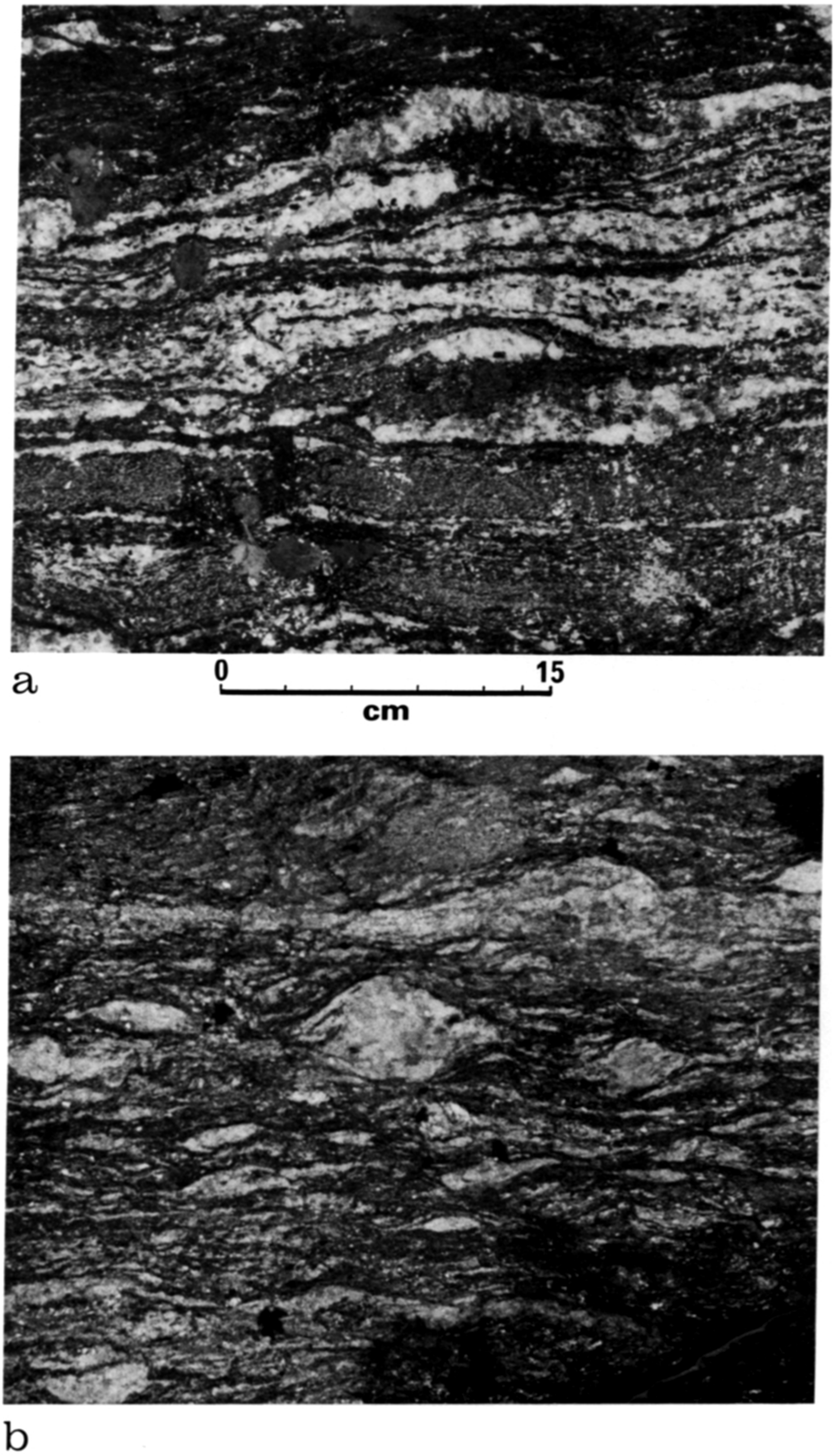
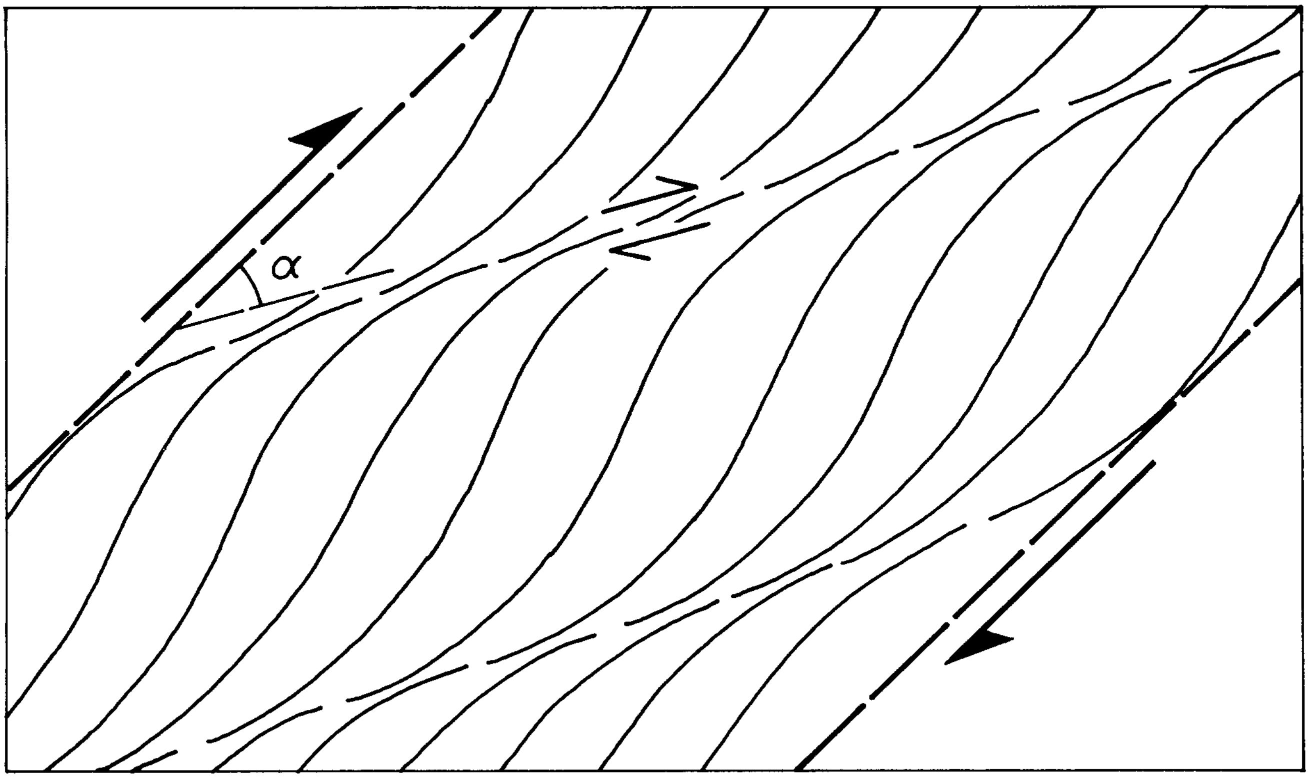


Fig. 2. Contrasting features of Glenfinnan division migmatites outside and within the Sgurr Beag slide zone. (a) 200 m from slide zone; quartzo-feldspathic stringers and lits are elongate and form a pre-D_2 (sliding) foliation. (Grid ref: NH195673. (b) Within high strain area of slide zone; stringers and lits disrupted into augen as a result of D_2 strain. (Grid ref: NH197676).

a



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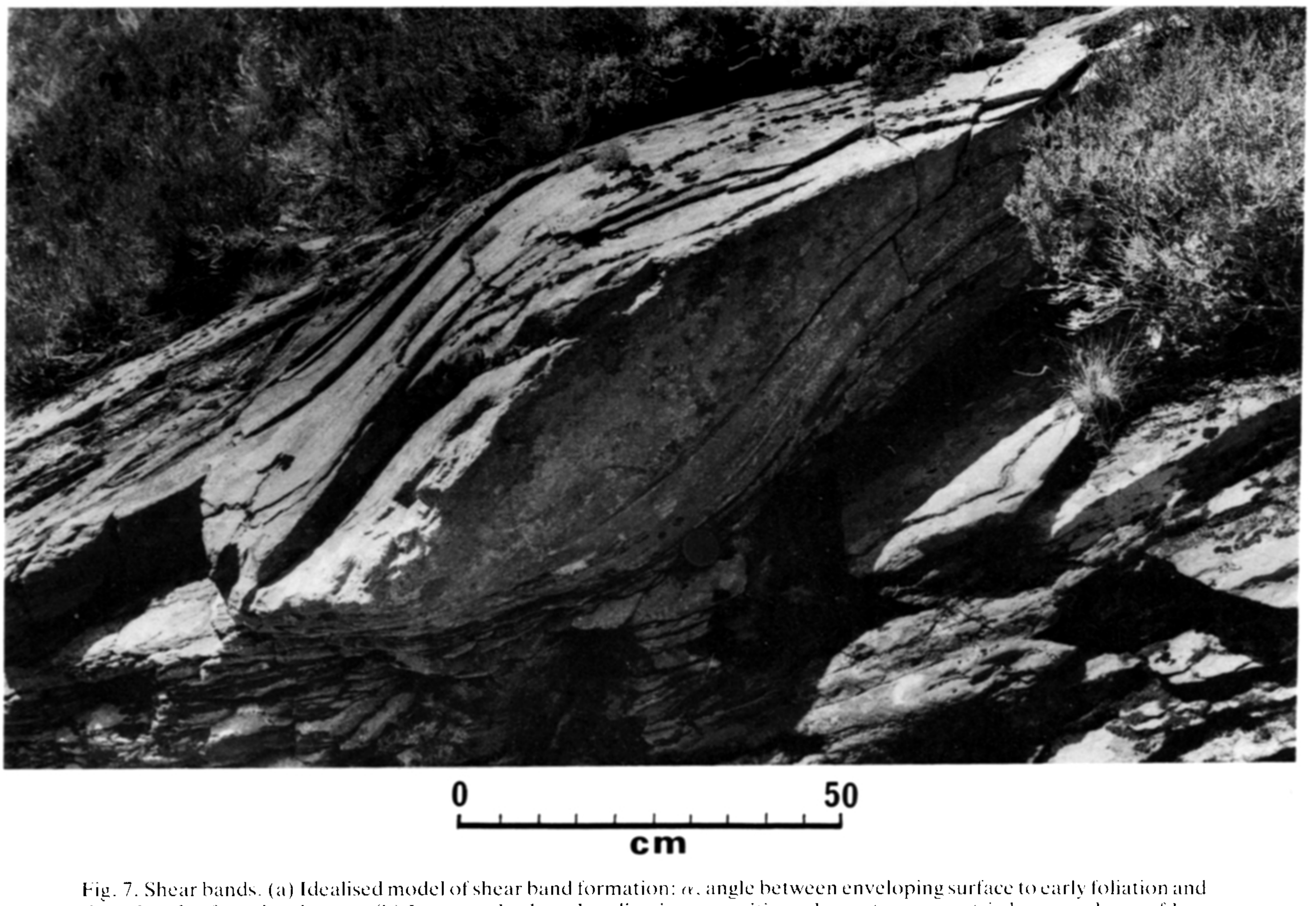

Fig. 7. Shear bands. (a) Idealised model of shear band formation: α, angle between enveloping surface to early foliation and shear band referred to in text. (b) Large-scale shear banding in psammitic rocks; note asymmetric lozenge shape of low strain pod indicating sense of shear (cf. [a]); intensity of mylonitic foliation increases towards ends of lozenge, that is into shear bands (Grid ref: NH095741).

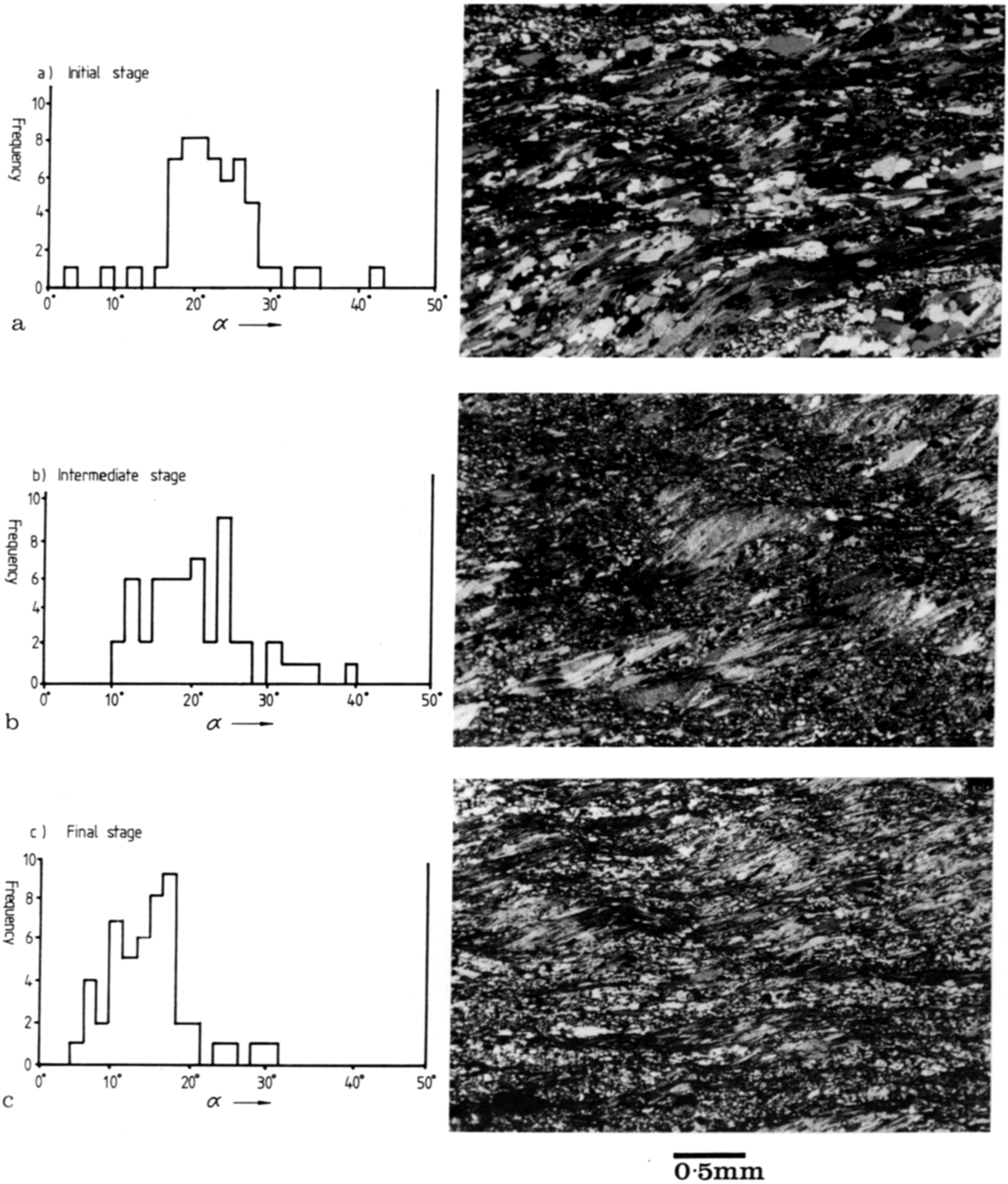

Fig. 8. Progressive development of shear bands in pelitic rocks. (a) Mica schist marginal to mylonite zone illustrating pre-mylonitization grain sizes and fabric and the beginnings of grain size reduction and shear band formation. Note range in α with mean at *c.* 22° (Grid ref: NH187798). (b) Intermediate stage in mylonite zone showing increase in number of shear bands and increase in grain size reduction. Relict white micas remain in low strain lozenges. Note reduction in mean α (Grid ref: NH163869). (c) Severe grain size reduction in mylonitized mica schists (cf. [a]). Note mean α at *c.* 15° (older shear bands have rotated) but generation of new shear bands (α = 25–30°) (Grid ref: NH144894).

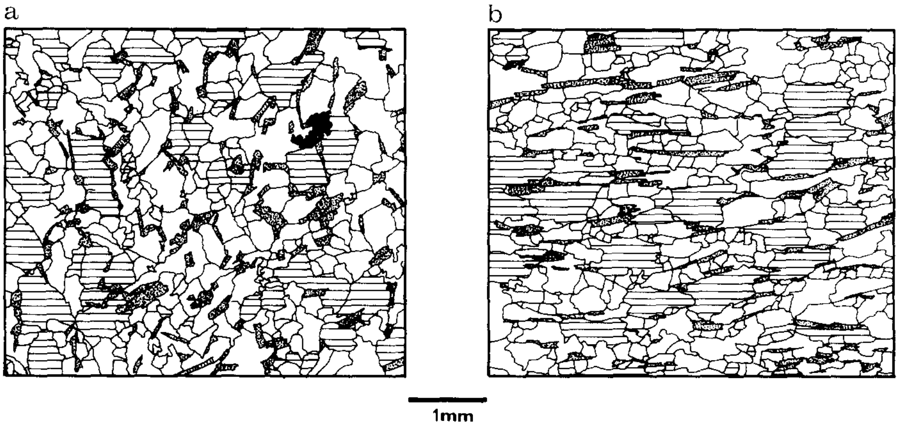

Fig. 3. Contrasting textures and fabrics within psammitic rocks of the Morar division. (a) Inverbroom psammite outside slide zone; note random orientation of micas (stippled) and plagioclase (lined); quartz (white). (Grid ref: NH237668). (b) Meall a Chrasgaidh psammite from within slide zone; note preferred shape (and crystallographic) orientation of mica and elongation of plagioclase parallel to mica fabric (Grid ref: NH199667).

fabrics of earlier phases of deformation and metamorphism (Powell *et al.* 1981, Baird 1982). Possible cross-cutting relationships to lithological banding (modified bedding) of adjacent Moine rocks have been reported only at Ranochan near Glenfinnan (Fig. 1a) (Baird 1982). Elsewhere, the slide zone parallels the lithological banding. Within the Fannich area, the Sgurr Beag slide zone outcrop includes the boundary between the Meal an t'sithe pelite and the Meall a Chrasgaidh psammite (Fig. 1) and it is parallel to lithological banding on all scales. Its initiation and development coincided with the D_2 phase of a local D_1 to D_4 deformation sequence.

As elsewhere, (Tanner *et al.* 1970, Rathbone & Harris 1979) the Sgurr Beag slide zone in Fannich is associated with the emplacement of thin (2 cm–1.5 m thick) slices of Lewisian basement at high levels in the Moine lithostratigraphic succession; the latter represented by thin bands of hornblende + epidote-rich rock found within Moine psammites in the highest strain areas of the slide zone.

Rathbone & Harris (1979) described a number of features related to the progressive increase in strain associated with the Sgurr Beag slide zone: rotation of fold hinges, reduction of fold interlimb angles, decreases in the bedding/foreset angles of cross-bedded units, and reduction in the angular discordance between foliation and early quartz veins. Thus, angular discordances between planar elements in low strain rocks outside the slide zone were found to decrease progressively into the highest strain zones where near perfect parallelism of all planar features is achieved.

In the Fannich area, a similar progressive increase in strain is observed approaching the boundary between the Meall an t'sithe pelite and Meall a Chrasgaidh psammite. Although evidence of syn-slide folding is sparse, the D_2 foliation becomes progressively more intense as the slide zone is approached and a coarse extension lineation is developed in psammites adjacent to the slide. The lineation is defined by elongate grains of quartz and feldspar, and alignment of the basal planes of micas and mica shape. It is weak outside the slide zone (over 800 m from the slide), but becomes progressively more intense into the slide zone until the fabric approaches that of an $L \geq S$ tectonite (Flinn 1962). The lineation generally trends towards 130–140° (Fig. 5f).

In the Morar division rocks to the west of, and structurally below, the slide zone, foreset beds and oblique quartz veins progressively approach parallelism with a foliation defined by the alignment of mica basal planes as the slide zone is approached over a distance of 800 m (Fig. 3b). Parallelism is achieved in a 50 m wide, platy zone, within the Meall a Chrasgaidh psammite where it abuts the Meall an t'sithe pelite of the Glenfinnan division. The slide zone foliation is a composite fabric comprising modified bedding, S_1 and S_2.

In the Glenfinnan division rocks, F_2 folds, together with an axial-plane S_2 schistosity, rework an earlier coarse migmatitic fabric. Quartzo-feldspathic lits become increasingly flattened and planar towards the slide zone and develop augen structures adjacent to the contact with the Meall a Chrasgaidh psammite (Fig. 2).

The progressive reduction in grain size in psammites, described by Rathbone & Harris (1979) within the slide zone at Garve (Fig. 1), is not seen in Fannich. Here, instead, quartz grains change from equidimensional, in low strain areas, to strongly elongate in high strain zones as a strong preferred shape, and crystallographic orientation of mica progressively develops (Fig. 3).

Preliminary studies of quartz c-axis orientations for low-strain cross-bedded Moine psammites in the Fannich area, reveal random patterns (Fig. 4a), whereas a single girdle fabric lying approximately perpendicular to the extension lineation is found in the most highly strained psammites in the slide zone (Fig. 4b). Such girdle patterns are found in mylonitic rocks where they have been interpreted as having formed during simple shear (Burg & Laurent 1978, van Roermund *et al.* 1979, Lister & Williams 1979). The direction of shearing, given by the sense of asymmetry of the girdle from Fannich is compatible with overthrusting towards the northwest if the conclusions of White *et al.* (1982) are correct.

The metamorphic contrast between the Morar and

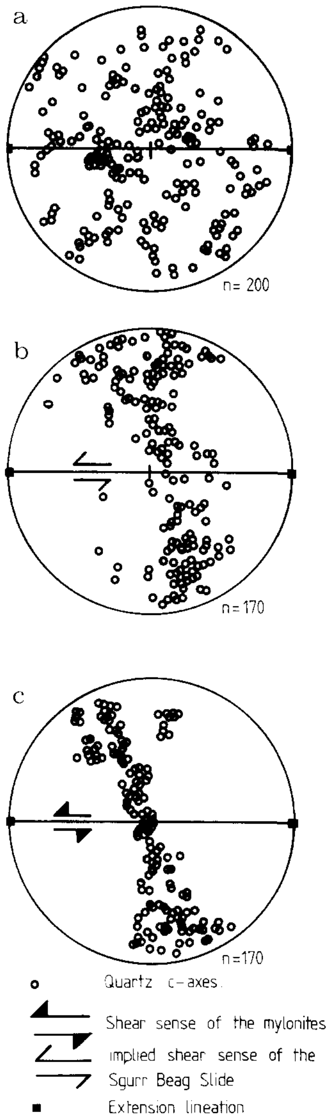

Fig. 4. Quartz c-axis fabrics from psammitic rocks of the Ullapool–Fannich area. All projections are lower-hemisphere equal-area. Foliation planes are shown by a horizontal line; extension lineations by squares on primitive. (a) Inverbroom psammite outside slide and mylonite zones. Note lack of preferred orientation (Grid ref: NH237668). (b) Meall a Chrasgaidh psammite within slide zone. Note development of girdle fabric at c. 70° from extension lineation; intersection of girdle and foliation plane lies at c. 90° to lineation, cf. (c). (Grid ref: NH162736). (c) Mylonitic Inverbroom psammite from thrust zone. Note typical mylonitic girdle fabric. (Grid ref: NH085750).

Glenfinnan division rocks lying respectively below and above the Sgurr Beag slide zone throughout its outcrop, is difficult to define exactly in terms of grade, due to the paucity of appropriate index minerals in pelitic rocks (Winchester 1974). However, Powell *et al.* (1981), using the mineralogy of sporadically developed calc-silicate bands as grade indicators, have described an apparently abrupt change in metamorphic grade within the slide zone in the SW Moine. The metamorphic pattern is attributed to syn-metamorphic movement across the slide zone which, not only displaced contemporary isotherms, but also reworked an early metamorphic complex. The slide zone emplaced hot rocks, possibly at kyanite grade or above, over cooler rocks which were at almandine grade (Powell *et al.* 1981, p. 672). In the Fannich area, in the absence of other evidence, the superposition of Glenfinnan division migmatitic pelites over the non-migmatitic Sgurr Mor pelite of the Morar division (Fig. 1), provides qualitative evidence of a similar break if the formation of migmatites is dependent upon temperature, the composition of plagioclase and alkali feldspars, the ratio of quartz : alkali feldspar : plagioclase feldspar and the availability of water, alone (Winkler 1976). If no tectonic break were present between the two pelites in Fannich, the preferential migmatization of the Meall a t'sithe pelite should depend solely upon its higher susceptibility to migmatization. However, the An content of plagioclase and the alkali feldspar : plagioclase : quartz ratios of the Meall an t'sithe and Sgurr Mor pelites are similar; both pelites containing dominantly oligoclase–andesine and ratios of alkali feldspar, plagioclase and quartz are 1 : 3 : 4.

The regional distribution of migmatitic rocks throughout the Glenfinnan division outcrop, and the apparent lack of a spatial association of migmatites with slide zones in much of the Northern Highland Moine schists seemingly precludes migmatization as a result of enhanced fluid flow during shearing along slide zones.

Minimum displacements across the Sgurr Beag slide zone in the SW Moine outcrop are 15 to 20 km, assuming overthrusting towards the northwest (Powell *et al.* 1981). In Fannich, the extension lineation and quartz c-axis fabrics associated with the slide zone imply northwestward overthrusting. The most westerly outcrop of this slide zone is at Loch a Bhraoin (Fig. 1) from where it can be extrapolated further eastwards, above ground surface, until it reappears at Garve (Fig. 1); a total horizontal distance of 30 km. Taking the probable amplitude of post-slide major folds into account and the absence of Glenfinnan division rocks below the slide along the whole of this section, a minimum displacement of 50 km can be deduced.

POST-SGURR BEAG SLIDE DEFORMATION

Mylonites above the Moine Thrust in the Ullapool area (Fig. 1) are, as shown later, interpreted as forming during and after the third phase of folding in Fannich. Although the Fannich area and Moine Thrust belt lie only 12 km apart across strike, straightforward correlations of deformation phases can not be made on the basis of fold style or orientation alone. Strongly inhomogeneous strain in the area has caused large variations of both style and orientation similar to those recorded in shear zones in Greenland (Esher & Watterson 1974) and modelled by Sanderson (1973) and Roberts & Sanderson (1974).

East of the Moine Thrust belt in Fannich, folds of the third phase of deformation consist of a series of symmetrical major folds trending N–S and overturned to the west (Fig. 1). The Sgurr Beag slide zone and the Glenfinnan division migmatites above the slide, form the core of a major F_3 fold, the Fannich synform (Fig. 1) which clearly deforms D_2 structures including the slide

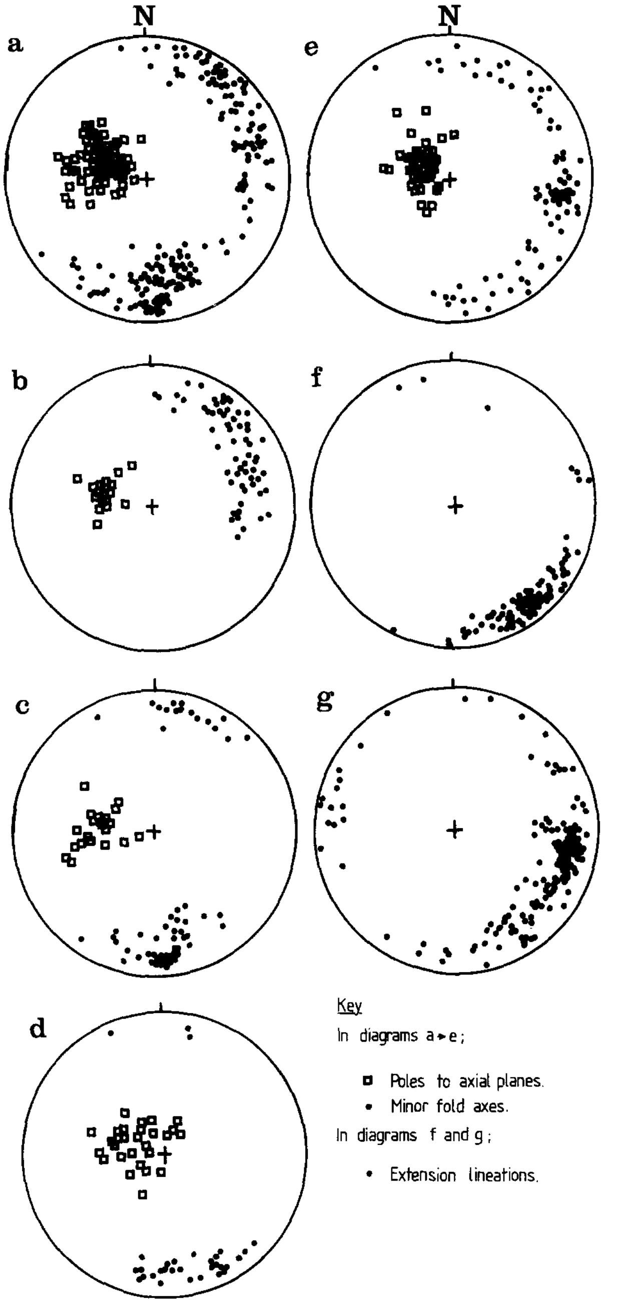

Fig. 5. Structural data for the Ullapool–Fannich area. Lower-hemisphere, equal-area projections. (a) D_3 minor fold hinges and axial planes in the Fannich area; note consistency in attitudes of axial surfaces compared with variation in plunge of axes within mean axial plane. (b), (c), (d) and (e) Attitudes of D_3 structural elements from sub-areas (a)–(d), respectively; see Fig. 1 for location of sub-areas. Note that in sub-area (d), closest to the Moine Thrust, the variation of axial trend within the mean axial plane is as great as that found in the Fannich area (diagram a). (f) Attitudes of extension lineations in rocks greater than 3 km from the thrust zone; these lineations relate to formation of the Sgurr Beag slide. (g) Attitudes of extension lineations within, and up to 3 km from the Moine Thrust zone; the plot includes lineations related to deformation during mylonitization and rotated 'slide' lineations.

zone fabrics. In pelites, a strong axial-plane fabric, crenulating the earlier, penetrative Sgurr Beag slide fabric, is associated with F_3 folds. However, in psammites, only a weak axial-plane fabric is developed at the hinge zones of minor folds. The axial planes of F_3, and the crenulation cleavage are co-planar, trending 010/45°E (Fig. 5a).

F_3 fold hinges are curvilinear, as was first noted by Sutton & Watson (1954); a geometry that is witnessed by the spread of hinge orientation within the mean axial planes of F_3 folds (Figs. 5b–e). The orientations of minor F_3 fold hinges reflect not only the regional variation seen in the major fold axes, but also exhibit considerable variation within and between sub-areas defined by single major F_3 fold limbs (Figs. 1 and 5b–e). When all folds of the Fannich area are considered, a spread of 180° in axial trend is developed (Fig. 5a). Variations of up to 180° can be seen in the trend of hinge lines for single minor folds, but within small areas they are generally parallel to adjacent major fold hinges.

Sub-area (a) (Fig. 5b) comprises part of the gently dipping limb of the Achnasheen antiform (Fig. 1); sub-area (b) (Fig. 5c) part of its steeply dipping western limb; sub-areas (c) and (d) comprise gently dipping rocks west of the Fannich synform, but (d) includes mylonitic rocks associated with the Moine Thrust zone. Traced westwards from Fannich, F_3 fold axial planes progressively flatten towards the foliation plane of the mylonites (Figs. 5b–e), fold profiles tighten, and the associated axial-plane crenulation schistosity becomes a penetrative fabric due to the breakdown of early micas. The orientation of minor fold hinges changes from distributions showing broad spreads of up to 85° to a girdle distribution through 180° [sub-area (d)]. In sub-area (d), F_3 folds are tight to isoclinal with flatter lying axial planes than those of F_3 in Fannich. In contrast to sub-areas (a), (b) and (c), the distribution of F_3 minor fold hinges shows a variation in azimuth of 180°, whilst within the mylonite belt there is a concentration of F_3 fold hinges parallel to the extension lineation associated with the mylonitic banding (Figs. 5e & g). The spread of 180° is, however, still observed when only the most highly strained rocks are considered. All the minor folds plotted in Fig. 5(e) are considered to be of the same generation; no interference patterns were seen; all fold axial surfaces are closely co-planar; and a strong axial-plane fabric is developed. They deform a regionally developed pegmatite suite. Because no evidence has been found for the existence of more than one generation of folds, the tight to isoclinal folds, which post-date the mylonite lineation, are interpreted as having formed later in a progressive single shear process rather than during a separate, later event (see also Bell 1978).

Esher & Watterson (1974) showed that folds formed as a result of simple shear should nucleate approximately perpendicular to the movement direction and rotate passively towards it as shearing continued. New folds formed during shearing would deform structures and fabrics formed earlier in the same process. The shear zone should, therefore, exhibit rotated (old) folds parallel to the movement direction and younger folds which deform earlier shear fabrics. The nucleation/rotation mechanism best explains the complete spectrum of fold orientations described above, and accords with those reported for many major thrust belts (Bryant & Reed 1969, Bell 1977, Williams, Pfiffner 1981).

Such rotation of fold axes towards the movement

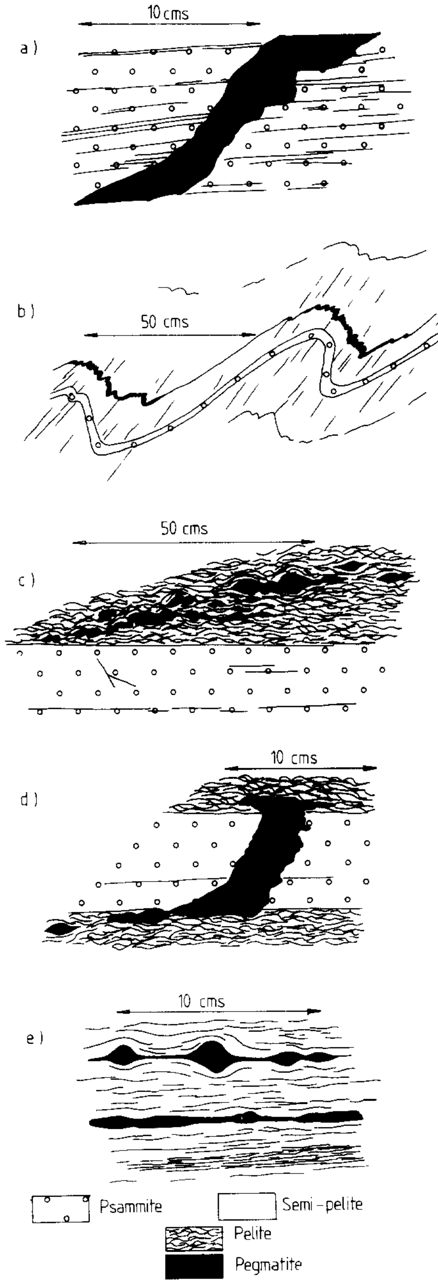

Fig. 6. Structural relationships of post-slide, pre-mylonite pegmatites. (a) Pegmatite cross-cutting highly strained psammite in slide zone (Grid ref: NH197678). (b) Pegmatite folded by minor D_3 fold (Grid ref: NH1897792). (c) Boudinaged pegmatite still recognizably oblique to pelitic layer, disrupted during layer-parallel shear during D_3 (Grid ref: NG203781). (d) Pegmatite cross-cutting psammite layer but boudinaged and rotated in pelite during D_3 deformation (Grid ref: NH144763). (e) Highly deformed pegmatite in semi-pelite mylonite; note parallelism of veins and mylonitic foliation (Grid ref: NH147895).

direction in the Moine Thrust zone was first postulated by Bryant & Reed (1969), and more recently proposed by McClay & Coward (1981). The Moine Thrust belt is, however, complicated by late folding which is probably related to the differential movement between thrust sheets (Elliott & Johnson 1980, Coward & Kim 1982).

RELATIVE TIMING OF MOVEMENTS

The evidence given above strongly suggests a difference in the age of formation and development of the Sgurr Beag slide zone, production of D_3 structures, and mylonitization. Further evidence is provided by the occurrence in the Fannich–Ullapool area of a suite of pegmatites that are common and widespread. Undeformed pegmatites, consisting almost entirely of quartz and K-feldspar with subsidiary plagioclase and pyrite, range from 2 to 10 cm in width, up to 5 m in length. Trace amounts of white mica and epidote are also present. Suites of cross-cutting pegmatites that might suggest different ages of pegmatite emplacement have not been seen.

In the Fannich area, these pegmatites intrude highly strained rocks of the Sgurr Beag slide zone, where they completely cross-cut and are unaffected by fabrics associated with the slide zone (Fig. 6a). Minor F_3 folds in Fannich deform the pegmatites (Fig. 6b) and the Sgurr Beag slide zone fabrics.

Further west, the pegmatites become progressively more deformed, and within the mylonites the pegmatites become highly attenuated. Large (1–2 cm diameter) K-feldspar porphyroclasts form augen, exhibiting strained, patchy extinction and brittle fracture. Quartz forms pressure shadows adjacent to the feldspars and highly strained stringers between the augen. These features are accompanied by a general grain size reduction and demonstrate that mylonitization followed pegmatite emplacement (Figs. 6c & d).

From the evidence given above and in the preceding section, it appears that a set of folds (F_3), which post-date formation of the Sgurr Beag slide zone and a regionally developed pegmatite suite, can be traced in a continuous traverse westwards from Fannich to the mylonites above the Moine Thrust. The evidence of changing fold styles, pegmatite deformation and the formation of a mylonitic foliation, indicate progressively increasing strain towards the mylonites and a link between mylonite formation and D_3 deformation. Additionally, mylonite formation and the development of the Sgurr Beag slide zone are clearly separate events.

DEFORMATION IN THE MYLONITE ZONE

Psammitic rocks

The strike of the Sgurr Beag slide foliation and the parallel, tectonically modified lithological/sedimentary banding is, in the area to the south of Loch Broom, oblique to that of the mylonites (Fig. 1) (see also Peach *et al.* 1913), a relationship which demonstrates that the mylonitic fabric was not everywhere developed parallel to the earlier foliation and banding of the Moine metasediments.

In psammitic rocks above and to the east of the Moine Thrust zone, the first indications of structures that relate to mylonite formation are sporadically developed small shear zones (analogous to the shear bands of Gapais & White 1982). As the thrust zone is more closely approached, these become more common, intensify, and then are superseded by general grain size reduction. A wide range of fabrics are present in psammitic rocks east of the mylonites. In the north, close to Loch Broom (Fig. 1), rare sedimentary structures are preserved in massive, banded psammitic units up to 2 m thick, which show only weak foliations and lineations related to early deformation phases. In the south, by Loch Braoin (Fig. 1), psammites lying within the Sgurr Beag slide zone exhibit a strong foliation and extension lineation; the rocks being $L \geq S$ tectonites.

Within 2 km of the Moine Thrust the early bedding/foliation planes are disrupted by the localization of strain in small, obliquely inclined shear bands less than 20 cm wide (Fig. 7). The geometry and sense of movement on the shear bands are consistent with those of other shear bands which have previously been reported from mylonite zones (Carreras *et al.* 1977, Platt & Vissers 1980, Gapais & White 1980). They occur throughout the area adjacent to the Moine Thrust, but are best developed in areas where the high strain zone of the Sgurr Beag slide closely approaches the Moine Thrust belt. In many places lens-shaped pods enveloped by shear bands contain relatively undeformed psammites exhibiting the early Sgurr Beag slide fabrics. The highly strained edges of lenses contain a mylonitic foliation with an associated extension lineation (Fig. 7b). As shear bands and F_3 axial plane-fabrics have not been seen together in outcrop their age relationships are not directly known. However, the reorientation of F_3 fold hinges within mylonitic rocks suggests that mylonitization followed, or was a late stage of, the D_3 deformation.

Platt & Vissers (1980) showed that shear band formation is due to a component of extension parallel to a pre-existing foliation or planar anisotropy. In the present case, the slight obliquity of the Sgurr Beag slide foliation and the Moine Thrust mylonite belt has meant that this early foliation lay in the extensional field of the mylonite-related deformation. In this situation, inhomogeneous deformation in the form of shear bands is dominant. Platt & Vissers (1980) described three possible mechanisms of shear band formation. Their model for non-coaxial deformation predicts that one of the shears would be dominant, dipping at a small angle to the foliation in the direction of movement (Fig. 7), a situation which appears to hold for the area west of Fannich. Unlike previously reported examples, the shear bands described above are on a mesoscopic scale, a feature that may relate to the contrast in scales of initial rock anisotropy; that is, between a fine-grained mylonitic fabric and the coarse foliation of the Sgurr Beag slide zone. In common with those described by Platt & Vissers (1980), the shear bands described here are progressively rotated toward the XY plane, that is, the mylonitic foliation, of the thrust zone (Fig. 8). Lenses formed between the shear bands become flattened, and the internal fabric approaches parallelism with the surrounding mylonitic foliation. However, relict pods occasionally remain within even highly mylonitic rocks.

Platt & Vissers (1980) described a cyclic process of shear band formation, including flattening of early shear bands, followed by formation of new shear bands. This process has not been observed in the psammites described here, but was observed in association with the breakdown of fabrics in pelitic rocks described later. The angular disconformity between shear bands, relict foliation and quartz and pegmatite veins, reduces progressively with intensification of the mylonitic foliation. The psammites are converted into a quartz–feldspar mylonite typical of those seen elsewhere above the Moine Thrust (e.g. White *et al.* 1982).

In psammites over 8 km from the thrust belt, quartz and feldspar grains have sizes of 250–500 μm and quartz exhibits only strained extinction. Approximately 6 km from the thrust, deformation has caused subgrain formation and banded extinction of quartz. Within shear bands, in psammites only 4 km from the thrust, quartz and feldspar are reduced to mylonitic grain sizes of 20–50 μm.

In the more homogeneous quartzo-feldspathic mylonites, quartz c-axis fabrics show a strong girdle oriented parallel to the XY plane of the strain ellipsoid deduced for mylonitization; it lies perpendicular to the extension lineation (Fig. 4c). This c-axis fabric resembles that predicted for simple shear (Lister & Williams 1979), and that reported by White *et al.* (1982) for the Moine mylonites of Eriboll. It does not, however, show the strong concentration of c-axes around the Y axis of the strain ellipsoid as seen in Eriboll (White *et al.* 1982).

Pelitic rocks

The anisotropic nature of early fabrics in the pelites of the Fannich–Ullapool area, strongly affected the way in which they were deformed as strain increased during the mylonitization event. Pelitic fabrics associated with the Sgurr Beag slide and peak metamorphism deformed initially by an extension crenulation involving shear band formation. Biotite is recrystallized within the shears, indicating that mylonitization was initiated above the biotite isograd, but replacement of biotite by chlorite in later shear bands indicates a progressive decline in temperature as the mylonitization process proceeded.

Although most lithologies in sub-areas (c) and (d), west of Fannich (Fig. 1) are psammitic, bands of pelitic and semi-pelitic material occur sporadically. These range from 1 cm to 2 m, but are generally around 50 cm, thick. In the east of sub-area (c) (Fig. 1), pelites have a strong S_2 (syn-Sgurr Beag slide) fabric comprising aligned micas which are crenulated by F_3 folds. In thin-section, the S_2 fabric is cross-cut by oblique shear bands, approximately 250 μm wide, which always show the same sense of asymmetry and thus, sense of movement. They dip more steeply to the west than the foliation, and have a sinistral shear sense when viewed toward the northeast indicating overthrusting towards the northwest. In most of sub-area (c), the shear bands are only spasmodically developed and exhibit a mean angle of about 25° to the earlier fabric. All minerals suffer progressive grain size reduction when traced into the shear bands, initial mean grain sizes of around 250 μm being reduced to 20–50 μm (Fig. 8a). No mineral differentiation occurs between sheared and unsheared zones and, therefore, following the reasoning of Platt & Vissers (1980), the deformation was near volume constant.

As strain increases towards the west, shear bands become more common. They cause breakdown of the early fabrics which only remain in the form of relict pods or lenses delimited by the shear bands (Fig. 8b). At this intermediate stage, the angle between shear bands and an enveloping surface representing the original fabric orientation, ranges from 10 to 25° (Fig. 8b). High-angle shear bands are seen cross-cutting fine-grained fabrics formed in earlier shears.

During shear band formation, biotite crystals appear to be reduced in grain size, and recrystallized more easily than muscovites which tended to remain as pods of large, strained grains. This observation agrees with those of Wilson & Bell (1979) who concluded that, during mylonitization, biotite deforms more easily than muscovite. The large muscovite grains eventually break down into shredded mats of fine muscovite flakes less than 100 μm long and 20 μm wide, and where this has occurred, shear bands show angles of only 10–15° from an enveloping surface (Fig. 8c). Low-angle reverse kinks are also present at this stage, showing the same sense of shear as seen in the shear bands.

Biotite is present in all pelites from the east of sub-area (c) to those within the mylonites, but in more highly strained pelites, green biotite and chlorite tend to replace the fox-brown biotite. Garnet, up to 250 μm in diameter, is found in the early high-grade non-mylonitic rocks to the east, and remains as partially chloritised augen within highly deformed pelites of the mylonite belt. Rotation, as witnessed by the oblique orientation of inclusion fabrics in garnet relative to the mylonitic fabrics, further attests to the reworking of earlier metamorphic mineral assemblages during mylonitization.

CONCLUSIONS

The Sgurr Beag slide zone is present in the core of the Fannich synform and as an outlier in the flat belt west of Fannich (Fig. 1). In this area it approaches to within 2 km of the Moine Thrust zone and thus, uniquely, allows direct comparison of those deformation features attributable to formation of the slide and mylonite zones. The slide zone was deformed during D_3 of the local deformation sequence, whilst the mylonite forming event in the Moine Thrust belt occurred syn to post-D_3. Deformation fabrics, structures, and mineral assemblages formed under amphibolite facies conditions associated with the peak of Caledonian metamorphism and slide movement, are reworked and retrogressed during mylonitization.

In view of the evidence and interpretation presented, it would appear that, at least in the Fannich–Ullapool area, Read (1934) was correct in interpreting the formation of mylonite in the Moine Thrust zone as subsequent to the deformation and metamorphism of the Moine schists.

In a flat belt, lying east of and adjacent to the thrust zone, the early Sgurr Beag slide foliation lies sub-parallel to the mylonite foliation plane and has been rotated into the extension field related to the mylonite forming event. Consequent attenuation, resulting from simple shear nearly parallel to the early fabric, gave rise to the formation of 'non-coaxial' type shear bands. Initial deformation during mylonite formation occurred at biotite grade, but biotite was retrogressed to chlorite within shear bands formed late in the history of progressive mylonite formation. The shear bands described exhibit a much larger range in size than previously reported, ranging from less than 1 mm long, in pelites, up to 2 m in length in some psammitic lithologies. In common with other examples, however, their formation is related to the strongly anisotropic nature of a pre-existent fabric, in this case that produced by movement on the Sgurr Beag slide zone.

Much discussion has recently centred on the geometry of the Moine Thrust zone east of its present outcrop and the mechanism responsible for its movement (see review by Coward 1983). Two plausible models have been proposed: the thin-skinned model (Elliott & Johnson 1980, Coward 1980, 1983) predicting a shallow trajectory for the Moine Thrust zone; and the crustal duplex model of Soper & Barber (1982) which predicts a sigmoidal path steepening east of its present outcrop but flattening at depth to join a flat lying ductile shear zone in the lower crust.

The present study shows that mylonite formation associated with the earliest Moine Thrust zone deformation was initiated at biotite grade. If estimates of movement on the Moine Thrust in excess of 70 km (Coward 1980, Elliott & Johnson 1980) are correct, the trajectory of the thrust zone must be shallow for at least that distance in order for deformation to have been initiated at biotite grade, having already decayed from higher metamorphic grades (i.e. those associated with formation of the Sgurr Beag slide zone).

Isotopic studies (Kelley unpubl. data) support the structural and textural evidence for a difference in age between initial movements in the Moine Thrust zone and those in the Sgurr Beag slide zone, and thus, whilst the Sgurr Beag slide zone is most likely to be Caledonian in age (Rathbone & Harris 1979, Baird 1982, Powell *et al.* 1981), it formed under metamorphic conditions that suggest depths well in excess of 15 km (Powell *et al.* 1981). In contrast, at the present level of erosion, the stable minerals in the mylonites of the Moine Thrust zone suggest formation at 15 km or less. Such differences imply a time lapse between movement on the Moine Thrust and Sgurr Beag slide zones sufficient to allow for uplift to levels appropriate to biotite and lower grades of metamorphism. The extent of this time interval is not yet, however, precisely known.

The Sgurr Beag slide brought up rocks from considerable depths during metamorphism and thus could be regarded as broadly coeval with peak Caledonian metamorphic activity at *c*. 450 Ma. However, K–Ar mica cooling ages from Fannich (Kelley unpubl. data) record uplift through the 300 and 350°C isotherms at *c*. 425 Ma. If this uplift relates to final ductile movements on the Moine Thrust zone it may suggest a 25 Ma separation in time between slide zone movements and marginal thrusting.

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