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The kinematic and metamorphic history of the Sgurr Beag Thrust, Ross-shire, NW Scotland

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Abstract

This paper presents a field and microstructural study of a Caledonian amphibolite-facies shear zone within the Moine rocks of Northern Scotland. The shear zone, the Sgurr Beag thrust, is an important tectonic break within the Moine nappe of Ross-shire and is the structurally highest and oldest of the foreland-propagating thrust system the youngest and lowest of which marks the Caledonian front in Britain. Microstructures and quartz *c*-axis analysis show that fabrics formed during nappe emplacement were thoroughly recrystallised before or during peak Caledonian metamorphic conditions. One segment of the shear zone was reactivated as a north-directed thrust with retrograde reworking of annealed metamorphic textures. Quartz-rich mylonites from the reactivated zone display asymmetric or single-girdle quartz *c*-axis fabrics consistent with north-directed overthrust shear, except within and immediately beneath an allochthonous orthogneiss sheet of Archaean basement. Here, quartz *c*-axis fabrics have orthorhombic symmetry, implying that the orthogneiss unit and the thin smear of psammitic mylonites accreted to its base extended coaxially as a rigid sheet while the softer quartz-rich mylonites of the enclosing Moine accommodated the late non-coaxial strain. The thrust zone was probably reactivated within the old footwall and by ductile extension of the hanging wall along localised zones of intense non-coaxial strain. This conclusion emphasises the complexity and longevity of Caledonian ductile deformation. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Faults within the middle crust are typically broad ductile shear zones which coincide with major breaks in lithostratigraphy, structure and metamorphism. The boundaries between mid-crustal shear zones and their wall rocks are difficult to detect due either to the penetrative nature of the deformation or to the subparallelism of the shear zone fabric to those from which it developed (Sanderson, 1982). As a result, the movement sense within and displacement across mid-crustal shear zones cannot readily be determined, especially where metamorphic contrasts between juxtaposed units are now negligible. As an aid to unravelling kinematic histories in high-grade metamorphic environments, the study of small-scale shear criteria, including microstructures and crystallographic fabrics, has proved invaluable (Simpson and Schmid, 1983; Law et al., 1986; Passchier and Simpson, 1986; Platt and Behrmann, 1986).

This paper reports the results of a microstructural and petrofabric analysis of a major Caledonian shear zone, the Sgurr Beag ductile thrust, within the Late Proterozoic Moine Supergroup of the northeast Scottish Highlands, which marks a tectonostratigraphic break between two lithostratigraphic groups (Johnstone et al., 1969; Tanner et al., 1970; Roberts et al., 1987) the original disposition of which was discussed by Soper et al. (1998). The analysis was carried out to investigate the value of quartz crystallographic fabrics imposed in such a ductile shear zone in assessing its gross kinematics and its probably complex tectonic and metamorphic history.

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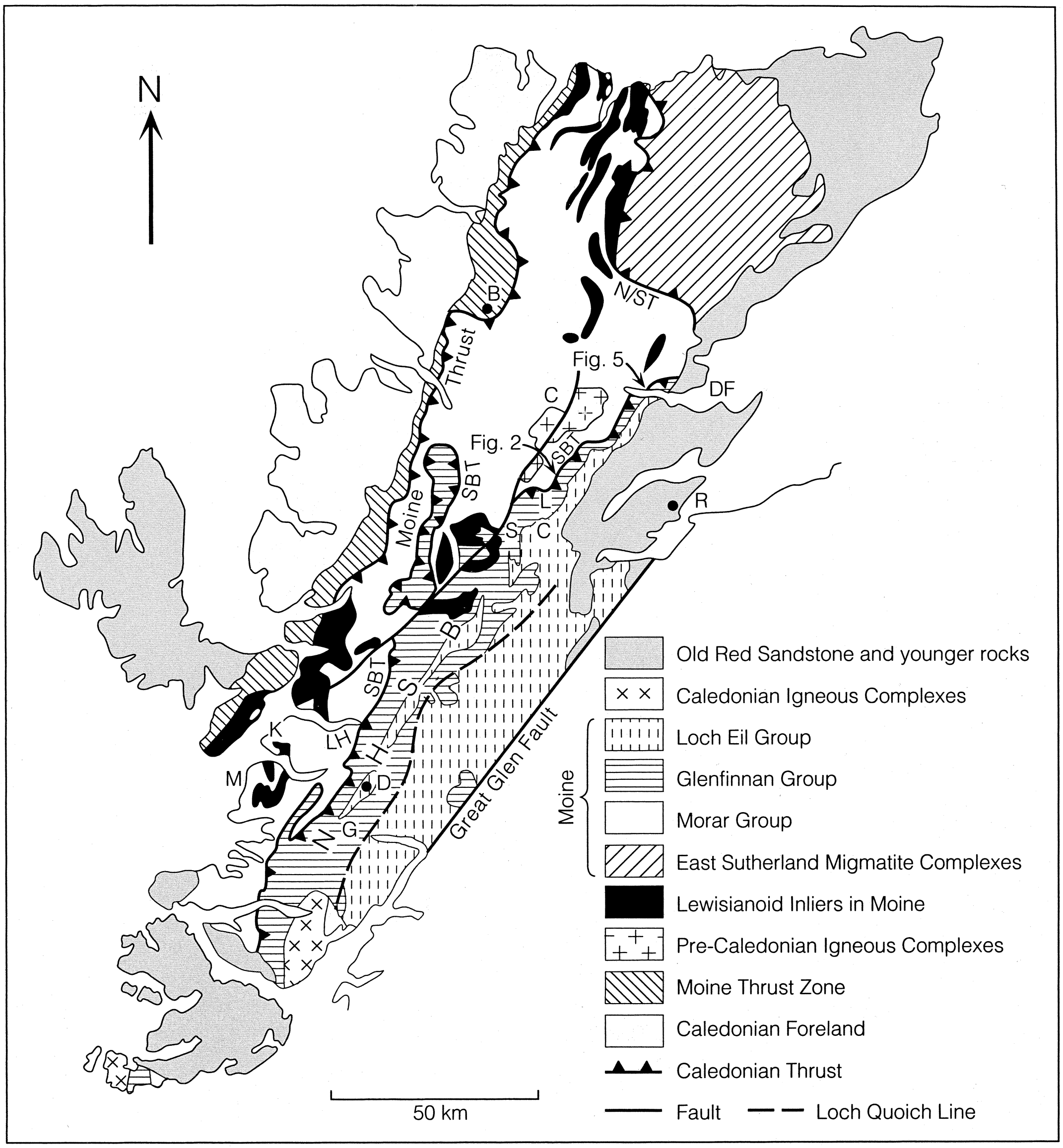

Fig. 1. Generalised geological map of the Scottish Highlands northwest of the Great Glen Fault, showing the Moine lithostratigraphic groups, Lewisian (Archaean) inliers, major Caledonian structures and localities mentioned in the text. Note the position of Figs. 2 and 5. B = Borrolan; C = Carn Chinneag; D = Dessary; DF = Dornoch Firth; G = Glenfinnan; NHSB = Northern Highland steep belt; K = Knoydart; L = Loch Luichart; LH = Loch Hourn; M = Morar; N/S T = Naver/Swordley thrust; R = Rosemarkie; SBT = Sgurr Beag thrust; SC = Strathconon.

2. Geological setting

The Moine supergroup of NW Scotland (Fig. 1) comprises Upper Proterozoic metasedimentary rocks within which inliers of pre-Moine basement and numerous pre-, syn-, and post-orogenic igneous bodies were incorporated during deformation and metamorphism (Harris and Johnson, 1991). During Caledonian orogenesis, the Moine rocks were emplaced northwestwards across the Moine thrust belt onto its foreland of Lewisian (Archaean) gneisses with their unconformable late Proterozoic (Torridonian) and Lower Palaeozoic (Eriboll and Durness groups) sedimentary cover. The Moine thrust belt essentially comprises the Caledonian front in Scotland and is believed to be the southerly extension of the Caledonian thrust front in eastern Greenland (Higgins and Phillips, 1979, fig. 1, and references therein).

Several laterally persistent zones of anomalously high strain internally dissect the Moine. These zones have been interpreted as ductile thrust faults of regional significance (Tanner et al., 1970; Tanner, 1971; Powell, 1974; Rathbone and Harris, 1979; Rathbone et al., 1983; Barr et al., 1986; Grant, 1989; Holdsworth, 1989). They are interpreted as individual members of a WNW-, foreland-directed, crustal-scale duplex of Caledonian age within which the Moine thrust itself is the westernmost, lowest and youngest. The eastern-

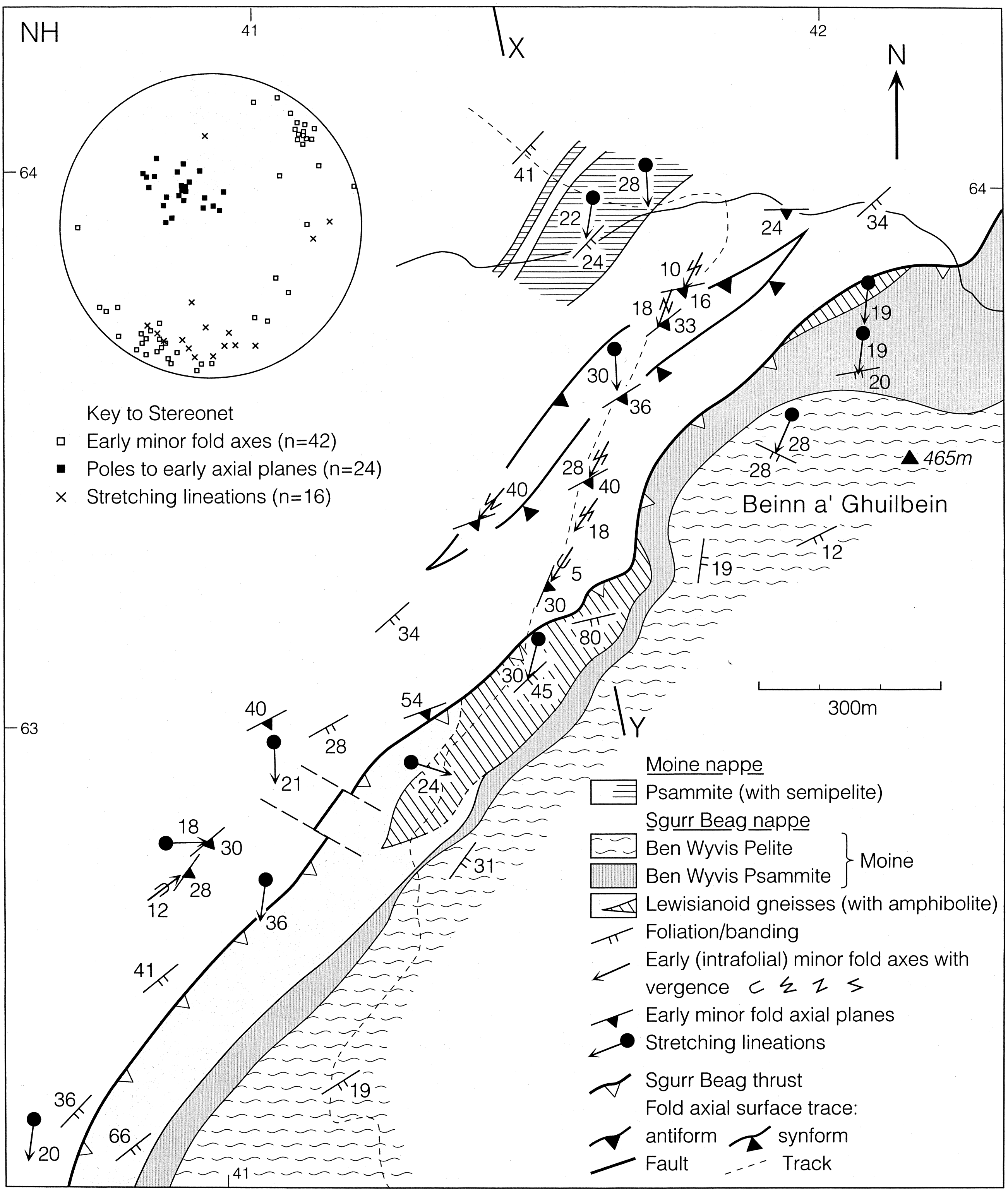

Fig. 2. Geological map and structural data of the area adjacent to the Sgurr Beag thrust zone of the Beinn a' Ghuilbein area, near Garve. For location, see Fig. 1. X–Y is the line of section analysed in terms of petrofabric data in Fig. 4. The intrafolial fold pair is included to indicate that it was probably coeval with or severely modified by the N-directed late thrusting.

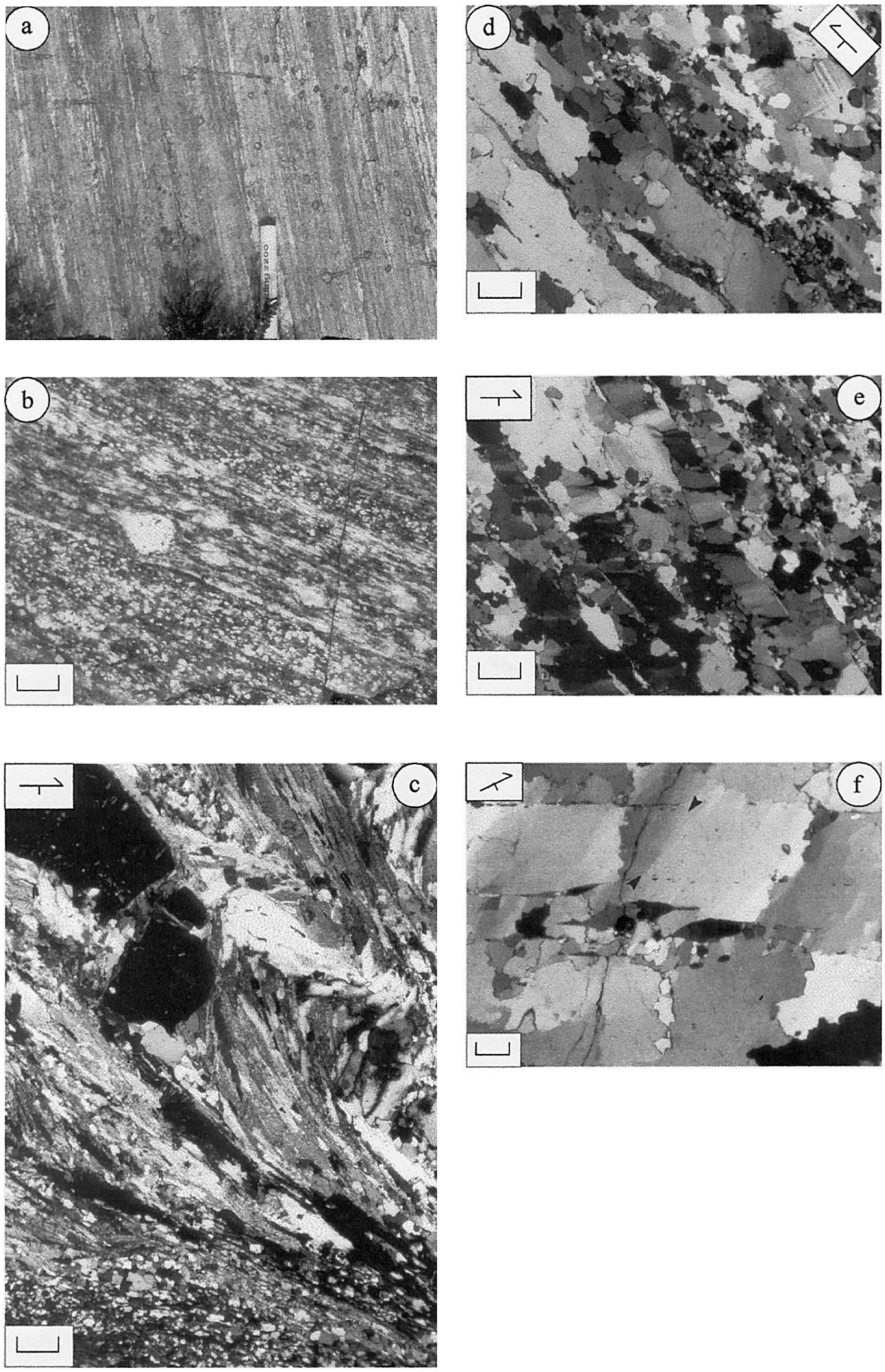

Fig. 3. Photographs and photomicrographs of the Garve tectonites. (a) and (b) Finely laminated grey psammite incorporating lenticular subconcordant quartzo-feldspathic veins and segregations, typical of the Morar Group psammites within 100 m of the thrust; the pen in (a) is approximately 15 cm long and the scale bar in (b) is 1.8 cm; (a) is a loose block. (c) Crenulated muscovite grains between shear bands in the Ben Wyvis Pelite (NH 4177 6339). One of the shear bands produced the fine-grained domain at the bottom of the photomicrograph; plane of thin section strikes 206° and dips 83° NNW (looking ESE). (d) Elongate quartz grains subparallel to foliation in Morar Group psammite 45 m below thrust (NH 4154 6323); plane of thin section strikes 240° and dips 80° SE (looking NW); note the finer grain size associated with the recrystallised feldspar domain. (e) Elongated quartz grains carrying a flat-lying set of sub-boundaries; 50 cm below thrust (NH 4153 6321); plane of thin section strikes 180° and dips 80° W (looking E). (f) Asymmetric feldspar grains associated with normal-sense dip-slip shear within concordant quartz veins 50 cm below thrust; note flat-lying grain sub-boundaries in quartz crystals; (NH 4153 6321); plane of thin section strikes 176° dips W at 82° (looking E). Scale bar in all photomicrographs is 0.33 mm.

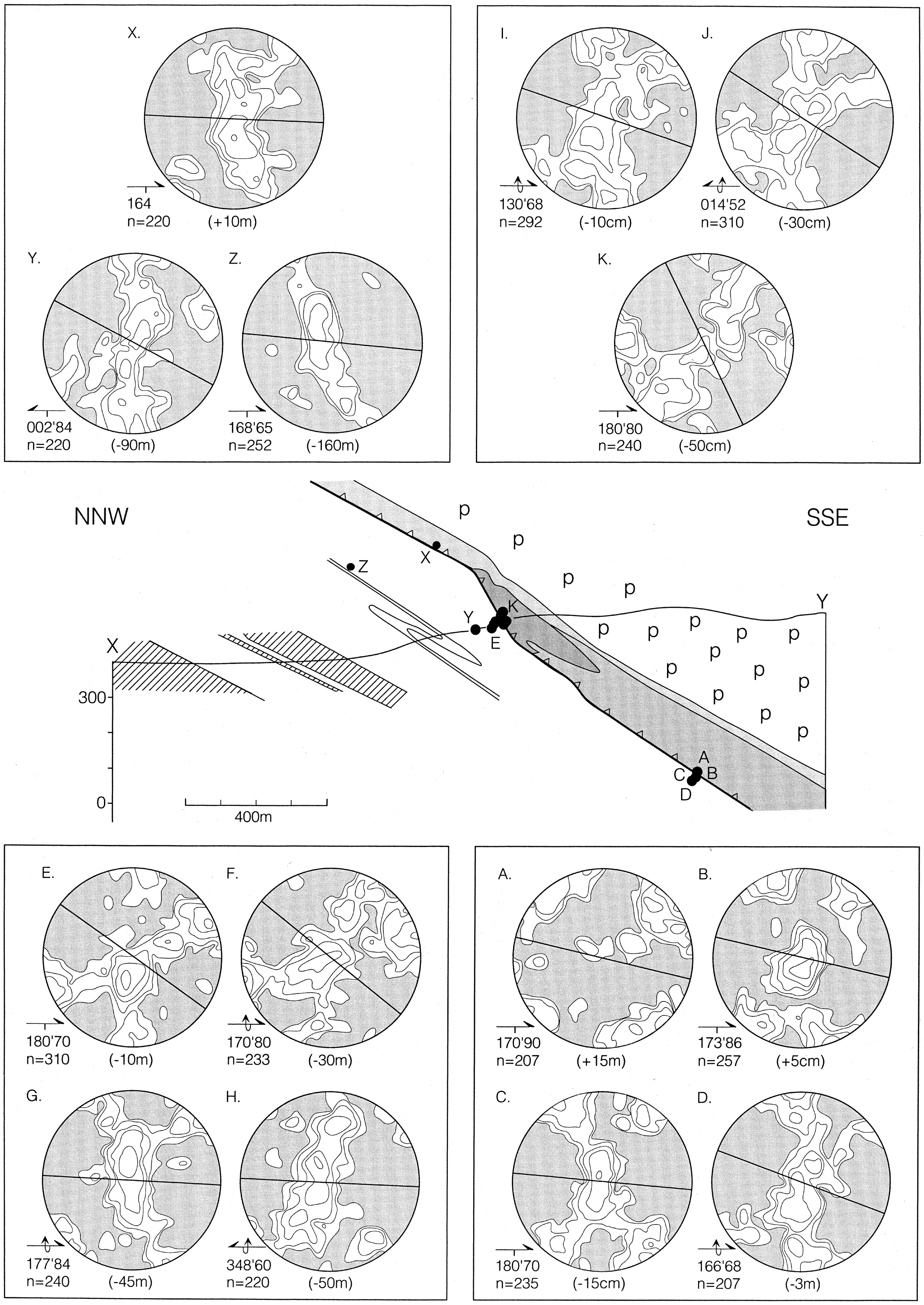

Fig. 4. Detailed quartz petrofabric data from the Sgurr Beag thrust zone of the Beinn a' Ghuilbein area. For location, see Figs. 1 and 2. Line of section is shown in Fig. 2. In each case n = the number of grains measured; the orientation of the thin section is shown by conventional notation; the true distance of the orientated sample used is shown in metres (m) or centimetres (cm) above (+) or below (−) the plane of the thrust. The aim of the contouring is to highlight the *c*-axis maxima and the topology of the fabric skeleton. A minimum of 200 quartz *c*-axes were measured from each sample and plotted on equal-area, lower hemisphere, spherical projections; the plane of the projection in each case contains the macroscopic lineation and the pole to the foliation surface. In each projection the foliation is vertical and the lineation within the plane of foliation is horizontal. Contours follow the sequence 0.5, 1.0, 2.0, 4.0, 8.0 … *c*-axes per 1% area. Specimens F, G, H, I and J lie between the locations of E and K but are too closely spaced to be shown on this scale; note that their distance from the thrust is indicated on the quartz diagram itself. For interpretation of the diagrams, see text.

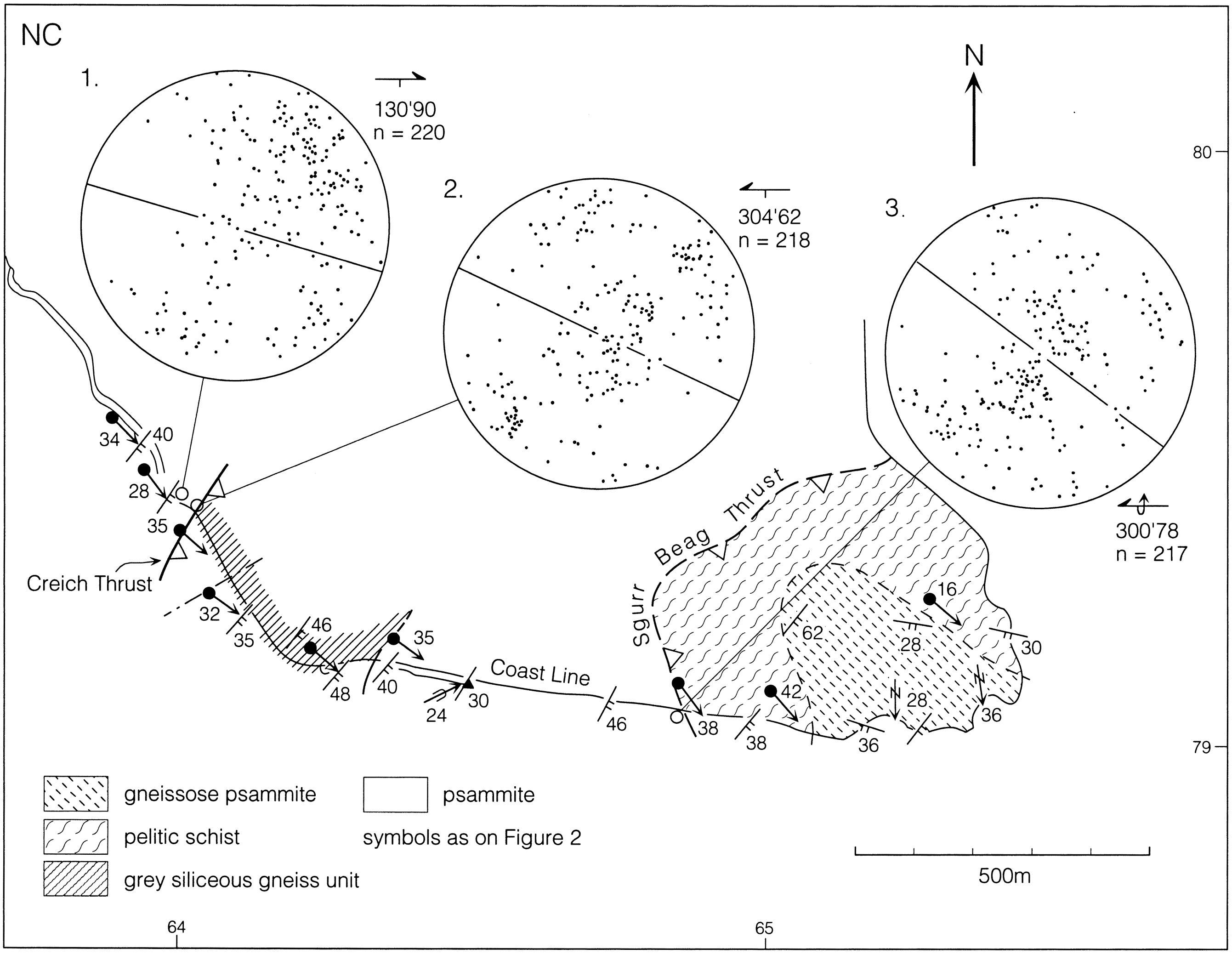

Fig. 5. Geological map and petrofabric data of the area adjacent to the Sgurr Beag thrust on the Creich Peninsula, Dornoch Firth. For location, see Fig. 1.

most, oldest and highest is the Sgurr Beag thrust (Tanner et al., 1970) which regionally separates the Morar (lower and older) and Glenfinnan (upper and younger) lithostratigraphic groups of the Moine. Radiometric age dates from igneous bodies have been used to constrain the thrust movements as early Caledonian (Roberts et al., 1984; Powell and Phillips, 1985; Barr et al., 1986). For example, the timing of the movements in the Moine thrust zone is constrained by the 430 ± 4 Ma, U–Pb age of the Loch Borrolan syenite (van Breemen et al., 1979a) (Fig. 1) during or after thrusting and the upper Arenig–lower Llanvirn biostratigraphic age of the youngest Durness Group limestones (Higgins, 1967). The Glen Dessary syenite (Fig. 1) emplaced at 456 ± 5 Ma (U–Pb) (van Breemen et al., 1979b) carries the axial planar foliation associated with the regional-scale folds of the Sgurr Beag thrust, while the Carn Chuinneag granite (Fig. 1) dated at 555 ± 10 Ma (Rb–Sr) (Pidgeon and Johnson, 1974) carries the *LS* fabric associated with the Sgurr Beag thrust.

Caledonian ductile thrusts are characterised by belts of platy blastomylonitic rocks in which strong stretching lineations and other structural features indicative of large strains, such as sheath folds, are conspicuous. Some also incorporate persistent thin layers of metabasic and metasedimentary strata (e.g. British Geological Survey (Scotland) Sheet 72W Kintail, 1984). These are believed to have been derived from the deeply eroded basement complex onto which the Moine succession was deposited (Holdsworth, 1989; Soper et al., 1998). The Sgurr Beag thrust was largely responsible for emplacing sheets of basement rock at high structural levels within central Ross-shire (Tanner et al., 1970). These sheets have not been recorded south of Loch Hourn (Fig. 1), but the ductile thrust is thought to persist southwards where it has been traced, albeit with increasing uncertainty, on the basis of contrasts in metamorphic grade between the largely psammitic Morar Group and the regionally overlying pelitic and psammitic hanging wall Glenfinnan Group strata. Structural criteria (see Rathbone and Harris, 1979 and Rathbone et al., 1983) suggest zones of highly strained rocks some hundreds of metres thick. On this basis Roberts et al. (1987) assigned the Glenfinnan Group and the contiguous Locheil Group to a single tectonostratigraphic unit, the Sgurr Beag nappe. Along its length, the Sgurr Beag thrust emplaced kyanite-grade Glenfinnan Group gneisses onto rocks now of only slightly lower metamorphic grade (Tanner, 1971).

A train of en-échelon, upright, generally upward-facing folds having highly curvilinear hinge lines comprise the Northern Highland steep belt (Fig. 1; Leedal, 1952; Soper et al., 1998), a zone of NNE–SSW trending, steeply inclined strata up to 25 km in width. The axial surface trace of a major asymmetric synform marks the eastern limit of this belt of highly deformed Moine separating it from an eastern 'flat belt' in which foliations and remnant bedding are generally gently dipping and pre-synform folds are subrecumbent and locally curvilinear about a N–S-trending stretching lineation (Roberts and Harris, 1983; Holdsworth and Roberts, 1984). This synform axial surface trace defines the Loch Quoich line (Clifford, 1957; Fig. 1) and has been interpreted as the eastern limit of severe upright reworking of previously deformed and metamorphosed Moine rocks within which the West Highland granite gneiss and a swarm of mafic intrusions had already been emplaced and deformed (Soper and Harris, 1997). The Sgurr Beag thrust (Tanner, 1971; Powell et al., 1981; Rathbone et al., 1983; Kelly and Powell, 1985) predated the deformation that produced the steep belt (see e.g. Roberts et al., 1987).

Because the Sgurr Beag thrust predated the formation of the Northern Highland steep belt over much of its outcrop it has been folded by it or passively rotated into its present-day, steeply dipping orientation (Rathbone et al., 1983). Outside and to the east of the steep belt the plane of the Sgurr Beag thrust dips consistently ESE at an angle which rarely exceeds 40°. In NE Ross-shire, it can be traced with this orientation southwestwards from the shores of the Dornoch Firth to where it intersects the Strathconon fault. This area largely escaped the severe Caledonian reworking characteristic of the steep belt and is therefore suitable for carrying out a detailed kinematic study of an early Caledonian ductile fault zone where it appears to have been least disturbed by subsequent reworking. Two small sections of the thrust zone have been mapped at a scale of 1:10 000, one located to the north of the village of Garve, the other, the Creich Peninsula, on the shores of the Dornoch Firth (Fig. 1).

Microstructures and petrofabrics have been used elsewhere with varying degrees of success to detail kinematic and strain-path histories (e.g. Burg and Laurent, 1978; Lister and Hobbs, 1980; Law et al., 1984; Lister and Snoke, 1984). These have been examined in this study to assess the sense of movement within the Sgurr Beag thrust zone and to investigate its strain history. In both sections selected for these studies, detailed maps are presented (Figs. 2 and 5, respectively). These are complemented by descriptions and illustrations of representative textures and microstructures (Figs. 3 and 6, respectively). Quartz *c*-axis fabrics from the Garve area are shown in Fig. 4, while those from the Creich Peninsula are incorporated into Fig. 5. In all the samples selected for petrofabric analysis, the orientation of at least 200 quartz *c*-axes was measured using standard universal-stage techniques. The measured sections were cut parallel to the mesoscopic lineation and perpendicular to the foliation within what is known as the 'plane of movement', i.e. the inferred *XZ* plane of finite strain. The data were contoured using a Kalsbeek counting net and are displayed on lower hemisphere equal-area projections.

3. Beinn a'Ghuilbein, by Garve

3.1. Field relationships and mesoscopic structure

The Sgurr Beag thrust zone is exposed (e.g. U.K. National Grid reference NH 415 632) on the slopes of Beinn a' Ghuilbein (NH 442 635), 3 km northeast of Garve (Figs. 1 and 2). The shear zone comprises, from bottom to top, a thick (~500 m) succession of quartz-rich psammites, a thin sheet of feldspathic and hornblendic orthogneisses, reminiscent of the basement Lewisianoid rocks of the Scardroy sheet of central Ross-shire (Sutton and Watson, 1962), and Glenfinnan Group psammitic and pelitic gneisses. The thrust plane, dipping at ~40° SSE, is mapped at the base of the orthogneiss sheet. The pelitic gneisses of the Glenfinnan Group incorporate concordant pegmatite sheets, one of which, the Carn Gorm pegmatite, has yielded a 750 Ma muscovite Rb–Sr age (Long and Lambert, 1963). On textural grounds, Wilson (1975) concluded that this pegmatite was emplaced before shearing within the thrust zone; subsequently Wilson and Shepherd (1979) showed that the shearing overprinted the nearby, structurally lower Carn Chuinneag granite (~555 Ma) (U–Pb zircon) (Pidgeon and Johnson, 1974). These two structural studies are consistent with deformation in the Sgurr Beag thrust zone being Caledonian.

The lower siliceous and feldspathic psammites are typical of the Morar Group of Ross-shire and Inverness-shire (Holdsworth et al., 1994). Cross-bedding is common about a kilometre below the thrust plane (e.g. NH 401 637) younging toward the overlying basement unit, thus indicating that the latter is probably allochthonous and not lying in a fold core. The footwall psammites become strongly foliated towards the thrust (Fig. 3a) and develop a macroscopic mineral lineation on their foliation surfaces. This lineation plunges ubiquitously south. Gneissose segregations, comprising arrays of quartzo-feldspathic veins orientated subparallel to the lithological banding are ubiquitous within 200 m of the thrust. These two-feldspar segregations are strongly deformed (Fig. 3b) within 50 m of the thrust, undergoing grain-size reduction as witnessed by the presence of occasional feldspar porphyroblasts enveloped by fine beards of recrystallised quartz and feldspar. Barr (1985) considered these veins to be the products of subsolidus segregation, the growth of which was triggered by grain size reduction during mylonitisation.

The orthogneiss sheet is blastomylonitic adjacent to the underlying psammites but is coarsely gneissose 15 m or more above its base. The lowermost unit of the overlying Glenfinnan Group is a thin, platy psammite, referred to locally as the Ben Wyvis Psammite (Wilson, 1975). This psammite passes upwards abruptly into garnet–staurolite–kyanite pelitic gneisses of the Ben Wyvis Pelite. Both hanging wall metasedimentary units incorporate pods and lenses of garnetiferous amphibolite which are the highly deformed and metamorphosed remnants of an early suite of basic intrusions.

Minor folds are sparse within the shear zone; those observed are typically isoclinal, plunging at moderate angles towards the NE or SW, while adjacent to the thrust they are transposed by the mylonitic schistosity. A late, brittle flexure steepens the foliation at the northern termination of the basement sheet. This feature, which is associated with a set of kink-type buckle folds, may have developed as a result of late differential displacements on the strongly anisotropic foliation.

Common minor structures within the Ben Wyvis pelite are discrete, narrow, flat-lying zones in which the gneissose fabric is overprinted by sets of low-amplitude, asymmetric crenulations (Fig. 3c). In thin section, the limbs of these crenulations are seen to be the loci for intense grain-size reduction (Fig. 3c) in which finely disseminated chlorite anastomoses around fine-grained, equant quartz and feldspar. These asymmetric crenulations formed in response to extension oblique to the layering, consistent with northerly directed overthrust displacement.

3.2. Microstructures, textures and quartz c-axis fabrics

Psammites belonging to both the Morar and Glenfinnan groups are composed of variable amounts of quartz, plagioclase (An_{10}–An_{34}), microcline and muscovite, with accessory biotite, allanite and garnet.

Quartz grain size throughout the shear zone is heterogeneous, even on the scale of the thin section. More than 200 m beneath the thrust, grains are typically equant and have uniform dimensions (c. 300 μm in diameter), except in the more siliceous lithologies where late grain growth is more pronounced. Towards the thrust plane, the shape and size of quartz grains vary according to lithology. In quartz-rich lithons, individual grains are not equigranular and can be as large as 0.5 cm, usually having serrated or lobate grain boundaries (Fig. 3d). By contrast, quartz grains within feldspar-rich lithons, are more equant and of a size similar to the accompanying feldspar (c. 50 μm).

Within 50 m of the thrust, both quartz and feldspar have experienced increasing degrees of dynamic recrystallisation (White, 1976), including the development of intracrystalline deformation substructures (Fig. 3e) such as undulatory extinction, subgrain boundaries, deformation bands and, more rarely, marginal polygonisation. Whilst there is strong evidence of large strains and considerable dynamic recrystallisation in this zone, quartzo-feldspathic segregations which are the most promising indicators of shear sense in these rocks are either symmetrical or yield equivocal or conflicting evidence (see for example Fig. 3b).

Feldspar porphyroblasts up to 1 cm in diameter are important components of the quartzo-feldspathic segregations of the footwall. While typically augen-shaped, they seldom show asymmetry. The only unequivocal examples of asymmetric feldspars lie within a set of foliation-parallel, though probably late, quartz veins observed in a psammite sample from 50 cm beneath the thrust at the northern end of the basement sheet outcrop (Fig. 3f). These show a dip-slip sense of displacement to the SSE.

The 14 quartz *c*-axis fabric determinations from the shear-zone mylonites at Garve are located on the cross-section in Fig. 4. All show a strong preferred orientation. Their distribution with respect to the mesoscopic mylonitic foliation and stretching lineation indicates that they were the flow plane and flow direction, respectively. The polarity of flow deduced from the asymmetric fabrics (e.g. D, X and Z) suggests that the movement sense was predominantly thrust-sense shear to the north, but that in the vicinity of the frontal ramp (especially E, F and H) the asymmetry indicates that, here, a reversal in the flow polarity occurred. Fabrics from within the Lewisianoid sheet, but close to its base (A and B) consist of double maxima symmetrically disposed about the foliation. Fabrics obtained within 50 cm of the thrust plane but below it (e.g. C, I and J) possess an orthorhombic symmetry, suggesting that coaxial strains (Christie, 1963; Law et al., 1986) were important in this domain.

From the microstructural and fabric work, a marked spatial variation in these elements can be detected

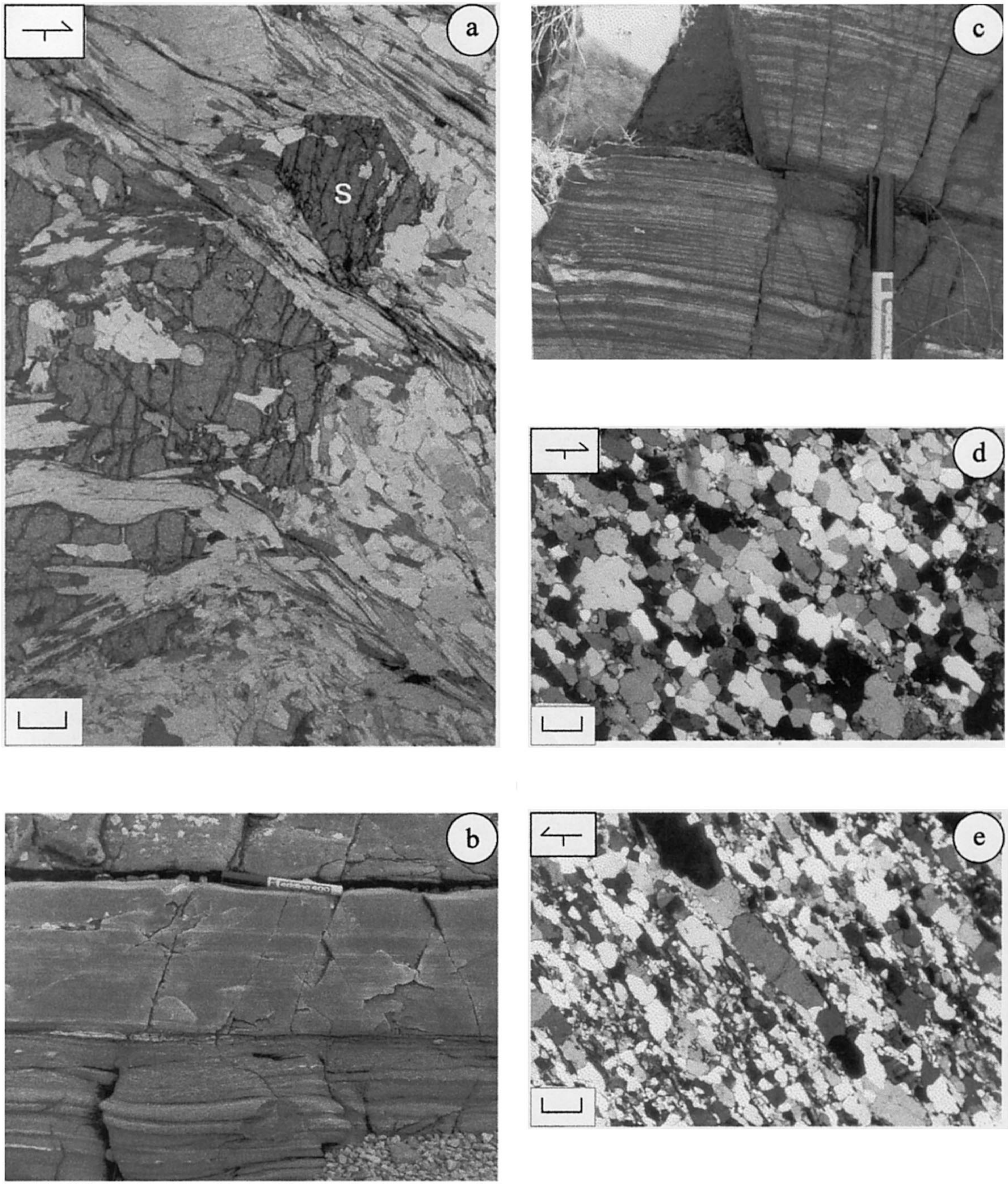

Fig. 6. Photographs and photomicrographs of the Creich tectonites. (a) Photomicrograph of pelite with subhedral garnet and staurolite from a few metres above the Sgurr Beag thrust (NH6487 7904); plane of thin section strikes 146° and dips 60° SW (looking NE). (b) Finely laminated feldspathic psammite, about 10 m below the Creich thrust (looking E) (NH 6400 7943). (c) Streaky feldspathic gneiss band within hornblende-bearing grey gneiss (looking NE) (NH6410 7922). (d) Photomicrograph of psammite 30 m below Creich thrust; note equant quartz grains lacking strong preferred orientation. Thin section strikes 130° and is vertical (looking NE). (e) Photomicrograph from section 50 cm below Creich thrust; note ribboned quartz aggregates comprising equant grains lying between trails of recrystallised feldspar. Plane of thin section strikes 304° and dips 62° SW (looking NE). Pen in photographs is 15 cm long and scale bar in photomicrographs is 0.33 mm.

within the Sgurr Beag thrust zone at Garve summarised in Fig. 7(a):

1. rotational strains were important in the history of the shear zone. However, this is only reflected in fabrics obtained more than 50 cm below the thrust, and is rarely detectable in the microstructure;
2. *c*-axis fabrics in siliceous rocks located within 50 cm of the thrust plane comprise symmetric Type 1 cross-girdles. These indicate that recrystallisation occurred during plane-strain, coaxial deformation;

3. asymmetric feldspar grains and quartz fabrics from the flexure adjacent to the northern termination of the Lewisianoid sheet, indicate that normal-sense, dip-slip shear was important in this domain (e.g. Figs. 3f and 7);
4. two shear zones dipping gently to the north deform the pelites in the hanging wall.

4. The Creich peninsula, Dornoch Firth

4.1. Field relationships and mesoscopic structures

The Creich peninsula (Fig. 5) displays the most northerly known exposures of the Sgurr Beag thrust zone. A few hundred metres to the north of this headland, a late wrench fault displaces the Glenfinnan Group to the east where it must lie beneath the Old Red Sandstone cover.

The trace of the Sgurr Beag thrust is placed at the base of a highly sheared, garnet–tourmaline–staurolite pelitic schist (Fig. 6a) which is taken to be the basal unit of the Glenfinnan Group. This schist becomes progressively coarser grained towards the east. At the eastern end of the peninsula the pelite is overlain by a coarsely banded psammitic gneiss, carrying sheets and pods of garnetiferous amphibolite, which occupies the hinge region of an open, southward-plunging synform.

Three siliceous units have been identified beneath the Sgurr Beag thrust. The immediate footwall is formed by a 300-m-thick, flaggy red psammite of Morar Group aspect. Sandwiched between this and a lower red psammite are 250 m of grey siliceous gneiss, incorporating layers of concordant, highly deformed granite pegmatite, bands of hornblendic gneiss and rare ultramafic pods. Sporadic, tight-to-isoclinal folds of variable hinge orientation have been observed in the two upper units.

On the basis of lithological similarity, Strachan and Holdsworth (1988) correlated the middle siliceous grey gneiss unit with rocks lying within the Kilbreck Formation of the Naver nappe, central Sutherland. This unit also resembles, albeit at a much higher state of strain, the gneissose basement rocks described by Rathbone and Harris (1980) from the Rosemarkie inlier (Fig. 1) on the northwestern shores of the Moray Firth. As a result of these similarities, the grey gneiss unit is interpreted as an allochthonous sheet of pre-Moine basement lying with tectonic contact upon the lower psammite (Fig. 6c). Its lower boundary is referred to here as the Creich thrust. To the south, the Creich thrust either cuts up-section laterally to disappear beneath the Sgurr Beag nappe or, more likely, is not distinguishable in the field because of the absence of obvious basement rocks in the hanging wall of the thrust plane.

4.2. Microstructures, textures and quartz c-axis fabrics

Quartz-rich specimens from the three siliceous units beneath the Sgurr Beag thrust were found to share the same microstructures. All are granoblastic and comprise quartzose lithons, incorporating equant quartz grains and thin, lenticular aggregates of polygonal feldspar; neither shows signs of intracrystalline deformation. In the lower psammite (Fig. 6d) 50 cm below the Creich thrust, the ribboned quartz aggregates composed of equant grains, lying between trails of fine-grained, recrystallised microcline, may signify a higher state of strain than had been imposed on the rock figured in Fig. 6(e). The latter shows an aspect ratio much lower than the 5:1 estimated for the rock shown in Fig. 6(d). The quartz *c*-axis fabrics from these rocks (Figs. 5, 6d and e) both show diffuse, weakly asymmetric patterns consistent with normal-sense, dip-slip shear to the SE. In the upper psammite, below the Sgurr Beag thrust, the fabrics are diffuse but show a maximum centred on the plane of mesoscopic foliation and a generally weakly developed symmetry.

The Creich pelite contains large garnet porphyroblasts up to 1 cm in diameter which are wrapped by sheaths of biotite relating to the regional schistosity (the S_2 of Strachan and Holdsworth, 1988) (Fig. 6a). The garnets carry a crudely orientated internal S fabric subparallel to the external schistosity and, along their margins, show signs of having overgrown an early biotite sheath. No clear-cut sense of asymmetry could be deduced from the textural relationships observed in the sections studied or on similarly orientated outcrop surfaces. Associated staurolite porphyroblasts, whose growth marks the metamorphic peak, grow randomly across the S_2 schistosity (Fig. 6a).

5. Contrasts between texture, microstructure and quartz fabrics Garve and Creich

The equigranular textures which characterise the tectonites from the Creich thrust zone (Fig. 5d and e), have triple grain-boundary intersections which approach 120° and are consistent with either recovery penecontemporary with work hardening and/or to subsequent annealing during peak metamorphism at least at staurolite grade. The irregular textures from Garve, with serrate or lobate boundaries and complex grain intersections, closely resemble textures produced by strain-induced boundary migration in metals and ceramics (Poirier, 1985, p. 73). Variation in grain size between different lithons reflects differing degrees of quartz grain growth. This was possibly driven by freeenergy contrasts resulting in the formation of dislocation-free nuclei at the expense of grains with high dislocation densities, and causing a reduction in grain-boundary area as large grains develop. The effects of grain growth are more pronounced in the quartz-rich lithons than in the domains containing a greater proportion of other minerals, notably feldspar. This is due to the grain-boundary pinning effects of other mineral components. Psammites adjacent to the thrust are more feldspathic than those further away and they have a finer grain size. This contributes to and may entirely explain the reduction in grain size adjacent to the thrust reported by Rathbone and Harris (1979). The textural differences between Morar Group psammites from Garve and those from Creich suggest different recrystallisation histories. This is supported by the presence at Garve and absence from Creich of dynamic recrystallisation microstructures such as marginal polygonisation of feldspar, evidence of grain-boundary migration and the development of deformation bands in quartz. These are products of strain increments distorting the crystal lattice through dislocation creep (Poirier, 1985). It is concluded that, at Creich, peak progressive metamorphism, at staurolite grade or above, overprinted mylonite textures within the Sgurr Beag thrust zone, while at Garve, there is evidence for local retrogressive reworking within a segment of the thrust zone after the peak of metamorphism. The presence of chlorite in narrow deformation zones in the staurolite- and kyanite-bearing Ben Wyvis Pelite above the thrust implies that the reworking developed at chlorite grade.

6. Discussion

The term 'strain-path partitioning' has been used to refer to situations where two contrasting domains of strain co-exist during one deformation. Partitioning of this sort has been interpreted from the Loch Eriboll, Glencoul and Skye regions of the Moine thrust zone (Law et al., 1984, 1986; Law and Potts, 1987), and in the Betic Cordilleras of Spain (Platt and Behrmann, 1986). Law et al. (1984) found *c*-axis fabrics in detrital quartz grains within the upper and central levels of the Arnaboll and Upper Arnaboll thrust sheets symmetrically disposed, both in terms of skeletal outline and density distribution, with respect to the mylonitic foliation and lineation. In the lower, intensely recrystallised levels of the Upper Arnaboll thrust, quartz *c*-axis fabrics from recrystallised tectonites are asymmetrical with respect to the mylonitic foliation and lineation; the sense of asymmetry is consistent with shearing involving non-coaxial deformation. At the Stack of Glencoul, Law et al. (1986) found that, at distances less than 20 cm beneath the Moine thrust, *c*-axis fabrics are asymmetrical with respect to the foliation and lineation. In contrast mylonites located at greater distances beneath the thrust were found to have *c*-fabrics which are symmetrical with respect to foliation and lineation. The gradual transition from symmetrical to asymmetrical fabrics located near the margins of thrust sheets was interpreted to indicate the development of a vorticity gradient within these mylonites.

Recent work by Camilleri (1998) on the Windermere thrust (Nevada) in the inner zone of the Sevier orogen is, at first sight, relevant to this study, especially as it was carried out in an area where the footwall rocks lack the complexities of polyphase overprinting, and essentially only the thrust-related fabrics accompanying progressive Barrovian metamorphism are observed. Although the Garve and Creich areas of the Sgurr Beag thrust outcrop were selected for the present study to avoid the effects of severe overprinting in the Northern Highland steep belt, there is still sufficient evidence for pre- and post-thrusting tectonic activity to produce considerable ambiguity. Camilleri's (1998) interpretation of the Windermere thrust zone suggests that the footwalls of thick thrust sheets undergo coaxial deformation during thermal metamorphism and progressive metamorphism and that hotter, deeper levels in the footwall are characterised by penetrative plane strain and flattening induced by rising isotherms and footwall collapse. Attempts to apply this attractive model to the more complex Sgurr Beag thrust zone, however, present some problems. The work of Rathbone and Harris (1979) showed decreasing strain downwards from the thrust plane with, in many instances, cross-bedding, only weakly deformed, being preserved a hundred metres or so below the thrust plane. In the case of the Garve exposures, as elsewhere along the thrust, the intensely flattened fabrics implying the maximum strain coincide with rocks immediately adjacent to the thrust. If this zone is a relic of an earlier episode of thrusting, it cannot have formed simply by progressively increasing strain with depth; witness the weakly deformed cross-bedding below this structural level. If explicable in thermal terms, the presence of the most highly deformed rocks as a primary feature of the thrust zone could be the result of the 'contact' metamorphic effect of the thrust sheet. It is thought to have originated deep in the orogen where it was already undergoing amphibolite-facies metamorphism and to have over-ridden the structurally higher, probably, at the time significantly cooler, Morar Group rocks of the footwall (see e.g. Powell et al., 1981; Barr et al., 1986). The difference between the thrust regimes in the Scottish Northern Highlands and that in Nevada may thus be that the thrusting in Scotland did not begin until regional metamorphism was well advanced and it demonstrably occurred after a major orogenic episode involving the emplacement

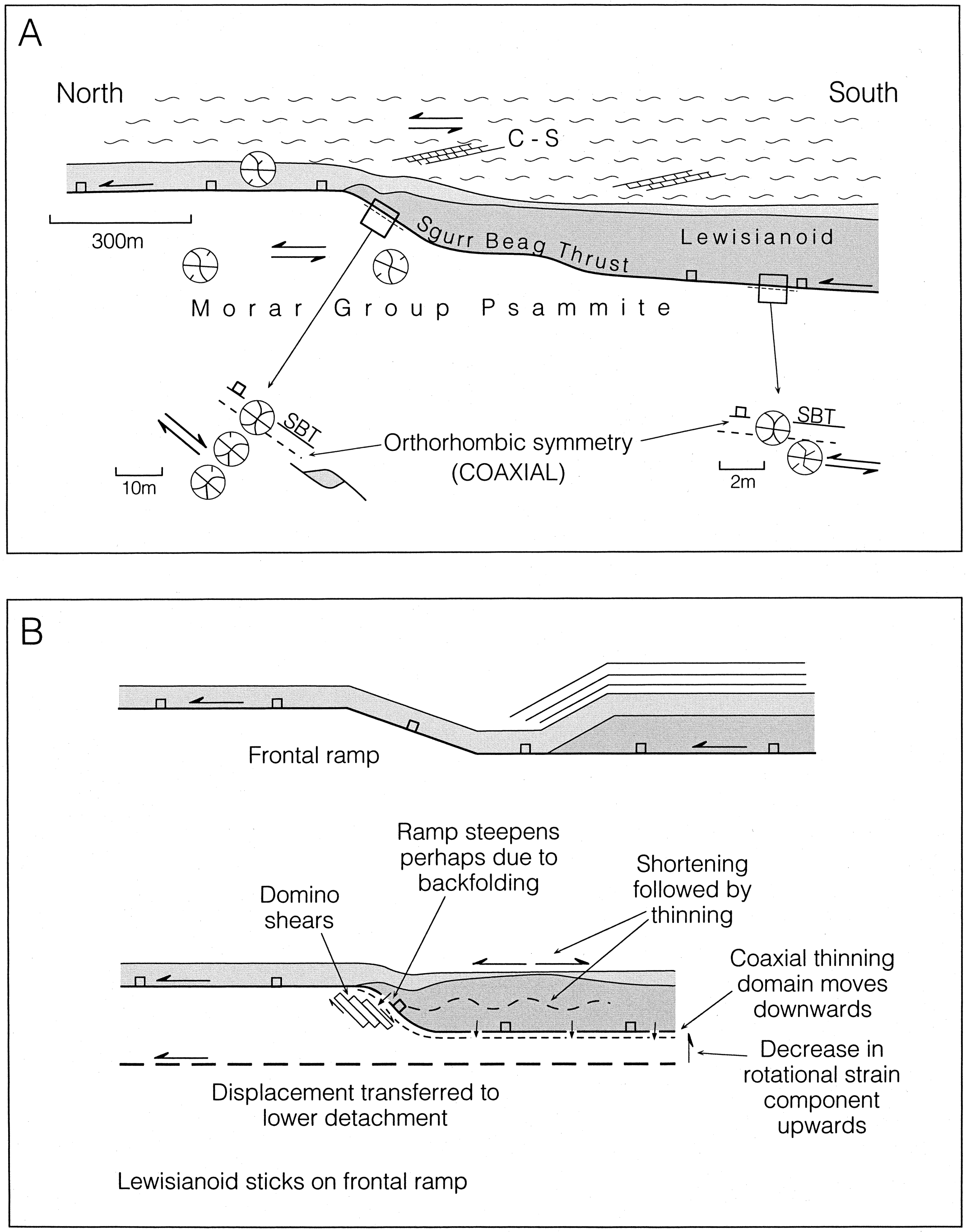

Fig. 7. (a) Summary of the quartz fabric distribution and shear indicators recorded in the Sgurr Beag thrust zone at Bein a' Ghuilbein (Garve). (b) Model for the late strain history of the Sgurr Beag thrust zone at Garve.

of major fold nappes and the onset of regional migmatisation (see Soper et al., 1998 and references therein); whereas, in Nevada, the development of Barrovian metamorphism and the loading of the thrust sheets appear to have been broadly coeval and causally linked.

If strain-path partitioning occurred within the Sgurr Beag thrust zone at Garve it cannot easily be explained within the context of a vorticity gradient of the type associated with thrust discontinuities such as those described from the Moine thrust zone (c.f. Law et al., 1986, 1987). The unusual situation of a domain of coaxial strain straddling a thrust plane could arise, however, if this domain were overprinted, in this case very locally and abruptly, by late coaxial strains. Computer modelling of such overprinting predicts that *c*-axis fabrics should be symmetrical in skeletal outline but have an asymmetrical density distribution (Lister and Williams, 1979). There is no convincingly consistent asymmetry of density distribution in the fabrics with orthorhombic symmetry described above (specimens A, B, C, I, J and K) while the lineation trends and orientation of the finite strain axes, as inferred from the *c*-axis pole figures, do not differ significantly between domains. We conclude, therefore, that the formation of the domain of coaxial deformation was either earlier than, or contemporary with, the non-coaxial, simple shear deformation. If the latter is true the magnitude of the simple-shear strain in the Lewisian thrust sheet and within the 50 cm-thick zone immediately beneath it was either so great as to mimic coaxial shear deformation or the two were able to coexist. If the former is true, could a thin domain of coaxial strain survive along a thrust plane within a broad zone of non-coaxial deformation?

Because the Sgurr Beag nappe, a regional-scale structure, was probably emplaced before the peak of regional metamorphism at approximately mid-amphibolite facies it seems reasonable to conclude that, following the peak of metamorphism, the textures, microstructures and quartz *c*-axis fabrics would be similar to one another at Garve and Creich, which are not far apart on the scale of the region. On textural grounds the shear zone at Garve has been shown to have been reworked under retrogressive metamorphic conditions after the peak of regional metamorphism, whereas there is no evidence for this at Creich. An answer to the above question probably therefore lies in the nature of the reworking processes. If, for example, the shear zone was reworked via the development of a new thrust zone within the previous footwall then shearing in this zone could have reset the *c*-axis fabrics of the original Morar Group mylonites, but left the original thrust plane intact. Given a concurrent drop in metamorphic grade and the dry crystalline nature of the shear zone, the feldspathic and hornblendic rocks of the orthogneiss sheet would probably have behaved as a competent unit within a 'strain-softened' incompetent envelope of quartz- and quartz–mica-rich Moine rocks. As a result, this rigid sheet and a thin smear of Morar Group mylonites accreted to its base could have either remained undeformed during the reworking, and so retain a vestige of an earlier coaxial strain history, or could have deformed by pure shear extension. The former model is more consistent with the thermal metamorphism model involving the over-riding high-grade thrust sheet. However, the latter hypothesis seems the more likely because the evidence from Creich suggests that the quartz *c*-axis fabrics surviving at the metamorphic peak were manifestly weak, in contrast to the strongly developed coaxial fabrics at Garve.

We believe that the deformation history of the Sgurr Beag thrust zone, NE Ross-shire can be summarised as follows: there have been at least two episodes of movement within the thrust zone. The trend of the stretching lineation at Creich indicates that the early movement most probably transported the Sgurr Beag nappe to the NW, as has been interpreted at other localities across the Northwest Highlands (Rathbone et al., 1983; Barr et al., 1986). The shear zone was subsequently recrystallised during the Caledonian, staurolite-grade, thermal metamorphic peak. As the region cooled, the Sgurr Beag thrust zone was again a locus for shearing. During this reworking event, a vorticity gradient developed such that a broad shear zone at least 200 m in width developed between the Morar and Glenfinnan groups, in which deformation was predominantly non-coaxial (approximately simple shear) and consistent with north-directed overthrusting; however, the orthogneiss sheet and a thin smear of Moine mylonite accreted to its base behaved as a rigid pod which contemporaneously extended in a coaxial (pure shear) manner.

7. Regional implications

The above kinematic history and the means by which it was deduced have implications for the tectonic history of the Moine as a whole and for similar studies in other moderate-to-high-grade metamorphic terrains. Domains of contemporaneous coaxial and non-coaxial deformation are inferred to have existed during reactivation of a mid-crustal thrust. Late flow within the Sgurr Beag thrust shear zone can be modelled by a homogeneous component of coaxial strain and a superimposed component of non-coaxial strain (Fig. 7b). Late Caledonian, north-directed thrusting, demonstrated in this paper, appears to be unique to the Ross-shire Moine. How this event relates to regional Caledonian tectonics is not known but it is possible that the thrust was reactivated due to the local collapse of the thickened welt formed during the development of the Northern Highland steep belt situated to the southwest which manifestly formed later than the early displacements on the Sgurr Beag thrust.

A third implication concerns the use of stretching lineations as a means of defining kinematic axes. Whilst the validity of this technique is not in dispute it is clearly essential to date the lineation in terms of local tectonics; in this study, interpreting the lineation at Garve as it is interpreted elsewhere in the Moine, i.e. coeval with the formation of the early phase of Sgurr Beag thrust development, rather than postdating the main metamorphic peak could have led to an erroneous interpretation of the shear zone history.

All of the microstructures and *c*-axis fabrics discussed in the study of the Garve area postdate the peak of metamorphism whereas the initial emplacement of the nappe predated or was contemporaneous with it. It is only in zones of post-metamorphic peak reworking or in shear zones which escaped strong recrystallisation during the peak metamorphism (Grant, 1989) that fabrics with monoclinic symmetry are preserved. Rocks within the Moines in which amphibolite-facies metamorphism was attained either during or after the early deformation episodes may not preserve the early *c*-axis fabrics imposed at that time, or as is the case at Creich, preserve them only in a very diffuse way. If this is generally the case, rock textures in metamorphic terrains such as the Moine would be largely products of the last increments of strain or recrystallisation and therefore document only late kinematic histories.

8. Conclusions

A microstructural and petrofabric examination of highly strained rocks adjacent to the Sgurr Beag thrust, NE Ross-shire, has revealed the following:

1. Thermal annealing before or during peak metamorphism in conjunction with late Caledonian deformation almost completely obliterated microstructures and petrofabrics relating to nappe emplacement in the Garve area.
2. Marked contrasts in the *c*-axis fabric and textural history of the shear zones at Garve and the Creich peninsula can be used to deduce that the former has had a more protracted deformation history than the latter, with deformation continuing beyond the Caledonian metamorphic thermal peak.
3. During reworking after the metamorphic peak, the Sgurr Beag thrust zone was reactivated as a northward-directed thrust with evidence for localised dip-slip.
4. Two *c*-axis fabric domains have been described within the Sgurr Beag thrust zone at Garve. At distances of less than 50 cm beneath the thrust plane and within the allochthonous orthogneiss sheet, *c*-axis fabrics are symmetrical with respect to the foliation and lineation, defining a domain of coaxial strain. At distances greater than 50 cm beneath the thrust plane and in the Glenfinnan Group gneisses, *c*-axis fabrics are asymmetrical with respect to the foliation and lineation, and are consistent with a non-coaxial strain path involving overthrusting to the north. Strain compatibility considerations suggest that late flow within the shear zone can best be modelled with a homogeneous component of coaxial strain and a superimposed component of non-coaxial strain; the latter increased in magnitude downwards into the footwall towards a late thrust and upwards into soft pelitic schists.
5. Microstructures and petrofabrics of mid-amphibolite-facies, Moine ductile shear zones have been overprinted by late events and probably do not accurately record the full kinematic history. This has implications for petrofabric interpretation in similar metamorphic terrains where the stability of microstructures goes largely unquestioned.

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