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Progressive deformation structures associated with ductile thrusts in the Moine Nappe, Sutherland, N. Scotland

ROBERT E. HOLDSWORTH

Department of Geological Sciences, University of Durham, Durham DH1 3LE, U.K.

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Abstract—In the deeper parts of mountain belts, polyphase structural sequences observed at outcrop-scale can arise due either to overprinting of regionally distinct deformation phases (e.g. reworking, changes in orogenic boundary conditions), or to localized controls that bring about transient changes in the patterns of ductile flow. These are unlikely to be mutually exclusive processes, and examples from Scotland demonstrate that, once regionally separate events are delimited using radiometric evidence, it is possible to isolate complex deformation sequences arising due to local controls.

In the western Moine Nappe of Sutherland, the dominant structures were formed during Caledonian ductile thrusting towards the WNW, whilst earlier (?Precambrian) phases are relatively minor in importance. Two groups of Caledonian folds and fabrics are recognized in many exposures: *main phase* (D_2) structures which are broadly contemporaneous with ductile thrust fabrics, and later *secondary phase* (F_3) folds. The latter can be divided into two geometric groups: *sheath-fold types* which formed initially as WNW-overturned buckles subsequently modified by ductile shearing; and *asymmetric types*, which are commonly open folds apparently formed with axes close or sub-parallel to the thrust transport direction. Secondary structures show a close spatial association with high strain zones along ductile thrusts, and can be shown to have formed during the later stages of thrusting in certain critical exposures. I propose that they may form due to strain perturbations resulting from variations in the relative rates of ductile flow within the mylonites. Where differential shearing occurs due to *flow-normal* perturbations, wrench-related asymmetric fold types may form. In contrast, secondary sheath-fold structures may result from localized compression phases caused by *flow-parallel* perturbations.

Local flow-perturbation models may be appropriate in situations where the distribution of later structures is apparently related to spatial variations in strain intensity and/or there is a strong geometric and kinematic similarity between sets of folds and fabrics. If such features are not observed, a regional polyphase sequence is more likely, and it is therefore necessary to obtain radiometric dates (or some other independent source of data) to demonstrate a time separation.

INTRODUCTION

OROGENIC belts are commonly characterized by complex patterns of polyphase deformation, which are usually placed, using structural and metamorphic criteria, into relative chronological sequences (D_1, D_2, D_3, etc.). However, whilst it is often possible to order structures in this way on the scale of single exposures or small areas, difficulties may arise when local sequences are correlated over wider areas to establish a series of regional deformation 'events'. Traditionally, correlation of fold phases and fabrics has tended to rely on geometric criteria such as similarity in style and orientation. A strict adherence to this method can lead to mis-correlation and the establishment of spurious or over-complicated deformation sequences (Park 1969, Williams 1985, Tobisch & Patterson 1988). Recent studies have highlighted three main problems.

(a) Individual structures or structural associations may display complex geometric arrangements such as folds with highly curvilinear hinges (Cobbold & Quinquis 1980), or cleavages that transect broadly contemporaneous folds (e.g. Powell 1974).

(b) Deformation on a large scale within orogenic belts is commonly heterogeneous and/or diachronous, so that sequences of structures may have irregular spatial or temporal distributions (e.g. Williams 1985, Tobisch & Patterson 1988).

(c) Studies in regions such as thrust belts (e.g. Butler 1982, Coward & Potts 1983), mylonite zones (e.g. Bell 1978, Bell & Hammond 1984) and accretionary prisms (e.g. Knipe & Needham 1985) have demonstrated that localized polyphase sequences of structures can form during single, progressive deformational phases. Folds, fabrics and faults may develop in different places and at different times in response to localized controls such as flow perturbations or footwall topography.

The recognition of such complications has provided significant insights into the geometric, kinematic and dynamic evolution of deformed terrains (for example, see Elliott 1976, Coward & Potts 1983, Platt & Behrmann 1986).

This paper examines examples of structures from Precambrian Moine and Lewisian rocks in Scotland, where the deformational complexity has been appreciated for many years (e.g. Ramsay 1963, 1967). In this region, structural correlation is unavoidable for the purposes of understanding chronology and large-scale structure. Radiometric dating studies (see Powell & Phillips 1985) suggest that there are likely to be at least two distinct phases of deformation and associated metamorphism because the Moine rocks appear to have suffered two major phases of orogenesis: Precambrian (*ca* 1000 Ma) and Caledonian (*ca* 470–430 Ma). Hence the Moine represents a *reworked terrain*, in which there is a rational (radiometric) basis for recognizing structures which are chronologically distinct (e.g. see Powell *et al.* 1983). However, whilst distinct deformation phases may be present on a regional scale, it is also necessary to determine whether certain local polyphase structural sequences may have been produced during single progressive deformational events. This will allow the viability and required flexibility of correlation methods to be assessed, and, if certain diagnostic criteria can be recognized, may permit polyphase sequences of differing origin to be distinguished.

THE MOINE NAPPE, SUTHERLAND

The rocks of the northern Highland Moine lie within the internal part of the Caledonian thrust belt in Scotland, and in Sutherland can be subdivided into three large metamorphic thrust sheets (Fig. 1): (from west to east) the Moine, Naver and Swordly nappes. Each tectonic unit has distinct stratigraphic, structural and metamorphic characteristics as each represents previously separated crustal segments which have been juxtaposed by WNW- to NW-directed movements along the major, bounding Caledonian ductile thrusts (Fig. 1) (Moorhouse & Moorhouse 1983, 1987, Barr *et al.* 1986, Holdsworth 1987, 1989, Moorhouse *et al.* 1988, Strachan & Holdsworth 1988). In the Moine Nappe, the Caledonian age proposed for ductile thrusting is based on two important constraints.

(1) The WNW- to NW-directed ductile thrusts and associated folds are geometrically and kinematically similar to undoubted Caledonian fold and thrust structures in the underlying Moine thrust zone which affect rocks of Cambro-Ordovician age (Holdsworth 1987, 1988, 1989).

(2) The ductile-thrust fabrics can be traced with confidence southwards into Ross-shire (Strachan & Holdsworth 1988) where they are seen to deform the *ca* 555 Ma Carn Chuinneag granite (Fig. 1) (Long & Lambert 1963, Pidgeon & Johnson 1974).

Pre-thrusting structures in the Moine Nappe of Sutherland comprise an early bedding-parallel foliation, rare minor folds and a weak N- to NNE-trending mineral lineation (Holdsworth 1987, 1989). Detailed analyses of facing patterns in the region suggests that the Moine succession was largely right way-up prior to ductile thrust-related deformation, so that there is no evidence for earlier, major folds. However, the pre-thrusting deformation is associated with metamorphism to at least garnet grade, forming the peak mineral assemblages; the syn-thrusting Caledonian metamorphic overprint is everywhere mildly retrogressive (Barr *et al.* 1986, Holdsworth 1987, 1989). The pre-thrusting phenomena in the Moine Nappe may represent Precambrian features if they can be correlated with an early phase of deformation and garnet grade metamorphism that predates intrusion of the Carn Chuinneag granite in Ross-shire (Long & Lambert 1963, Wilson & Shepherd 1979, Barr *et al.* 1986).

The Moine Nappe in Sutherland contains units of originally high-grade Lewisian basement which have been interleaved by Caledonian ductile thrusting and folding with a cover sequence of Moine metasediments. The Moine rocks are predominantly psammites, and form a uniform lithological succession, except in local regions where subordinate bands of semi-pelite, pelite and meta-igneous amphibolite are developed. In contrast, Lewisian rocks are diverse, comprising interbanded units of acid, intermediate and basic gneiss, with occasional horizons of metasediment. Intense shearing

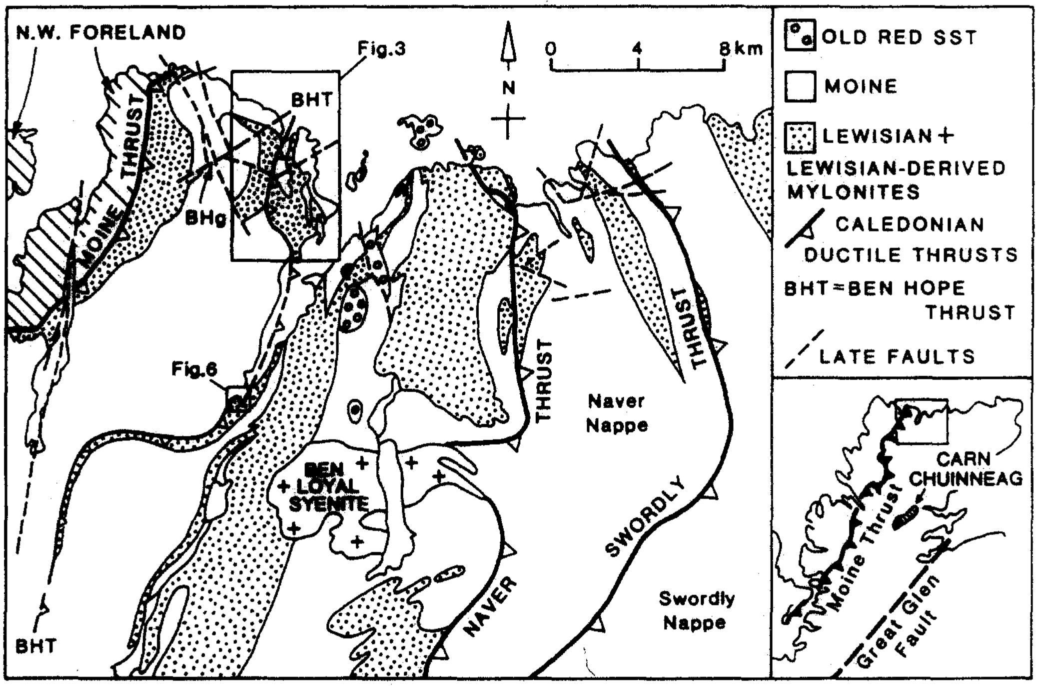


Fig. 1. Simplified geological map of the Caledonian ductile thrust belt in Sutherland, showing major ductile thrusts, nappes and late brittle faults. BHT = Ben Hope Thrust; BHg = Ben Hutig. Boxes indicate locations of Figs. 3 and 6. Inset: location of Sutherland area in Scotland, and location of Carn Chuinneag granite.

and retrogression during tectonic emplacement has frequently converted the original gneisses into banded schists. Localized units of basal conglomerate (notably the Strathan Conglomerate; see Fig. 3) mark the unconformity between Moine and Lewisian rocks. Elsewhere, the tectonic strain has obliterated any trace of discordance, so an unconformable relationship can only be inferred from the originally higher grade character of the Lewisian rocks (Holdsworth 1989).

DUCTILE THRUSTING AND ASSOCIATED FOLDS

Main phase

Folds and fabrics directly related to the main phase of Caledonian ductile thrusting usually form the second phase of structures recognized locally in exposures, 'D_2'. A gently ESE-dipping schistosity is ubiquitous, and in micaceous or hornblendic rock-types forms a tight crenulation fabric that may become transposed in areas of intense deformation. With little change in orientation, the schistosity intensifies into broad zones of high strain, up to 80 m thick, associated with ductile thrusts forming distinct belts of platy mylonites (Fig. 2a). Lewisian inliers often form highly deformed thrust-slices carried in the hangingwalls of Caledonian ductile thrusts (Fig. 1). An ESE- to SE-plunging mineral lineation is widespread and is most intense in the mylonitic high strain zones. Relict *S–C* fabrics are locally preserved within the heavily recrystallized mylonites, and shear-sense indicators (mica fish, shear bands, etc.) suggest overthrust movements towards the WNW–NW, parallel to the mineral lineation (Holdsworth 1989). The schistosity forms an axial-planar foliation to numerous folds that represent the dominant Caledonian structures observed at all scales in the region. Detailed structural analyses (Holdsworth 1987, 1988, 1989) suggest that the folds formed initially as WNW- to NW-overturned buckles whose hinges lay at high angles to the thrusting direction. Subsequent shearing associated with ductile thrust movements resulted in rotation of fold axes towards the direction of tectonic transport (cf. Escher & Watterson 1974), so the majority of hinges now plunge at low angles to the ESE, sub-parallel to the Caledonian mineral lineation. As a result, the folds also display tight sheath geometries on all scales, as manifested by the widespread preservation of 'eye structures' (Fig. 2b) (Cobbold & Quinquis 1980). Many Lewisian inliers lie in the cores of large-scale Caledonian anticlinal sheath folds (e.g. see Holdsworth 1988).

Secondary phases

In parts of the Kyle of Tongue region (Fig. 1), a series of folds (local 'F_3') are observed to deform the main phase Caledonian folds (F_2), together with their associated linear and planar fabrics. Ranging in scale from millimetres to hundreds of metres, these F_3 folds are mostly restricted to the ductile thrust imbricate in the Talmine–Ben Hutig area and, further south, to the immediate hangingwall region of the Ben Hope Thrust (Fig. 1).

Minor F_3 folds (mm- to m-scale) are best developed in the Talmine area (Fig. 3), and are mostly restricted to rocks which display two characteristics.

(1) The main syn-thrusting fabric is intense and mylonitic; that is, the rocks lie in regions of high strain spatially associated with ductile thrusts.

(2) The rocks have a strongly layered anisotropy due to interbanding of differing rock types, such as Lewisian-derived schists and heterogenous units of Moine pelite or amphibolite.

These folds are typically disharmonic structures, forming open-to-tight buckles (Fig. 2c), plunging generally eastwards, although fold axes locally show considerable variations in orientation (Figs. 2c & d and 4). Senses of overturning and axial-plane orientation are irregular, with variations in the latter occurring about an axis roughly parallel to the mean plunge of the main phase Caledonian lineation (Fig. 4). Two types of minor F_3 fold geometry can be distinguished in the region (Fig. 5).

(a) Highly curvilinear, close-to-isoclinal *sheath fold types* that commonly display up to 160° of hinge curvature about an ESE-plunging axis over distances of a few metres (Fig. 2d, NC 5780 6408, 578 653). When preserved in their original NNE–SSW orientation, these folds are always overturned towards the WNW (Fig. 5), and refolding of the main phase folds and mineral lineation is prominent (Fig. 2d).

(b) Gentle-to-tight *asymmetric types* that plunge mostly eastwards, displaying little detectable hinge line curvature. Fold axes lie parallel, or at low angles to the main phase mineral lineation, although refolding of the latter may be obscured by the development of a strong rodding-fabric parallel to local F_3 axes (cf. Wilson 1953, Holdsworth 1987). Whilst the asymmetric types have hinges that lie close to the direction of tectonic transport, the degree of fold axis rotation that has occurred due to shearing is unlikely to be great because interlimb angles are usually large ($\geq 60°$) and strain is low.

In addition to small-scale compressional structures, secondary extensional shear bands are widely developed on a mm- to cm-scale in mica-rich lithologies (e.g. NC 5888 6507). These structures always dip more gently WNW than the foliation and are best observed in regions where asymmetric F_3 folds are absent.

Major F_3 folds are all asymmetric types, mostly with large interlimb angles ($\geq 90°$) which often affect areas of uniform rock units outside zones of intense deformation. In the Talmine area (Fig. 3), a series of major E-plunging folds deform much of the ductile thrust imbricate structure, causing marked changes in the strike of the regional foliation.

EVIDENCE FOR PROGRESSIVE DEFORMATION

The progressive nature of the Caledonian deformation indicated by the main-phase structures has previously been discussed by Holdsworth & Strachan (1988) and Holdsworth (1989). In summary, several suites of minor intrusions in the Moine Nappe cross-cut main phase (F_2) folds, but are deformed by fabrics indistinguishable from the main phase schistosity and mineral lineation in adjacent country rocks. Hence, the folds probably formed during the initial stages of the deformation, whilst at least some of the strain responsible for the formation of the ductile thrust fabrics occurred at a later stage during a single progressive phase. The observation that ductile thrusts persistently cross-cut main phase folds is consistent with such a suggestion, as are local examples of interference patterns formed by the interaction of developing main phase sheath fold structures (Fig. 2e).

The relative timing of secondary phase (F_3) folding and ductile thrusting can be determined at a critical locality along the Ben Hope Thrust (Fig. 1) at Kinloch Broch (Creag an t-Strathain; Figs. 6a–c). A mesoscopic secondary fold pair tightly folds the lower (thrust) contact of the Lewisian, together with the upper boundary of an underlying garnetiferous pelite unit and an intervening horizon of psammite (Figs. 6a & c). The fold pair is disrupted by a low-angle thrust that passes from the common limb downwards to cut out the synform as it is traced south (Figs. 6a & c). The thrust is mostly unexposed, forming a distinct area of flat and poorly exposed ground west of the hill-top. However, the contact is visible at NC 5517 5295, where a narrow ($\leq$10 cm thick) zone of white mica-rich schist separates garnetiferous pelite from psammite. Traced northeast, the thrust apparently becomes banding parallel within the garnetiferous pelite because the lower boundary of the latter is unaffected (Fig. 6c). The F_3 fold pair appears to form the southwest side of a larger, originally WNW-verging sheath-fold structure, much of which has been eroded away (Fig. 6c). At NC 553 531, a thin unit of psammite lies within the pelite in the core of an isoclinal 'eyed' secondary synform (Figs. 6a & c) that may represent the along-strike equivalent of the synform to the southwest (Fig. 6c).

In the common limb of the F_3 fold pair, numerous small-scale secondary folds plunge shallowly between east and south (Fig. 6b), with individual hinges showing up to 80° of curvature within single exposures (e.g. NC 5506 5282). The main Caledonian mineral lineation passes around obliquely orientated fold hinges (Figs. 6b & c), and confirms their secondary (F_3) character. Several examples of earlier isoclinal main phase folds are also refolded by these secondary structures (e.g. NC 5507 5288). The Ben Hope Thrust is characterized by a thick (80 m) belt of platy mylonites in both the overlying Lewisian and sub-adjacent Moine rocks (Holdsworth 1989). The ductile thrust fabric can be traced into the region of the mesoscopic fold pair where it is refolded to produce a locally well defined secondary crenulation cleavage (Fig. 2f). However, the intensity of the early fabric is significantly reduced in both Moine and Lewisian rocks, and the fold pair constitutes an 'augen' of reduced strain compared to immediately adjacent levels along strike. Traced southwest of the summit, the secondary folds tighten and rotate progressively towards an easterly plunge sub-parallel to the main thrust-related lineation (Figs. 6b & c). The secondary folds, 150 m southwest of the summit, have a form virtually identical to main-phase structures as a consequence of the strain intensity (Fig. 6c). Thus it appears that the secondary structures responsible for folding the thrust contact are progressively 'smeared-out' by intense deformation indistinguishable from that recognized along other parts of the Ben Hope Thrust where an apparently straightforward, planar zone of mylonites is exposed. A *syn-thrusting* age for the secondary folding is the most likely explanation in view of the structural relationships preserved. The thrust cutting the secondary folds could then be viewed as a localized semi-brittle failure of a resistant lower strain augen, which acted as a local stress concentrator during the later stages of ductile thrust movements.

A syn-thrusting origin for other secondary folds in the western Moine Nappe seems likely for two important reasons.

(1) Sheath-fold type secondary structures are geometrically identical to the Kinloch Broch example, and all appear to have formed due to modification of folds originally overturning in a direction parallel to the direction of thrusting.

(2) Most F_3 secondary folds are restricted to regions of intense deformation, implying that there is a close link between their formation and the ductile thrusting process.

DISCUSSION

A model of secondary fold formation

The preservation of asymmetric *S–C* fabrics within the platy mylonites associated with ductile thrusting in Sutherland implies that the deformation in these zones approximates to a banding-parallel non-coaxial flow (Lister & Snoke 1984). The asymmetric and sheath-fold geometry secondary folds resemble 'syn-mylonitization' structures recognized widely in many mylonitic zones (Carreras *et al.* 1977, Bell 1978, Cobbold & Quinquis 1980, Lister & Williams 1983, Bell & Hammond 1984, Evans & White 1984). Such phenomena are frequently attributed to the amplification of local perturbations in ductile flow which can arise due to spatial variations in one or more rheological parameter(s). These include strain rate, deformation mechanisms, metamorphic reactions, fluid pressure and mechanical anisotropy (Cobbold 1976, Carreras *et al.* 1977, Berthé & Brun 1980, Cobbold & Quinquis 1980, Lister & Williams 1983, Platt 1983).

The presence of a flow perturbation like that shown schematically in Fig. 7 (cf. Coward & Potts 1983, Ridley 1986) leads to the establishment of local flow velocity gradients within the banding surface which, in turn, will produce localized distortions in the strain field. The

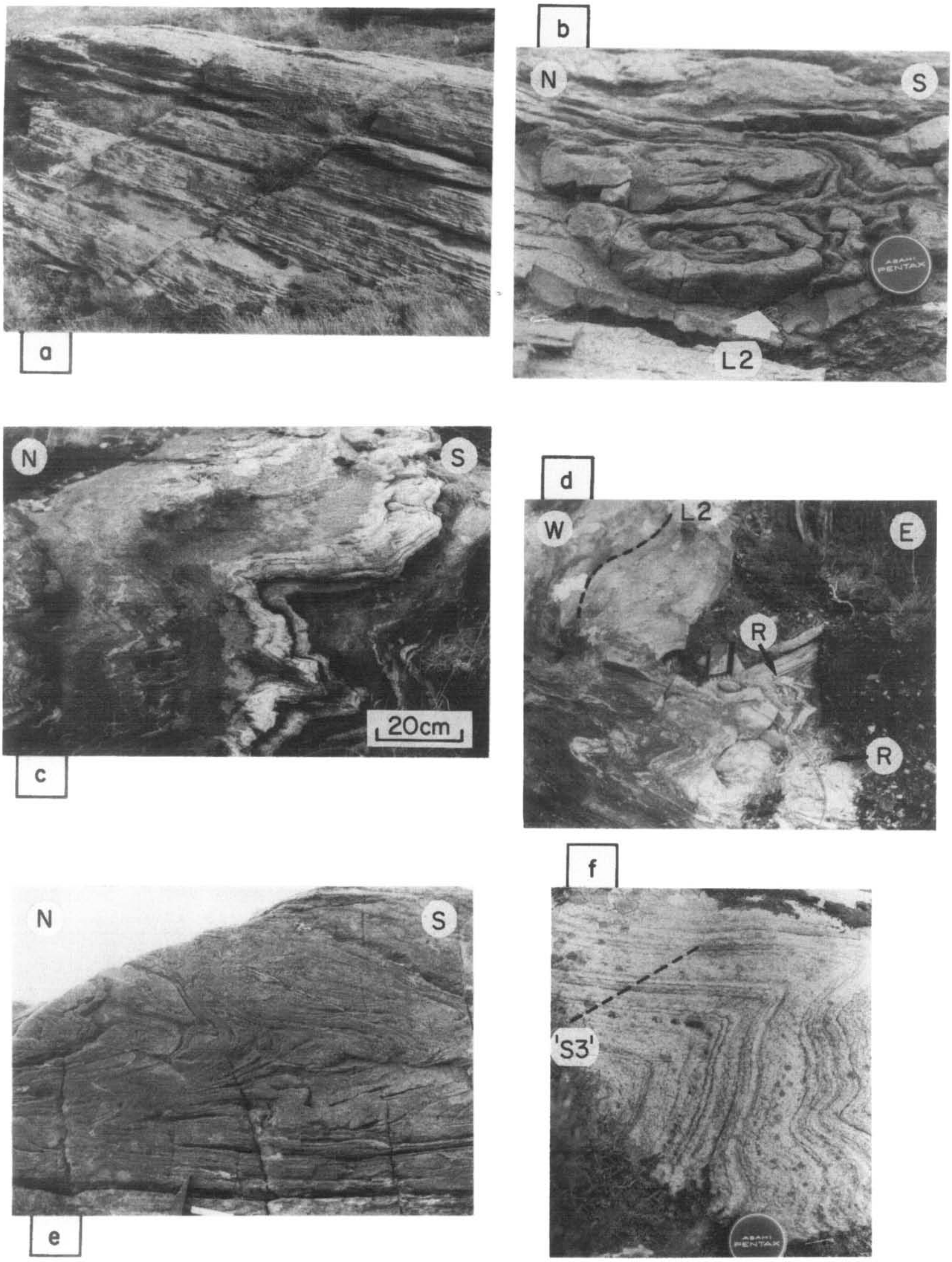


Fig. 2. (a) Platy Moine psammitic mylonites along the Ben Hope Thrust, Creag Riabhach Beag (NC 5001 5234). The rocks are grey–green in colour due to enrichment in white mica, and contain numerous concordant quartz plates; both features may reflect enhanced fluid-flow. (b) Main phase (F_2) eye-structure in Moine psammites, Creag Mhor (NC 5847 6455). Note the strong mineral lineation (L_2) plunging down the central axis of the sheath fold. (c) Typical asymmetric F_3 folds in mylonitic Lewisian-derived schist (NC 5712 6256). (d) Sheath-fold geometry F_3 folds deforming platy Lewisian mylonites. L_2 lineation and earlier (?F_2) isoclinal folds (refolds marked 'R') (NC 5589 6307). (e) Complex interference produced by the interaction of progressively evolving main phase (F_2) sheath folds in Moine psammites, Creag Mhor (NC 5852 6457). Shapes resembling all three interference patterns are preserved in the exposure. (f) Secondary (F_3) folds refolding platy mylonitic fabric in Moine psammites, Kinloch. Note the well developed crenulation fabric, 'S_3' (NC 5513 5290). In all photographs, lens cap is 50 mm across, unless otherwise indicated.

resulting changes in the rate of shear strain *parallel* to the direction of flow will generate zones of local compression and extension (Platt & Vissers 1980, Platt 1983) that may lead to the generation of buckle folds (overturning in the direction of flow) and shear bands (dipping in the direction of flow), respectively (Fig. 7). In addition, changes in rates of shear strain *normal* to the direction of flow will generate local zones of differential wrench movement. Coward & Potts (1983) have demonstrated that differential shear strains in this instance can lead to the formation of asymmetric buckle folds whose axes will lie markedly oblique, or even almost parallel to the direction of flow (Fig. 7).

The circular perturbation geometry shown in Fig. 7 assumes that the flow velocity gradients are equal in all directions. In reality, this condition may not be achieved, resulting in the development of elliptical or more complex perturbation shapes. A directional variation in relative velocity gradients will influence the strain distribution produced and hence the types of minor structure that may form. Thus, in the case of F_3 secondary structures, asymmetric fold geometries may be generated by flow perturbations in which the shear-strain gradients are highest in directions normal to flow, i.e. local wrench strains dominant (Fig. 7). Northward-verging folds would form due to local dextral shears, whilst S-verging folds would reflect sinistral movements. Conversely, folds with axes roughly orthogonal to flow and shear bands could develop in situations where shear-strain gradients are highest in directions parallel to flow, i.e. local layer-parallel strains dominant (Fig. 7). Subsequent ductile shearing could then accentuate small initial curvatures in fold axes to form F_3 sheath fold structures (cf. Cobbold & Quinquis 1980). Alternatively, F_3 sheath folds could form in association with perturbations where the shear-strain gradients are roughly equal in all directions. In this case, orthogonal and obliquely orientated folds, with or without sets of shear bands, might develop and link together simultaneously forming initially arcuate, curvilinear structures so that all the structures shown in Fig. 7 could form at once.

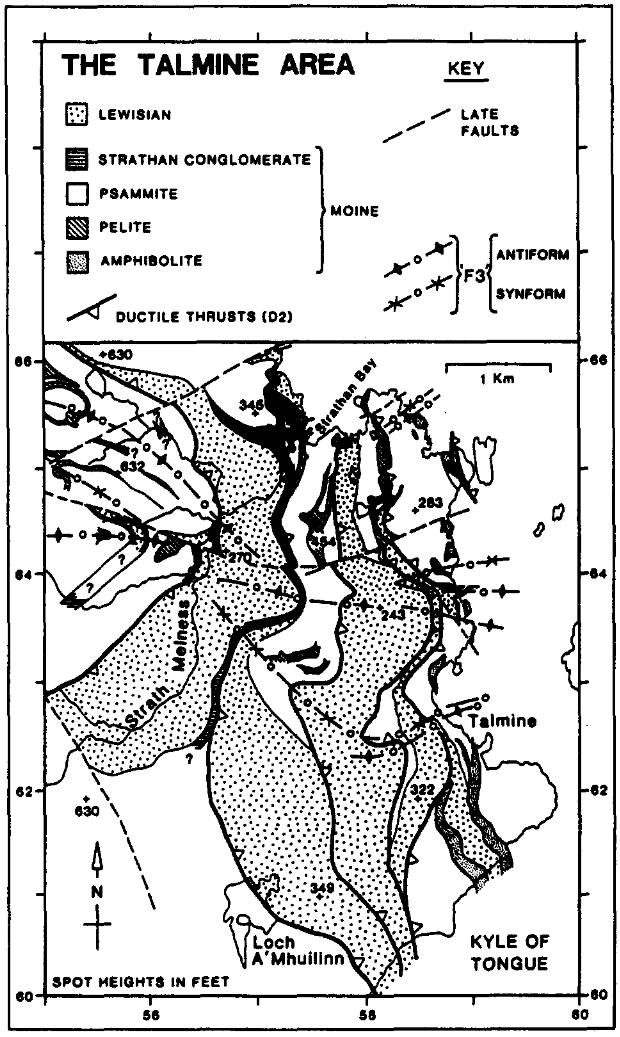


Fig. 3. Simplified geological map of the Talmine area (after Holdsworth 1987).

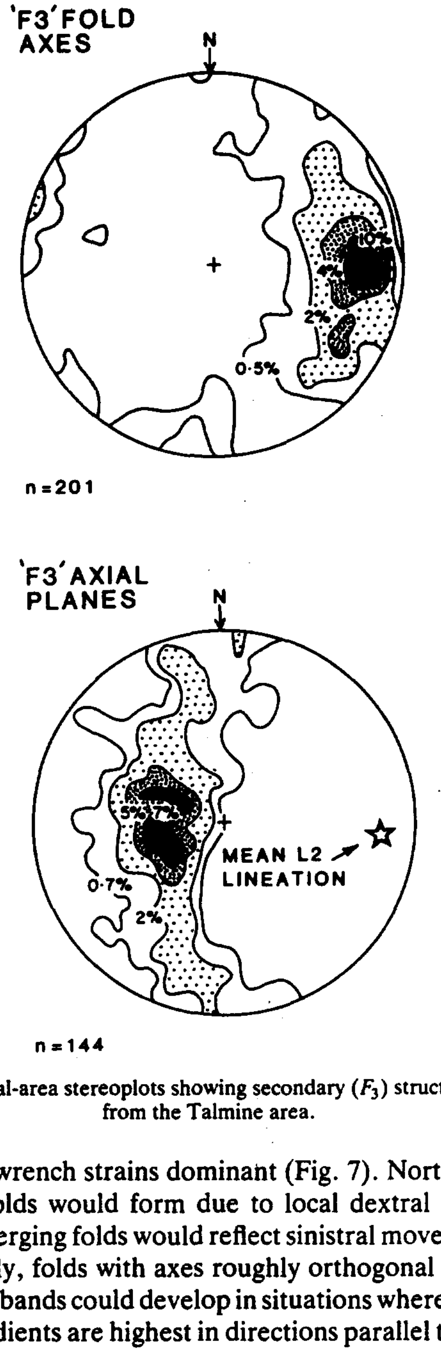
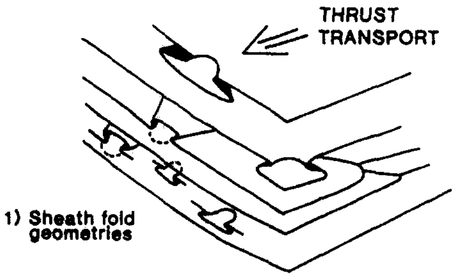
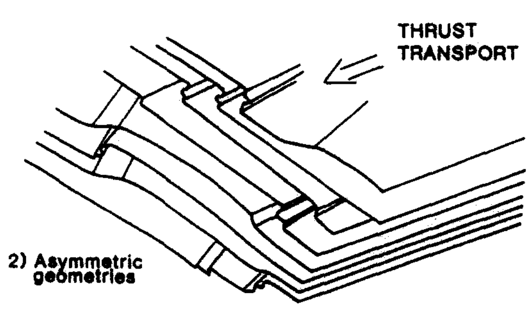


Fig. 4. Equal-area stereoplots showing secondary (F_3) structural data from the Talmine area.

It would seem, therefore, that many of the F_3 structures in W. Sutherland could form in response to flow perturbations within the mylonites. In addition, Ridley (1986) has pointed out that the presence of layers with variable relative viscosity in multilayer sequences may lead to strain partitioning when the bulk deformation involves both thrust and wrench related shearing. This occurs because whilst all the layers will be constrained to deform at a constant strain rate in response to wrench shears, thrust-related shear strains may be concentrated into units having lower viscosity. A large-scale partitioning process of this type could explain why all the F_3 folds that deform rocks outwith of the high strain zones are open asymmetric types. If the ductile-thrust mylonites were strain softened, as seems likely (see below), adjacent zones of lower strain could effectively behave like more viscous layers in a multilayer sequence. Transient differential displacements along ductile thrusts could then conceivably generate sufficient wrench-related strains to form major asymmetric F_3 folds whose axes would lie at low angles to the thrust transport direction. Once again, N- and S-verging structures would reflect dextral and sinistral senses of shear, respectively. Several major F_3 folds in the Talmine area are seen to fold higher ductile thrusts whilst apparently rooting downwards into structurally lower mylonite zones (Fig. 3). This suggests that if such a large-scale partitioning of thrust and wrench strains occurs, deformation affects the hangingwall regions of individual ductile thrusts (cf. thrust zones in general, e.g. Butler 1982). Holdsworth (1987) has shown that several large-scale asymmetric F_3 folds deforming Moine rocks at the western margin of the Moine Nappe around Ben Hutig (Fig. 1) root downward into the underlying mylonites associated with the Moine Thrust.



Close ← isoclinal folds – axes curvilinear – single folds pairs show variable vergence, but in sections parallel to thrust transport verge towards foreland (WNW).



Open ← tight folds – axes show little curvature – Z-folds parallel to, or CW of thrust transport (– lineation), S-folds parallel to, or ACW of thrust transport.

Fig. 5. Sheath-fold and asymmetric-type secondary (F_3) fold geometries associated with the ductile thrusts in W. Sutherland. If the asymmetric folds represent differential shearing perturbation structures, the S- and Z-geometry fold pairs reflect dextral and sinistral movements, respectively (see Fig. 7).

Regional significance

The distribution of the F_3 structures seems to imply that the zones of secondary deformation were largely restricted to those areas close to thrusts established during the main-phase movements. This contrasts with the regionally penetrative nature of the main deformation phase, and suggests a narrowing, or partitioning of high strain zones with time on a larger scale. This could conceivably arise due to a decrease in the regional temperature or an increase in the strain rate. Alternatively, a more localized control such as strain softening within the developing mylonites may be of importance (see Holdsworth 1989).

If the perturbation and large-scale partitioning model is correct, it has major implications for structural correlation methods in rocks of this type. Flow perturbations can arise due to local rheological controls acting in different locations at different times. Thus, while I propose that the secondary structures have broadly common origins, it is not meaningful to correlate individual structures precisely in a chronological sense. This suggestion is confirmed by the local occurrence of secondary folds overturned in one direction that overprint structures identical in style overturned in the opposite direction (e.g. NC 5857 6228, 5667 6289). The synthrusting 'age' also means that it is misleading to refer to the secondary folds as a distinct deformation 'event', because this would imply that they have formed in response to a change in the externally applied boundary conditions.

CONCLUSIONS

In rocks like the Moine, which have probably undergone at least two cycles of orogenesis, there is clearly a basis for the identification and correlation of deformation phases. However, structural studies must rely on a parallel program of radiometric dating (or some other independent data source) so that phases may be separated, with certainty, in time. The present work has attempted to demonstrate that some groups of structures within the Moine rocks can also be attributed to localized progressive deformation. If possible, it would be useful to define certain structural criteria that distinguish polyphase sequences formed by local factors from those formed by separate regional 'events'. Based on the evidence examined here, there seem to be two important sets of criteria.

(1) The kinematic significance of structures needs to be carefully assessed using field-data such as geometry, shear-sense indicators and fold-lineation relationships. If groups of structures can be shown to display significant kinematic similarity, a flow perturbation and partitioning model may need to be considered. If the structures are kinematically different, a separate origin may

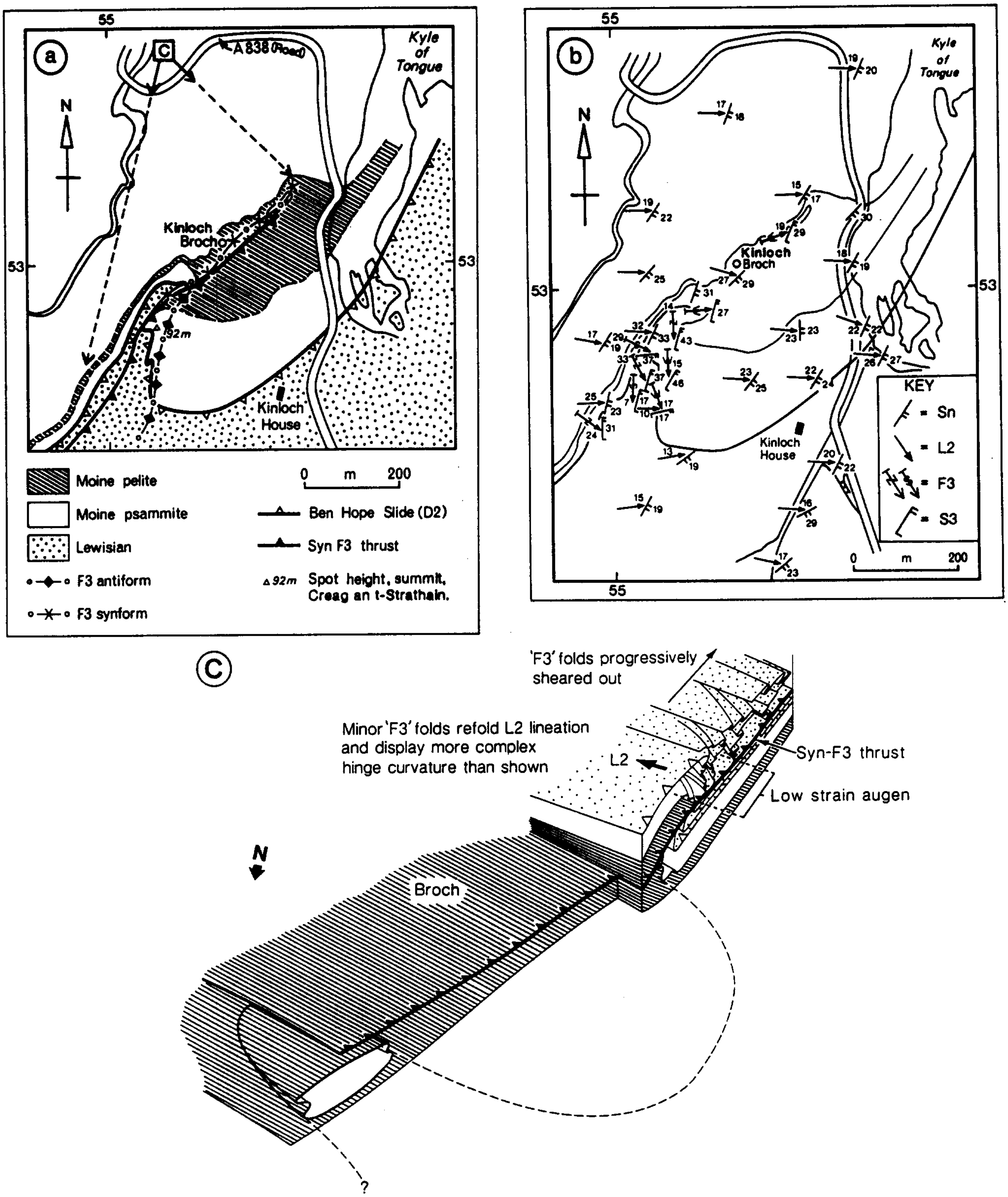


Fig. 6. (a) Simplified geological map, Creag an t-Strathain, Kinloch. For location, see Fig. 1. Field of view for (c) is also shown. (b) Unshaded version of (a) showing minor structural data in the region. Readings taken at centre of strike bars (planar features) and/or points of arrows (linear features). S_n = lithological banding; L_2 = mineral lineation (folded by minor F_3 structures); F_3 = secondary minor fold axes and vergence; S_3 = F_3 axial planes. (c) Three-dimensional cartoon showing suggested secondary (F_3) fold and ductile thrust relationships in the Kinloch region; view looking south (see a). Key as in (a). See text for further details.

be a more appropriate alternative (e.g. see Holdsworth & Roberts 1984).

(2) The distribution of structures in relation to the variations in strain intensity is of major importance (Tobisch & Patterson 1988) and can provide insights into why certain areas display different structural histories compared to others. In the present example, one of the most important observations is that the majority of secondary structures are restricted to high strain zones associated with ductile thrusts.

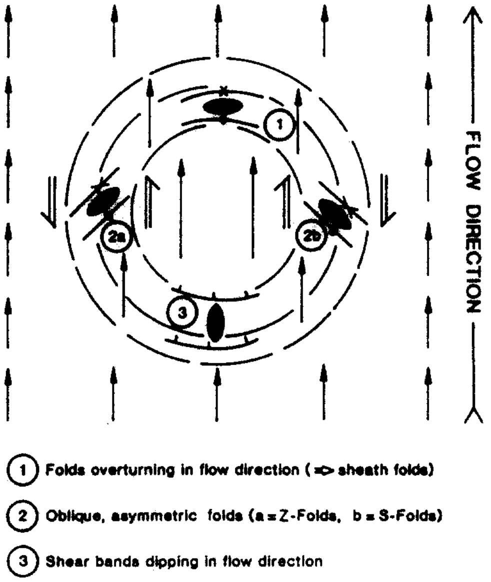


Fig. 7. Plan view of a flow perturbation in the plane of mylonite banding during non-coaxial flow (after Ridley 1986). In this instance, a local increase in relative flow velocity is assumed; a local decrease will result in a kinematically identical mirror-image configuration. The relative flow velocities are indicated by the sizes of the arrows. Predicted two-dimensional strains and minor structures are shown diagrammatically. Note that dextral and sinistral differential shears form asymmetric folds with opposite senses of vergence. The circular form of the perturbation is entirely schematic.

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