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Transport-parallel cross folds within a mid-crustal Caledonian thrust stack, northern Scotland

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Abstract—Cross folds are typically associated with zones of anomalous foliation trend that lie at high angles to orogenic strike. This case study concentrates on a region of transport-parallel cross folding developed by buckling during Caledonian ductile thrusting within the Moine and Naver Nappes of northern Scotland. Detailed structural analysis reveals a systematic angular relationship between the trend of tectonic transport, fold axes, and the vergence of minor folds. Large-scale cross folding is considered here to be related to wrench-dominated differential shearing during thrust-sense displacements along an important, possibly out-of-sequence structure, here termed the Ben Blandy Shear Zone. This suggests that patterns of folding within the internal parts of the Caledonian orogen in Scotland are principally controlled by the kinematic constraints imposed by low-angle thrusting. Thus, early, 'main-phase' folding is associated with the initiation and propagation of ductile thrusts, whilst later, secondary structures, including cross folds can be related to the development of flow perturbations during displacement along well-established, regionally important detachments. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

The term cross fold has its origins in the early structural studies of the Alps (e.g. Heim 1921) where two sets of folds were identified trending sub-parallel and at high angles to the orogenic strike, known respectively as 'longitudinal' and 'transverse or cross' folds (Stoces & White 1935). Cross folding is often considered to be synonymous with refolding (e.g. Hills 1972), and Sutton (1960) has suggested that cross folds are a characteristic feature of all polydeformed terrains in the internal parts of orogenic belts. Various interference patterns produced by cross folding have been documented (e.g. Reynolds & Holmes 1954). Fabrics developed axial planar to cross folds may locally overprint the 'regional' foliation at high angles and they typically strike parallel to the large-scale tectonic transport direction. Interpretations of cross folding include the occurrence of orogen-parallel shortening events (e.g. Wilson 1953), regional constrictional strains (e.g. Stringer & Treagus 1980), regional-scale curvilinear (sheath) folding (e.g. Dearman 1969, Sanderson 1973), deformation above lateral culmination walls (e.g. Elliott & Johnson 1980, Butler 1982), complex 3-D oblique strains (e.g. Treagus & Treagus 1981) and lateral-tip strain phenomena (e.g. Coward & Potts 1983).

The Proterozoic Moine metasediments of the Scottish Caledonides (Fig. 1) have undergone orogenesis in the Precambrian (*ca* 850–1000 Ma) and Lower Palaeozoic (Caledonian; *ca* 470–430 Ma) (Powell & Phillips 1985, Harris & Johnson 1991, Holdsworth *et al.* 1994). Some polyphase structural sequences can be attributed to the overprinting of Precambrian and Caledonian orogenies (e.g. Powell *et al.* 1983, Barr *et al.* 1986), but other local polyphase structural sequences are thought to have arisen due to progressive deformation cycles spatially associated with high strain zones (Holdsworth 1990, Alsop & Holdsworth 1993). In this paper, we describe examples of large-scale cross folds developed in the Moine rocks of Sutherland, northern Scotland (Fig. 1) and suggest that they formed due to differential displacements along associated ductile thrusts. Within this study, cross folds are defined as '*upright to overturned, open-to-tight folds developed transverse to the regional foliation trend with axes that plunge sub-parallel or at low angles (<20°) to the direction of tectonic transport*'.

CALEDONIAN STRUCTURES

The Moine rocks of Sutherland are divisible into two major metamorphic thrust sheets, the Moine and Naver Nappes bounded by major WNW- to NW-directed Caledonian ductile thrusts (Figs. 1 and 2; Moorhouse &

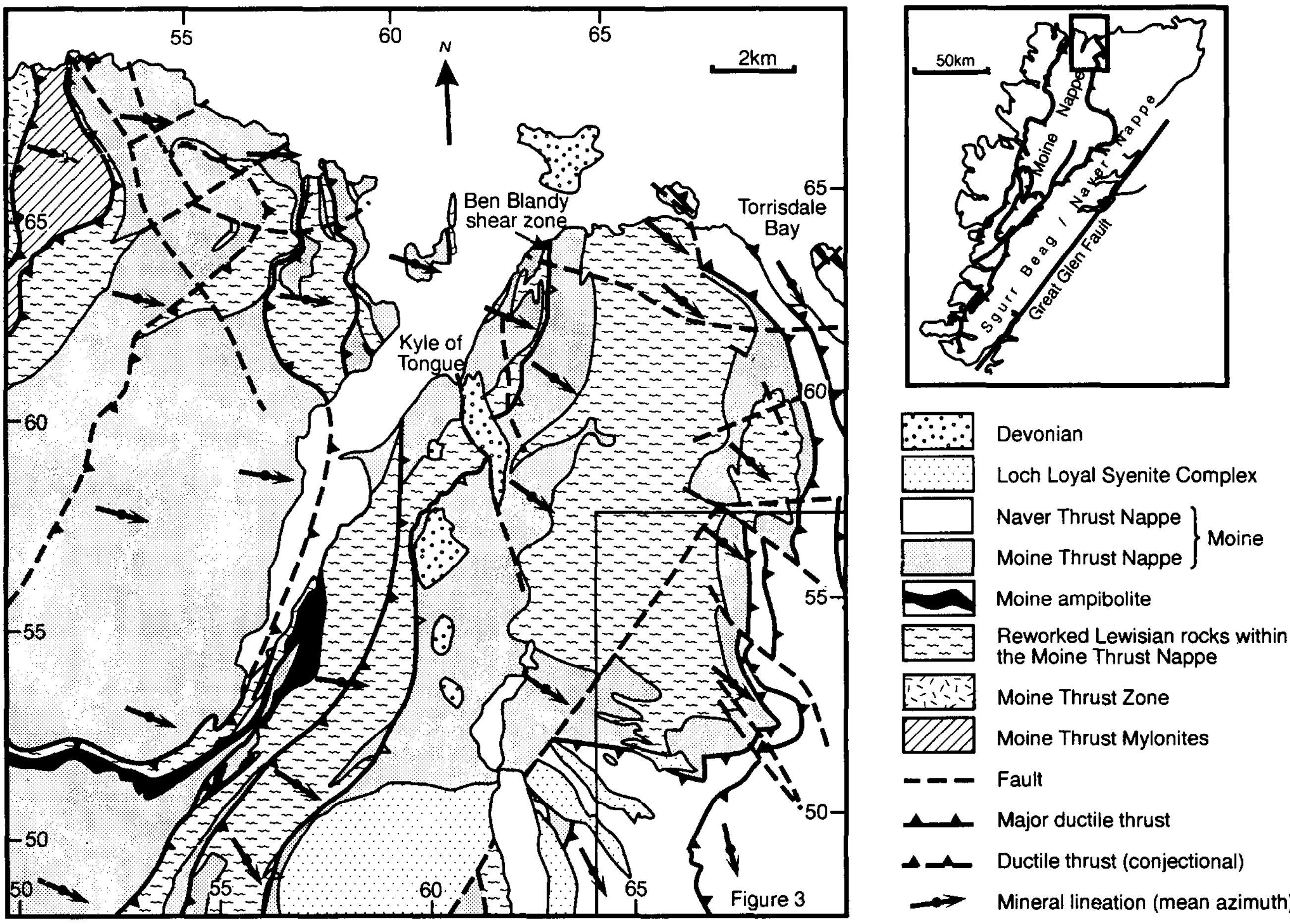

Fig. 1. Simplified geological map of the Moine and Naver Nappes in the Tongue area (based on Holdsworth *et al.* in press) also showing mineral lineation trends. Important NW- to WNW-directed Caledonian ductile thrusts are also shown (solid triangles), together with the Ben Blandy Shear Zone (open triangles). The location of Fig. 3 is indicated by the box. The inset map shows the location of the Tongue area in relation to northern Scotland and highlights major Caledonian nappes.

Moorhouse 1983, Barr *et al.* 1986, Moorhouse *et al.* 1988, Holdsworth 1989). A regional metamorphic inversion in the nappe pile is thought to have resulted from development of a foreland propagating system of ductile thrusts during progressive denudation, with successively later (more westerly) thrusts formed under decreasing temperatures and pressures (Barr *et al.* 1986, Holdsworth & Grant 1990). The Moine rocks of the Moine and Naver Nappes are mainly psammites, with subordinate semipelite, pelite and meta-igneous amphibolite (Holdsworth *et al.* 1994). They are interleaved with Archaean–Palaeoproterozoic Lewisian orthogneisses which are considered to form the high-grade basement upon which the Moine sediments were originally deposited (Peach *et al.* 1907). Large Lewisian inliers appear to lie within the low strain cores of major antiforms; other basement units are interleaved as thrust-slices carried in the hangingwalls of Caledonian ductile thrusts (Holdsworth 1989).

Main phase structures

Most of the ductile deformation in the Moine rocks in Sutherland is related to Caledonian thrusting (*ca* 470–430 Ma) under upper greenschist to middle amphibolite facies conditions (Powell & Phillips 1985, Holdsworth 1989). Caledonian structures generated during ductile thrusting consistently represent the second and dominant phase of deformation (D_2) recognised in local exposures. A gentle to moderate ESE-dipping composite foliation ($S_n/S_1/S_2$) forms the dominant fabric which intensifies into broad zones of high strain platy mylonite associated with D_2 ductile thrusts (Fig. 2). A strong, variably transposed S_2 crenulation cleavage is developed axial planar to tight-to-isoclinal, reclined F_2 sheath folds on all scales, with axes that lie mainly sub-parallel to a pronounced, ESE- to SE-plunging mineral elongation lineation (L_2) defined principally by quartz. The lineation is most intense in the high strain zones adjacent to the ductile thrusts, where shear sense indicators (shear bands, mica fish) suggest overthrust movements towards the WNW or NW (Holdsworth & Grant 1990). This lineation defines the axis of finite extension and lies sub-parallel to the Caledonian transport direction (Barr *et al.* 1986). The lineation shows a well-defined swing in orientation from gently ESE-plunging in the west adjacent to the Moine Thrust system to SSE-plunging in the east adjacent to the Naver Thrust (Fig. 1).

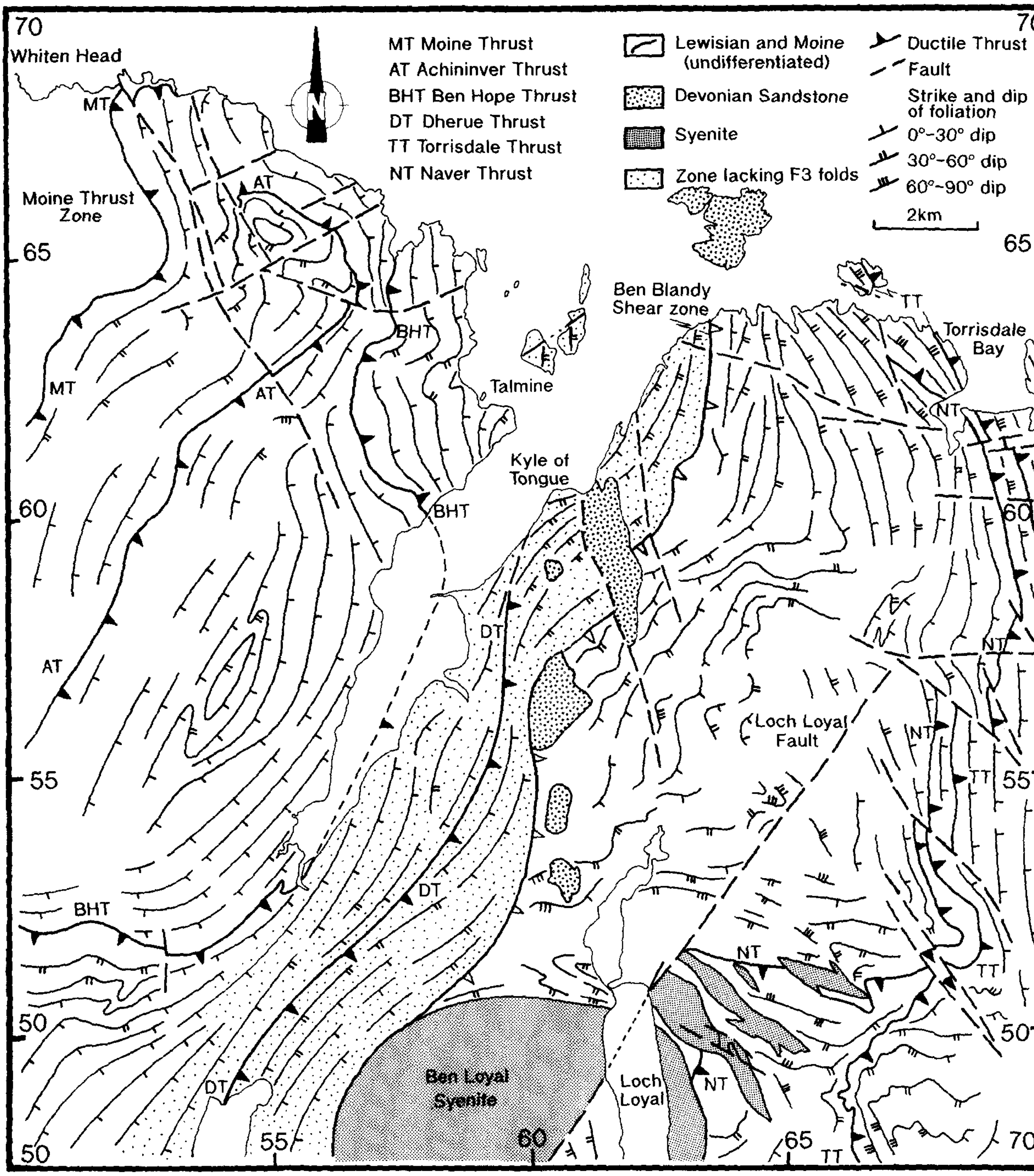

Fig. 2. Simplified foliation form line map of the Tongue area also showing important D_2 ductile thrusts (location as Fig. 1). Major F_3 folds are defined by the form lines. Note that F_3 folds are largely absent in the zone indicated by stippling.

Secondary phase structures

West of the Kyle of Tongue, a series of km-scale 'F_3' buckle folds are developed within a series of tectonic units bounded by D_2 ductile thrusts producing pronounced swings in regional strike (Holdsworth 1989, 1990, Alsop & Holdsworth 1993). F_3 folds developed parallel to the WNW-directed transport direction display variable vergence and define a major structural culmination NW of Talmine (Fig. 2). Further south, WNW-vergent folds west of the Kyle of Tongue define a transport-normal culmination sub-parallel to the regional foliation which bows-up and folds the overlying Ben Hope Thrust (Alsop & Holdsworth 1993) (Fig. 2). The geometry and distribution of the buckle folds suggests that they are related to large-scale flow perturbation patterns developed along the underlying Moine Thrust mylonite zone (Alsop & Holdsworth 1993).

The most prominent cross folds east of the Kyle of Tongue are defined by a large-scale pair of secondary (local F_3) buckles which fold the Naver Thrust, here termed the Borgie Antiform and the Ben Stumanadh Synform (Fig. 3). In the south, these structures are cross-cut by a series of little deformed, NW–SE-trending syenite intrusions belonging to the late Caledonian (*ca* 426 Ma) Loch Loyal Syenite complex (Robertson & Parsons 1974, Halliday *et al.* 1987). In the hinge and northern limb of the Borgie Antiform, the regional

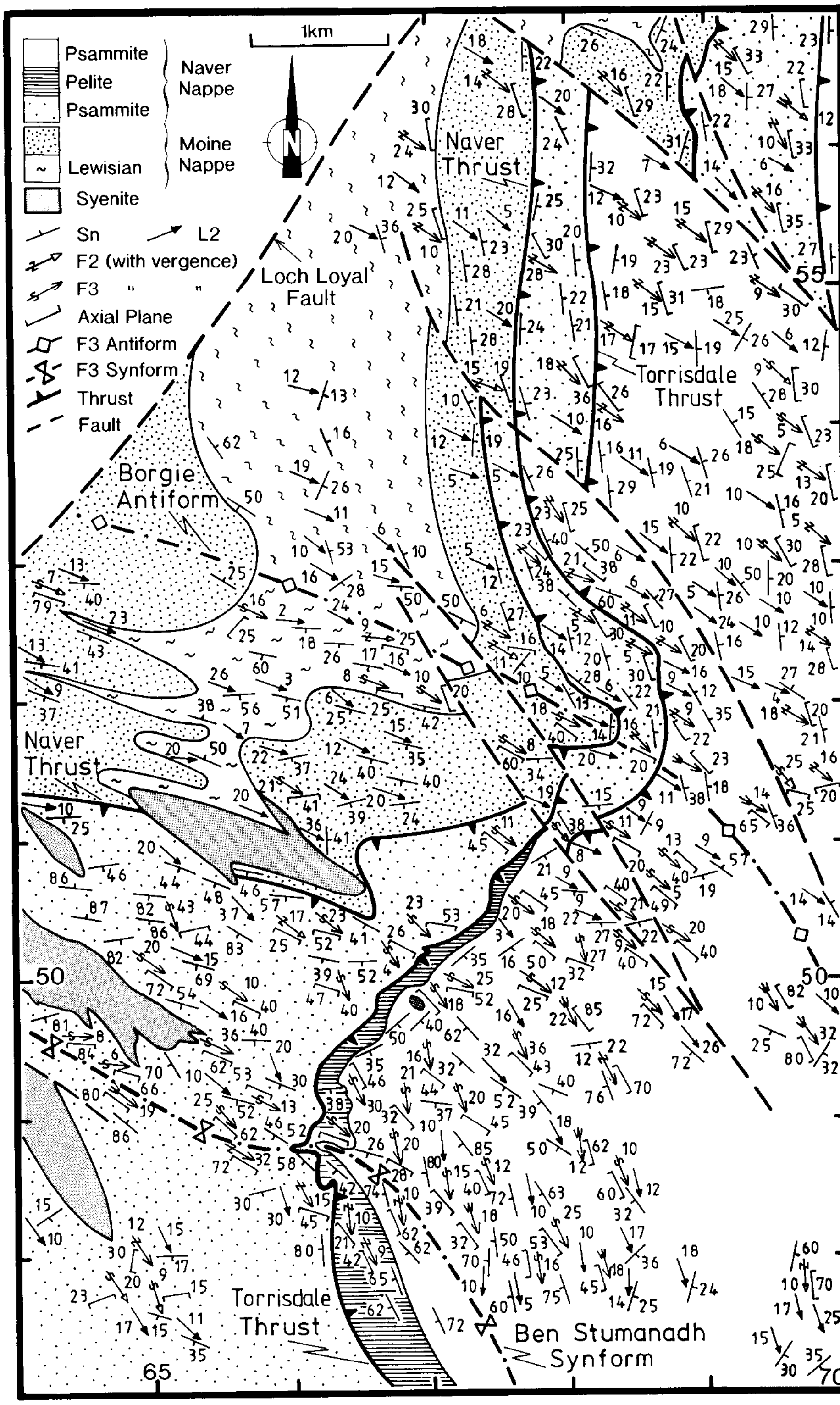

Fig. 3. Detailed structural map of the Borgie Forest–Ben Stumanadh area showing the F_3 Borgie Antiform and Ben Stumanadh Synform folding the Naver and Torrisdale thrusts (see Fig. 1 for location).

foliation (S_n) dips gently towards the east, whilst on the southern limb, the foliation is folded to dip gently to moderately S or SW (Fig. 3). The poorly exposed southern limb of the Ben Stumanadh Synform also dips moderately to steeply SW, suggesting that this fold is tight and overturned to the NE. At a mesoscopic (metre) scale, open-to-tight F_3 buckle folds deform all earlier structures including the S_2 fabric and the L_2 quartz mineral lineation, e.g. at NGR [NC68975149], although many F_3 minor fold hinges are sub-parallel to L_2. In some regions, 'F_3' type folds refold earlier 'F_3' folds with opposed senses of vergence producing open type III interference patterns, e.g. at [NC69545332]. However, as no consistent pattern of overprinting structures can be defined, such features are thought to be localised phenomena formed during protracted deformation.

This implies that 'F_3' folds should not be considered as strictly contemporaneous structures resulting from a regional 'D_3' event as they may arise due to more localised kinematic controls within zones of shearing.

Within the northern limb of the Borgie Antiform, minor F_3 folds plunge gently towards the SE, whilst the associated axial planar zonal (mm–cm scale) S_3 crenulation cleavage of S_2 dips marginally more steeply towards the ENE than the regional foliation (S_n) (Fig. 3). In the hinge region of the Borgie Antiform, F_3 folds plunge gently towards the SE and are associated with an axial-planar zonal crenulation cleavage which is variably oriented about the mean F_3 plunge that is also broadly coincident with the regional orientation of L_2 (Fig. 3). On the southern limb of the Borgie Antiform, and in the hinge and southern limb of the complementary Ben Stumanadh Synform, minor F_3 fold axes plunge gently towards the SSE with an associated S_3 crenulation cleavage dipping moderately to steeply SW to SSW. Open-to-tight asymmetric folds with axes plunging at low angles to L_2 form the dominant F_3 fold style on all scales in the region east of the Ben Blandy Shear Zone (Fig. 2). Highly curvilinear F_3 folds displaying up to 110° of hinge line curvature, e.g. at [NC 66015201], are locally developed in high strain zones, but the majority of folds display large interlimb angles and cylindroidal hinges that cannot be explained using a sheath fold model. Although F_3 minor folds are mainly sub-parallel to the mineral elongation lineation (Figs. 3 and 4a), detailed analysis of F_3 fold geometry and orientation reveals a systematic relationship with respect to the tectonic transport direction. For example, 'Z' vergent F_3 folds with NE-dipping axial planes are dominant on the northern limb of the Borgie Antiform, whilst 'S' vergent folds with SW-dipping axial planes dominate on the southern limb. Minor 'Z'-verging folds display a small clockwise skew in relation to L_2 (Fig. 4b), whilst 'S'-verging folds define an equivalent anticlockwise asymmetry (Fig. 4c). Neutral verging 'M/W' F_3 folds do not display a marked skew in relation to tectonic transport (Fig. 4d).

The regional swing in the trend of L_2 from SE-plunging in the north of the Borgie area to S-plunging in the southern portion is mirrored by the similar change in the orientation of F_3 fold axes (Fig. 3). Thus, in the structurally highest part of the Naver Nappe, both the L_2 lineation and sub-parallel F_3 fold axes swing rapidly clockwise into S-plunging orientations (Fig. 3). In the absence of any evidence to suggest that the lineation and F_3 fold pattern is a consequence of later deformation, it would appear that the primary (D_2) tectonic transport direction was variable (*cf.* Barr *et al.* 1986). The F_3 folds therefore appear to follow the pre-existing D_2 linear anisotropy generated during ductile thrusting.

REGIONAL FLOW PERTURBATION MODEL

F_3 folds developed within and adjacent to mylonite zones associated with ductile thrusts can be related to flow perturbation patterns generated within the underlying detachments. The development of a perturbation in flow results in local flow velocity gradients and variations in the rate of shear strain (Coward & Potts 1983). Holdsworth (1990) and Alsop & Holdsworth (1993) suggested that F_3 folds in the Talmine area and west of the Kyle of Tongue reflect flow perturbations developed at all scales along underlying ductile thrusts (Fig. 5). Differences in fold orientation and geometry can be attributed to differences in the shape of individual flow perturbations. Thus, buckle folds with axes normal to transport will be generated in perturbations where velocity and shear strain gradients are greatest parallel to the direction of flow. Conversely, more open buckle folds will be generated with hinges sub-parallel, or at low angles to transport in association with perturbations where velocity and shear strain gradients are greatest normal to the direction of flow, i.e. wrench-dominated shearing. Situations intermediate between these two extreme cases will generally develop highly curvilinear fold geometries (Holdsworth 1990). Alsop & Holdsworth (1993) identified west of the Kyle of Tongue two major regions of large-scale flow perturbations that they related to transient variations in displacement along the underlying ductile Moine Thrust.

To the east of the Kyle of Tongue, the Ben Blandy Shear Zone forms a sharply defined tectonic boundary which separates a region affected by abundant F_3 folds to the E (hangingwall), from a region generally lacking F_3 folds on any scale of the W (footwall) (Fig. 2). F_3 sheath fold geometries are locally predominant in the zone of high strain associated with the Ben Blandy Shear Zone, e.g. at [NC613578], indicating a protracted deformation history similar to that observed along other major ductile thrust zones in Sutherland (Holdsworth 1990). In the hangingwall of the Ben Blandy Shear Zone, the large-scale, transport-parallel Borgie Antiform and Ben Stumanadh Synform are open-to-tight structures which are not highly curvilinear and cannot therefore be interpreted as sheath folds. They appear to root downwards into the Ben Blandy Shear Zone and we propose that they formed in response to wrench-dominated differential shearing. As this shear zone seems to act as a basal decollement, the differential shearing must reflect variations in the rates of displacement along this major, ductile detachment (Fig. 5). This suggests that at least two major NW–SE elongate wrench-dominated flow perturbations are centred on the Borgie Forest–Ben Stumanadh region (Fig. 5). No corresponding zone of cross folding can be defined west of the Ben Blandy Shear Zone (Fig. 2), suggesting that wrench-dominated displacements are partitioned in a manner analogous to linked lateral ramp–flat systems in foreland thrust belts (e.g. Boyer & Elliott 1982).

The Ben Blandy Shear Zone is unusual in the Moine Nappe as it carries no Lewisian slices in the hangingwall (Fig. 1). It does not appear to follow thrust 'rules' as it places younger Moine rocks over older Lewisian basement rocks in the footwall. The shear zone notably coincides with a 10°–15° 'jump' in the otherwise smoothly-swinging trend of the L_2 lineation (Fig. 1).

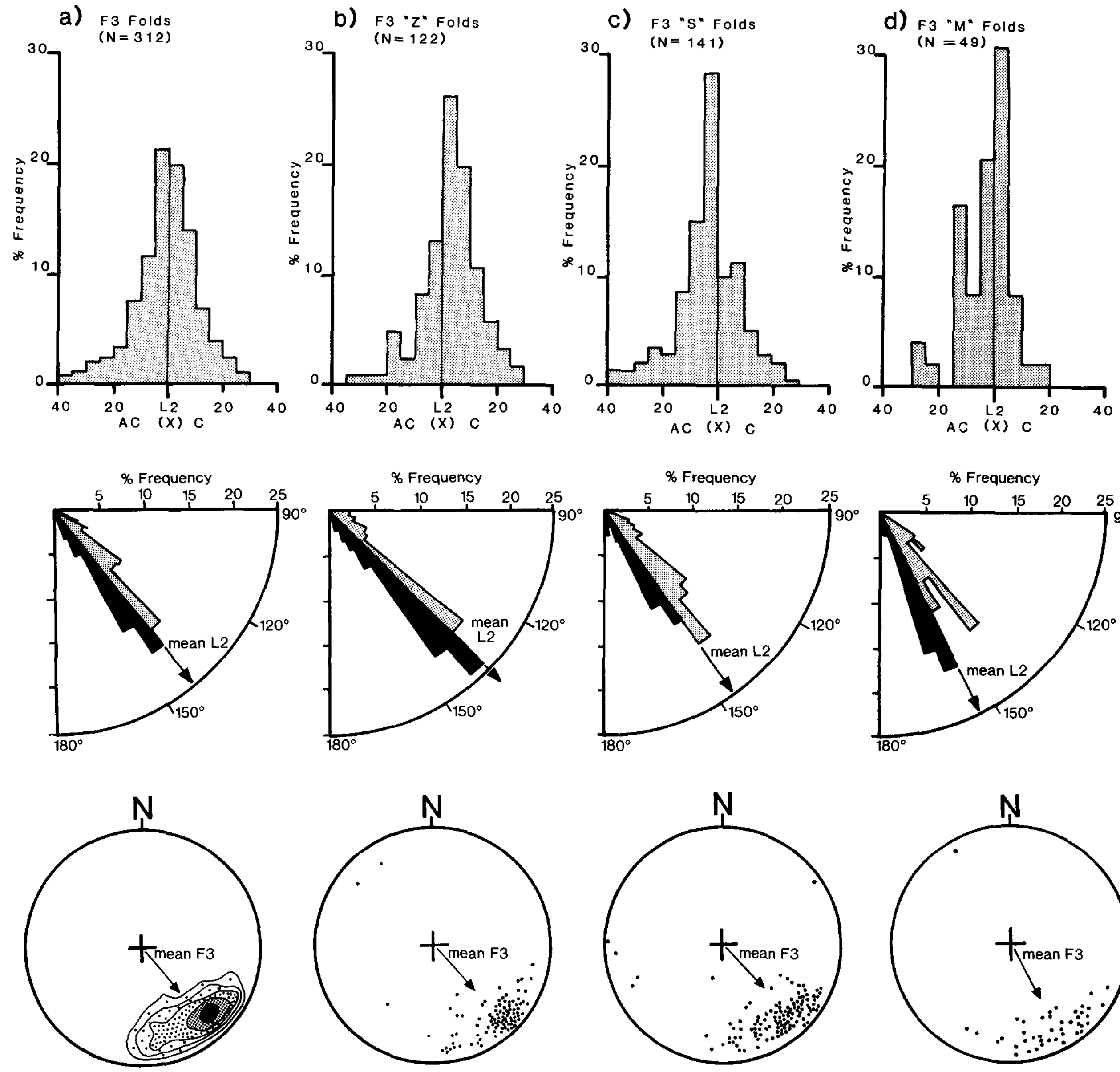

Fig. 4. Structural analyses of F_3 data collected from the Borgie Forest–Ben Stumanadh region. For each F_3 fold geometry (S, Z or M/W), frequency distribution histograms are oriented relative to the adjacent L_2 mineral lineation, (AC, anticlockwise of L_2; C, clockwise of L_2). Adjacent rose diagrams portray the distribution of trends of F_3 fold axes. Equal-area lower-hemisphere projections of F_3 structural data are contoured at 1, 2.5, 5, 10 and 15% intervals.

These features may indicate that the Ben Blandy Shear Zone is an out-of-sequence thrust disrupting the previously folded and imbricated rocks of the Moine Nappe.

CONCLUSIONS

In the light of this and other structural studies in Sutherland (e.g. Holdsworth 1989, 1990, Holdsworth & Grant 1990), it is suggested that fold structures in internal thrust sheets form during two distinct stages in the displacement history. An early set of main phase buckle folds forms during the *initiation* and *propagation* of ductile thrusts, i.e. the regional F_2 folds in Sutherland (Holdsworth 1989). Associated, and often intense, ductile strains often lead to modification of these folds into sheath-like geometries. A distinctly later secondary phase of buckle folds may then form either parallel or transverse to the orogenic strike, which relate to underlying variations in thrust *displacement* along regionally important detachments. The F_3 folds in Sutherland include both longitudinal and transverse structures, but cross folds are dominant on all scales (Fig. 5). Large-scale folds appear to detach along two major structures, the Moine Thrust and the Ben Blandy Shear Zone. These results suggest that the patterns of Caledonian folding in the Moine and Naver Nappes are controlled principally by the kinematic constraints imposed by a ductile thrusting framework. This also illustrates that use of the term 'cross fold' is meaningful when applied on a large scale with reference to the direction of tectonic transport, although the more general use of this

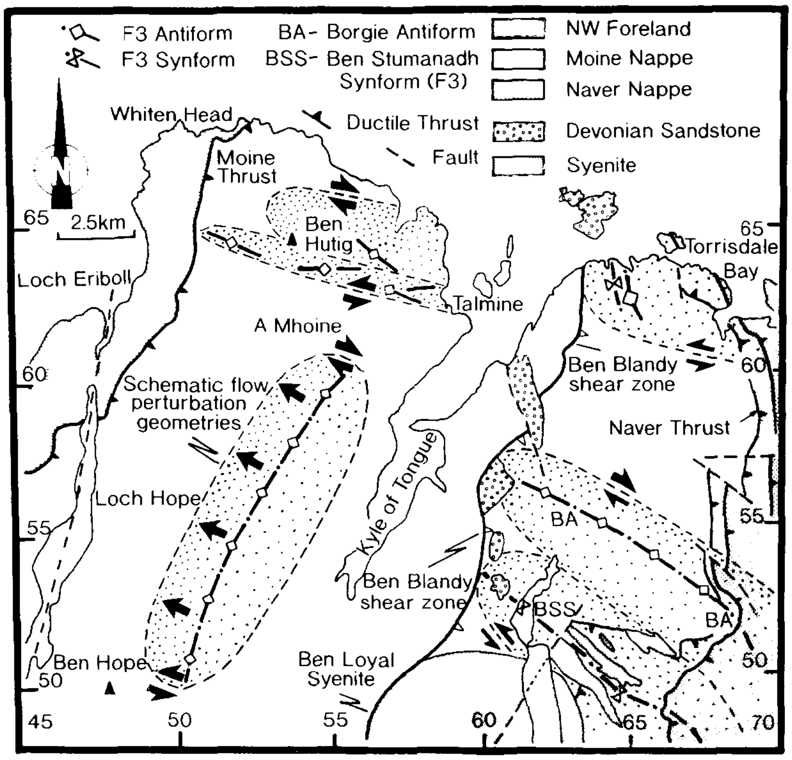

Fig. 5. Map showing regional flow perturbations (stippled) in the hangingwall of the Ben Blandy Shear Zone and Moine Thrust.

term in regions of refolding may be unwise (e.g. Ramsay & Huber 1987 p. 487).

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