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Vergence and facing patterns in large-scale sheath folds

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Abstract

The careful geometric analysis of minor structural detail elucidates the relationships and evolution of associated large-scale curvilinear hinge geometries, developed during WNW-directed Caledonian thrusting exposed in Neoproterozoic Moine psammites of the Moine Nappe. Reversals in the polarity of *structural facing* associated with minor folding, mark the position of major sheath folds which parallel transport. Upwardly convex sheaths (closing in the direction of thrust transport) cored by older gneissose basement inliers are termed *culminations*, whilst those opening in the transport direction (and cored by Moine psammites) are termed *depressions*. Sheath folds are bisected by transport parallel and foliation normal (culmination/depression) surfaces which separate not only the reversals in facing, but also delineate zones of minor fold hinge obliquity into clockwise and anticlockwise domains relative to the transport direction. The sense of obliquity of minor Z and S folds is thus dependent on position with respect to the surfaces of culmination and depression and *not* the fold axial surfaces. Surfaces of culmination and depression may be superimposed on original overturned antiformal and synformal folds to produce a variety of dome (culmination on antiform), saddle (depression on antiform), inverted saddle (culmination on synform) and basin (depression on synform) configurations. The curvilinear hinges of minor folds may also be asymmetrical about the transport direction and *within* the plane of the regional foliation to define patterns of *fold hinge-line vergence*. Classical concepts of fold limb vergence may thus relate to larger antiformal and synformal hinges, whilst the fold hinge-line vergence defines major curvilinear hinges associated with culminations and depressions. Major sheath folds may therefore be interpreted in terms of both minor fold hinge-line and limb vergence, coupled with fold axis obliquity and reversals in the polarity of structural facing. The ability to recognise consistent and reliable structural relationships between facing and hinge obliquity at small scales indicates that the regional deformation process forms a linked and coherent system through several orders of magnitude.

1. Introduction

Within regions of intense ductile shearing, the rotation of fold hinges towards the transport (X) direction is a well established phenomenon (Bryant and Reed, 1969; Sanderson, 1973; Escher and Watterson, 1974; Rhodes and Gayer, 1977; Bell, 1978; Williams, 1978). Rotation of fold hinges which initiated in a direction orthogonal to shear may result in the generation of extremely curvilinear hinge geometries referred to as sheath folds (Carreras et al., 1977; Quinquis et al., 1978; Minnigh, 1979; Berthe and Brun, 1980; Cobbold and Quinquis, 1980; Henderson, 1981; Lacassin and Mattauer, 1985). Precise definitions of such folds have been rather vague. Ramsay and Huber (1987) clearly distinguish them as folds with a hinge-line variation of more than 90° (see Skjernaa, 1989). Many recent textbooks in structural geology, e.g. Twiss and Moores (1992), Davis and Reynolds (1996), associate sheath folds directly with shear zones. This is somewhat misleading, since the rotation of fold hinges and the development of curvilinear folds is simply a reflection of high heterogeneous strain, as illustrated by the widespread recognition of sheath folding in regional-scale zones of intense mid-crustal deformation (Platt, 1983; Holdsworth and Roberts, 1984; Ghosh

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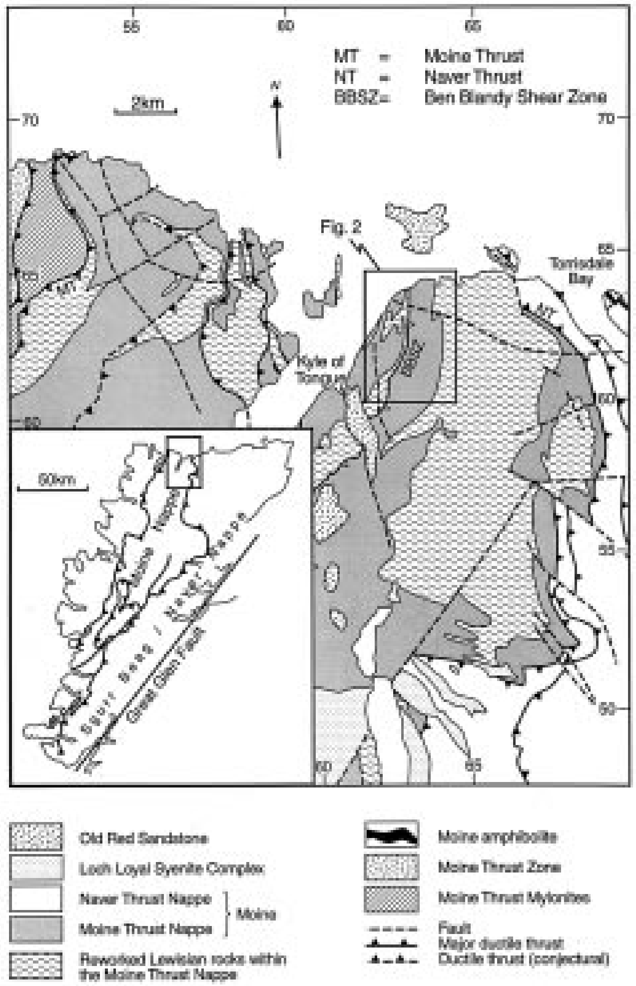


Fig. 1. Simplified geological map of the Moine and Naver Nappes in the Kyle of Tongue region, highlighting the location of the Sleiteil study area. Important NW-to-WNW-directed Caledonian ductile thrusts are shown with solid barbs. The reference grid relates to the UK National Grid with the map area falling within the NC prefix quadrangle. The inset map shows the location of the Tongue area in relation to northern Scotland and highlights major Caledonian thrust nappes.

and Sengupta, 1987). Whilst large scale (regional) examples of sheath folds are cited (e.g. Boyle, 1987; Vollmer, 1988; Park, 1988; Goscombe, 1991; Alsop, 1994) together with outcrop-scale studies (e.g. Mies, 1993; Crispini and Capponi, 1997), there has to date been little progress in relating the geometry and orientation of minor parasitic folds to larger (kilometre-scale) sheath fold hinges.

This study focuses on exceptionally well exposed curvilinear hinge geometries developed in Precambrian Moine metasediments and underlying Lewisian orthogneiss deformed during Caledonian ductile thrusting in northern Scotland (Fig. 1). The rocks preserve a wealth of structural and sedimentological minutiae, enabling detailed patterns of minor fold vergence, obliquity and facing to be determined and related to the geometry and structural evolution of larger scale curvilinear fold hinges. This study demonstrates that minor structures display consistent and predictable three-dimensional relationships to major structures. Such features may be used to identify major sheath fold geometries even in regions of moderate to poor exposure.

2. Regional tectonic setting

The Proterozoic Moine metasediments of the Scottish Caledonides have undergone two major periods of orogenesis, during the Precambrian (ca. 850 Ma) and Lower Palaeozoic (Caledonian 470–430 Ma) (see Holdsworth et al., 1994 and Harris, 1995 for reviews). It is structures associated with the later Caledonian Orogeny which dominate the regional geology in NW Sutherland and they are the focus of this paper.

Major WNW-to-NW-directed Caledonian ductile thrusts segment the Moine metasediments of Sutherland into two major metamorphic thrust sheets, the Moine and Naver Nappes (Fig. 1). Metamorphic grades are highest towards the east in the Naver Nappe where the metasediments are migmatised, leading to the development of banded gneisses, and diminish to greenschist facies in the more westerly Moine Nappe (Holdsworth, 1989a; Holdsworth et al., 1997, 1999; Alsop and Holdsworth, 1993). This pattern indicates a regional metamorphic inversion associated with the development of a foreland (westerly) propagating ductile thrust system during progressive denudation (Barr et al., 1986; Holdsworth, 1989a).

Although discordances are now largely obscured by the effects of ductile shearing, an original unconformity between older, acidic to intermediate orthogneisses (correlated with the Late Archaean to Palaeoproterozoic Lewisian complex) and younger Moine psammites may be reasonably inferred due to the contrast in texture and metamorphic grade, together with localised occurrences of a basal Moine conglomerate (Figs. 2 and 3a) (Mendum, 1976; Holdsworth, 1989a; Soper et al., 1998). Sedimentary structures (cross laminations, graded bedding) preserved in localised areas of lower strain (Fig. 3b) within psammite adjacent to the gneiss, consistently indicate younging away from the gneiss.

In the Moine Nappe of western Sutherland, Lewisian orthogneiss inliers are considered to have been emplaced into Moine rocks during regional Caledonian deformation (D_2). The consistent pattern of younging of Moine psammites away from gneissose inliers, coupled with the absence of earlier major F_1 folds suggests that prior to D_2, the Lewisian–Moine interface had a simple planar form. The presently observed geometries and patterns of younging in the

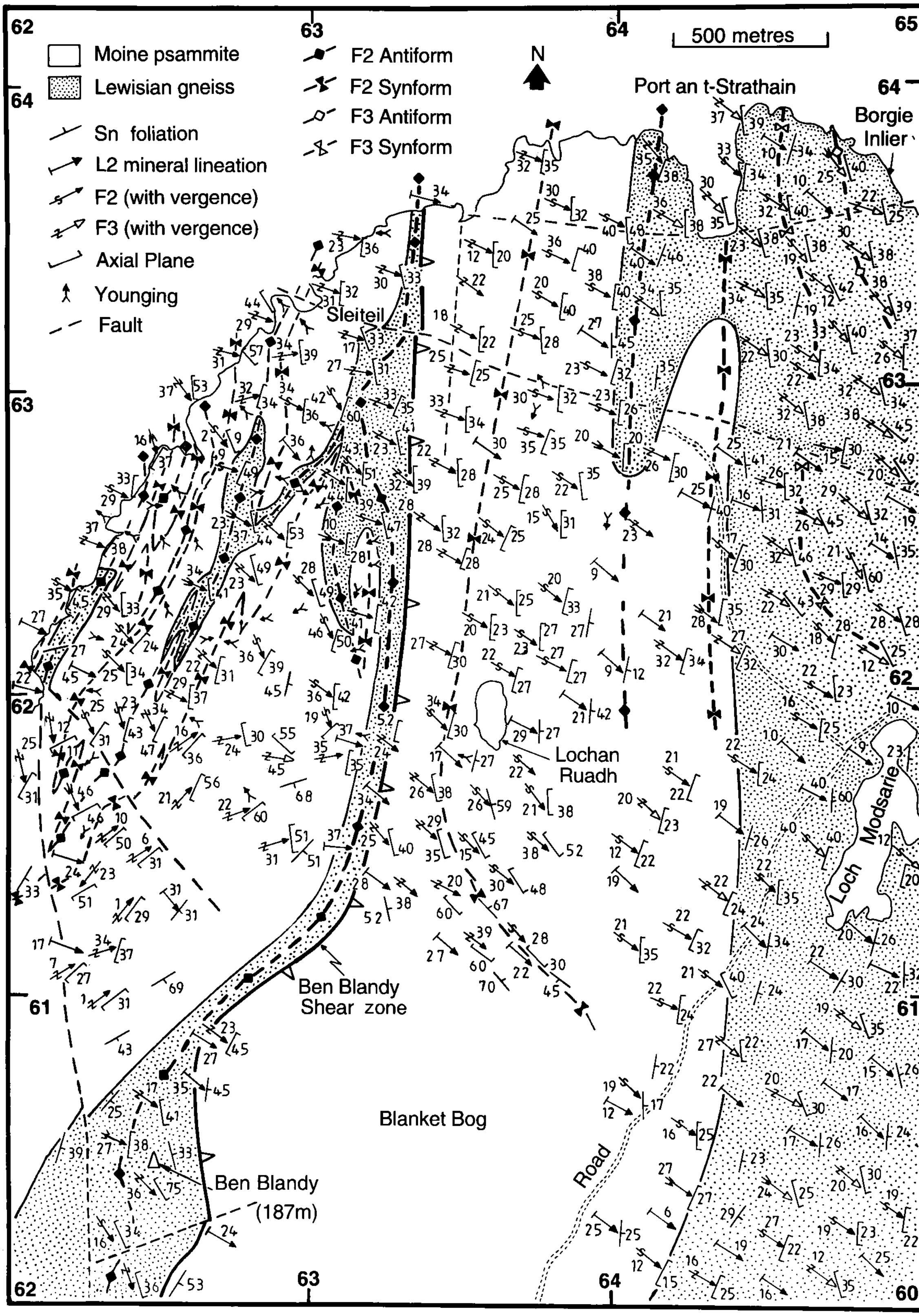
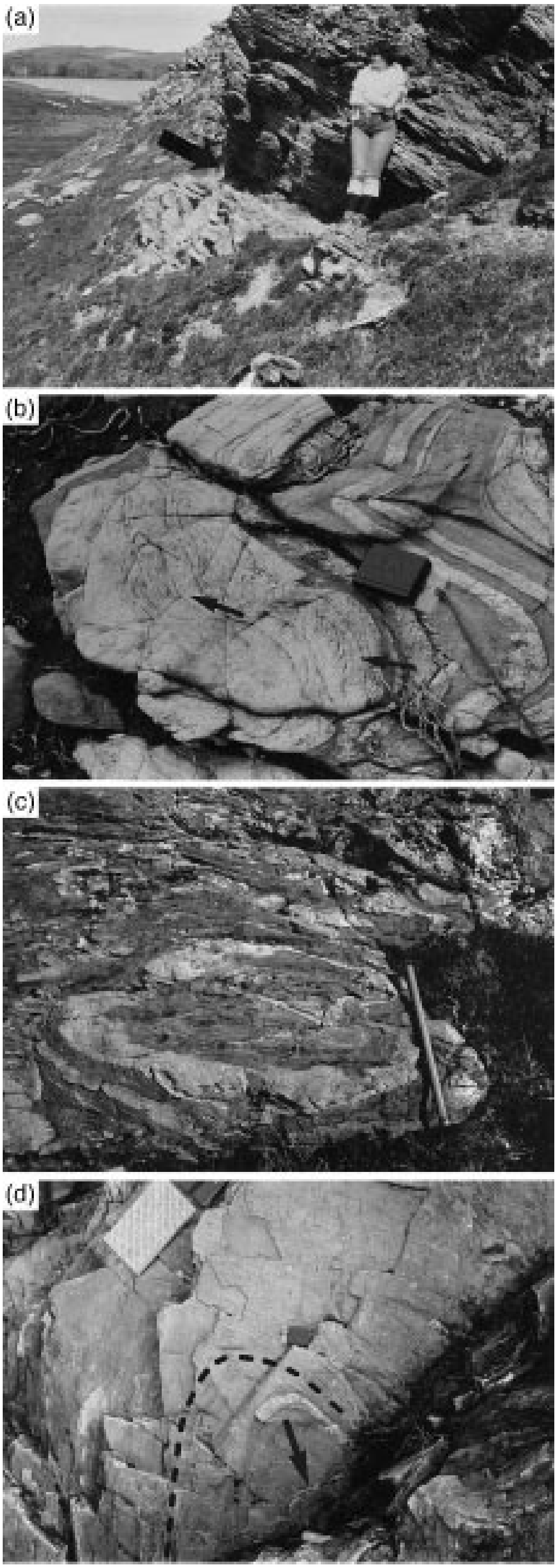


Fig. 2. Detailed structural and lithological map of the Sleiteil area highlighting gneissose inliers within Moine psammites and showing the position of F_2 axial traces. There is a general coincidence of F_2 antiforms with gneissose inliers, and synforms with Moine psammites. Minor igneous intrusions are omitted. Refer to Fig. 1 for location.



Moine Nappe may therefore be entirely attributed to (D_2) Caledonian deformation in Sutherland. The regional Caledonian foliation (S_n) dips gently towards the ESE, and intensifies into broad regions ($\sim$100 m) of well developed mylonitic schistosity and pronounced SE-plunging mineral lineations associated with higher strain and WNW-directed ductile thrusts (Holdsworth and Grant, 1990). The Lewisian is emplaced in two major structural settings—as (anticlinal) fold cores and as thrust slice inliers (Holdsworth, 1989a). The present study is concerned with the former mechanism where Lewisian gneiss forms the cores of curvilinear anticlines developed on a kilometre-scale in the well exposed Sleiteil area of Sutherland, northern Scotland (Fig. 1).

3. Structural elements—Sleiteil area

The Sleiteil (*pronounced Shlee-tell*) area on the north coast of Sutherland is composed of acidic orthogneiss (Lewisian) which formed a basement to Moine psammites and interlayered subordinate pelite bands (Figs. 2 and 3a). Holdsworth (1987, 1988, 1989a) has demonstrated that cross laminations locally preserved within the psammites (Fig. 3b) consistently indicate younging away from the gneissose inliers. The structure is dominated by tight to isoclinal F_2 sheath folds on all scales (Figs. 2, 3c and d) and lies midway between two major D_2 ductile thrust zones in the Kyle of Tongue to the west and Torrisdale Bay to the east (Fig. 1).

The regional foliation (S_n) is a bedding sub-parallel fabric which dips gently towards the ESE on either side of the Ben Blandy shear zone, a high strain detachment zone of regional extent (Alsop et al., 1996; Holdsworth et al., in press) (Figs. 2 and 4a,e). Within the plane of the foliation, a well developed mineral elongation lineation (L_2) defined principally by elongate quartz and feldspar aggregates plunges gently towards the ESE in the footwall of the shear zone, and towards the southeast in the hanging wall (Figs. 2 and

Fig. 3. (a) Inverted Moine–Lewisian contact inferred to be a sheared unconformity (arrowed), 500 m southwest of Sleiteil. The figure is standing on the contact between sheared hornblendic gneisses (Lewisian basement) and underlying pebbly psammites (Moine cover) (NC 6281 6283). (b) Interbedded, cross-laminated (arrowed) Moine psammites and micaceous psammites folded by SW- (right) facing F_2 folds. Looking down plunge towards the southeast (NC 6278 6157). (c) Well developed F_2 eye-structure in Moine psammites and micaceous psammites viewed down the L_2 mineral lineation towards the ESE (NC 639 634). (d) View of S_2 surface in Moine psammites showing curved S_0/S_2 intersection lineation (dashed line); the arc pattern is bisected by a moderate to weakly developed L_2 mineral lineation plunging shallowly ESE (arrowed) (NC 6272 6298).

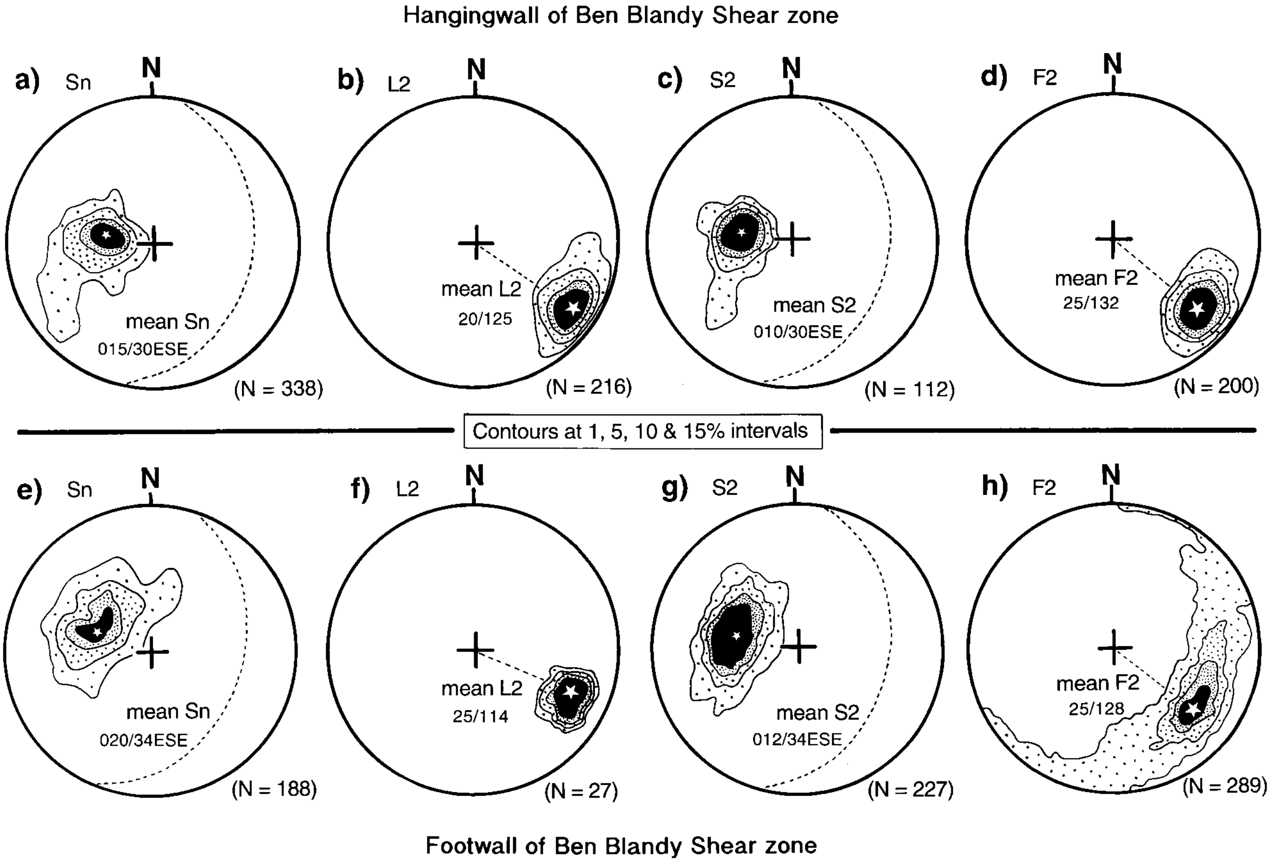


Fig. 4. Equal area lower hemisphere stereographic projections of contoured poles to planes and linear data collected from the Sleiteil area. Contour intervals are drawn per 1% area. (a)–(d) Data collected from the hanging wall (east) of the Ben Blandy shear zone. (e)–(h) Data from the (west) footwall. There is a slight clockwise shift in mean F_2 and L_2 orientations from the footwall to the hanging wall of the Ben Blandy Shear zone reflecting translation and foreshortening of the sequence on this structure. Refer to Fig. 2 for location and details of lithologies.

4b,f). Tight, generally SE-plunging F_2 folds of bedding with an associated gently SE-dipping axial planar S_2 cleavage also display a 4° swing in mean azimuth across the shear zone (Figs. 2 and 4c,d,g,h). Slight variations in the orientation of the dominant Caledonian structural elements may be attributed to D_2 juxtaposition and telescoping of originally more gentle variations across the Ben Blandy shear zone. On a larger scale, this swing in transport direction is also recognised throughout the Moine Nappe in Sutherland (Barr et al., 1986; Alsop et al., 1996). Gently SE-plunging, close F_3 folds locally refold F_2 structures and are associated with a gently SE-dipping axial planar crenulation cleavage. Variably orientated late-stage minor F_4 kink folds are interpreted by Holdsworth (1989b) as representing a gravitational collapse event in the Moine Nappe late in the Caledonian cycle.

The Sleiteil area is largely unaffected by late, large-scale folding and warping and therefore represents a suitable area for the careful analysis of minor structural detail associated with the D_2 sheath fold geometries.

3.1. Sleiteil—sheath folding

Whilst the majority of minor F_2 folds are sub-parallel to the gently SE-plunging L_2 lineation, a significant proportion of folds display an array of plunge azimuths within the gently ESE-dipping S_2 plane (Figs. 2 and 4c,d,g,h). Geometric and facing analysis in the west of the area suggests that the F_2 folds initiated as transport-normal, NNE-trending buckles, which overturned and faced upwards towards the WNW (Holdsworth, 1988, 1989a, b). Subsequent WNW-directed D_2 ductile shearing resulted in variable degrees of both clockwise and anticlockwise fold rotation towards the L_2 mineral lineation (marking the trend of tectonic transport), resulting in large-scale sheath fold geometries. Eye-structures are very widely preserved on all scales (Fig. 3c). The detailed relationships between large-scale curvilinear folding and associated minor structures are important for the understanding and recognition of sheath folds, and are described in detail below.

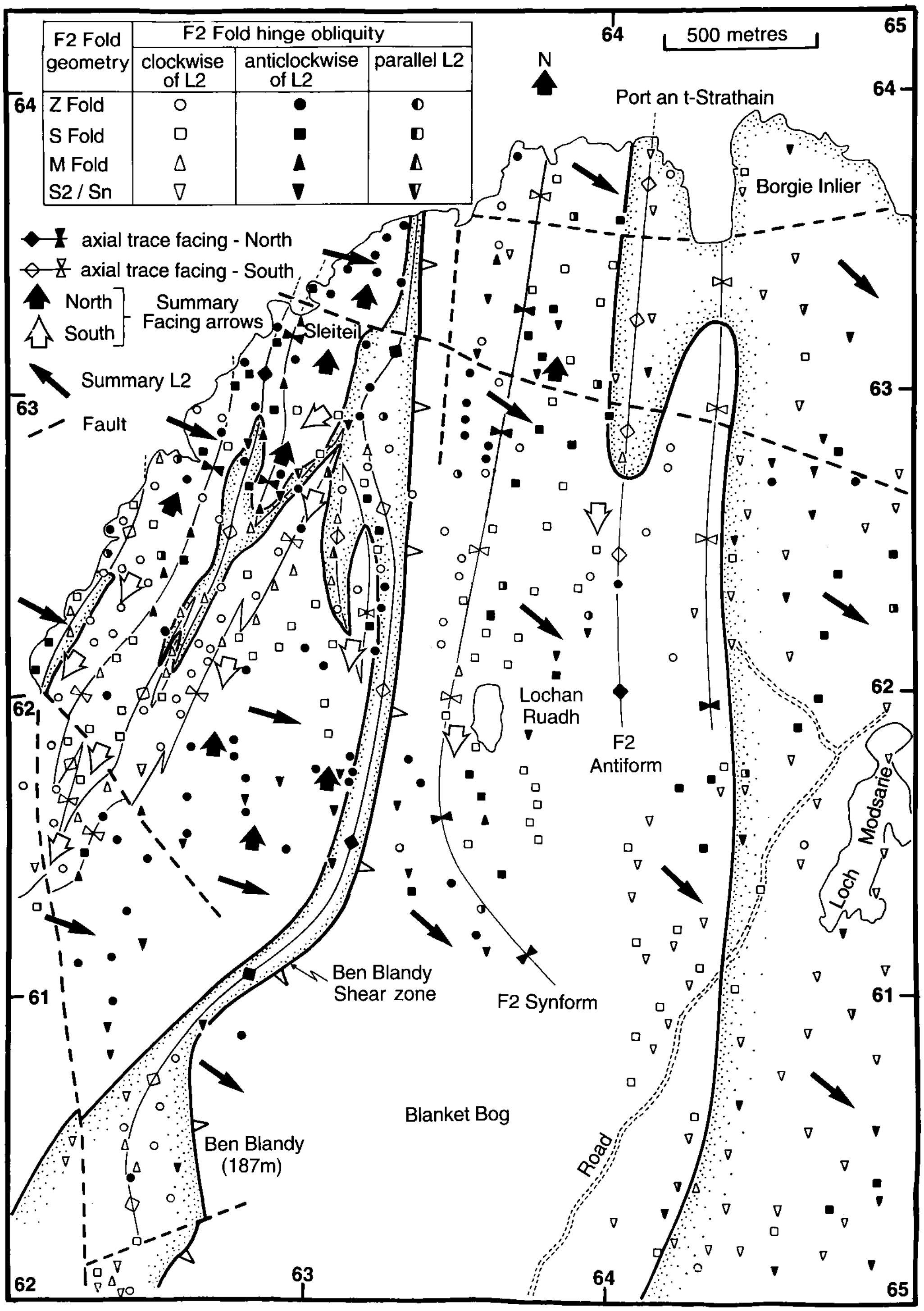


Fig. 5. Detailed map of structural analysis within the Sleiteil area illustrating the vergence and facing relationships of minor F_2 folds, together with the relative obliquity between F_2 hinges and the L_2 mineral lineation. Fold hinge obliquity is measured relative to the adjacent mineral lineation rather than computed mean orientations. A consistent relationship exists between the direction of fold facing and sense of obliquity of minor F_2 hinges. Refer to Fig. 2 for details of lithologies and orientations of minor structures.

3.2. Minor fold vergence

Minor folds typically display distinct patterns of asymmetry or vergence related to their position on associated major fold structures (Bell, 1981). Minor fold geometry is conventionally described using long-limb–short-limb relationships, in terms of Z, S and M folds (when viewed down fold plunge). Such patterns of fold

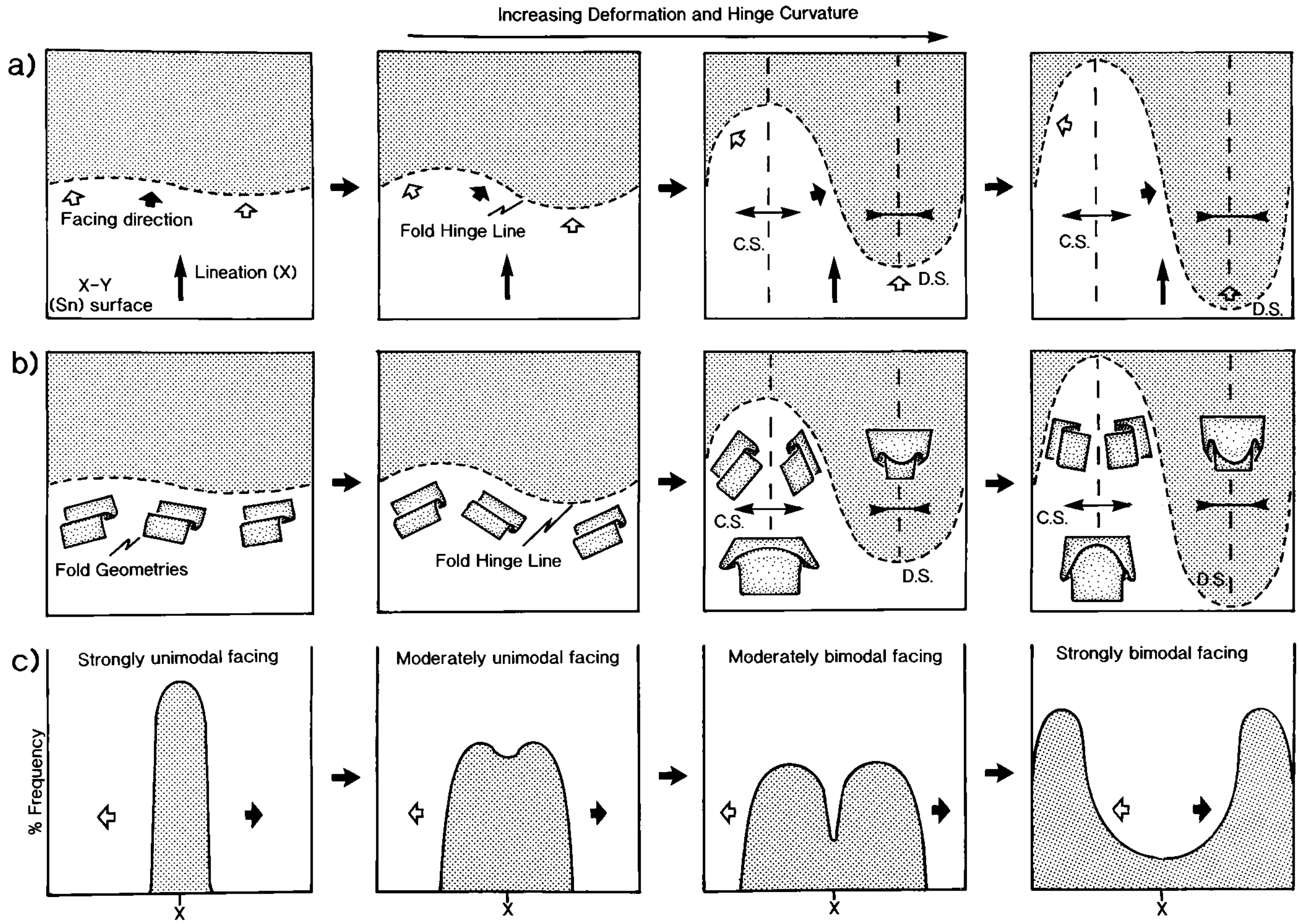


Fig. 6. Summary diagram illustrating increasing deformation and hinge line curvature within the X–Y plane associated with (a) divergence of facing directions on fold limbs and (b) rotation of minor fold geometries resulting in double vergence and sheath fold structures. (c) shows associated frequency distribution histograms of facing directions relative to transport (X) and highlights the strongly bimodal patterns generated by intensely curvilinear hinge lines. C.S.—Culmination Surface closing upwards in (thrust) transport direction, D.S.—Depression Surface closing downwards in X–Y surface.

vergence help define the location of major fold axial traces, with reversals in the sense of minor fold asymmetry across the strike of the axial plane and associated cleavage. In areas where minor folds are absent, it may also be possible to use reversals in the cleavage–bedding relationships across major structures (cleavage vergence, Bell, 1981).

Intense ductile deformation typically results in a rotation of fold hinges towards the transport direction marked by the mineral lineation (Escher and Watterson, 1974; Mies, 1991). Portions of folds which initiated with hinges broadly orthogonal to shear may rotate in both a clockwise and anticlockwise sense (viewed in the X–Y plane from above) resulting in highly curvilinear hinge geometries. A single fold pair which undergoes opposing senses of rotation at either end will display mirror image geometries when viewed down plunge ('double vergence' patterns of Holdsworth and Roberts, 1984). A consequence of both clockwise and anticlockwise rotations operating along the length of an originally consistent fold geometry is that rotated minor folds will display either a Z or S asymmetry depending on the sense of rotation. Such rotations therefore result in reversals in minor fold and cleavage vergence *along* the strike of the axial plane and associated cleavage.

Detailed mapping in the Sleiteil area reveals across strike changes in minor fold vergence related to the axial surfaces of major folds cored by Moine psammite (synclines) or Lewisian gneiss (anticlines) (Fig. 2). Importantly, consistent *along-strike* changes in fold vergence which may be traced on a kilometre-scale are also observed. Examples of such *along-strike* reversals in minor fold vergence are most clearly observed within Moine psammites 1 km due west of Lochan Ruadh at NC 626620 (Figs. 2 and 5).

Thus, *strike-normal* reversals in minor fold vergence define the axial surfaces of larger folds, whilst *strike-*

parallel changes coincide with the apices of major curvilinear fold closures. Curvilinear folds which are convex up when viewed in the inclined axial (X–Y) surface (and therefore typically closing in the direction of thrust transport) are here termed culminations, whilst those which are convex down (and opening in the thrust transport direction) are named depressions. A geographical reference frame should be used to describe recumbent sheath folds. Culminations and depressions are bisected by foliation-normal and transport-parallel culmination/depression surfaces which intersect the surface along culmination/depression traces (Fig. 6). Clearly, folds with opposing (anticlinal/synclinal) closures will be encountered along the foliation-normal culmination/depression surfaces when crossing fold axial surfaces (Fig. 6). This will result in a complex network and interplay between culmination, depression and axial surfaces (see below).

3.3. Minor fold facing

Fold facing may be defined as *the direction, normal to the fold hinge, along the fold axial plane, and towards the younger beds* (Holdsworth, 1988). The curvilinear hinge geometry of sheath folds will result in an arc of facing azimuths, with the direction of facing in the 'unrotated' nose of a fold being up to 90° from those recordings measured in the sheared and rotated portions of the fold hinge (Fig. 6a). As the direction of facing is obviously dependent on the sense of relative fold rotation, regions of curvilinear folding are therefore characterised by strike-parallel reversals in the polarity of minor fold facing (Holdsworth and Roberts, 1984; Holdsworth, 1988). The position of minor fold-facing data relative to culmination/depression surfaces (marking opposing senses of rotation) is the dominant factor governing the polarity of minor fold facing (Fig. 6a,b).

A well defined bimodal pattern of facing, with maxima normal to the transport lineation is indicative of well developed (and evenly sampled) sheath folding, with hinge curvature through an arc of 180°. Broader patterns of bimodal distribution maxima are consistent with more open patterns of hinge curvature (Fig. 6c). In regions where fold axes have suffered only limited rotation, a weakly bimodal pattern of facing with maxima at less than 90° to transport is developed. In situations where no fold rotation has occurred, the facing directions will define a unimodal pattern centred about the transport direction (Fig. 6c). The scale of the sheath culminations and depressions is critical when analysing major structures in the field, as all mapping may take place on one side of a regional-scale culmination/depression plane. This biased sampling of the overall structure will typically result in a unimodal or highly asymmetrical bimodal pattern of facing associated with broadly consistent fold vergence and hinge lineation obliquity as the majority of minor folds will have rotated in the same sense.

Reversals in the polarity of facing in the Sleiteil area from NNE-to-SSW-directed correspond well with the previously described *along-strike* changes in minor fold vergence (Figs. 2 and 5). This results in the establishment of well defined (north or south) facing domains, the boundaries of which correspond to the culmination and depression traces (Figs. 5 and 6). As would be anticipated, the domain boundaries are typically WNW–ESE-trending and parallel to tectonic transport. However, in some situations the boundaries are transferred along major fold axial planes, the axial traces of which are developed oblique (e.g. NC 630626) or normal (e.g. NC 625619), to the trend of transport (Fig. 5). These relationships suggest that whilst culmination and depression surfaces are typically transport parallel and foliation normal (Fig. 6), they may be offset along foliation-parallel transfer zones, resulting in a linked, en-échelon stacking of foliation normal domains. The foliation and lineation are notably compatible and consistent in orientation throughout the linked system (Figs. 2 and 5). Thus, the mapping of foliation-normal culmination/depression surfaces across strike reveals marked strike-parallel shifts in the culmination/depression traces. Such transfer (or relay) zones may coincide with the lateral terminations of *individual*, foliation-normal culmination/depression surfaces. The three-dimensional form of culminations and depressions are governed by the original geometry of the initial folding coupled with subsequent, variable components of both foliation-parallel and foliation-normal shear acting within zones of heterogeneous deformation (see Holdsworth, 1990). Major culminations and depressions may thus in part reflect overall spatial and temporal patterns of displacement associated with regional deformation cells.

3.4. Minor fold/lineation obliquity

Folds may initiate at low angles or sub-parallel to the transport direction due to a variety of controlling mechanisms including foliation-normal differential shear (Coward and Potts, 1983; Ridley, 1986; Alsop et al., 1996) and control exerted by pre-existing linear anisotropies (Watkinson and Cobbold, 1981). However, folds which initiate at high angles to tectonic transport require increasingly large strains to rotate from sub-parallelism ($\sim 20°$) with the shear direction into complete parallelism. Skjernaa (1980) estimates that simple shear strains in excess of 100 would be necessary to accomplish this, with resultant extension parallel to the fold axes exceeding 1000%. In nature, therefore, this precise co-linearity is rarely achieved and consequently a small angle of obliquity is com-

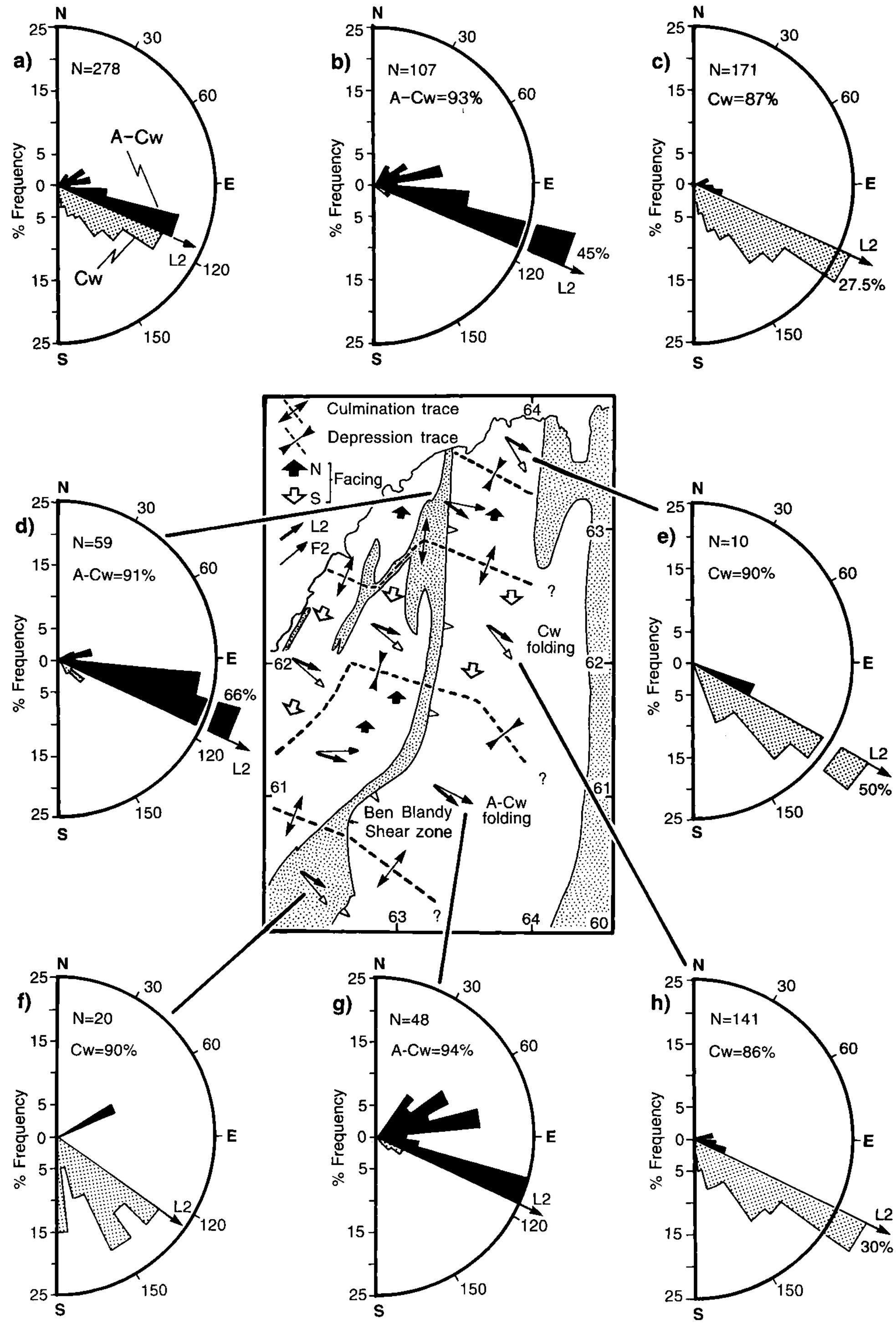


Fig. 7. Rose diagrams showing the trends of minor F_2 fold hinges in the Sleiteil area. Petals comprise 10° arcs orientated relative to the mean L_2 lineation. F_2 fold hinges anticlockwise of the adjacent L_2 mineral (transport) lineation are shown in the solid ornament, whilst those developed in a clockwise sense are shown in stipple. Structural subareas on the central map are separated by culmination and depression traces associated with reversals in the patterns of facing (see Fig. 5). (a) Summary of F_2 data from all domains. (b) Summary of F_2 data from north-facing domains [93% anticlockwise (A-Cw) of L_2]. (c) Summary of F_2 data from south-facing domains [87% clockwise (Cw) of L_2]. (d)–(h) F_2 data from individual facing domains illustrated on the map. The graphs highlight the strong correlation between the polarity of fold facing and relative obliquity (to the L_2 lineation) of minor F_2 hinges.

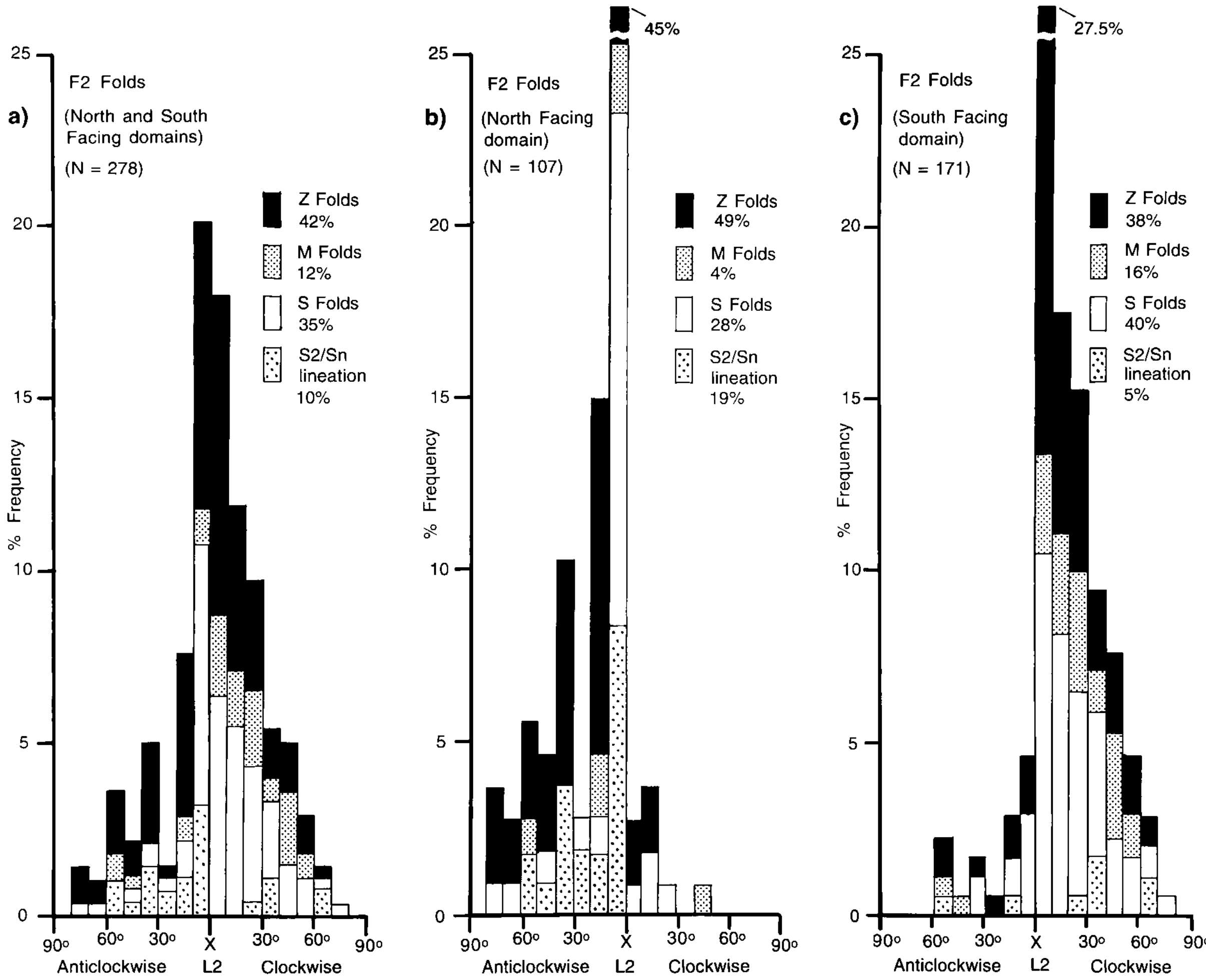


Fig. 8. Frequency distribution histograms of F_2 fold hinge data orientated relative to adjacent L_2 (X) and separated in terms of fold geometry. (a) Summary histogram of all F_2 hinge data. (b) Summary histogram of F_2 folds from north-facing domains. (c) Summary histogram of F_2 folds from south-facing domains. Note that the relative obliquity between minor F_2 fold hinges and the L_2 lineation is governed not by fold geometry (Z, S or M), but by facing domains and position relative to culmination and depression planes. See Fig. 7 for location of domains.

monly preserved between the fold hinge orientation and the transport direction. This should not be confused with the 'separation angle' of Hansen (1971) which refers to the angular differences of drag folds which are *generated* about the slip direction, but which do not undergo significant subsequent rotation. The angular relationship between the fold hinge and lineation may be described as clockwise or anticlockwise [when viewed on the axial (X–Y) plane from above] and indicates the sense of obliquity of the fold hinge compared to the lineation. The opposite ends of original, gently curvilinear whaleback folds developed broadly normal to the shear direction will rotate in opposing senses, resulting in a reversal in the fold hinge–lineation relationship. Thus, culmination/depression surfaces will mark regions of opposing sense of obliquity into clockwise and anticlockwise domains.

The sense of fold hinge/lineation obliquity is independent of strike-normal changes in minor fold vergence across major sheath fold axial surfaces, but will correspond with strike-parallel reversals in minor fold asymmetry. The position of minor folds relative to culmination/depression surfaces (marking opposing senses of rotation and facing domains) is therefore the dominant factor governing the obliquity relationships.

Within the Sleiteil area, the orientation of minor F_2 fold hinges relative to the adjacent L_2 mineral lineation was mapped (Figs. 2 and 5). Analysis indicates that systematic reversals in the sense of lineation/hinge obliquity correspond with the previously described switches in the polarity of facing coupled with along-strike changes in the vergence of minor folds. Obliquity data may be further analysed in terms of the sub-areas defined by along strike reversals in minor fold vergence and switches in the polarity of fold facing to define N- or S-facing domains bounded by culmination and depression surfaces.

The majority of minor F_2 fold hinges are developed within 20° of the adjacent L_2 mineral lineation (Fig. 7a). However, north-facing domains are characterised

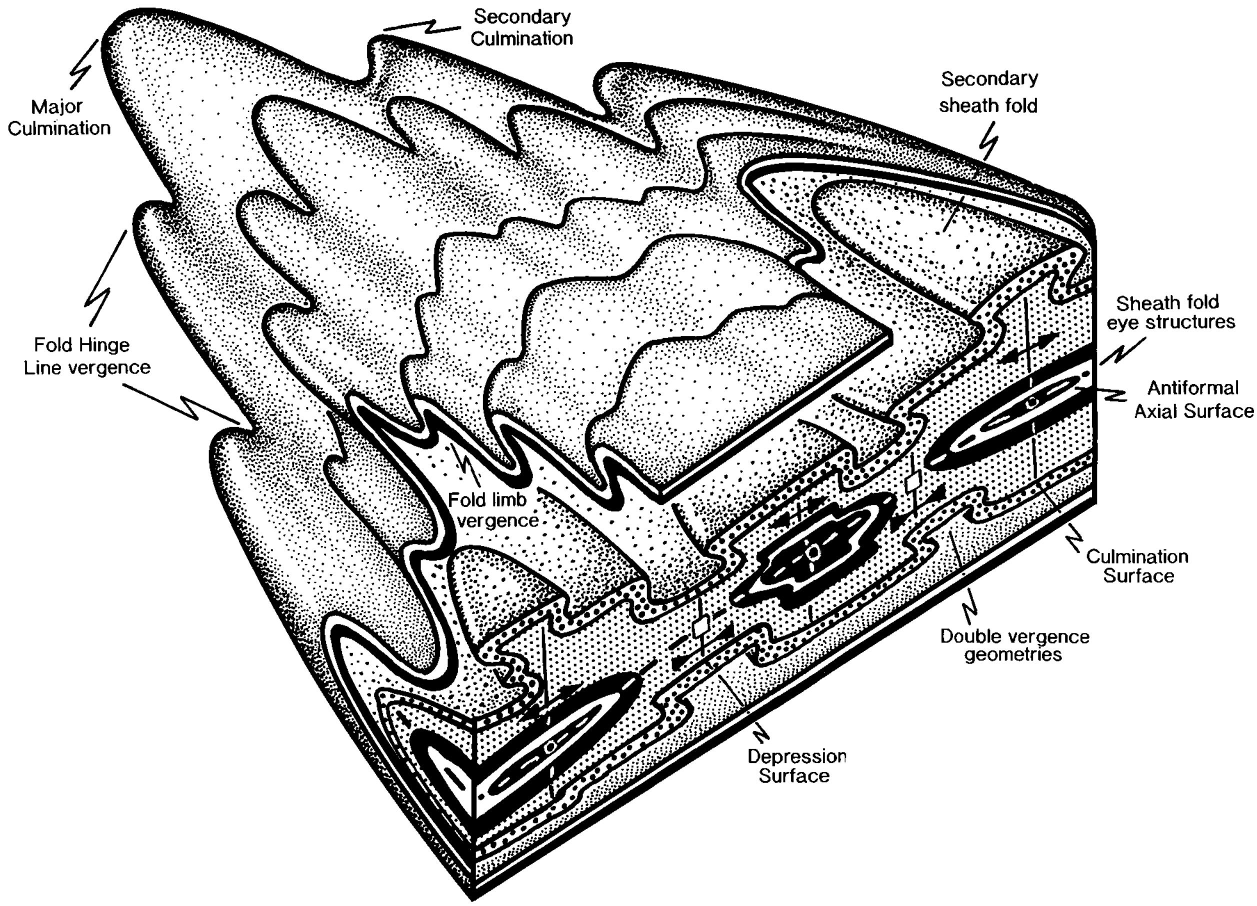


Fig. 9. Schematic three-dimensional sketch illustrating the geometry of a major antiformal, sheath culmination with both minor fold limb vergence and fold hinge-line vergence highlighted. Cross-sectional views across culmination and depression surfaces display double vergence and elliptical eye structures characteristic of curvilinear hinge geometries.

by minor F_2 fold hinges developed in an anticlockwise sense to the L_2 mineral lineation (Fig. 7b) and are found on the northern sides of major culmination traces (Fig. 7d,g). South-facing domains are associated with F_2 hinges preserved in a clockwise sense to the L_2 mineral lineation (Fig. 7c) and are located on the southern sides of culmination traces (Fig. 7e,f,h).

Analysis of the vergence (Z,S,M) of minor folds and the sense of hinge/lineation obliquity clearly shows that there is no simple correlation between minor fold geometry and the sense of obliquity (Fig. 8). This relationship indicates that a model in which folds are *generated* oblique or sub-parallel to transport in zones of differential shear is not appropriate in this situation (see Alsop et al., 1996 and references therein). The sense of fold hinge/lineation obliquity provides data which are ~90% consistent with the domains defined by *along-strike* reversals in minor fold vergence and facing, and supports the location of major culmination/depression surfaces shown on Fig. 7. Thus, it is the location of these major culmination/depression surfaces which controls the sense of minor fold facing, hinge/lineation obliquity and the *along-strike* reversals in minor fold vergence.

3.5. Minor fold hinge-line vergence

The extreme curvilinearity characteristic of major sheath fold hinges is typically portrayed as defining a smooth parabolic arc through angles of up to 180°. However, original localised variations in hinge obliquity about the transport normal will result in opposing senses of hinge rotation during shearing, thus generating minor sheath folds (Skjernaa, 1989). Systematic variations in initial hinge orientation about the transport normal have long been recognised in low grade terrains (e.g. Wood, 1974; Wood and Oertal, 1980) and may be associated with an irregular whaleback geometry developed during initial fold nucleation, propagation and amplification (e.g. Dubey and Cobbold, 1977). These variations are exaggerated during shear to generate distinct patterns of curvilinear

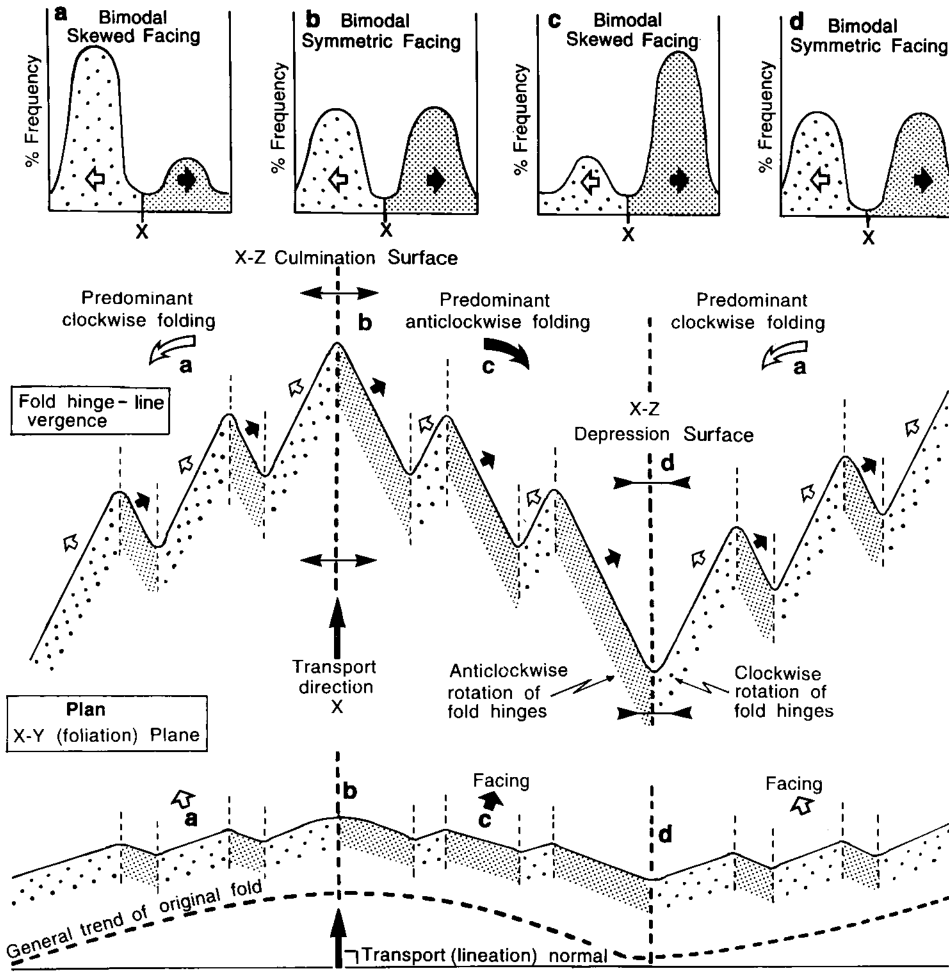


Fig. 10. Plan of (*X–Y*) foliation surface showing schematic fold hinge-line vergence geometries and resulting patterns of minor fold facing as frequency histograms. The lettering of frequency diagrams corresponds to position relative to culmination and depression surfaces. The corresponding geometry of original broadly transport-normal whaleback folding is shown at the base of the diagram. Increasing shear results in asymmetric whaleback hinges defining patterns of curvilinear hinge-line vergence, which are associated with reversals in facing.

minor *fold hinge-line vergence* within the foliation (*X–Y*) plane. This will be displayed by both minor fold hinges and corresponding bedding–cleavage intersections provided the cleavage is more-or-less axial planar to the folds (Fig. 3d).

Thus, asymmetric sigmoidal plunge patterns recorded within the cleavage plane are exactly analogous to fold limb vergence. Patterns of fold hinge-line vergence related to short hinge–long hinge segments are associated with reversals in the sense of hinge/lineation obliquity and facing polarity (Figs. 9 and 10). Examples of such fold hinge-line vergence developed on a mesoscopic scale may be mapped in the Sleiteil area at NC 630629.

Whilst fold limb vergence defines the position of major fold axial surfaces, fold hinge-line vergence relates to the location of major sheath culmination and depression surfaces (Fig. 10). The predominant pattern of fold hinge-line vergence defines these surfaces, with subordinate short hinge segments being associated with localised atypical domains marked by an opposing sense of hinge/lineation obliquity, facing reversals and strike-parallel fold (limb) vergence changes. Facing patterns are typically characterised by a bimodal skewed distribution (Fig. 10). In the nose regions of large-scale sheath folds, a symmetrical M or W pattern of sigmoidal plunge is developed and this is associated with bimodal symmetrical facing patterns (Fig. 10).

4. Curvilinear hinge geometries

Transport-parallel and foliation-normal culmination/depression (*X–Z*) surfaces are developed at right angles to fold axial (*X–Y*) surfaces to define an overall orthogonal system of fold symmetry. An original gently curvilinear antiform which undergoes progress-

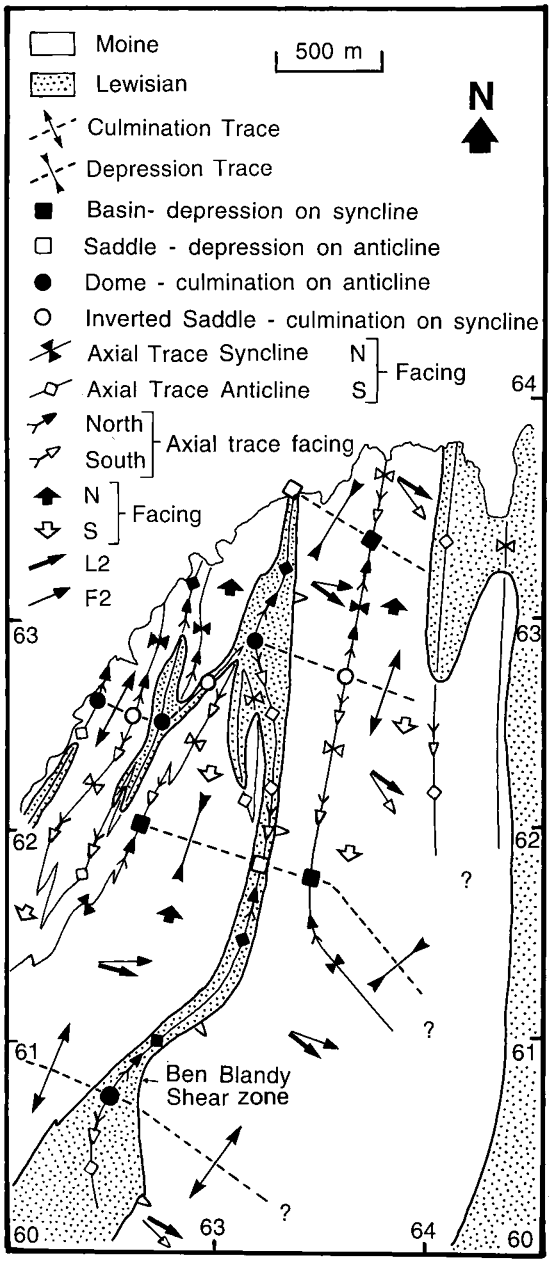


Fig. 11. Simplified structural map of the Sleiteil area summarising consistent reversals in facing and minor F_2 fold hinge/L_2 obliquity relative to larger scale axial surfaces and culmination/depression surfaces. Refer to Figs. 2, 5 and 8 for further details. The interplay between anticlines, synclines, culminations and depressions is highlighted by the resulting configurations.

ive shear may display (end member) dome geometries where a culmination is superimposed, and a saddle where a depression subsequently develops (Figs. 11 and 12). Similarly, a synform will display (end member) basinal geometries where a depression is superimposed, and inverted saddles where a culmination is subsequently established. The resulting curvilinear hinge geometry is therefore dependent on the interplay and spatial association between the original surfaces that define the large-scale antiforms/synforms and culminations/depressions.

Within the Sleiteil area, major antiformal anticlines cored by Lewisian basement orthogneiss are alternately transected at approximately 1 km intervals by culmination and depression traces (Fig. 11). This results in thickened Lewisian outcrops within dome intersections, interspersed with thinned Lewisian outcrops along strike at saddle configurations. The spacing of culmination/depression planes is a consequence of the gross original buckle fold hinge geometries and orientations. This is dependent on a variety of factors including lateral heterogeneity of deforming horizons, layer anisotropy and viscosity contrasts, strain rate and interference of adjacent folds (e.g. Dubey and Cobbold, 1977; Johnson and Fletcher, 1994).

5. Conclusions

1. The current study demonstrates that the positions of larger (kilometre-scale) curvilinear folds are defined by distinct and systematic reversals of minor fold-facing patterns.
2. Regions of consistent ($\sim$90%) minor fold hinge/lineation obliquity coincide with the structural domains defined by the facing patterns.
3. Localised reversals in facing and fold obliquity (within larger domains) are associated with fold-hinge line vergence within the foliation (X–Y) plane.
4. Major planes of culmination and depression interact with the axial surfaces of antiforms and synforms, resulting in a range of dome and basin configurations that account for the observed distribution and extent of basement (Lewisian) and cover (Moine) units on a large scale.
5. This study extends the concept of vergence to three-dimensions in curvilinear folds using *fold hinge-line vergence*, a concept exactly analogous to two-dimensional fold limb vergence.
6. The close correspondence between predicted and observed patterns of vergence, obliquity and facing suggests that this technique can be applied in less well exposed regions (or in areas where younging evidence is not preserved) in order to define regional-scale sheath fold culminations and depressions. As such, the method could also be applied as a predictive tool for sub-surface geological exploration of folded stratiform mineral deposits (Park, 1988).
7. The techniques described allow a significantly more complete description of the three-dimensional structural geometry of regions of intense ductile defor-

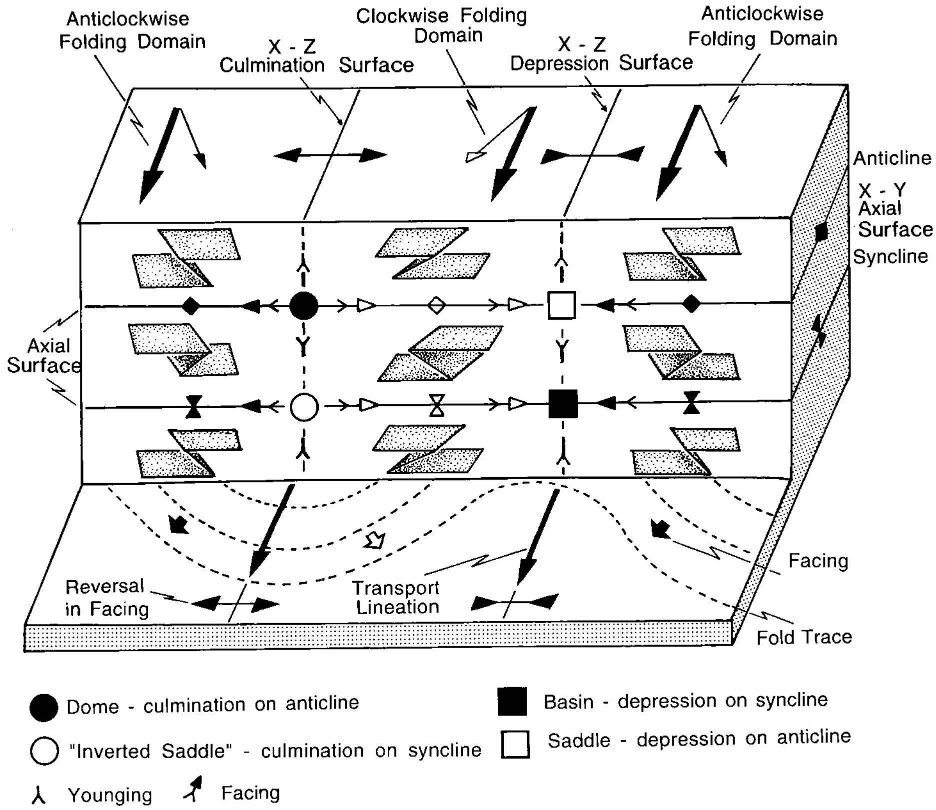


Fig. 12. Schematic three-dimensional diagram relating reversals in facing, minor fold obliquity and minor fold geometry to position relative to larger scale axial surfaces and culmination/depression surfaces. Three-dimensional interplay between anticlines, synclines, culminations and depressions produces the four interference scenarios which are illustrated.

mation that characterise the internal regions of orogenic belts.

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