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A structural analysis of the Moine Thrust Zone between Loch Eriboll and Foinaven, NW Scotland

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Abstract—The northern part of the Moine Thrust Zone as exposed around the valley of Srath Beag, Sutherland was developed by thrusts propagating in the tectonic transport direction. Deformation on any particular thrust surface evolved from dominantly ductile to dominantly brittle with time.

The foreland has been progressively accreted onto the overriding Moine thrust sheet by duplex formation, a process which has continuously folded the roof thrust and the rocks above its hanging-wall. Fold culminations and depression can be related to lateral ramps which may give the rocks above the hanging-wall a complex history of extensional and compressional strains normal to the transport direction.

Folds within the thrust zone are laterally independent because they are controlled by short lived variations in deformation style on an evolving thrust footwall topography. Therefore there may be no correlation between structures across or along the thrust zone. This variation limits the construction of balanced cross sections as structure cannot be projected onto particular section lines.

INTRODUCTION

THE FRONT of the Caledonian orogenic belt in the Northwest Highlands of Scotland has an outcrop length of 200 km. This front, the Moine Thrust Zone, is exposed immediately south of Loch Eriboll around the valley of Srath Beag (Fig. 1). This area was important to early workers (e.g. Lapworth 1885, Peach *et al.* 1888, 1907) who recognised that Moine rocks had been translated over an undeformed Cambrian cover succession which rests on Lewisian basement. Recent work has suggested a sequence of thrust sheet emplacement whereby the uppermost thrusts moved last (e.g. Soper & Barber 1979). This sequence has been contested by others (Barton 1978, Coward 1980, Elliott & Johnson 1980) who argue for propagation of thrusting into the foreland, that is parallel to the northwesterly transport direction. The whole thrust zone now dips at 8° to the east due to late Caledonian or Mesozoic tilting (Coward 1980).

This paper aims first to discuss field observations in the valley of Srath Beag (Fig. 1) and then to discuss the structural evolution of the Moine Thrust Zone in Srath Beag with particular reference to:

(1) the sequence of thrusting;

(2) deformation associated with thrust sheet translation and

(3) the evolution of thrust sheet shapes within the thrust zone.

The stratigraphy of the Cambrian cover sequence over which the Moine rocks have been thrust was first deciphered by the Geological Survey (e.g. Peach *et al.* 1907) and later refined by Swett (1969). Measured thicknesses are:

Durness Formation		not present
An t-Sron Formation	Serpulite Grit Member	8 m
	Fucoid Beds Member	20 m
Eriboll Formation	Pipe Rock Member	80 m
	Lower Quartzite Member	75 m

The Durness Formation has been removed tectonically. Swett (1969) could demonstrate no variation in stratigraphic thicknesses of either the Eriboll or An t-Sron Formations along thrust zone strike, and thickness consistency is assumed normal to strike.

Figure 1 acts as a reference diagram for locations in the text. The key is common to all diagrams, although the An t-Sron Formation may be divided into two members, in which case the Fucoid Beds are stippled and the Serpulite Grit is unornamented. All directional references are to Grid North, Grid references in the text are in square brackets.

TECTONIC DOMAINS

Several distinct, thrust-bounded domains can be recognised. These are classified on lithological content, geographic position and structural level. Each type will be discussed and critical evidence for their relative emplacement ages will be presented.

An Lean Charn to Leathad na Surraig

Flaggy, unmylonitised Moine rocks outcrop at the highest structural levels, on An Lean Charn [NC 420520] (Fig. 1). An early, planar fabric is folded around flat-lying, northwest-verging, isoclinal structures which locally develop an intense axial planar schistosity. Kink banding of the schistosity is restricted to discrete, strike-parallel zones. Post-dating these two deformation phases is a widespread, gentle warping by low amplitude, long-wavelength, upright folds with no detectable associated fabric. Their axial planes commonly strike NW–SE with local variations of up to 45°.

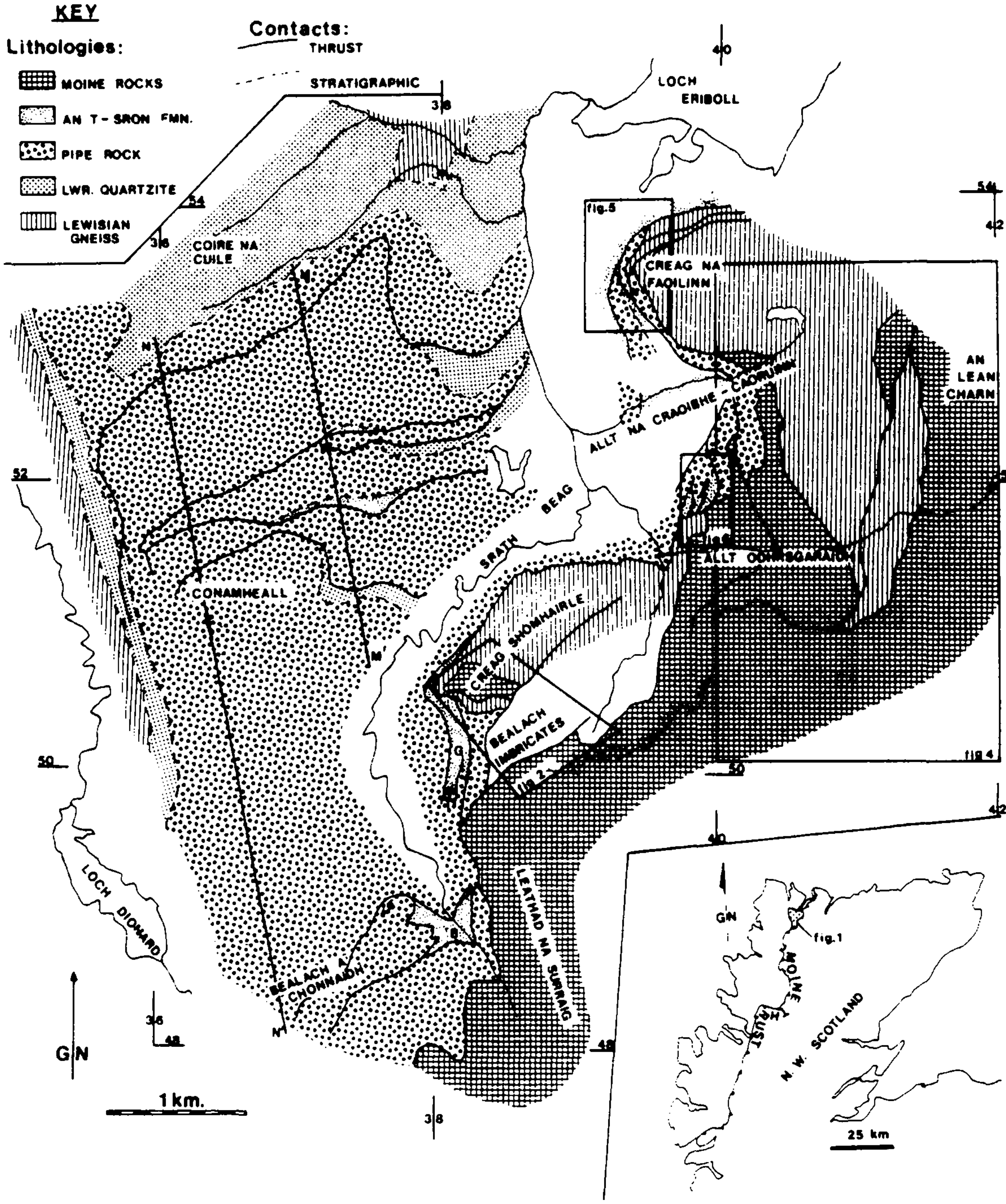

Fig. 1. Simplified geological map of the ground between Loch Eriboll and Foinaven. B = Bad an t-Sluic. G = Ghlomaich duplex. Sections N–N' and M–M', see Fig. 8. Inset: regional location map. Abbreviations used in the following figures: ALC, An Lean Charn; CF, Creag na Faoilinn; CS, Creag Shomhairle; CST, Creag Shomhairle thrust; G, Ghlomaich duplex; GN, Grid North; L, Lewisian rocks; M, Moine rocks; MT, Moine thrust; n, number of data points; PR, Pipe Rock; S, Serpulite Grits and V = H, vertical/horizontal scale relationship.

Discrete mylonitic zones are occasionally present in Moine rocks. These zones strike parallel to the isoclinal fold schistosity with either a steeper or equal dip.

At the base of the flaggy Moines is a flat, ductile shear zone marked by the development of a considerable thickness of mylonite (c. 150 m). This exhibits a complex history of folding and fabric generation which is nowhere laterally consistent. Many of the folds are morphologically similar to sheath folds described by Cobbold & Quinquis (1980) and so may be produced as a result of anisotropic instabilities during progressive shear. Although the fold style is similar to that of the isoclinal folds within the flaggy Moines above, these folds need not be coeval. As well as outcropping at the base of the flaggy Moines, Moine-derived mylonites appear interleaved with both Lewisian and Cambrian mylonites and as klippen to the west of the main Moine Thrust trace. These sites are discussed individually.

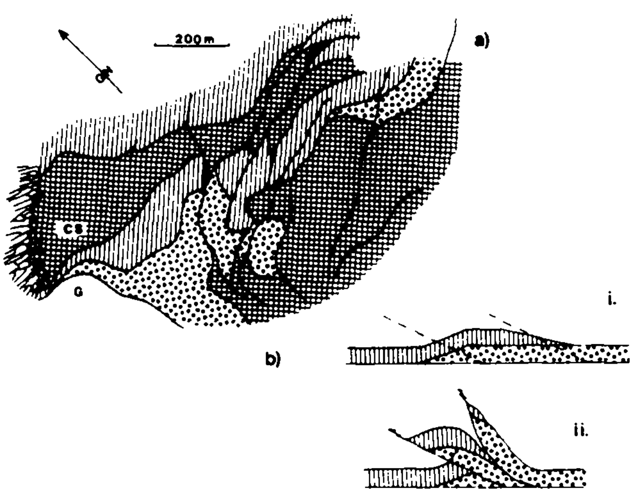

Fig. 2. The Bealach area, Creag Shomhairle. (a) Map. All contacts are thrusts generally dipping to SE. (b) Schematic cross sections (NW–SE). (i) prior to imbrication, (ii) post imbrication. Moine rocks are unornamented.

Creag Shomhairle

The Bealach area [NC 38505] (Fig. 1) shows Cambrian Pipe Rock interleaved with Moine mylonites, the contacts display no brittle fault features. The Moine mylonites have an additional NW-verging fold phase with an associated axial planar foliation which locally overprints the background mylonite fabric. The new foliation is restricted to the hanging-wall of each thrust, is parallel to the thrust surface and becomes of decreasing importance in thrust sheets towards the northwest.

Both mylonitic and non-mylonitic Lewisian, Pipe Rock and Moines are interleaved north of the Bealach (Fig. 2a) as layers out of sequence. The following is suggested as an evolutionary model (Fig. 2b). Moines were thrust over the Lewisian, which was accreted onto the thrust slice. This composite sheet was then thrust over Pipe Rock. During later translations the three part sheet was imbricated, interleaving the three lithologies. The stack of imbricated early thrusts is here termed the Bealach Imbricate Stack.

On Creag Shomhairle (Fig. 1), Lewisian gneiss can be found in several deformation states. These are recognised by the relationship between pegmatites and gneissic banding. Concordancy of pegmatites to gneissic banding is considered to be the product of Caledonian tectonics. This deformation state is here termed 'concordant' Lewisian. Original, intrusive relationships, where pegmatites are discordant to gneissic banding, is shown by 'discordant' Lewisian. Concordancy is demonstrable in mylonitic zones, particularly in the Bealach Imbricate Stack.

At NC 381505 imbricate structures are folded around a large, upright synform of complex geometry (Fig. 3) which post-dates the Bealach Imbricate Stack. A comparable, though smaller-scale fold has developed to the north of Creag Shomhairle at Allt Odhrsgaraidh [NC 398518] (Fig. 6). It is significant that these folds are at the lateral terminations of the Lewisian sheet. Minor warping of the structurally lower contact of the sheet, the Creag Shomhairle thrust, is not recorded in the higher thrust sheet because of the low amplitude of the folding.

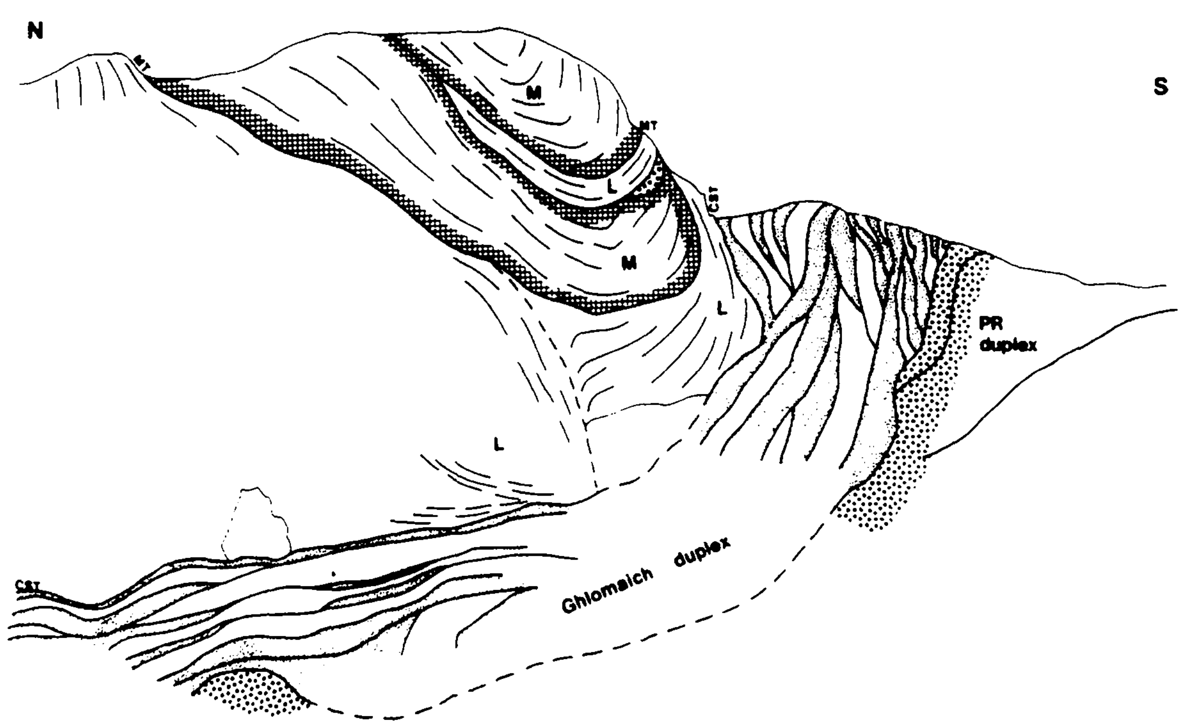

Fig. 3. Structural relationships on the west face of Creag Shomairle. This view is of a vertical section, 300 m high. The Bealach Imbricate Stack (above CST) consists of Moines (cross-hatched border), Lewisian (unornamented) and Pipe Rock. The Ghlomaich duplex consists of Fucoid Beds (stippled) and Serpulite Grits (unornamented).

The Craoibhe-caoruiun Imbricate Stack

Moine, Lewisian and Eriboll Quartzite derived mylonites with a thickness of more than 850 m outcrop to the west of An Lean Charn [NC 420524] (Fig. 4). Interthrusting of these units occurs from a microscopic to the outcrop scale, although there is an overall sequence with the higher structural levels occupied by Moine mylonite, thrust above Lewisian, above Eriboll Quartzite. This stack of thrust sheets is here termed the Craoibhe-caoruiun Imbricate Stack.

Deformation in the Craoibhe-caoruiun Imbricate Stack is more pervasive than in the analogous Bealach Imbricate Stack. The fabric of both the 'concordant' Lewisian and the mylonites dips gently to the ESE and encloses low-intensity deformation pods of discordant Lewisian and in some places unmylonitised Eriboll Quartzite (e.g. NC 402520). The stack has been thickened by several generations of thrusts with the final incorporation of Eriboll Quartzite, comparable to the incorporation of Pipe Rock in the Bealach Imbricate Stack. More precise correlation between the two stacks seems at present unwarranted.

At NC 403518 and in the Allt na Craoibhe-caoruiun stream section, minor folds of the mylonitic fabric are oblique to the NE–SW axial trend prevalent in the Craoibhe-caoruiun Imbricate stack. The generation of folds with anomalous orientations will be discussed later. Within this stack variation in fold axis orientation increases up section and towards the east.

Immediately west of Creag na Faoilinn summit [NC 396535] and forming its northwest face is an area of interthrust Pipe Rock and discordant Lewisian (Fig. 5). The Lewisian is in a similar deformation state to that of the Creag Shomhairle area and is separated from the overlying Craoibhe-caoruiun Imbricate Stack by several metres of intense mylonite of uncertain parentage. This mylonite is at the same structural level as the Moine mylonites on Creag Shomhairle.

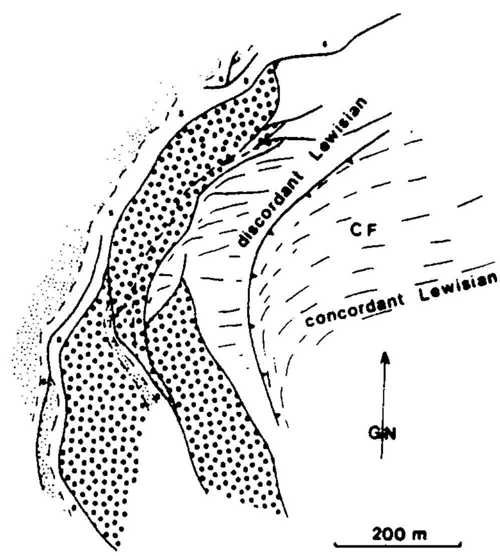

Fig. 5. Structural relationships on Craeg na Faoilinn. Foliation strike lines are marked in concordant Lewisian (gneissic banding and pegmatites are concordant) and discordant Lewisian (gneissic banding and pegmatites are discordant). Both are unornamented.

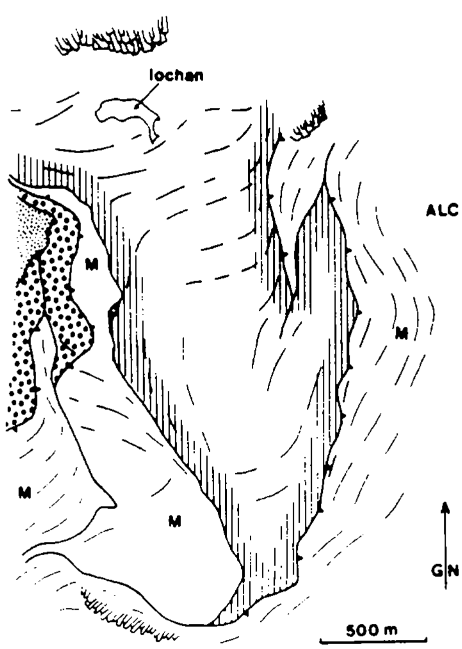

Fig. 4. Map of the ground west of An Lean Charn. All contacts are thrusts dipping SE (MT is ornamented). Foliation strike lines are marked in Moines (unornamented) and Lewisian.

As at Creag Shomhairle, the floor thrust to the Lewisian thrust sheet of Creag na Faolinn is warped by a monocline facing north.

Thickened An t-Sron Formation

A floor thrust to the described high thrust sheets outcrops at various structural levels in the underlying Cambrian strata, from within Pipe Rock to the top of the Serpulite Grits. Only in the southern part of the Bealach and in the Craoibhe-caoruiun Imbricate Stacks does subsequent imbrication of these lower formations involve the higher thrust sheets, elsewhere their floor thrusts act as roofs to the lower duplexes. A number of these duplexes are intraformational, incorporating only the An t-Sron Formation. These are described from south to north.

At Bad an t-Sluic [NC 382488] (Fig. 1) a thickened pile of Fucoid Beds underlain and overthrust by Pipe Rock has been mapped. A maximum six-fold thickness increase of this one member can be measured. Along strike the floor thrust drops into Pipe Rock and the duplex exhibits only a three fold replication.

To the north both the floor and roof thrusts are in Pipe Rock, hence the duplex contains only one member. At [NC 380504] the Ghlomaich duplex has developed (Fig. 5). This duplex contains both Fucoid Beds and Serpulite Grit Members but the roof thrust is in Fucoid Beds as these form the contact with the overlying Bealach Imbricate Stack. The duplex developed after Fucoid Beds had been thrust over the Serpulite Grits since a repeated stratigraphy has been subsequently imbricated. Underlying Pipe Rock is not involved, the duplex being intraformational with respect to the An t-Sron

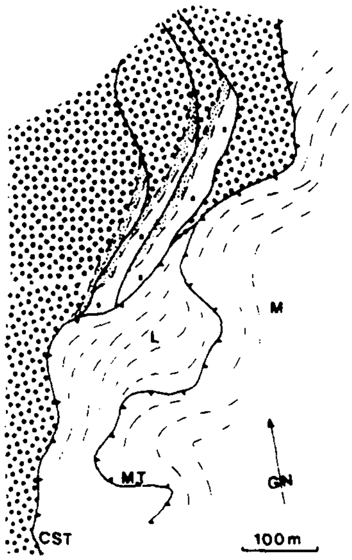

Fig. 6. Map showing the structural relationships at the Starbeg duplex, Allt Odhrsgaraidh. Foliation strike lines are marked in Moine and Lewisian rocks.

Formation at this location. The floor thrust has a problematic hanging-wall relationship with Serpulite Grits locally in direct contact with underlying Pipe Rock. Extension faults are not evident to account for the missing Fucoid Beds.

The northern limits of the Ghlomaich duplex are not exposed, but at NC 385513 the Creag Shomhairle thrust has a footwall in Pipe Rock. The footwall composition is continuous until just north of Allt Odhrsgaraidh [NC 398518]. Here the footwall bounds the An t-Sron Formation which has been thickened to give the Strabeg-duplex (Fig. 6). A three-fold thickening can be measured.

Again the northern limits are not exposed, although it seems probable that between the Strabeg duplex and the Allt na Craoibhe-caoruiun stream section both the floor and roof thrusts are in Pipe Rock. This stream section, between 46 m and 145 m O.D. is composed entirely of An t-Sron Formation. Outcrop does not extend away from the stream so lateral constraints and possible transitions are unknown. There is a six-fold intraformational thickening with the two members retaining their undeformed proportions.

On Creag na Faolinn [NC 392534], below a thickened pile of Pipe Rock, with one incorporated An t-Sron Formation sequence, is an intraformational duplex (Fig. 5). Serpulite Grits are largely confined to the duplex roof with local, small scale interleaving with Fucoid Beds. These small structures are laterally inconsistent and thicken the formation duplex by microduplex development. Folds strike 070 ± 15° and face northwest.

Pipe Rock duplexes to the east of Srath Beag

South of Creag Shomhairle no Lewisian or Cambrian is interleaved with Moine mylonites. Pipe Rock, the footwall to the Moine thrust, is laterally involved in the Bealach Imbricate Stack. Below the high level Pipe Rock horses are the intraformational An t-Sron duplexes and their lateral transitions. Their floor thrusts roof the lower Pipe Rock duplexes at NC 380504.

Pipe Rock deformation is commonly confined to discrete, bedding-parallel zones along which develop high shear strains which are reflected by mylonites and cataclasites. At NC 380504, bedding planes are planes of no finite longitudinal strain with undeformed circular pipe-markers. Mylonites are dominantly restricted to hanging-walls above imbricate thrusts, the rocks below the footwalls remaining little deformed.

The Conamheall Duplex

Superb exposure on Conamheall [NC 364514] exhibits classic thrust geometries (Peach *et al.* 1907). The floor thrust is in Lower Quartzite, the roof probably in the Serpulite Grits and these are respectively the lowest and highest component members in the duplex. No higher thrust sheets are incorporated and the duplex is a projection of the Pipe Rock duplexes east of Srath Beag.

The Conamheall Duplex is largely composed of Pipe Rock which has imbricated in response to thrusting on many scales. The thrusts can be recognised by repetition of subzones within the Pipe Rock (Hallam & Swett 1966). Despite Hallam & Swett's (1966, p. 106) work showing that these subzones are "neither laterally continuous nor everywhere in the same order", the foreland succession in the field area shows no lateral variation in the subzones. Repetitions therefore are considered to be of tectonic rather than of depositional origin. A further, independent, field guide for thrust detection is the increase in shear strain towards displacement surfaces.

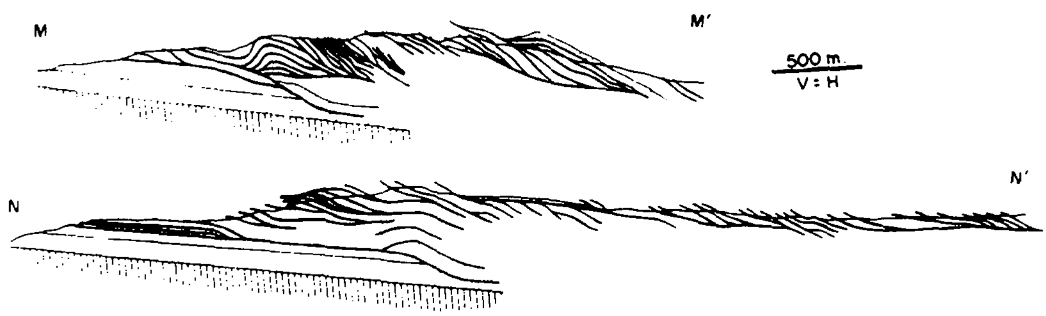

Fig. 7. Cross sections M–M′ and N–N′ drawn through the Conamheall duplex. Pipe Rock is unornamented, the fine stipple is An t-Sron Formation. All thick lines are thrusts, movement to NNW.

Outcrop mapping has revealed thrusts with 50–100 m spacing on the ground. Locally total exposure reveals thrusts with as little as 10 cm separation implying a complicated stair-step trajectory with ramps as small as 10 cm. This feature prevents accurate determination of the duplex floor thrust in the northwest of the field area. All Pipe Rock horizons are deformed with local variations in both orientation and magnitude of flattening. This implies a decollement surface, presumably a thrust, below the Pipe Rock as far to the northwest as Coire na Cuile [NC 365535].

South of Coire na Cuile [NC 370536] there has been considerable bedding-parallel slip and minor ramp development. Frontal ramps outcrop as spaced monoclines facing either NW or SE with an implied climb of under one metre.

Cross sections M–M′ and N–N′ (Fig. 7) are drawn parallel, 800 m apart, through the duplex. Data have not been projected onto the section lines because of the uncertainty in connecting various thrusts at depth. Both sections show large, upright antiforms which tilt structurally higher, southeastern thrusts and folds but do not affect structures to the northwest. Comparison of the two sections shows that many folds and thrust surfaces cannot be traced laterally since the folds decrease in amplitude and the thrust surfaces anastomose.

Textural development of the Pipe Rock in this duplex is heterogeneous with both brittle and ductile processes operating on a particular fault surface. None of the several generations of cataclasis and mylonite development can be traced laterally. There is no simple relationship between the geometry of a particular thrust surface and the textures associated with it.

THE SEQUENCE OF THRUSTING

There are two thrust propagation models (Elliott & Johnson 1980).

(1) Overstep, subsequent thrusts propagated back into the tectonic hinterland.

(2) Piggy-back, thrusts propagated into the foreland.

Peach *et al.* (1907) and more recently, Soper & Barber (1979) have argued for overstep models which have low thrust sheets overthrust by younger, higher sheets. Lower structures, therefore, are truncated against high thrust surfaces.

Elliott & Johnson (1980) and Coward (1980) consider the higher thrusts develop first and are carried passively by lower movements. These lower thrusts anastomose with or truncate higher, older thrusts. Within the present area there is a tendency for greater deformation and fold interference with structural height. This implies that folding, and therefore thrusting, was propagated into the foreland.

Detailed studies already described here show the interthrusting of Moine, Lewisian and Eriboll Quartzite from which a sequence is derived (Fig. 2).

(1) The emplacement of Moine rocks over Lewisian with associated mylonite development.

(2) The thrusting of this two-component sheet over Eriboll Quartzite.

(3) Later imbrication of Eriboll Quartzite with the higher thrust sheets from a floor thrust probably in Eriboll Quartzite.

As this three-component imbricate stack is folded by, but does not truncate, lower duplexes (Fig. 3) it predates them. Thus a piggy-back sequence of thrust propagation is true for both the lower and higher imbricates and is summarised in Fig. 8.

Balancing of the thrust belt using the method of Hossack (1979) requires a thickened, but now eroded, pile of An t-Sron Formation above the roof of the Conamheall Duplex. The An t-Sron intraformational duplexes east of Srath Beag could be the eastern roots of the eroded roofs.

The Moine Thrust

The Moine Thrust has been placed at the base of the high level imbricate stacks by previous workers (Soper 1971, Soper & Wilkinson 1975, Soper & Barber 1979, Mendum 1979). Their Moine Nappe (thrust sheet) contains Cambrian rocks and Lewisian basement which have been translated in an overstep model. These workers consider the Bealach and Craoibhe-caoruiun Imbricate Stacks to be part of the Moine Nappe.

It has been shown here that the high level imbricates have lateral transitions which outcrop below the disjointed trace of the Moine Thrust (as defined by the above authors). These observations do not support an overstep interpretation. Indeed the concept of an intact, unmodified Moine Nappe resting on a discrete, mappable

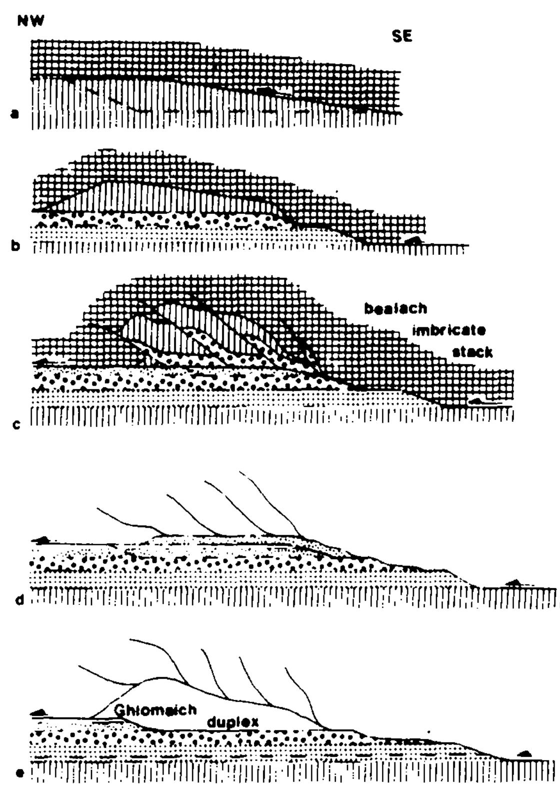

Fig. 8. Schematic cross section evolution, Creag Shomhairle area.

Moine Thrust is inapplicable since higher thrust sheets are interthrust with lower sheets after emplacement by subsequent imbrication. So it is necessary to redefine the Moine Thrust and thrust sheet.

Elliott & Johnson (1980) state that thrusts carry thrust sheets of their particular name; therefore, the Moine Thrust (*sensu stricto*) in the Eriboll area, carries a sheet composed entirely of Moine rocks and their derivatives. Elsewhere in the thrust zone Lewisian inliers within the Moine Thrust Sheet have been reported (e.g. Barton 1978) but these are not found in the Eriboll area. Hence this early Moine Thrust (*sensu stricto*) translated only Moine rocks which have been interthrust and have incorporated other units by subsequent imbrication.

Mylonites which occur at high structural levels contain intrafolial folds which have coincident axial traces to the lower, demonstrably post-Moine Thrust (*sensu stricto*), mylonites. Indeed mylonites have been generated in the lowest, latest thrusts in the thrust zone. Clearly this refutes the interpretation of Mendum (1979) who, on metamorphic grounds, considered that mylonites formed solely in D_1, a deformation event entirely prior to and independent of Moine Thrust displacement. It is proposed here that D_1 is merely an early part of a single, progressive deformation sequence throughout the Thrust Zone and need not be everywhere coeval.

Lewisian Thrust Sheets

Lewisian rocks were accreted onto the Moine Thrust (*sensu stricto*) hanging-wall by collapse of its footwall at frontal ramps. A series of these far-travelled horses (cf. Elliott & Johnson 1980) outcrop in the area; for example, one of the highest constitutes part of the Craoibhe-caoruiun Imbricate Stack. The least deformed Lewisian, at Creag na Faolinn, appears to be the last Lewisian horse to be incorporated in the imbricate stack. The Lewisian of Creag Shomhairle forms a similar, though not necessarily coeval, structure. Its accretion onto the thrust zone is laterally independent of Lewisian accretion elsewhere, and locally dependent on the Moine Thrust footwall ramp pattern.

Barton (1978) suggested that the Lewisian/Moine contact is sedimentary. This is unlikely because the rough criterion of shear zone width being proportional to displacement (Ramsay & Graham 1970) indicates far greater displacement on the Moine Thrust (*sensu stricto*) than on the other thrusts. Indeed, the term "far-travelled horse" may be misleading as some horses may have travelled further than others. Their accretion may have continued throughout Moine thrust displacement while the thrust remained in Lewisian rocks.

THE DEVELOPMENT OF FOLDS AND FABRICS WITHIN THE THRUST ZONE

The evolution of the thrust zone by piggy-back tectonics allows fold and fabric generation to be classified into two broad sites. The first of these (1) is limited to the thrust surfaces themselves; fabrics produced here being the direct product of shear zone development. The second site (2) is the entire body of rock above the hanging-wall of a particular thrust surface. The rocks above the hanging-wall are folded as a result of the topography of the thrust surface and the pattern of horses accreted onto the hanging-wall. Each site has specific types of fold and fabric generations

Isoclinal folds

These are restricted to zones of intense strain at the top of the present outcrop of the thrust sheet pile. Although the majority of folds within the mylonites are intrafolial with hinges trending northwest, there are isoclinal folds of the mylonitic fabric which also refold the northwest trending folds with NE–SW axes. Rather than ascribe these fold trends to distinct deformation events (Soper & Wilkinson 1975) it is suggested here that the isoclinal folds have developed with axes predominantly normal to the tectonic transport direction in response to anisotropic instabilities within the mylonite (Cobbold & Quinquis 1980). Progressive shearing rotated these axial traces into the transport direction (Escher & Watterson 1974). It is uncertain whether these folds were originally produced solely by simple shear or by this mechanism acting on an earlier layer parallel shortening component. Simple shear has been localised on discrete, axial planar shear zones which show mylonite generation within the isoclinal folds.

Textural implications

Many workers have considered that the mylonites formed prior to brittle thrusting (e.g. Elliott & Johnson 1980, p. 72), and Soper & Wilkinson (1975) interpret the Moine Thrust as a late brittle feature, a model refined by Elliott & Johnson (1980) who consider the mylonites to have formed a tectonic stratigraphy through which a wholly brittle Moine Thrust stair-stepped.

Lensoid, flat, brittle deformation zones of brecciated mylonite are common within the Craoibhe-caoruiun Imbricate Stack and on Leathad na Surraig (cf. Fig. 1; e.g. [NC 402527] and [NC 388483]). These zones are discontinuous within the ductile mylonites and show complex polyphase fabric generations. Cataclasis increases in importance deeper in the thrust sheet pile. This apparent enigma of high level ductility and low level brittle deformation can be explained by considering the thrust sequences already discussed. The conclusion so reached is that early thrusts are dominantly ductile with an increased propensity to cataclasis later in thrust zone development. That suggests a greater overburden on presently higher, rather than lower, thrusts at the time of their displacement. These higher thrusts have reached their present structural levels by subsequent displacement on lower thrusts. Long term evolution of strain rates or other environmental conditions besides overburden may also be of importance in the sequence of fabric type.

Within the Conamheall Duplex fault-breccias are formed below ductile quartzite mylonites which form the hanging-wall to particular imbricate thrusts. This distribution can be explained by continued displacement on a single thrust, moving rocks which have locally undergone ductile deformation over rocks which have been deformed by brittle processes. Therefore it is imprudent to assume that fabrics in the hanging-wall formed under the same conditions as those in the footwall since the two can be juxtaposed by later displacement.

The distribution of brittle zones within ductile deformation belts can be explained by the models presented by Sibson (1980) and Sibson *et al.* (1981). The model invokes brittle cataclasic processes during local seismic slip within an otherwise ductile shear zone in response to short-lived local variations in conditions such as strain rate or pore fluid pressures. Thus, brittle zones may develop continuously throughout translation of a chiefly ductile Moine Thrust.

Open folds

Open folds deform all thrust sheets within the thrust zones, including the structures already described. The early structures are probably the result of shear within the thrust zone and formed during emplacement, while the open folds are probably a consequence of thrust geometry and formed in their present site. Any footwall irregularities in the underlying thrust sheets are transmitted upwards, passively folding the rocks above the hanging-wall. Frontal ramps will produce folds with axes normal to the tectonic transport direction, while lateral ramps produce folds parallel to it. Probable examples of these lateral ramp generated fold culminations and depressions are dramatically displayed at Creag Shomhairle [NC 381505] (Fig. 3). The monoclines above the Strabeg and Creag na Faolian An t-Sron intraformational duplexes are further examples. Probably all these fold culminations were produced by passive warping of thrust sheets by preferential horse accretion onto part of the hanging-wall.

The effects of ramp-generated folding increase at higher structural levels within the Conamheall duplex. Bedding poles plot as a girdle in the tectonic transport direction for a frontal-ramp dominated system and as a girdle normal to the transport direction for lateral ramp domination. The amount of scatter on data increases with structural level (Fig. 9).

It has not been possible to establish the relationship to fabric development of folding above the hanging-wall. The open folds on An Lean Charn already described have a widely-spaced axial planar schistosity although the precise origin of these folds is uncertain. Shear bands (Cobbold 1977) are formed in belts of intense fabric anisotropy and may be produced in response to extensional strains resulting either from transport differential movement of the thrust sheets or from folding as part of the rocks above the hanging-wall to a lower thrust surface. Many quartz-filled vein arrays in Moine rocks on Leathad na Surraig (Fig. 1) which clearly post-date any other deformation may be related to extension due to folding of the rocks above the hanging-wall.

LATERAL VARIATION WITHIN THE THRUST ZONE

Despite an assumed consistency of stratigraphy within the thrust zone there is a remarkable heterogeneity of structure. Hanging-wall sequence diagrams from two locations (Figs. 10 and 11) show that the thrust zone is composed of a complex assemblage of anastomosing duplexes. As each horse is accreted to the base of the overriding thrust sheet it generates folds in the overlying structures. Statistically, the probability of lateral variations in the structure is increased with the number of ramps. Thus a complex stair-step trajectory through the Pipe Rock has a greater scope for variable horse-stacking configurations than a simple, single-step trajectory. This

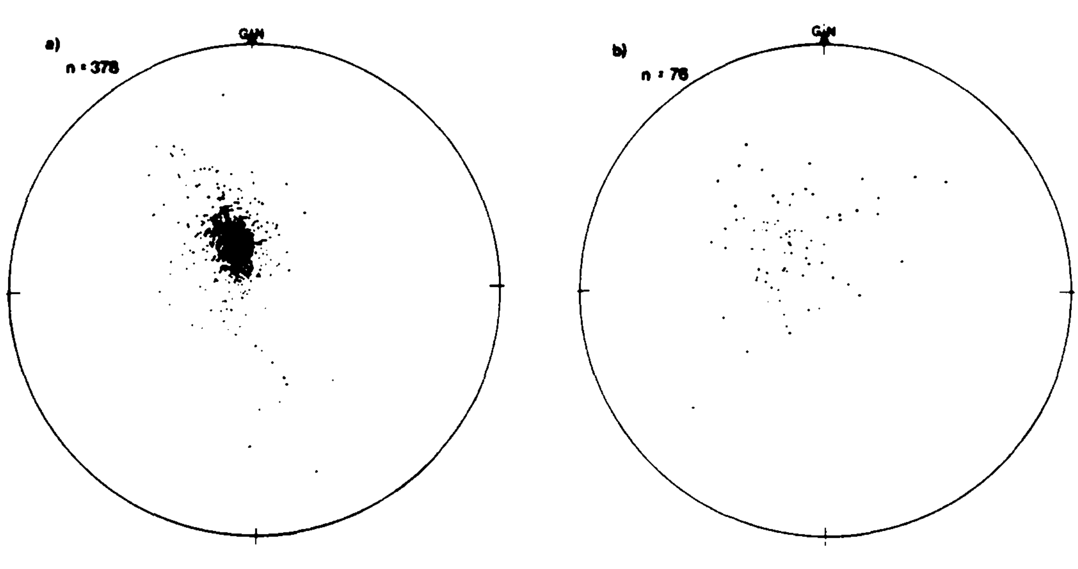

Fig. 9. Poles to bedding, Pipe Rock. (a) West of Srath Beag. (b) East of Srath Beag (Wulff nets).

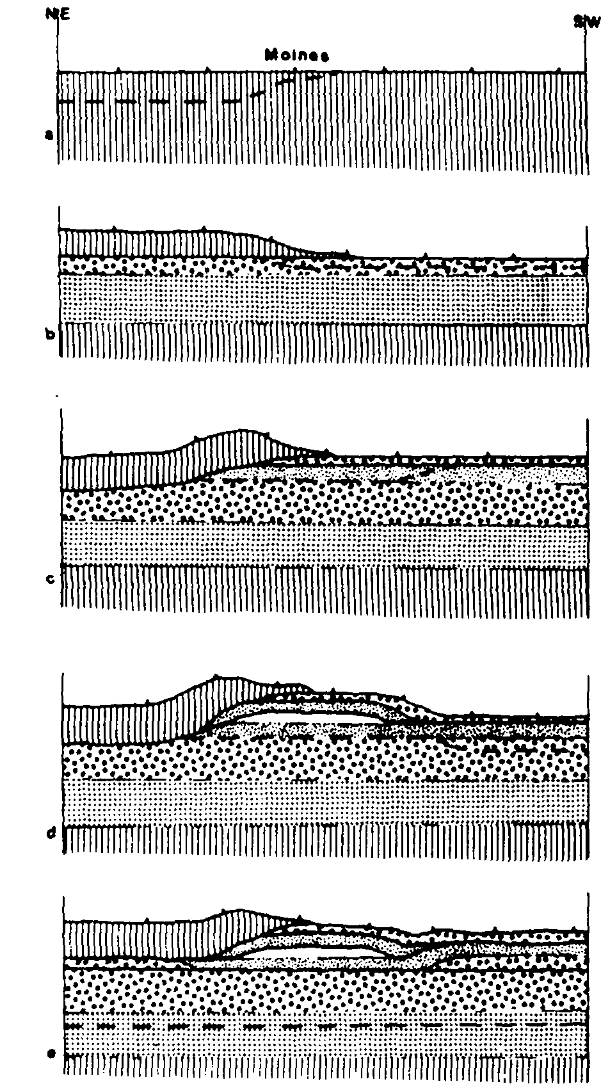

Fig. 10. Schematic hanging-wall evolution through Creag Shomhairle. Insipient thrusts are dashed (Bealach Imbricate Stack is not illustrated).

may account for the amount of lateral change on Conamheall as shown by both the lateral termination of folds and thrust anastomosis. As stated before, these folds cannot be correlated along the thrust zone. This complicates the construction of cross sections as used by Elliott & Johnson (1980) to calculate displacement on particular duplexes. As these authors did not recognise lateral variation with duplexes, the accuracy of their cross sections and hence their displacement estimates is uncertain.

The consequences of horse accretion for rocks above the hanging-wall

Any folding of structures above the hanging-wall by a lateral ramp dominated thrust surface topography will result in a length change of the rocks above the hanging-wall relative to the footwall. The hanging-wall sequence diagrams (Figs. 10 and 11) show this; the roof thrusts to the duplexes do not balance with footwall rocks.

Since the lateral terminations of thrust zones can be considered fixed, the changes in length of the hanging-wall

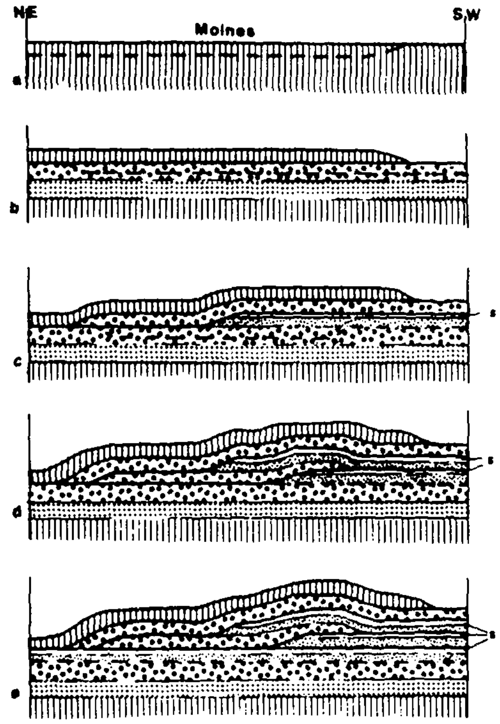

Fig. 11. Schematic hanging-wall evolution, Creag na Faolinn to Allt na Craoibhe-caoruiun.

must be accommodated internally. The resultant strains will initially be extensional; normal to the movement direction due to local horse accretion. As more horses are accreted laterally onto the thrust sheet, the roof thrust will fold, compressing rocks above the hanging-wall (Fig. 12). Further horse accretion will repeat this sequence. A particular rock above the hanging-wall could gain a complex history of extensional and compressional strains with thrust zone displacement.

TECTONIC TRANSPORT DIRECTION

The assumed tectonic transport direction to the northwest throughout this paper can be tested using two geometric techniques. The first of these utilizes the reorientation of lineations oblique to the principal axes of the shear zone strain ellipsoid, into the X-direction (cf. Escher & Watterson 1974). All linear features on the mylonitic, shear planes are considered to be in dynamic equilibrium with this X-direction, indicating extremely high shear across the zone.

Figure 13 shows fabric/shear plane intersections and fold hinge orientations on mylonite planes. These indicate a transport direction on a broad NW–SE axis. The scatter of both apparent displacement axis and foliation is probably due to folding of the mylonite after active displacement across the belt. Folding above lateral ramps will increase the spread of foliation orientation and hence the spread of apparent displacement axes.

This method can only determine the displacement axis and does not resolve the movement direction on it. Late foliations at high angles to the earlier, gentle, southeast-dipping fabric give a movement (cf. Ramsay & Graham

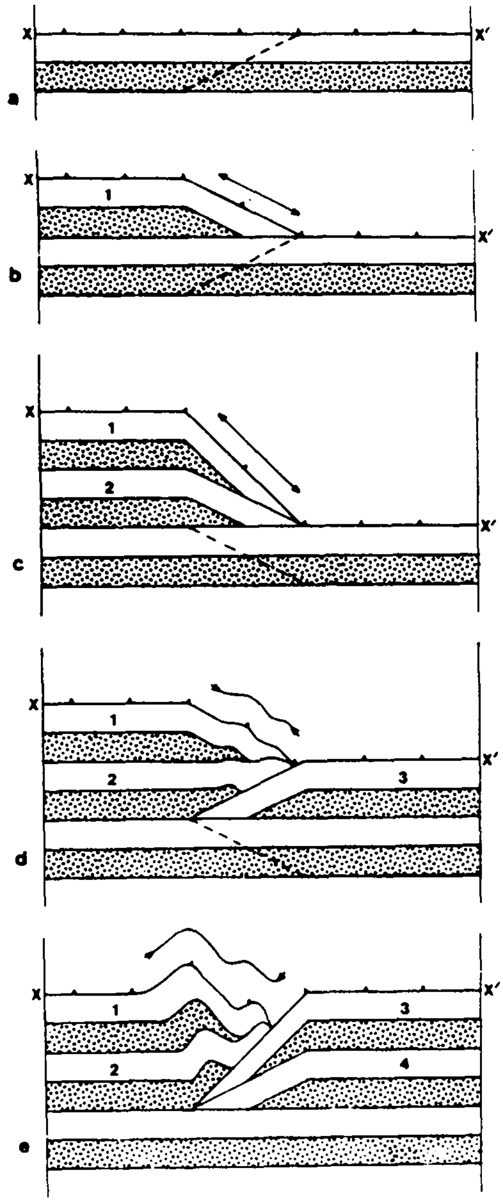

Fig. 12. Predicted hanging-wall strains due to sequential horse accretion, hanging-wall diagrams. Deformation here is limited to the walls of the culminations (i.e. the rocks above the hanging-wall overlying lateral ramps).

1970) to the northwest. This is substantiated by the consistent, northwest-facing intrafolial folds.

The second transport direction indicator is the so-called 'Bow and Arrow' Rule (Elliott & Johnson 1980) which states that the poles to bedding within horses have a symmetrical distribution about the tectonic transport direction. This assumes that thrust surfaces cut up stratigraphic section with displacement and with a symmetrical distribution of lateral ramps. The second assumption is valid only for a complete statistical sample of footwall symmetries; hence the method is restricted to regional applications. Bedding measurements from throughout the Conamheall duplex are symmetrical about 160° (Fig. 10a), a significant deviation from the apparent transport direction for the higher imbricates. The difference can be explained by a skewed lateral ramp distribution either in the lower, Conamheall Duplex, in the higher thrust sheet or a combination of the two.

DISPLACEMENT

Traditional measures of displacement on faults use offset of correlatable markers but the absence of such correlatives between the thrust zone and foreland in northern Sutherland precludes that technique. However, total shortening and thickening of formations by imbrication can give bulk strain measurements and hence displacements of duplexes. This approach has been used by Elliott & Johnson (1980) who have drawn and restored to undeformed state several balanced cross sections.

Southeast of Bealach a' Chonnaidh [NC 377482] (Fig. 1) a thickened pile of Eriboll Quartzite between a projected sub-Cambrian unconformity and the Moine thrust is measured at 720 m. This gives a thickness increase ratio of 4.5. If the figure is taken as an average over the outcrop width of the Conamheall Duplex (6 km), the pre-shortened width was 27 km.

The restored section does not totally account for displacement across the duplex. Considerable bed-parallel slip has been recognised in the Conamheall

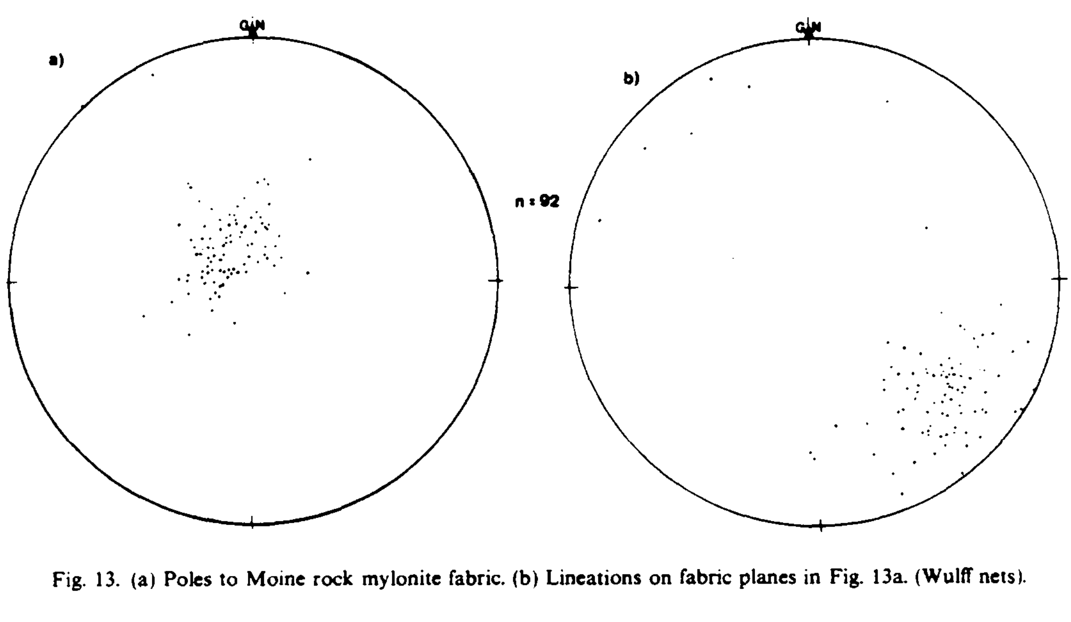

Fig. 13. (a) Poles to Moine rock mylonite fabric. (b) Lineations on fabric planes in Fig. 13a. (Wulff nets).

Duplex which is not accounted for in the above method. The slip cannot be accurately determined; 27 km is probably a gross underestimate across the duplex.

Displacement on the Moine Thrust (*sensu stricto*) is at least 11 km over Cambrian rocks since Moine rocks outcrop at Faraidh Head, Durness [NC 390710]. Projection of this displacement into the field area may not be justified because of lateral variation within the thrust zone. Some of this 11 km movement may be taken up by displacement on a lower thrust or by duplex development. In either case the Moine Thrust and thrust sheet could be carried passively above the hanging-wall of lower thrusts.

CONCLUSIONS

The Moine Thrust Zone in the field area has propagated by a piggy-back sequence of thrusts during the translation of Moine rocks towards the northwest. Elsewhere in the thrust zone a late, possibly reactivated, Moine Thrust disrupts this sequence but this does not occur in the Srath Beag area. The sequence of thrusting from top to bottom was broadly followed by the development of different deformation styles. The earliest, highest thrusts are mostly ductile shear zones with significant, but not major, brittle belts. Cataclasis increases down into the lower duplexes. The development of these deformation styles is probably the result of transient variations in strain rate in a regionally evolving strain field. Since these are probably caused by local increases in stress, there can be no correlation of fabrics and folds generated directly from translations processes. An early, pre-Moine thrust deformation event to produce the mylonites as envisaged by Soper & Wilkinson (1975) is not required. Fabric development was a continual process with thrust sheet displacment rather than a series of distinct events.

A corollary of the piggy-back sequence is the concept of net accretion of horses of rocks below the footwall onto the hanging-wall of the thrust zone. This accretion, and subsequent translation, folds all higher structures above the hanging-wall. The geometry of these folds will be largely controlled both by footwall topography and horse dimensions. A complex stair-step frontal ramp trajectory will increase the probability of variable horse accretion configurations. The effects of the accretion are shown by fabric orientation within the thrust sheets; a progressive dispersion of fabric orientation occurs with structural height. Frontal ramp dominated systems spread orientations in the tectonic transport direction and lateral ramp dominated systems spread normal to the transport direction. All lineations or foliations are also folded so that if these are considered palaeotectonic transport direction indicators the transport direction is apparently folded, which may prevent its accurate determination.

Since folds above the hanging-wall are produced by largely independent lateral accretion patterns they cannot be correlated through the thrust zone. Complex accretion patterns prevent reasonable projections of structures onto cross section lines. If these cross sections are used to determine net displacement, previously unrealised errors are incorporated into the estimate. Failure to recognise the reconstructed ramp–flat ratio on a stair-step profile may result in considerable underestimation of displacement on a particular duplex.

As higher thrust sheets are folded by both horse accretion and footwall topography, strain induced above the hanging-wall must be accommodated internally. Strains due to horse accretion will initially be extensional normal to the tectonic transport direction, followed by compression. This continual process provides a solution for many otherwise anomalous strains in thrust sheets.

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