Journal of Structural Geology, Vol. 6, No. 1/2, pp. 89 to 99, 1984
Printed in Great Britain

0191-8141/84 $03.00+0.00
Pergamon Press Ltd.

The strain and textural history of thin-skinned tectonic zones: examples from the Assynt region of the Moine thrust zone, NW Scotland

M. P. COWARD

Department of Earth Sciences, University of Leeds, Leeds LS2 9JT, U.K.

(*Accepted in revised form* 29 *July* 1983)

Abstract—The Moine thrust zone at Assynt is a classical example of a foreland propagating, thin-skinned thrust zone, ideal for an examination of thrust-related folds, deformation textures and strains and complex incremental strain history. Divergent transport directions, oblique trending folds, duplex zones and extensional strains normal to the main transport direction may all be explained in terms of thrust propagation, leading to the development of oblique to lateral ramps. The majority of thrusts cut up section from basement to cover in the transport direction but there is also localised extensional flow and thinning of the thrust sheets. In northern Assynt, the thrust zone involves a wide vertical zone of sinistral shear, within which forethrusts, backthrusts and associated folds and cleavages are oblique to the general transport direction. It is suggested that north of this shear, the thrusts moved further, probably under a thicker cover, while to the south, movement was more intermittent, probably under a thinner cover. This variation is probably due to a change in thrust geometry in the Moines, east of the Moine thrust zone, causing a variation in gravitational potential along the length of the Moine thrust.

INTRODUCTION

In recent years there have been advances in our knowledge of the tectonics of the Caledonian Moine thrust zone mainly from the application of concepts developed in the thin-skinned thrust regions of the Rocky Mountains and Appalachians (cf. Barton 1978, Elliott & Johnson 1980). Probably the best area in the Moine thrust zone for analysing small-scale structures associated with thrust tectonics is the Assynt region (Fig. 1), and this paper aims to describe and discuss some of these structures, their relationship to Caledonian tectonics and their importance in determining the driving mechanisms of the thrusts. The concepts described and developed here are probably applicable not only to thin-skinned tectonic terrains but also to deeper level, higher-grade shears. Many orogenic belts may be considered as large-scale examples of thrust belts, with structures developing above low-angle ductile decoupling zones (cf. Brewer *et al.* 1981).

The rocks of the Moine thrust zone were first described in detail by Peach *et al.* (1907). They form the northwest boundary to the Caledonian orogen in Britain. The foreland to the northwest consists of Proterozoic Lewisian gneiss, locally overlain by non-metamorphosed mid- to upper-Proterozoic Torridonian sandstones and then by Cambro-Ordovician sediments. These sediments consist of about 200 m of quartzites of which the lower part, the Basal Quartzite, is barren, while the upper part, the Pipe Rock, contains vertical worm burrows. In undeformed rock these pipes are normal to bedding and circular on the bedding planes and thus make ideal strain markers (cf. Coward & Kim 1981, Wilkinson *et al.* 1975). The quartzites are overlain by dolomitic shales and sandstones, the Fucoid Beds, then by a 10-m thick grit (the Serpulite Grit) and the highest Cambro-Ordovician sediments are a thick sequence of limestones and dolomites (the Durness Limestone). In the Moine thrust zone, this sequence is imbricated by thrust sheets varying from centimetric to kilometric scale (see sections in Peach *et al.* 1907) and is overlain by Proterozoic sediments, the Moines, deformed and metamorphosed by Proterozoic and Caledonian events (Brook *et al.* 1977, McClay & Coward 1981).

In the Assynt area there is a large bulge in the Moine thrust zone (Fig. 1) exposing several large thrust sheets, such as the Glencoul and Ben More sheets, above the Sole thrust, the floor thrust to the thrust system. From a re-analysis of Peach *et al.*'s (1907) data, Elliott & Johnson (1980) demonstrated that the Assynt bulge could be formed by the stacking up of these thrust sheets with the thrusts developing in piggy-back style, towards the west-northwest. Thus the lowermost thrust carried and re-orientated the higher thrusts. This concept, developed from Rocky Mountain tectonics (cf. Dahlstrom 1970), differed from the previous interpretations of the Assynt region, which suggested that the highest or easternmost thrusts formed late (Soper & Barber 1978, Parsons 1979). From restored cross-sections, Elliott & Johnson (1980) estimated a shortening of some 43%, that is approximately 10 km, for the Assynt imbricates. Similarly, from a correlation of open Proterozoic structures in the Torridonian sandstones, Elliott & Johnson (1980) estimated a displacement of 28 km for the Torridonian-carrying Ben More thrust sheet. The structural maps and sections of these Torridonian structures by Soper & Barber (1979), show a similar value of thrust displacement.

The maps and sections shown in this paper were made as part of a resurvey of the whole Moine thrust zone. They support the interpretations of Elliott & Johnson (1980) which were based on the original survey maps (Peach *et al.* 1907), though in detail the structures are more complex. An important observation is that there is a change in thrust geometry across Assynt, across a line

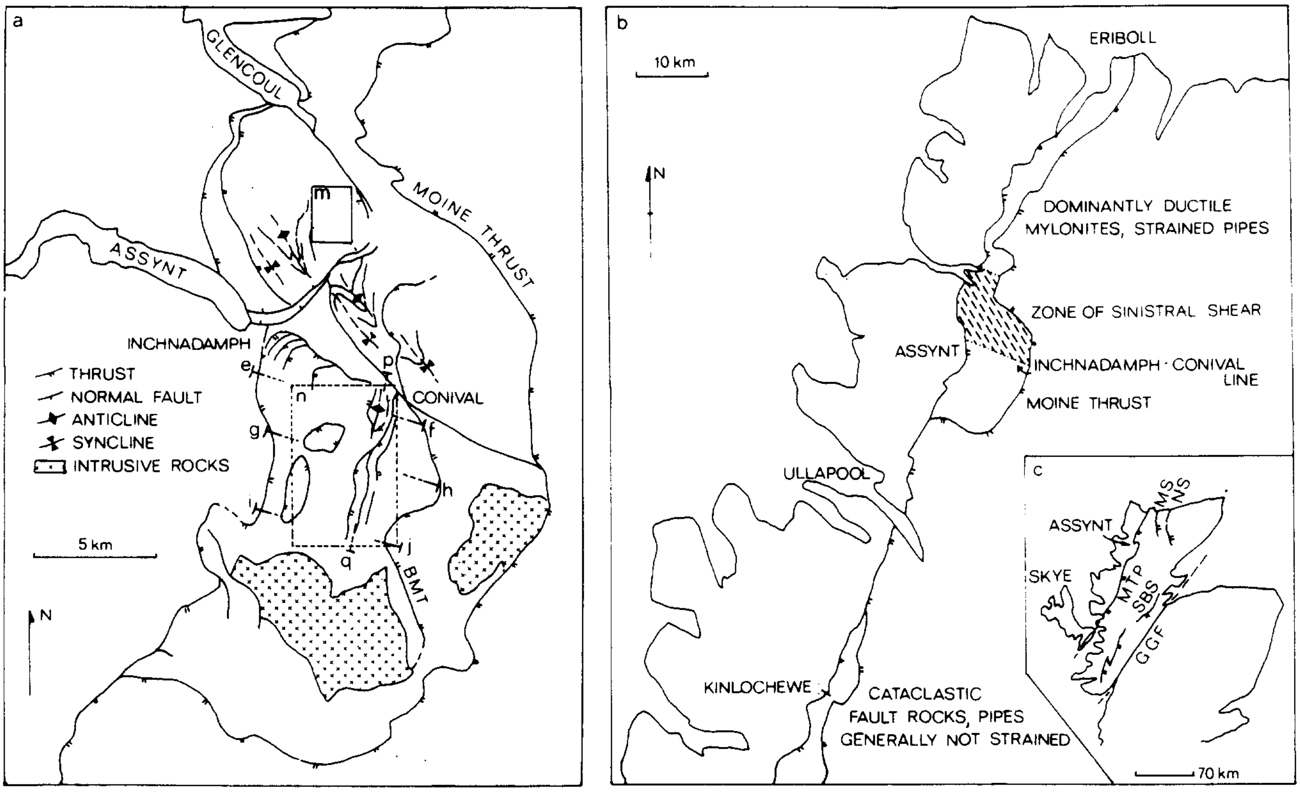

Fig. 1. (a) Simplified map of the Assynt area showing locations of other figures, the main thrust and the trends of folds north of the Inchnadamph–Conival line. (b) Location map for the northern part of the Moine thrust zone, showing the distribution of rock types and the zone of dextral shear. (c) Location map for NW Scotland. MTP, Moine thrust zone; SBS, Sgurr Beag slide; MS, Meadie slide; NS, Naver slide; GGF, Great Glen fault.

from Inchnadamph to Conival (Fig. 1). In this paper, the structures south and north of this line will be described separately.

There seems to be a change in dominant deformation mechanism and thrust style north and south of Assynt. In the northern part of the thrust zone, the thrust structures were dominantly formed by ductile deformation, though in any cross-section through the thrust zone, the fault rocks developed on the later, lower thrusts are more cataclastic. However, in the southern part of the Moine thrust zone south of the central Assynt region, cataclastic fault rocks are more important in some high-level as well as low-level thrusts. Thus in northern Assynt the Moine thrust zone is characterised by a thick zone of ductile mylonites as described by Peach *et al.* (1907) and Christie (1960), while in southern Assynt the Moine thrust is a much cleaner break, juxtaposing flaggy though often brecciated Moines or Cambrian rocks of the thrust zone.

There is a similar change in strain state along the Moine thrust zone. In the north, particularly in the Eriboll region, the Cambrian quartzites show evidence of layer-parallel shortening as well as shear, so that the pipes are elliptical on the bedding surfaces and often sheared so that they are no longer normal to bedding. However, in the south, these strains are less intense and often the pipes remain circular on bedding planes and normal to bedding. Thus in southern Skye, Potts (1982) records no strain from the pipes, even though the beds show large-scale tight, recumbent folds.

McClay & Coward (1981) considered these changes in strain to be due to variations in ease of slip on the thrusts. The corresponding change in dominant fault rocks, however, suggests a change in deformation conditions along the zone, from more ductile in the north, presumably with more steady state deformation, to more cataclastic in the south, with more intermittent, jerky fault movements. This change occurs across Assynt and thus an analysis of the change in thrust geometry across this region may be pertinent to models explaining changes in deformation mechanisms.

The structures will be described first for central Assynt (Figs. 1 and 3), then north Assynt (Figs. 1 and 6) and then for the thrust sheets recently found west of the Sole thrust (Figs. 6 and 8). For a review of thrust terminology, see papers by Dahlstrom (1970), Butler (1982b) and Boyer & Elliott (1982).

THRUST GEOMETRY OF ASSYNT

The thrust geometry of central Assynt

Figure 2 shows cross-sections through central Assynt and Fig. 3, a map of part of this area, shows the distribution and traces of the main faults and folds. From these, it is obvious that the easternmost thrusts formed first; they were carried in piggy-back style by lower thrusts and folded by structures developed on these lower thrusts. This is clearly shown in section i–j (Fig. 2), describing the structures north of the Ludeg River.

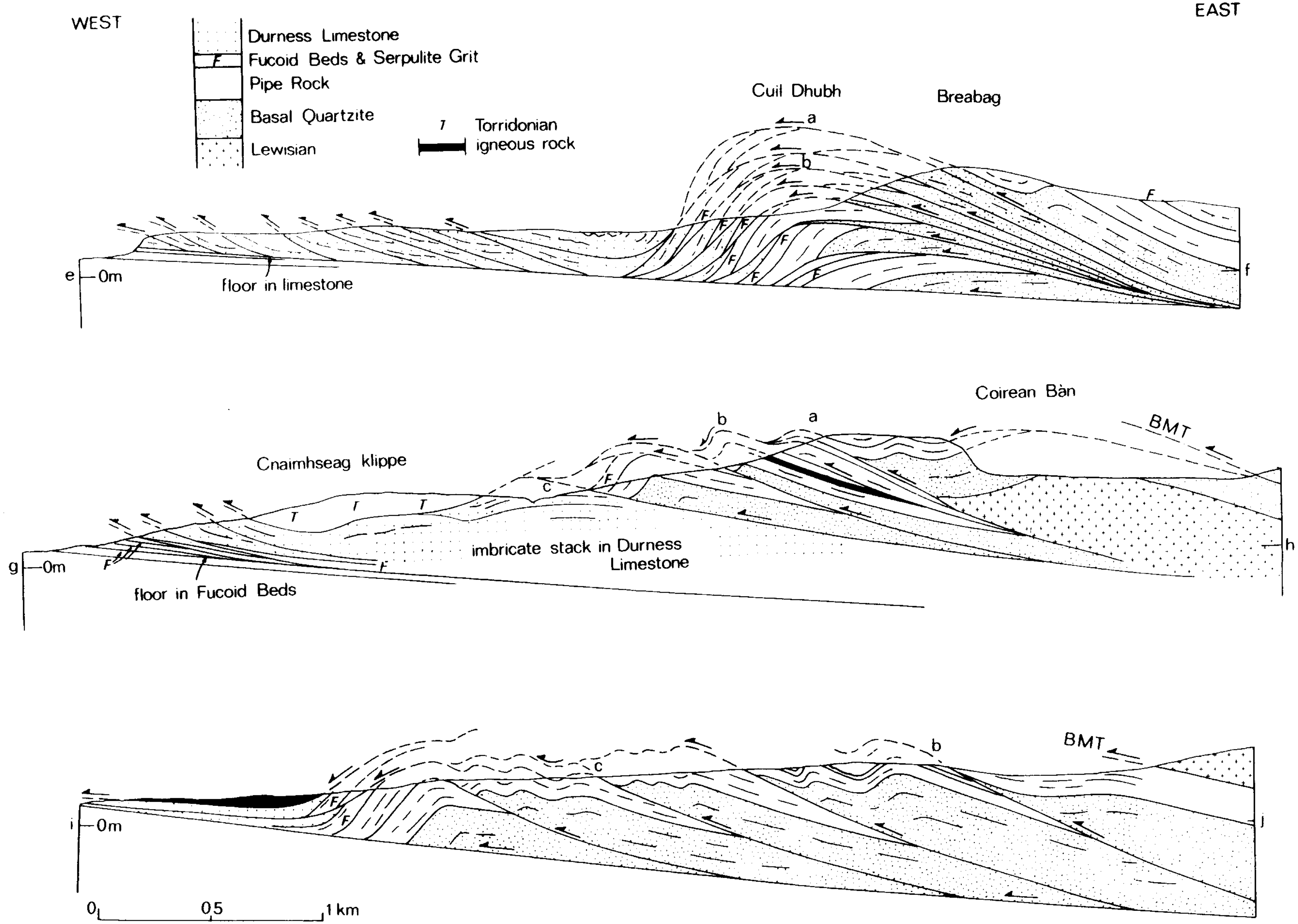

Fig. 2. Cross-sections through the central part of Assynt, for locations see Fig. 1 (a). Some thrusts are lettered to ease cross-reference between sections. 0m, sea-level datum.

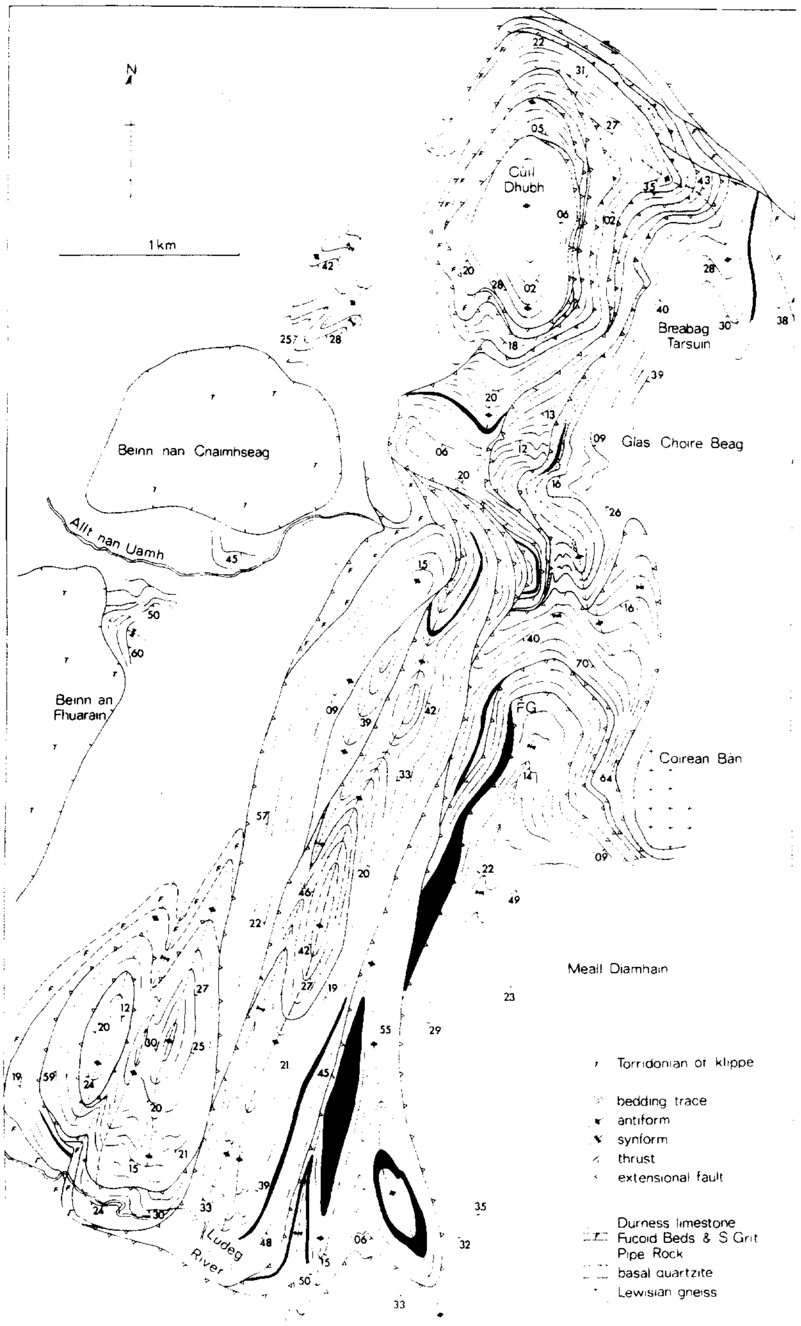

Fig. 3. Map of the imbricated lower Cambrian rocks, central Assynt. Location shown by box 'n' in Fig. 1 (a).

The folds were formed by two dominant processes. The first involved the buckling of the layers, producing westward-facing inclined to overturned folds with more intense strains on the overturned limbs. These folds presumably developed by a component of layer-parallel shortening, possibly due to the decrease in thrust transport near a thrust tip. Fischer & Coward (1982) have produced a model for the development of this type of structure, where, if movement continued after fold formation, a fault often branched off the original thrust to slice through the more deformed, steeply dipping fold limb and carry the anticline forward on the hangingwall. The traces of these folds thus mark thrust branch lines, originally developed from strained thrust tips. The second method of fold formation involved the stacking of imbricate fault-bounded horses as shown by the antiformal structure at Cuil Dubh (Fig. 2, section e–f and Fig. 3).

Folding by both the above methods locally produced downward-facing structures. Thus at Cuil Dubh the imbricate faults form a forward-dipping duplex (cf. Boyer & Elliott 1982), with downward-facing horses. Within each horse the thrusts cut up stratigraphic section in the direction of transport. As discussed by Boyer & Elliott (1982) the shape of such a duplex depends on the relative positions of the branch lines. Thus to make the structure shown in Fig. 2 the leading branch line (cf. Butler 1982b, p. 241) of each successive horse lies behind the leading branch line of the previously formed horse (Fig. 4).

The folds have variable plunges and form fold culminations and depressions. From a comparison of cross-

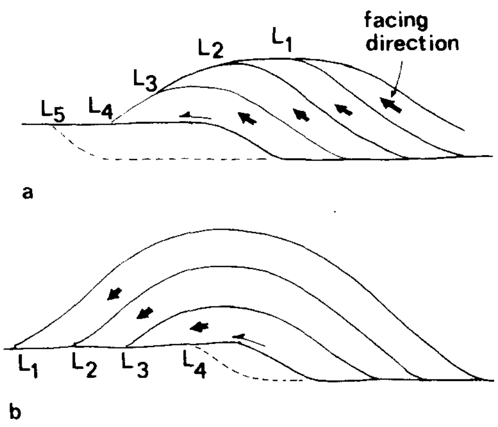

Fig. 4. (a) Upward- or foreland-facing duplex and (b) antiformal duplex stack. The leading branch lines (L) are numbered in sequence. Compare (b) to section e-f in Fig. 2.

sections in Fig. 2 and the strike-parallel section in Fig. 5, these culminations formed as a response to change in thrust geometry along the general strike of the belt. The thrusts changed level by means of lateral ramps, as shown in Fig. 5, producing a bulge or culmination above each lateral ramp. Erosion through such a culmination may produce a duplex window (cf. Boyer & Elliott 1982) as exposed at Cuil Dubh. West of Glas Choire Beag (Fig. 3) there is a major parallel-sided plunge depression trending WNW, presumably parallel to lateral ramps and hence to the thrust transport direction. Such parallel-sided lateral culmination or depression walls are generally useful in thrust belts for determining the tectonic transport direction. Note that one effect of this lateral fault climb is to produce a dome and basin outcrop pattern and the appearance of cross-folding due to fold interference.

The transport direction to the WNW is also indicated by tear faults, as shown northeast of Cuil Dubh. These tear faults generally develop during thrust movement, not later. They bound fault compartments and often allow different systems of imbricate faults to develop in each compartment.

The floor thrust to the whole system lies in Fucoid Beds in the south, but climbs slightly to the north to lie in lower Durness Limestone. Along section g–h (Fig. 2) folded and imbricated limestones extend eastwards several kilometres on the hangingwall of the floor thrust, but to the north and south they are cut out by thrusts carrying Basal Quartzite. Restored sections through this area indicate a minimum displacement of 10 km, that is 45% shortening. In the east, at Coirean Ban (Fig. 3), a fault carries Lewisian basement gneiss on its hangingwall.

The Torridonian rocks of the Beinn nan Cnaimhseag and Beinn an Fhuarain klippes (Fig. 3) are considered to be outliers of the Ben More thrust sheet (Peach *et al.* 1907, Elliott & Johnson 1980). They lie in a synclinal zone to the west-northwest of the thick imbricate stacks of Basal Quartzite and Pipe Rock (Fig. 2). Thus they are probably part of an early thrust sheet (the Ben More) folded by the stacking of structures beneath. The sections illustrated in Fig. 2 support this interpretation, similar to that of Elliott & Johnson (1982), rather than the original sections of the survey (Peach *et al.* 1907) which show the floor thrust to the limestone imbricates also folded. The eastern contacts of both klippes, however, are discordant to folds and thrusts in the underlying limestones. These fault contacts are thus out of sequence in the normal piggy-back succession, possibly formed by hinterland or overstep fault propagation (cf. Butler 1982b) but more likely associated with late extensional fault movement. Coward (1982, in press) records similar klippes of the Ben More sheet at the southern boundary of the Assynt bulge, also with extensional fault contacts.

The thrust sequence therefore involves: (a) a westward propagating thrust sequence, producing imbricate faults and associated folds in the Durness Limestone; (b) the emplacement of klippes, locally cutting down through the underlying imbricates and (c) the development of a thrust stack in Lewisian and Lower Cambrian quartzites producing the major zone of culminations from Breabag to the Ludeg River.

The thrust geometry of north Assynt

The structure of north Assynt has been described in several recent papers (Coward & Kim 1981, Coward 1982) and only a simplified tectonic map is given here (Fig. 1). Figure 6 of Coward (1982) shows a detailed map of fold and fault relationships north of Inchnadamph and Fig. 6 of this paper describes the imbricate fault systems near Loch Assynt.

As in central Assynt, the higher-level thrusts and their related folds are folded by structures developed above lower-level thrusts, that is, the thrusts developed in piggy-back fashion. Similarly, the thrust transport direction was to the WNW as determined from the trend of tear faults (Figs. 1 and 6). However, the major difference between these structures and the folds and thrusts in central Assynt is in their orientation. The fold hinges vary in trend from N–S to NW–SE, that is, from oblique to sub-parallel to the thrust transport direction (Figs. 1 and 6).

On the bedding surfaces, the pipes are elliptical with long axes also trending NW–SE to N–S (see Coward & Kim 1981). The ellipse long axes are not always parallel to the fold axes but trend more N–S and thus change orientation slightly around the folds. This discordance between ellipse axes and fold axes suggests a rotational component to the strain in the bedding plane section. Coward & Kim (1981) have described how these strains may be separated into two components; (1) layer-parallel shortening and (2) shear strains on planes normal to the main thrust plane but with the same movement direction as the main bedding-parallel thrust shear. A combination of these two components results in strain ellipses which have long axes oblique to the general thrust transport direction. It is suggested that the same sinistral shear strains shown by the pipes were also responsible for the development of the oblique trending folds; the shear strain would cause buckling of the beds and the trend of the hinges would depend on the combi-

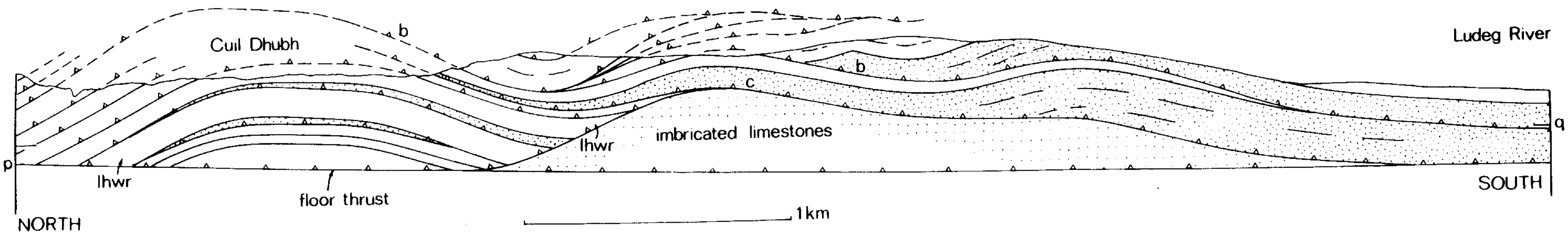

Fig. 5. Section through central Assynt, perpendicular to the thrust movement direction. For location see Fig. 1 (a) and for thrust lettering, a, b, c, and key to ornamentation see Fig. 2. lhwr, lateral hanging-wall ramp. Triangles are on the thrust hangingwall.

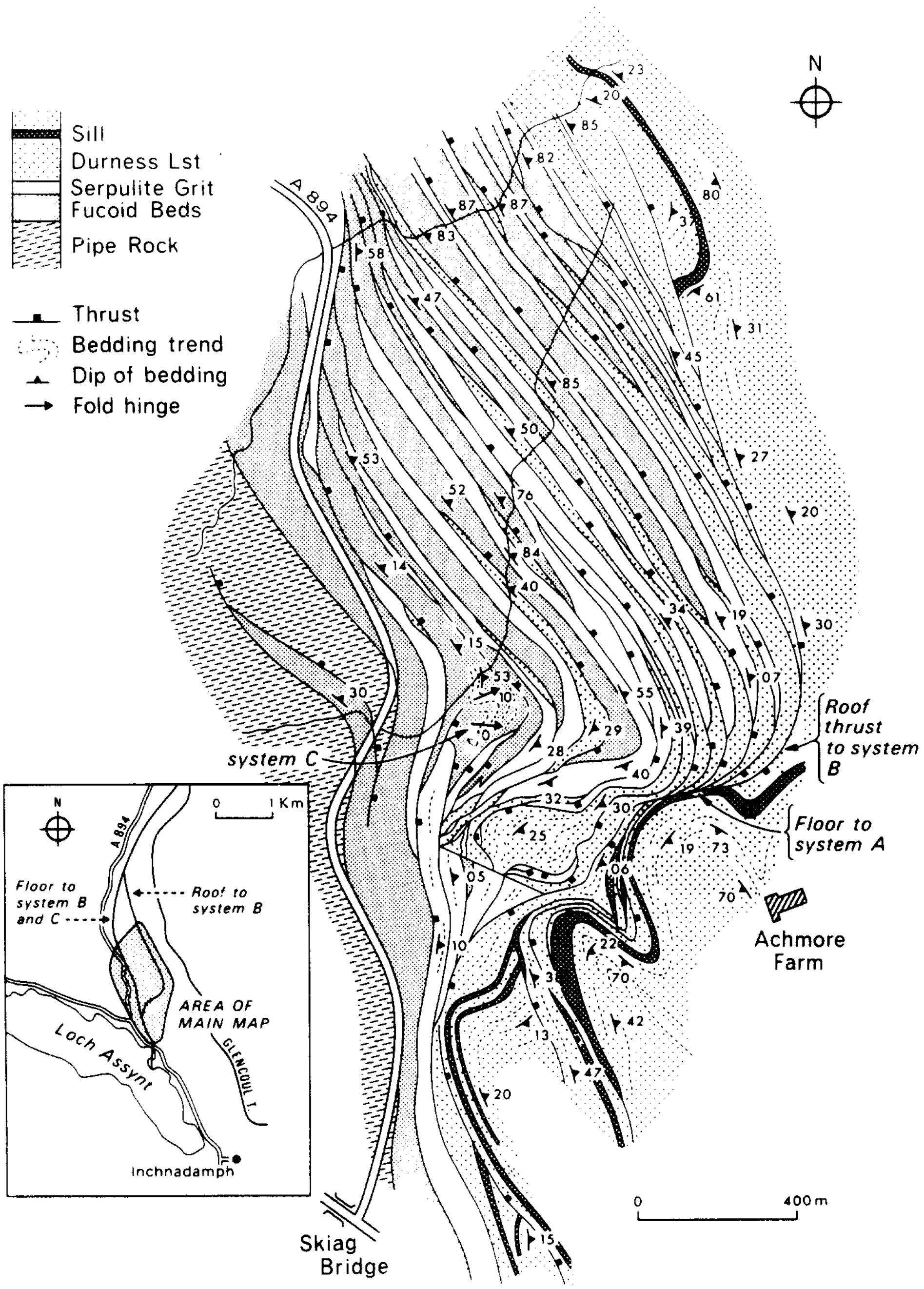

Fig. 6. Detailed map of the imbricate systems, NE of Loch Assynt, location map shown in inset.

nation of shear strain and layer-parallel shortening. Oblique trending folds and strain ellipses occur as far north as Glencoul and Loch More (Fig. 1), suggesting a wide zone (some 15 km) of differential sinistral movement. According to Coward & Kim (1981) the shear was heterogeneous, with a mean shear strain of $\gamma = 0.25$, suggesting a differential displacement of about 3 km across the whole zone.

This sinistral shear couple also affects the imbricate systems below the Glencoul thrust sheet as shown in Fig. 6, where the limestones of imbricate system A show NNW-trending folds, all facing to the SW. In the folded quartzites of the Glencoul sheet and limestones of system A, thrusts slice through the steep to overturned fold limbs and thus the thrust branch lines also trend NNW. As these thrusts propagated in a piggy-back fashion, the lower thrusts deforming higher-level structures, these obliquely trending branch lines represent originally obliquely-trending thrust tips. The folds developed by buckling due to the sinistral shear couple at these tips. In the quartzites and Lewisian gneisses at the eastern part of the Glencoul thrust (Fig. 7), some folds and thrusts face NE, that is there are backfolds and backthrusts also oblique to the thrust movement and presumably affected by the same shear couple.

The imbricates of system B (Fig. 6) involve Fucoid Beds, Serpulite Grit and the lowermost beds of the Durness Limestone. Few folds are shown by this system; it is a classic duplex zone with a floor thrust and a roof thrust equivalent to the floor thrust of system A (Fig. 6). However, the imbricate faults trend NW–SE, oblique to the WNW thrust transport direction as shown by compartmental tear faults (Fig. 6). These obliquely trending imbricates developed by the regularly spaced collapse of

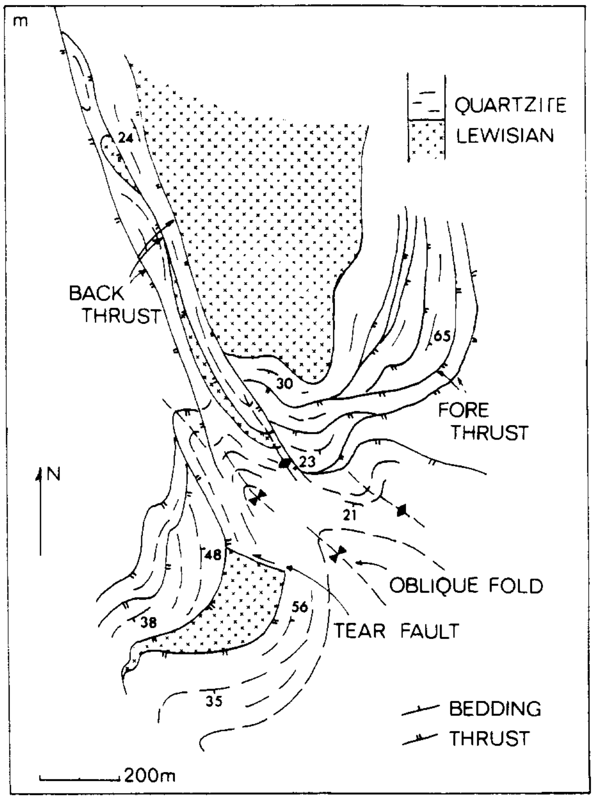

Fig. 7. Map showing oblique back- and fore-folds and thrusts, and tear fault indicating transport direction, in the central part of the Glencoul thrust sheet (location 'm' in Fig. 1a).

an obliquely trending footwall to the overlying thrust system. It is suggested that the oblique nature of the footwall collapse and hence the development of an oblique duplex zone, was due to the combination of a sinistral shear couple with shear due to thrust movement. Sanderson (1982) and Coward & Potts (1983) have shown that combinations of such simple shear systems lead to the development of a finite simple shear on a plane oblique to that of the main thrust movement, but with the same shear direction. The later imbricate faults, in the southern part of this duplex of system B, show hangingwall ramps facing to the N as well as the S (Fig. 6), that is, the later ramps do not show evidence for the sinistral shear couple.

The duplex zone of system B produces an obliquely trending culmination, folding the structures of system A (Fig. 6). Similarly the floor to system B is folded by oblique ENE-trending NW-facing folds, developed in system C (Figs. 6 and 8). These folds, in Fucoid Beds, have associated small-scale crenulations and an obvious cleavage. Thus the imbricate systems A, B and C develop in progressively lower beds in the Cambrian succession, each producing its own fold system, locally producing a cleavage and generally folding the imbricate systems formed earlier in the higher beds. The floor thrust to system C is often mapped as the Sole thrust to the Moine thrust zone (Peach *et al.* 1907). However, there are lower thrusts and small duplex zones in the Pipe Rock and Basal Quartzite below this Sole thrust and these will be described in a later section.

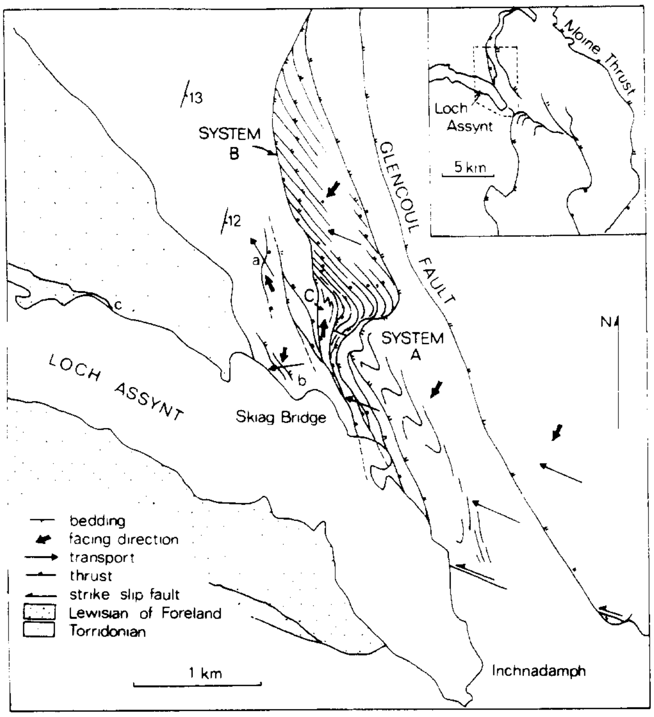

Fig. 8. General map of NW Assynt, showing imbricate systems and locations referred to in the text. The facing direction relates to the oblique folds and thrusts.

From a correlation of Lewisian structures in the Glencoul thrust sheet with those on the foreland, Coward *et al.* (1980) and Elliott & Johnson (1980) obtained an estimate of over 23 km displacement for the Glencoul sheet. Restoration of the structures in imbricate systems A, B and C gives a minimum displacement of 3 km, that is 50% shortening. The remainder of the displacement, over 20 km, must have taken place on the Glencoul thrust itself. The Glencoul thrust sheet is generally less than 1 km thick and thus the average angle of thrust climb in the north Assynt area, relative to bedding, is arctan ($^{1}/_{23}$) = 2.5°.

Not all this displacement has taken place on contractional faults. Northeast of Inchnadamph, extensional faults cut through the earlier folds and thrusts (see Fig. 6 in Coward 1982). The extensional faults can be traced into strike-slip and then contractional faults and together bound a large scoop-shaped surge zone (cf. Coward 1982) which has moved the western part of the Glencoul sheet some 1.75 km further to the northwest. The extensional faults probably flatten upwards to join reactivated, higher-level, low-angle faults. Thus the Moine thrust in eastern and southern Assynt has been reactivated by extensional fault movement; the surge zone in north Assynt is probably a downward scoop from this late movement zone (cf. Coward in press).

Part of the Glencoul sheet locally has extensional fault geometry and cuts down through the underlying stratigraphy. Imbricate system A (Figs. 6 and 8) is not considered to be a true duplex; the upper bounding fault has later extensional movement, removing the original roof and upper part of the duplex (cf. Coward 1982). Thus the fault at the base of the Glencoul sheet has similar geometry to that at the base of the Ben More sheet of the klippes in central Assynt. Northeast of Inchnadamph, the Glencoul sheet carries small listric normal faults, which flatten on the main floor fault. They are presumably associated with the thinning and extensional flow of the sheet. Similar extensional strains have been described from close to the Moine thrust at Glencoul (Coward 1983). Thus movement of the major sheets in Assynt was associated with extensional flow (Nye 1969, Ramberg 1981), the extensional structures being closely related in time to the thrusting.

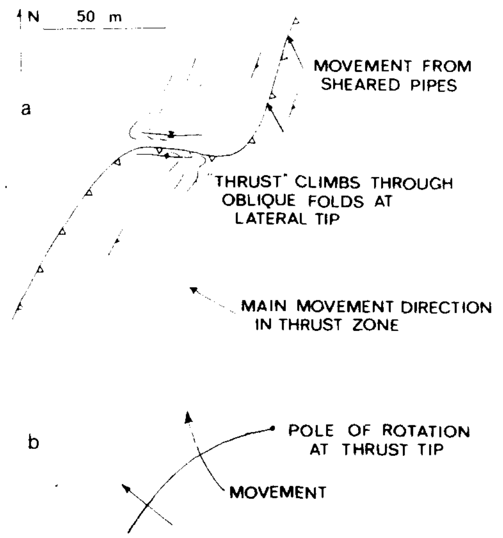

Fig. 9. (a) Detailed map of the fault zone at locality 'a' (Fig. 8). (b) Thrust movement about the pole of rotation at a thrust tip.

Geometry of the lowermost thrust sheets at Assynt, west of the Sole

As shown in Figs. 6 and 8, the Pipe Rock and Basal Quartzite beneath the Sole thrust, show several thrusts, associated folds and occasional thin duplex zones. The transport direction is less easy to ascertain in these rocks. Some of the pipes are sheared and these have been used to determine the transport direction at fault system *a* (Fig. 8). The facing direction of folds and imbricates cannot be used, as they are often oblique (Fig. 9). Slickensides and fibre growths on the bedding and other slip planes sometimes reflect flexural slip components around folds rather than the thrust transport. Thus the duplex zone at *b* (Fig. 8) shows slickensides trending 035 and 085°; the former are normal to fold hinges and branches lines, while the latter are presumed to represent the thrust transport direction.

The transport direction of these small faults diverges from the general WNW direction by about 30°. If these directions represent local thrust transport, the thrust must have shuffled forwards in a zig-zag fashion, the mean direction being approximately to the WNW (to 300°). However, there is another explanation for these divergent directions. The thrust at *a* (Figs. 8 and 9) is exposed near its lateral tip where displacement has largely died out in an oblique fold, though a thrust with only a few tens of centimetres displacement has climbed through the overturned limb to the north to shear the pipes and become almost bedding parallel. The lateral tip lies at the northern end of a thrust sheet, where the sheet should have suffered a vertical dextral shear couple. The observed movement direction in this tip zone is clockwise round from the main WNW movement. This suggests that the thrust was pinned at its lateral tip as shown in Fig. 9(b), and this tip acted as a pole of rotation for the end of the thrust zone. Further movement of the thrust could produce a further dextral shear couple and probably form another oblique fold. Thus at the duplex zone *b* (Fig. 8), where the oblique folds and thrusts suggest that this particular outcrop is near the southern tip of a thrust, the shear couple is sinistral and the observed thrust transport direction is anticlockwise from the general WNW movement. A simplified model for thrust propagation is given in Fig. 10 which suggests that if a thrust is pinned down at its lateral tips it can only grow forwards by: (1) having a radiating transport direction along its length leading to stretching along the strike of the thrust sheet and the development of non-plane strains and/or (2) developing a vertical shear couple near the tips and hence shear strains in the bedding surface with oblique folds and ramps. Alternative (i) has only been recognised in the region below the Sole thrust where the thrusts have relatively little displacement. Alternative (ii) is common in the main Assynt thrust zone where displacements are greater and lateral tip lines have often developed into lateral branch lines.

Thrusts also occur in the Precambrian rocks to the west. Locally (as at *c*, Fig. 8) the Torridonian sandstones and shales are cleaved by bedding-parallel shears. Apart from the obvious pre-Torridonian shear zones, there are also steep faults, of uncertain age, which affect the Lewisian basement and Torridonian cover and the whole thrust zone from the basal Cambrian uncomformity east into the main Assynt thrust mass, is uplifted to the south by approximately one kilometre, on a series of wide NW-trending flexures (Fig. 11). These flexures are easily identified from the change in trend and position of stratum contours on the Basal Quartzites. In the flexured zones, the Cambrian rocks show NE–SW extension in the form of small closely spaced fractures, boudinage and small normal faults. They locally thin the thrust zone and disturb the stratigraphic and thrust sequence. Limestones and igneous sills of thrust system A show numerous fracture arrays with fibrous infillings of calcite; the fibres suggest a NE–SW extension. An explanation for these flexural zones, with their extension normal

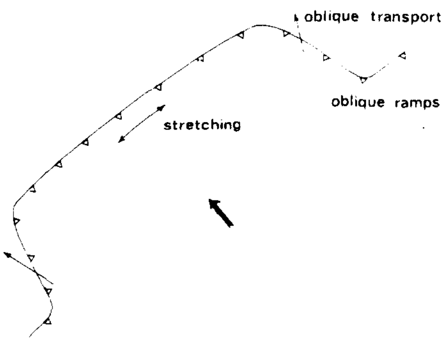

Fig. 10. One model for strains and varied movement in a thrust sheet pinned at its lateral tips.

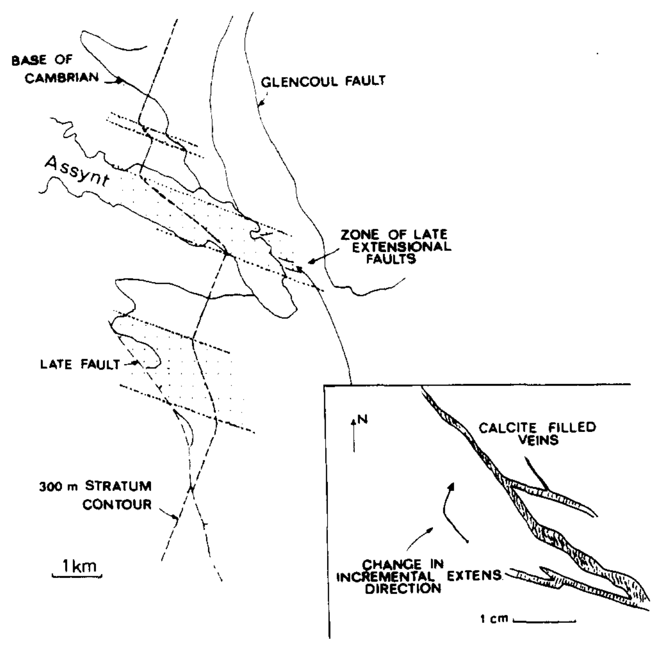

Fig. 11. Map of western Assynt showing the offset of the 300 m stratum contour by WNW-trending flexures, accompanied by NE-SW extension. Inset: detail of fibre-filled veins showing the change in incremental extension direction.

to the trend of the flexure, is that they represent lateral culmination walls (cf. Butler 1982b), formed above a hitherto unrecognised thrust at depth (Fig. 12). This deep level thrust is considered responsible for the uplift of the southern part of the Assynt zone.

CONCLUSIONS AND DISCUSSION

Thrust tectonics in general

The Assynt area exemplifies several concepts of thin-skinned tectonics, applicable not only to high-level thrust zones but also to deeper-level ductile shear zones. In many thrust zones, the faults develop and move in piggy-back fashion, the lower faults being youngest (Dahlstrom 1970, Elliott & Johnson 1980). Thus tip strains and folds in lower faults affect the higher fault sheets. This may lead to fold interference and the production of several phases of cleavage development. If lateral folds related to ramps or tip zones interfere, areas of cross folding may be produced. Sometimes the folds and minor thrusts develop out of a tip region, with the opposite sense to that of the main fault, giving rise to back-folds and back-thrusts. These structures may have only local importance, related to tip zones in some underlying thrust or shear zone; the structures may have no regional significance, that is fold phase numbers may have only local significance.

The structural and strain sequence may be complex; field studies, finite and incremental strain studies and textural studies may be needed to sort out the local kinematics. Usually within a shear zone, the finite extension direction will approach the shear direction with increase in strain and lie on the plane including the shear direction and pole to shear plane (Ramsay 1981). However, with differential movement as in a lateral tip zone, the extension direction will be oblique. Similarly, where a bed has been bulged up by the local stacking of thrusts beneath, to make a culmination zone, there will be extension normal to the transport direction (Butler 1982a). The incremental strain history as shown by fibre growth (cf. Ramsay 1981) will be complex, but should lead to an understanding of the sequence of extensional strains and hence of the local thrust history. These complexities in strain history must be sorted out if fabrics are to be used to determine shear directions and, on a larger scale, plate movement vectors.

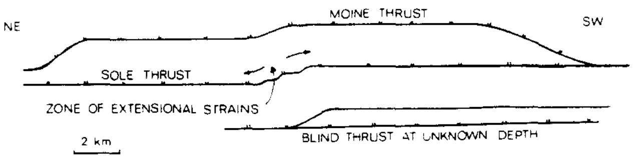

Fig. 12. NE-SW sketch cross-section through western Assynt showing the explanation for NE-SW extension and the flexures shown in Fig. 11.

The Assynt area

An example of the complex fold and strain history of a thrust zone is given from the Assynt area of the Moine thrust zone, where there are several different imbricate systems, each producing its own series of folds and thrust ramps in Cambro-Ordovician sediments. In the south, the folds and thrusts trend normal to the general transport direction but to the north, they are oblique. The Glencoul fault sheet is itself a zone of differential movement in north Assynt, producing extensional flow structures and faults at the rear in the east, and a zone of oblique folds and thrusts throughout most of the sheet. The main movement direction is to the WNW as shown by the trend of the tear faults, but the folds and minor thrusts face SW, indicating a sinistral differential movement component as would be formed on the southern tip of a major thrust.

Beneath the Glencoul sheet within the higher imbricate systems, folds and imbricate thrusts face SW, suggesting the same sinistral differential movement sense as in the Glencoul sheet. Most of the folds are due to buckling of the beds, probably in a lateral tip zone, though some folds are due to the stacking of lower imbricate faults. Later imbricate systems form NE-facing folds and thrusts. These folds are locally tight, produce a well-developed axial plane cleavage and fold the higher-level thrusts. These structures indicate a dextral shear sense. Within these imbricate systems the movement direction appears constant, to the WNW, but in later imbricate zones in the lower Cambrian rocks (previously considered to be part of the foreland), the movement direction as measured from fibres and sheared worm tubes is variable, WNW ± 30°. These anomalous movement directions occur near lateral thrust tips where the fault appears to almost die out. They may represent areas where the faults have been pinned and the rocks have tended to suffer bulk rotation around the pinned zones. The latest thrust movements

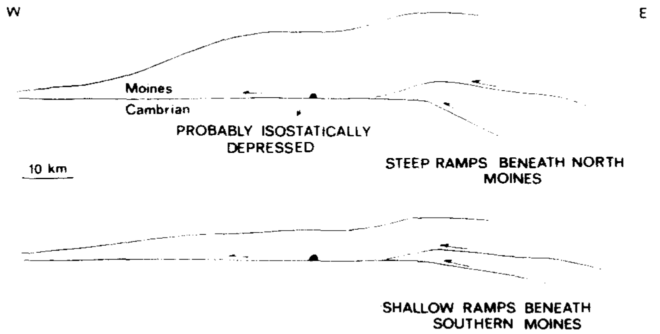

Fig. 13. Sketches showing the change in structure across the northern and southern portions of the western Moines and Moine thrust zone.

produced a major culmination in southern Assynt, raising the lower imbricate zones by over 1 km in the south. The preferred explanation to this, is that it originated by massive thickening of the basement rocks above a blind thrust zone in the west; back-thrusts from this zone have been recognized west of Assynt. There is considerable local NE–SW extension on the culmination walls as shown by fibre-filled gashes and large- and small-scale low-angle normal faults in the Cambrian sediments. These extensional strains, normal to the main transport direction make up the last local strain increments in the Moine thrust zone.

The Assynt area and the Caledonides

A model for thrust development in the Assynt area has to include the following conclusions.

(1) Much of the Moine thrust zone has moved forwards by gravitational spreading (cf. Coward 1983) as it generally involves thrusts which cut up section from basement to cover in the transport direction, but also involves localised extensional flow and thinning of the thrust sheets.

(2) In northern Assynt, the thrust zone involves a wide zone of sinistral shear about a vertical plane where the northern zone has moved further than that in the south. A differential displacement of about 3 km has been estimated for this zone, though this is small compared to the total displacement of well over 70 km for the Moine thrust zone as a whole (Elliott & Johnson 1980).

The more ductile deformation structures in the north compared with the less ductile, often cataclastic fault structures in the south, together with the above observations, suggest that the northern zone has moved further but more slowly, and probably under a thicker cover, while the southern zone has moved more intermittently, probably under a thinner cover. Soper & Barber (1982) estimate a cover thickness of over 10 km for the northern area. The explanation given in Fig. 13 suggests that the variation in cover thickness is due to a change in thrust geometry east of the Moine thrust outcrop.

If this change in geometry of the Moine structures is responsible for a change in tectonic cover along the Moine thrust zone and hence a change in structure, movement and movement rate, then there should be some lateral steps or ramps in the Moines east-southeast of the Inchnadamph–Conival line. Confirmation of this awaits further detailed structural work in this central part of the Moines.

REFERENCES

Barton, C. M. 1978. An Appalachian view of the Moine Thrust. *Scott. J. Geol.* **14**, 247–257.

Brewer, J. A., Cook, F. A., Brown, L. D., Oliver, J. E., Kaufman, S. & Albough, D. S. 1981. COCORP seismic reflection profiling across thrust faults. In: *Thrust and Nappe Tectonics.* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 501–512.

Brook, M., Brewer, M. & Powell, D. 1977. Grenville events in Moine rocks of the Northern Highlands, Scotland. *J. geol. Soc. Lond.* **133**, 489–496.

Butler, R. W. H. 1982a. A structural analysis of the Moine thrust zone between Loch Eriboll and Foinaven, NW Scotland. *J. Struct. Geol.* **4**, 19–29.

Butler, R. W. H. 1982b. The terminology of structures in thrust belts. *J. Struct. Geol.* **4**, 239–245.

Boyer, S. E. & Elliott, D. 1982. Thrust systems. *Bull. Am. Ass. Petrol. Geol.* **66**, 1196–1230.

Christie, J. M. 1960. Mylonitic rocks of the Moine thrust zone in the Assynt region, North-west Scotland. *Trans. Edinb. geol. Soc.* **18**, 79–93.

Coward, M. P. 1982. Surge zones in the Moine thrust zone of NW Scotland. *J. Struct. Geol.* **4**, 247–256.

Coward, M. P. 1983. The thrust and shear zones of the Moine thrust zone and the Scottish Caledonides. *J. geol. Soc. Lond.* **140**, 795–812.

Coward, M. P. & Kim, J. H. 1981. Strain within thrust sheets. In: *Thrust and Nappe Tectonics* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 275–292.

Coward, M. P., Kim, J. H. & Parke, J. 1980. The Lewisian structures within the Moine thrust zone. *Proc. Geol. Ass.* **91**, 327–337.

Coward, M. P. & Potts, G. J. 1983. Complex strain patterns at the frontal and lateral tips to shear zones and thrust zones. *J. Struct. Geol.* **5**, 383–399.

Dahlstrom, C. D. A. 1970. Structural evidence of the eastern margin of the Canadian Rocky Mountains. *Bull. Can. Petrol. Geol.* **18**, 332–406.

Elliott, D. & Johnson, M. R. W. 1980. The structural evolution of the northern part of the Moine thrust zone. *Trans. R. Soc. Edinb.* **71**, 69–76.

Fischer, M. J. & Coward, M. P. 1982. Strains and folds within thrust sheets: an analysis of the Heilam sheet, NW Scotland. *Tectonophysics* **88**, 291–312.

McClay, K. R. & Coward, M. P. 1981. The Moine Thrust Zone: an overview. In: *Thrust and Nappe Tectonics* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 41–54.

Nye, J. F. 1969. The motion of ice sheets and glaciers. *J. Glaciol.* **3**, 493–507.

Parsons, I. 1979. The Assynt alkaline suite. In: *The Caledonides of the British Isles—Reviewed* (edited by Harris, A. L., Holland, C. H. & Leake, B. E.). *Spec. Publs geol. Soc. Lond.* **8**, 677–680.

Peach, B. N., Horne, J., Gunn, W., Clough, C. T. & Hinxman, L. W. 1907. The geological structure of the Northwest Highlands of Scotland. *Mem. geol. Surv. U.K.*

Potts, G. J. 1982. Finite strains within recumbent folds of the Kishorn nappe, northwest Scotland. *Tectonophysics* **88**, 313–319.

Ramberg, H. 1981. The role of gravity in orogenic belts. In: *Thrust and Nappe Tectonics* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 125–140.

Ramsay, J. G. 1981. Tectonics of the Helvetic Nappes. In: *Thrust and Nappe Tectonics* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 293–309.

Sanderson, D. J. 1982. Models of strain variation in nappes and thrust sheets—a review. *Tectonophysics* **88**, 201–233.

Soper, N. J. & Barber, A. J. 1979. Proterozoic folds on the northwest Caledonian Foreland. *Scott. J. Geol.* **15**, 1–11.

Soper, N. J. & Barber, A. J. 1982. A model for the deep structure of the Moine thrust zone. *J. geol. Soc. Lond.* **139**, 127–138.

Wilkinson, P., Soper, N. J. & Bell, A. M. 1975. Skolithus pipes as strain markers in mylonites. *Tectonophysics*, **28**, 143–157.