Journal of Structural Geology, Vol. 4, No. 3, pp. 247 to 256, 1982.
Printed in Great Britain
0191-8141/82/030247-10 $03.00/0

Surge zones in the Moine thrust zone of NW Scotland

M. P. COWARD

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

(*Received* 19 *January* 1982; *accepted in revised form* 23 *April* 1982)

Abstract—The Caledonian thrust zones of Assynt show several examples of large fault-bounded structures, surge zones, up to 8 km^2 in extent, which have moved further than adjacent rocks. Extensional faults can be traced into strike-slip faults and then to contractional imbricate faults. There are also zones of extensional and contractional flow as shown by strained bioturbation marks in the Cambrian Pipe Rock.

Several other low-angle extensional fault zones have been recognized along the length of the Moine thrust zone, notably in the Kinlochewe district. Recognition of these extensional faults and local surge zones has solved several local problems such as the lack of continuity of the Glencoul thrust and the out-of-sequence character of some of the large low-angle faults. Though the thrust propagation direction was generally from east to west, in the transport direction, several of the eastern faults have been reactivated later and locally cut down as extensional faults. The 'so-called' Moine thrust shows extensional fault movement at several localities along its length.

The extensional structures and the surge zones suggest that body forces have been important in driving the faults rather than just a push from the rear. The Moines and Moine thrust zone were presumably driven to the WNW by gravity spreading and thinning of the main Scottish Caledonides.

INTRODUCTION

IT WAS in NW Scotland that much of the kinematics and mechanics of thrust zones, their shape and the development of their imbricate structures and deformation textures was first recognised. The name thrust was first applied by Geikie (1884) to the major planes of movement in NW Scotland. In the classic work by the Geological Survey, Peach *et al.* (1888, 1907) mapped out the thrusts in detail and showed that the Moine thrust carries deformed and metamorphosed Moine schists over Lower Proterozoic Lewisian Gneiss with its cover of late Proterozoic (Torridonian) and Cambro-Ordovician sediments. These Palaeozoic rocks consist of a basal quartzite, then bioturbated quartzite (the Pipe Rock), followed by a group of dolomitic shales (the Fucoid Beds), quartzites (the Serpulite Grit) and limestones (the Durness Limestone). In some places the Moine thrust carries Moines directly on to the Cambrian rocks of the foreland, but elsewhere the thrust zone is much thicker, with several major thrusts underlying the Moine thrust, each with a thick slab of Lewisian and Torridonian and/or Cambrian cover sediments. The transport direction of these sheets was to the WNW.

After the work of Peach *et al.* (1907) at the end of the last century, the Moine thrust zone received relatively little attention except for papers on the mylonites and the numerous fold phases affecting these rocks in the southern part of the thrust zone (e.g. Johnson 1960, 1961, Barber 1965, Kanungo 1956) and papers on rock textures and deformation mechanisms (e.g. Christie 1960, 1963, White 1979a, 1979b). There was little reanalysis of Moine thrust geometry until the work of Elliott & Johnson (1980) which applied to Scotland concepts of thrust geometry worked out in the Rocky Mountains and Appalachians. Elliott & Johnson (1980) used balanced cross-sections, stratigraphic separation diagrams and hanging wall sequence diagrams to interpret the Moine thrust zone. They argued that irregular horse accretion caused bulges in the overlying thrust planes and showed that the general sequence of thrust propagation was from east to west, in the transport direction. For this work, Elliott & Johnson (1980) used the original survey maps of Peach *et al.* (1907).

Recent re-mapping of the thrust zone by the present author has shown some discrepancies with the thrust concepts of Elliott & Johnson (1980) and these are important when considering the driving mechanisms of the thrusts. In the northern area, near Eriboll, the thrust geometry generally agrees with that described by Elliott & Johnson but to the south, in the Assynt district, there are problematical low-angle faults which post-date underlying folds and thrusts. Some of these faults have extensional geometry, that is, they cut down rather than cut up the stratigraphy in the transport direction (cf. Dahlstrom 1970). This paper describes these structures at Assynt and some similar structures at Kinlochewe and then discusses their significance in the Moine thrust zone and in the Caledonides of the Scottish Highlands.

THE GEOMETRY OF CONTRACTIONAL AND EXTENSIONAL FAULTS

The geometry of low-angle contractional fault zones has been fully described by Dahlstrom (1970) with discussion by Hossack (1979) and Elliott & Johnson (1980). The basic model is shown in Fig. 1 and a cross-section through a natural small-scale example from the Moine thrust zone at Kempie is shown in Fig. 2. The

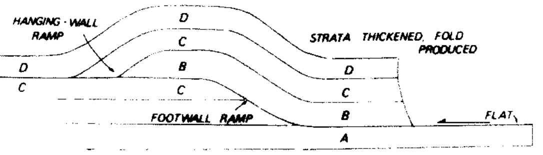

Fig. 1. Schematic model for a thrust (after Dahlstrom 1970) showing that contractional faults climb ramps in the transport direction, thicken the rock sequence and produce structurally necessary broad antiforms above and ahead of the footwall ramp.

main characters of thrust faults may be described as follows:

(a) Thrusts generally follow easy slip horizons, flats, which are generally parallel to bedding in well layered sedimentary rocks, but climb ramps in more competent units to cut up stratigraphy in the tectonic transport direction.

(b) Thrusts cannot thin a stratigraphic sequence, nor can they cut out beds. They cause bed repetition and stratigraphic thickening.

(c) Localized thickening produces structurally necessary folds characterized by broad, flat-topped anticlines and gentle limb dips, equivalent to the dip of the ramps. The anticlines develop above and towards the leading edge of the ramps and grow as the hanging wall ramp moves along the next flat.

Closely spaced compressional faults form an imbricate or schuppen zone (cf. Fig. 2). They generate from a sole or floor thrust and pass up into a roof thrust, defining fault-bounded packages or horses which in a group make up a duplex zone. Extensional faults may also occur as closely spaced schuppen zones, as shown by the example from near Elphin in the Moine thrust zone (Fig. 3).

The geometry of such low-angle extensional faults has been described by Dahlstrom (1970) and examples of large low-angle extensional faults have been given by Hunt & Mabey (1966) from Death Valley, California; Pierce (1963, 1973) from the Heart Mountain area of Wyoming and Graham (1981) from the French Alps of Provence. Syn-sedimentary extensional (growth) faults have been described by Crans *et al.* (1980). Dahlstrom (1970) has pointed out that there are many similarities between low-angle normal faults and low angle-thrusts, in that they tend to follow flats and ramps and may develop as imbricate sequences. There are however important differences, in that in low-angle normal fault terrains the section may be thinned by omission of stratigraphic units. A normal fault with listric form will

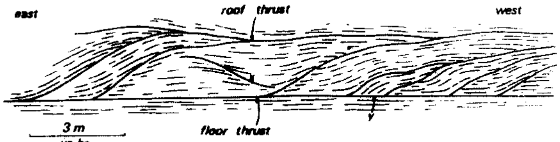

Fig. 2. Example of a small scale contractional duplex zone in well-bedded Durness Limestone at An t-sron, Kempie on the east shores of Loch Eriboll (locality K in inset map of Fig. 6). x and y mark zones where the faults cut down the stratigraphy, that is, they are local zones of extensional faulting.

produce a roll-over anticline in which the rocks dip towards the fault plane (Fig. 4). Normal faults with a stair-step trajectory should produce a series of folds as shown in Fig. 4.

THE ASSYNT AREA

Figure 5 shows the generalised geology of the northern Assynt area according to Peach *et al.* (1907). The Moine thrust in the east carries the Moine schists. This is underlain by the Ben More thrust carrying Lewisian Gneiss and Cambrian quartzites over similar rocks, and to the west the Beinn Uidhe and Glencoul thrusts carry Lewisian rocks on to imbricated Cambrian sediments. The floor thrust to this stack of thrust sheets lies variably in lower Cambrian quartzites, middle Cambrian Fucoid Beds and upper Cambrian Durness Limestone. The Glencoul thrust forms the lower boundary to one of the largest thrust sheets where displacement is at least 23 km to the WNW, as shown by the offset of Lewisian structures (Coward 1980, Elliott & Johnson 1980). This thrust is well exposed on the shores of Loch Glencoul and Loch Glendhu in northern Assynt but the trace of the fault through central Assynt is more problematical. Peach *et al.* (1907) suggested that it joined with the Beinn Uidhe thrust on the west side of Beinn an Fhurain and then with the Ben More thrust at the SE end of the Traligill valley (Fig. 5). Christie (1963) and Sabine (1953) agreed with this model and termed the whole thrust complex, the Assynt sheet. Bailey (1935) found little evidence for joining the Glencoul and Beinn Uidhe thrusts and he considered that the Glencoul thrust died out at Allt Poll an Droighinn (Fig. 5). In a recent paper (Coward & Kim 1981), I supported this view, partly based on strains in the Glencoul thrust sheet which indicated differential movement, possibly associated with the sticking of the Glencoul thrust at Allt Poll an Droighinn. Elliott & Johnson (1980) however considered that the thrust did not die out, but became a bedding-parallel thrust, with little stratigraphic separation and was, thus, difficult to detect on the map. According to Elliott & Johnson (1980), south of Allt Poll an Droighinn, the Glencoul thrust carries limestone over limestone and forms part of the Traligill imbricate zone (Fig. 5).

The new interpretation, based on detailed re-mapping of the area (Fig. 6), does not agree with any of the interpretations given above. Northeast of Assynt, the Glencoul fault carries Lewisian rock with a folded cover of Basal Quartzite and Pipe Rock over a Fucoid Bed–Durness Limestone sequence. The actual fault plane is generally obscured by peat, but north of Inchnadamph it is easy to map out (Fig. 6). Here it carries previously folded and imbricated Quartzite and Pipe Rock over limestone but the fault cuts down the stratigraphy and does not follow normal thrust rules (Fig. 6). Small imbricate faults branch off the Glencoul fault, but these are listric extensional faults which downthrow rocks to the NW, in the direction of movement.

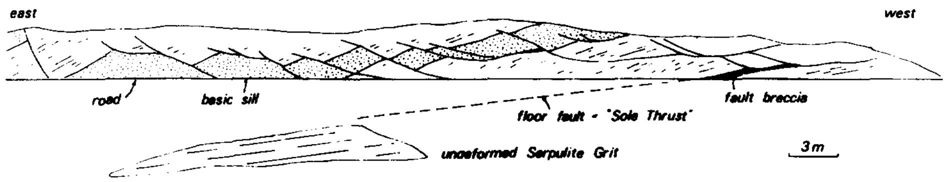

Fig. 3. Example of an imbricate zone of extensional faults from road cuts south of Elphin village in southern Assynt. The floor fault lies above the Serpulite Grit and outcrops as a zone of breccia at the western end of the section. Note that later extensional faults cut and displace this floor fault. The dip of the beds in the imbricate zone is some 10–15° steeper than the dip beneath the floor fault. This floor fault was mapped as the Sole thrust by the Geological Survey (Peach *et al.* 1907); it certainly joins with the Moine thrust 1 km to the south, at Knockan. Locality e on inset map, Fig. 6.

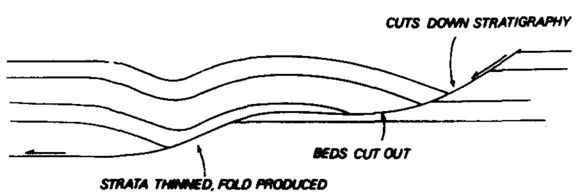

Fig. 4. Model for extensional faults (after Dahlstrom 1975) showing that the faults cut down in the transport direction, thin the rock sequence and produce structurally necessary folds above and ahead of the footwall ramp.

One large fault branches off the Glencoul fault near a major topographic feature southwest of Cnoc Dubh causing an indentation of the fault plane (Fig. 6). This obviously cuts across the overlying structures to the NW (Fig. 6) and can be traced for ~ 100 m to the ENE where it is folded by the major Cnoc an Droighinn fold. This major fold is itself cut across by a fault near the SE side of the Droighinn hill. To the southeast, and the north side of Glean Dubh (Fig. 6), the rocks bear no structural relationship to those on Cnoc an Droighinn, but there is a major fold in Cambrian rocks from Basal Quartzite to Durness Limestone and this fold is cut across by several normal faults with downthrow to the NW.

There is a major imbricate zone NE of Loch Assynt, affecting mainly the Fucoid Beds–Durness Limestone sequence. Near Loch Assynt, the strike of the faults is 340° but south of Inchnadamph (Fig. 6) the imbricate faults are largely confined to the Durness Limestone and trend at 030°. Between the two sets of imbricates there are faults trending approximately E–W, which not only offset the imbricate zone but also allow extra thrusts to develop on the northern side. These E–W faults can be traced into the normal faults which offset the Glencoul fault and offset folds in the Cambrian quartzites SE of Cnoc an Droighinn (Fig. 6).

To the northeast, the faults are locally lost in the peat bogs of Allt Poll an Droighinn (Fig. 6) but can be found again in the western slopes of Meall nan Caorach. Here, extensional faults dip to the NW and carry folded Cambrian rocks down over Lewisian Gneiss. These faults cut across previously developed folds. To the east the faults curve to become strike-slip faults with several splays. These become generally lost in the peat bogs east of Meall nan Caorach.

South of Glencoul, faults with extensional geometry drop the Lewisian Gneiss and Cambrian cover down to the NW; one particular fault can be traced up the Glen Beag valley into several normal faults in the SE part of Beinn Uidhe. A major normal fault has been traced along the west side of the Leathad Riabhach ridge (Fig. 7). To the north it is offset by a N 290° trending tear fault; to the south it bends round several SSW-dipping ramps (Fig. 7). The normal fault obviously post-dates thrusts within the Basal Quartzite on the Beinn Uidhe ridge. To the east along the A'Cailleach valley there are also steeply dipping back thrusts which carry Lewisian Gneiss to the east over quartzite (Fig. 7). However the age of these relative to the normal faults is not clear. Within the quartzite, west of the normal fault, there are large roll-over folds with several anticlines and synclines at the south of Leathad Riabhach. The roll-over fold profile changes, presumably due to changes in shape of the normal fault (Fig. 8); the synclines and anticlines are presumably due to changes in dip of the extensional ramps.

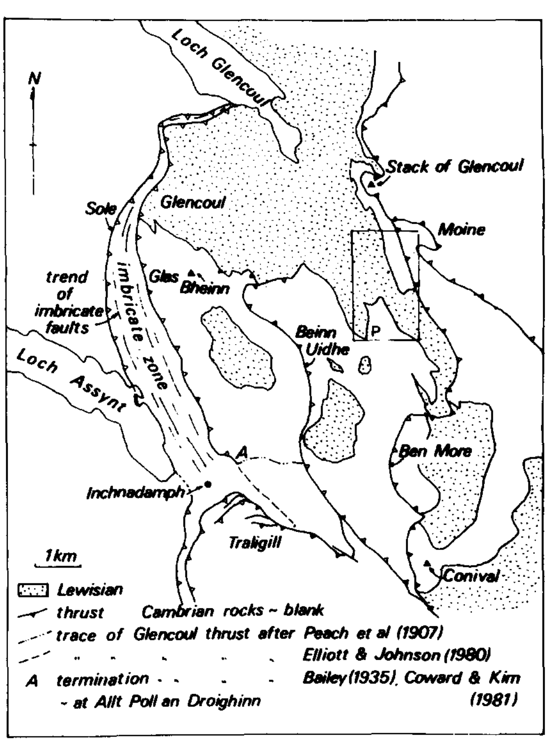

Fig. 5. Map of the Assynt area (for location, see inset of Fig. 6) showing position of thrusts (after Peach *et al.* 1907) and possible interpretations for the continuation of the Glencoul thrust south of Allt-Poll and Droighinn.

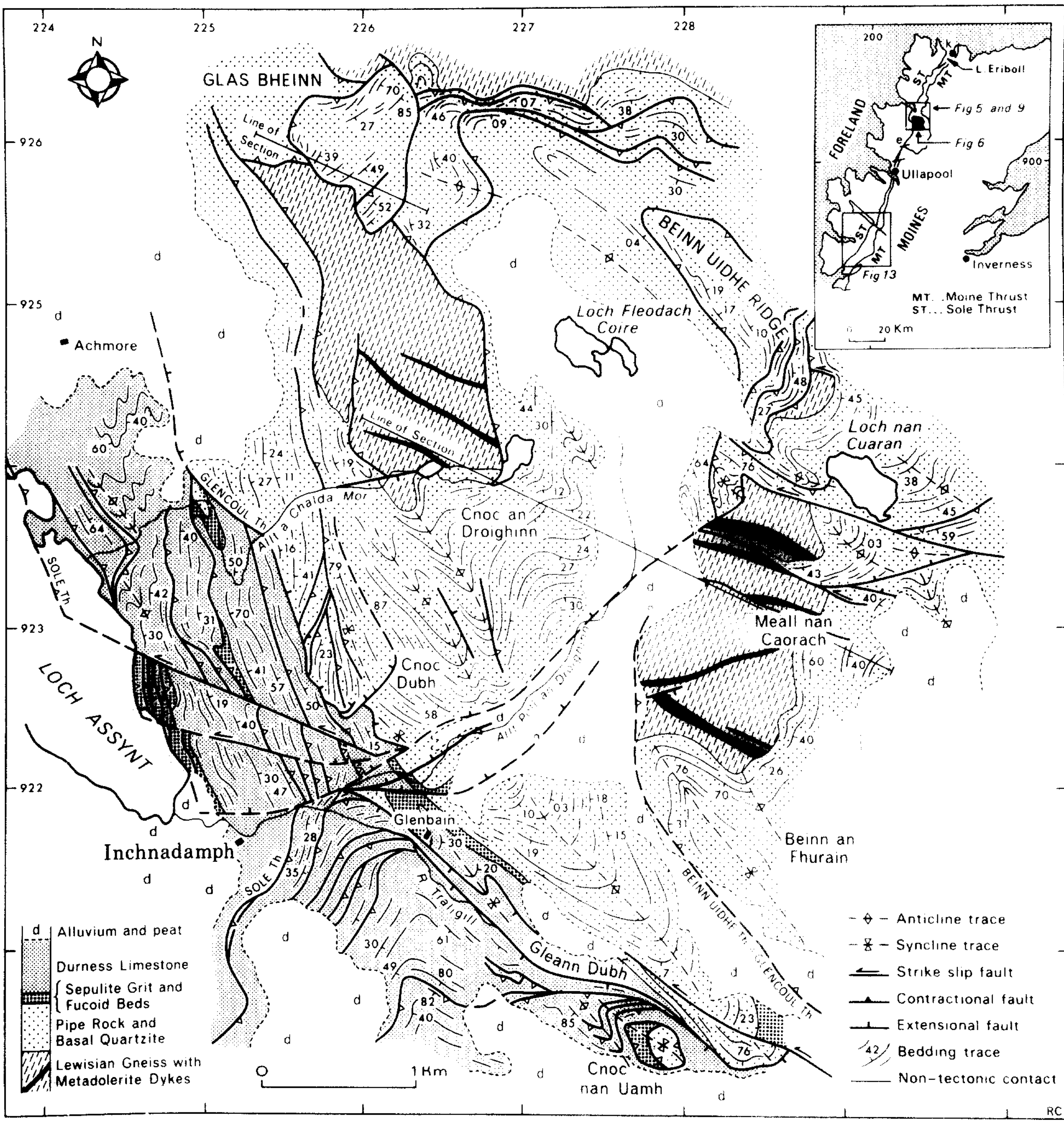

Fig. 6. Map of the area near Inchnadamph (shaded on inset map) showing the new interpretation of the structure. Where fault traces are uncertain they are shown with a dashed line.

Thus, it appears that the Beinn Uidhe–Glas Bheinn area of Assynt dropped down and moved more to the NW than the adjoining areas (Fig. 9). The Beinn Uidhe–Glas Bheinn area lies to the SE of a zone of curved imbricates, which change in trend from 060° at Glencoul to 340° near Inchnadamph (Figs. 5 and 9). This structure is, therefore, analogous to a large-scale avalanche structure and is here termed a surge zone. It is bounded by arcuate contractional faults in the imbricate zone to the NW and an irregular arcuate zone of extensional faults to the SE. The size of this north Assynt surge is some 8 km × 8 km. The amount of displacement is shown by the cross-section in Fig. 10 which plots the offset of the Lewisian–Cambrian unconformity in a section parallel to the movement direction. This movement direction is given quite accurately by the trend of the strike-slip faults and strike-slip boundaries to the surge. The displacement is 1.75 km, with a vertical displacement of some 500 m.

On Beinn an Fhurain, SE of the surge (Fig. 6), the Beinn Uidhe fault carries Lewisian Gneiss and Cambrian quartzite cover over upper Cambrian sediments. It is considered that this marks the original Glencoul fault before it was dropped to the NW on the major surge zone. Along most of this fault it is difficult to tell whether it cuts up or down section in the transport direction. To the SE, branches of this fault are folded round a major NW–SE trending anticline and on the southern limb the fault climbs up into limestone to join with the Traligill faults (Fig. 6). Some of these show extensional geometry

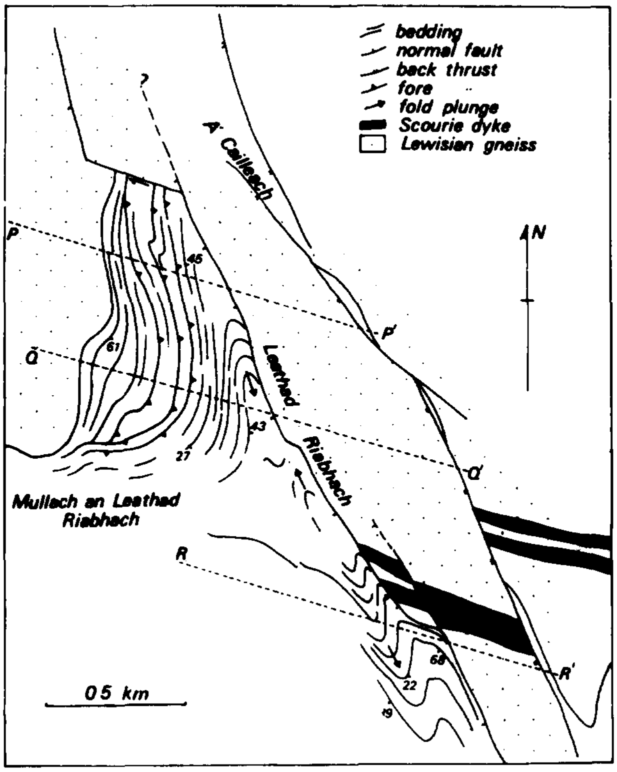

Fig. 7. Map of the Leathad Riabhach ridge area, E of Beinn Uidhe (box P in Fig. 5), showing the major extensional fault with associated ramps and tear faults, which cuts through earlier thrusts in the Basal Quartzite. The quartzite is shown with no ornament.

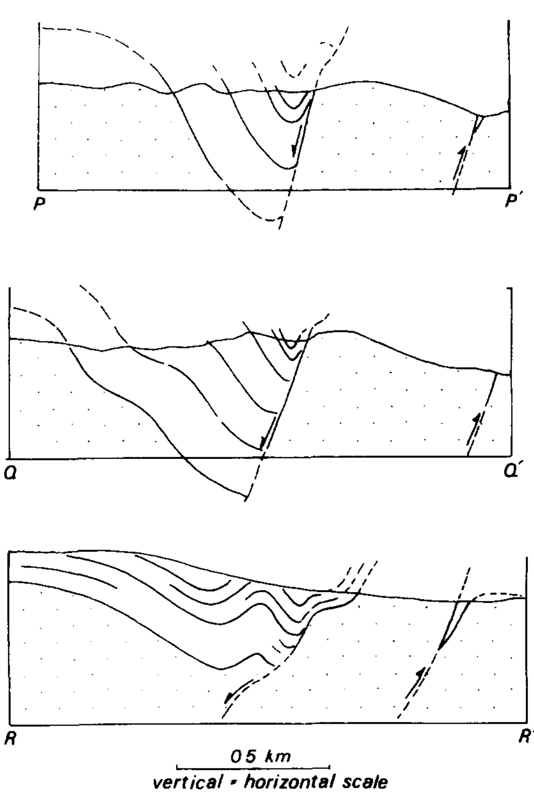

Fig. 8 Profiles through the roll-over folds associated with the normal fault along Leathad Riabhach. Section lines shown on Fig. 7. Ornament as for Fig. 7. The base line for sections is at sea level.

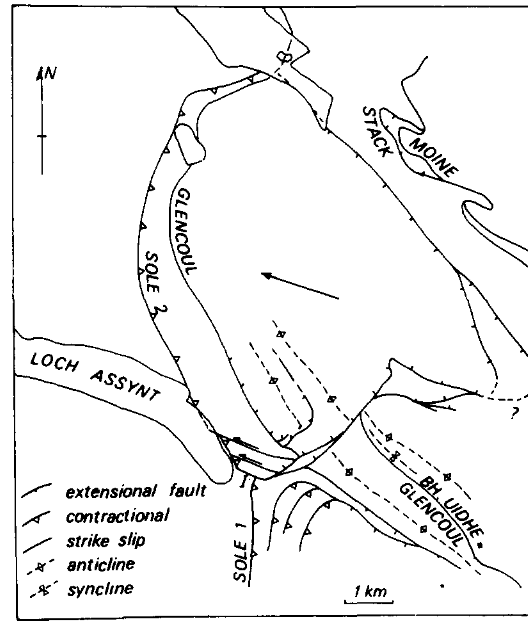

Fig. 9. Simplified map of the north Assynt area showing the positions of the major contractional, extensional and strike slip faults which define the surge zone. The question mark denotes areas of uncertainty. Location on inset map of Fig. 6.

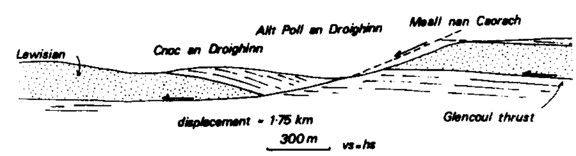

Fig. 10. Cross section line (southern line of Fig. 6) showing the displacement of the Cambrian/Lewisian contact by extensional fault(s) along the Droighinn valley. Note the change in dip of the beds defining a slight roll-over structure in the hanging wall on Cnoc an Droighinn.

in that the faults cut down the stratigraphy. This is well demonstrated by the main Traligill fault in the Traligill valley. South of Inchnadamph the Traligill faults appear to be contractional faults.

A small-scale example of a surge zone is shown in Figs. 6 and 11 from the summit ridge of Glas Bheinn. This is confined to Cambrian quartzites and has dimensions of only 1 km × 1 km, though it may of course be only the keel of a much larger structure. Low-angle extensional structures are also common in the SW part of Assynt in the Elphin–Knockan area, as have been described earlier.

Thus, in the Assynt area, the following structural sequence has been derived from the above data, the paper by Coward & Kim (1981) and recent detailed mapping.

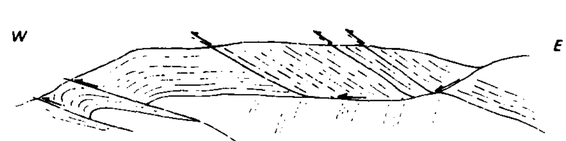

Fig. 11. Cross section (northern line of Fig. 6) through the small surge zone exposed at the top of Glas Bheinn.

(i) In what is now northern and western Assynt, faults developed above a floor thrust in the Basal Quartzite. These generally obeyed the rules of thrusting; they climbed stratigraphy and propagated towards the WNW. However, there were some zones of extensional flow as the extensional faults cut down to the floor thrust on Glas Bheinn (Fig. 9).

(ii) The major Assynt thrust sheet, as defined by Christie (1963), developed above a floor thrust in the underlying Lewisian Gneiss though this was irregular and locally both the footwall and hanging wall climb up into Durness Limestone (cf. Elliott & Johnson 1980). In the east, the Assynt thrust appears to have been a major contractional fault; a branch from the Assynt thrust, the Ben More thrust, climbs steeply through Torridonian and Cambrian rocks (Fig. 5). In the west, however, there may have been locally extensional flow as in parts of the Traligill fault system and the Glencoul fault system, as on Cnoc an Droighinn, the fault plane cuts down-section in the transport direction (Fig. 6). These extensional faults formed at the same time as some of the folds in the Assynt sheet as at Droighinn, one such fault cuts a syncline but is folded by the main Droighinn fold (Fig. 6). These folds are oblique to the transport direction and presumably were associated with differential movement of the Assynt sheet, whereas the northern part of the sheet moved furthest causing a sinistral shear couple to be applied to the sheet about a vertical shear plane (cf. Coward & Kim 1981, Fischer & Coward, in press). This shear couple would cause the numerous oblique folds as shown in Fig. 6. The long axes of strain ellipses on the bedding planes, as shown by deformed sections of originally near circular pipes, are also oblique to the transport direction, trending approximately N–S (Coward & Kim 1981). Certainly not all the movement of the Assynt sheet was by extensional flow; there are many thrust faults, often carrying oblique folds on their hanging walls. There are also back-thrusts in which the transport direction was to the ESE, directly opposite to the main direction (Fig. 7). These back-thrusts define 'pop-up' zones where material has been uplifted above converging faults and define regions of contractional flow. Some back-thrusts also carry oblique NW–SE trending back-folds in their hanging walls. Details of these will be given in a separate paper.

(iii) The Assynt sheet and Glencoul–Beinn Uidhe fault is itself folded by a large oblique antiform along the Traligill valley (Fig. 6). This fold probably developed above a floor thrust in the underlying Basal Quartzite. Following this there was the development of the main Glencoul surge moving the Glencoul thrust down 1.75 km to the NW from its original position along the line of the Beinn Uidhe thrust. Imbricate thrust faults formed in Fucoid Beds–Durness Limestone at the front of the surge and extensional and strike-slip faults formed at the back part of the surge. There was no folding during movement of this slab; the faults all cut through the previously developed folds.

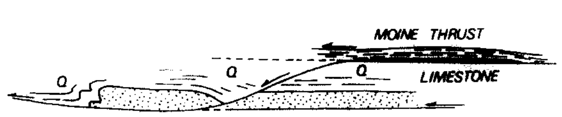

Fig. 12. Schematic cross section to show the possible link between the Assynt extensional faults and the major Stack and Moine fault zones.

There is no evidence for the extensional faults cutting the overlying Moine thrust, possibly the 1.75 km displacement in the main extensional fault was not enough to drop the Moine thrust to the present erosion level. Another possibility is that the extensional fault may flatten with height to become closer to parallelism with bedding. There is some evidence for extensional flow in the Cambrian Pipe Rock at the Stack of Glencoul (Fig. 5). Here the pipes show strain ellipses on the bedding surface with axial ratios of about 5 : 1 and long axes parallel to the transport direction (see also McLeish 1971). Wilkinson *et al.* (1975), however, have argued for a simple shear model for the strains at Glencoul, though their model requires the beds to be overturned. The author has not found any structural or stratigraphic evidence for such overturning and assuming no shortening of the thrust zone normal to the transport direction, the axial ratios indicate considerable thinning and layer parallel elongation of the quartzites at the Stack. There is no evidence of such strains in the underlying Lewisian rocks and presumably this thinning and extensional flow must overlie a decoupling zone in the Basal Quartzite. The decoupling horizon carries a thin sheet of Durness Limestone between the quartzite and the underlying Lewisian, also suggesting extensional flow with removal of most of the Cambrian strata. Figure 12 shows one possible cross-section through the area suggesting that this bedding parallel extensional flow may be related to the surge zone to the NW. Further work is required to support this argument for the link between the Moine thrust and the Glencoul surge zone.

THE KINLOCHEWE–KISHORN STRUCTURES

In contrast to the thrust zone in the north, the southern part of the Moine thrust zone involves thick sequences of Torridonian sandstone. At Kinlochewe and at Kishorn the Moine thrust is underlain by major low-angle faults, the Kinlochewe and Kishorn faults, which carry Torridonian and Cambrian rocks in a major recumbent fold, known as the Lochalsh syncline (Fig. 13). The gently dipping western limb of this fold shows little deformation but the overturned limb is well cleaved and passes upwards and eastwards to highly sheared Lewisian rock and then to the Moine thrust. This recumbent syncline thus seems to be related to the over-riding of the Moine thrust.

Figure 14 shows a cross-section drawn southwest of Kinlochewe. The Kinlochewe fault occurs in the valley, south of Kinlochewe village and also as a klippe on the hill Meall a Ghiubhais near Beinn Eighe. This section shows that the thrusts cuts down through the fold to the NW in the transport direction. In the NW, in the thrust

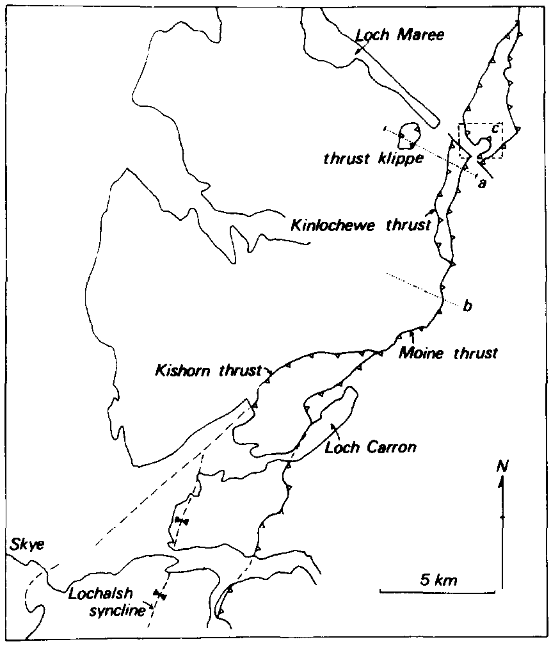

Fig. 13. Simplified map of the Kinlochewe–Kishorn area (locality shown in inset map of Fig. 6) showing the major faults and klippe.

klippe, it cuts the right-way-up limb of the fold but to the SE it cuts inverted beds. There is a similar apparent structural relationship between the Kishorn fault and the Lochalsh syncline to the south (Fig. 13). The fact that a fault cuts down through a fold is not conclusive evidence for extensional movement as this fault could have formed out of sequence, cutting through a previously formed eastward-inclined fold. However, northeast of Kinlochewe there is a half window through the Kinlochewe fault and a cross-section through this is shown in Fig. 15 (see also McClay & Coward 1981). The Kinlochewe fault cuts down stratigraphy in the footwall, from Durness Limestone in the SE to Pipe Rock quartzite in the NW. The later development of contractional imbricate faults beneath the Kinlochewe fault has caused the development of a pronounced bulge in the thrust plane (see McClay & Coward 1981) and this has been eroded to produce the half window.

The section in Fig. 15 is drawn approximately parallel to the transport direction, but if the section angle is varied slightly, through say ± 10°, the Kinlochewe fault still cuts down stratigraphy to the NW. The structure cannot be an oblique section through a lateral ramp, assuming a WNW transport direction.

Thus, the Kinlochewe fault has the geometry of an

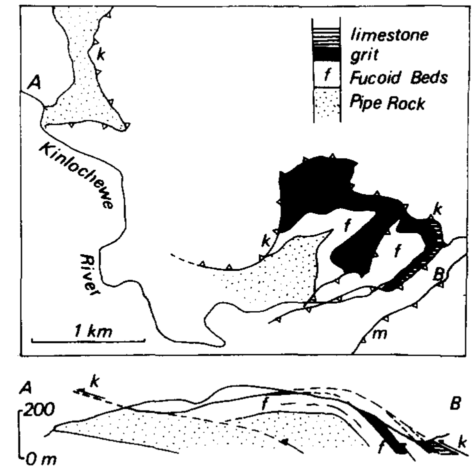

Fig. 15. Simplified map of the rocks in the footwall to the Kinlochewe fault, N. of Kinlochewe (box c in Fig. 13) and cross section showing that the fault cuts down stratigraphy from limestone in the ESE to Basal quartzite and Pipe Rock in the WNW (after McClay & Coward 1981). k = Kinlochewe fault, m = Moine fault.

extensional fault in the hanging wall and in the footwall. As it joins with the Moine thrust for part of the section between Kinlochewe and Kishorn then the Moine thrust must also have suffered this extensional flow (Fig. 16). The structural sequence in this area is considered to involve firstly the overthrusting of the Torridonian rocks by the Moine thrust, causing the Lochalsh fold, followed by the extensional fault with very low angle. This extensional fault must have climbed down section at different places along strike so that it sometimes carries the overturned limb of the Lochalsh fold to the NW over the foreland whilst elsewhere it carries only the Moines.

DISCUSSION

Extensional faults and surge zones

Figure 3 shows a series of listric normal faults branching from a sole thrust in the Durness Limestone, from the Knockan–Elphin area. However, many of the extensional faults are situated close to contractional faults. Figure 2 shows a small duplex zone from the shores of Loch Eriboll where the majority of faults cut up-section, but one cuts down-section. The age relationships of these extensional and contractional faults are not known. In Assynt there is a better understood relationship between extensional and contractional faults; the closed systems of contractional imbricate thrust faults and extensional and strike-slip faults (Fig. 9) define the surge zone where one part of the thrust zone has moved

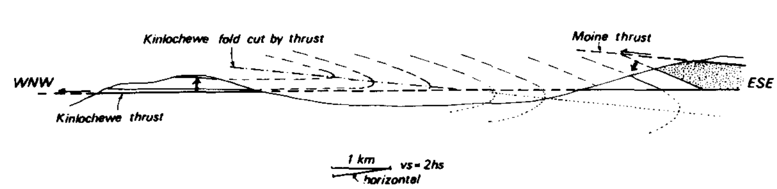

Fig. 14. Cross section (line a on Fig. 13) showing the form of the Kinlochewe fault, SW of Kinlochewe, cutting folded Torridonian rocks. Lewisian rocks are shown stippled.

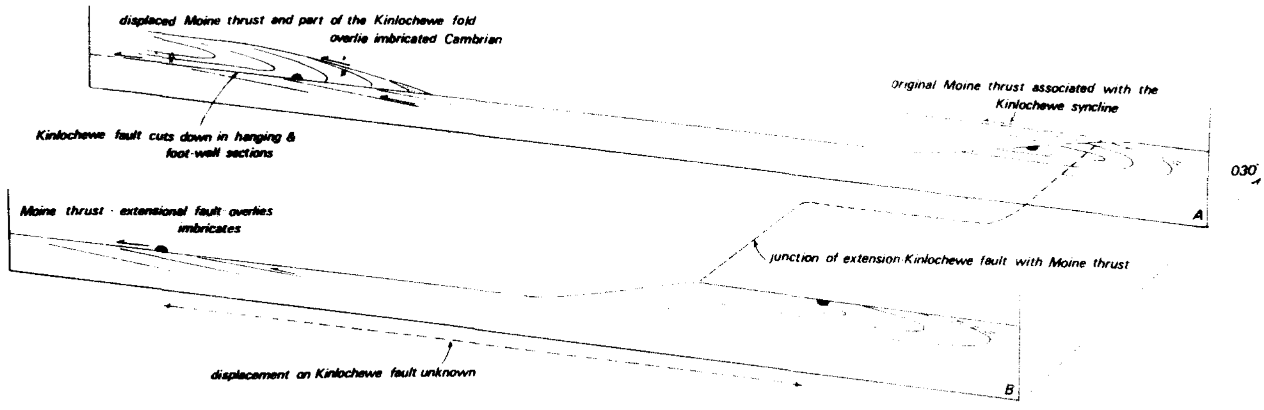

Fig. 16. Block diagram showing variation in the form of the Kinlochewe fault along its length. a and b shown in Fig. 13.

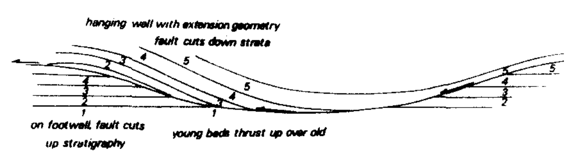

Fig. 17. Anomalous geometry in some contractional fault zones, where the hanging wall has extensional fault geometry and the footwall has contractional fault geometry. In this situation, it is possible for young rocks to be apparently thrust over old rocks.

further than the adjacent parts. As the imbricate thrust faults are arcuate and intensely developed in the frontal region of this surge, they are considered to be an integral part of the structure (Fig. 9). This may lead to a locally complex situation as at Cnoc an Droighinn where a hanging wall which shows extensional fault geometry is carried over a footwall which has collapsed to produce imbricate faults with contractional fault geometry (Fig. 17).

Arcuate trends of contraction and extensional faults are common in gravity induced structures such as landslips (Hansen 1965, Voight 1973), submarine slides in deltas (Cloos 1968, Mandl & Crans 1981) and ice falls

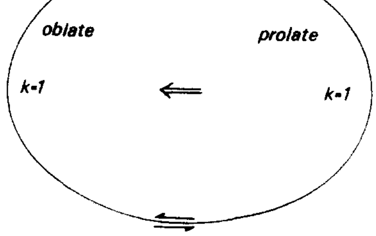

Fig. 18. Diagram to show the possible variation in ductile strain in a surge zone. Strains of $k < 1$ (oblate strains) occur in the zone of contractional flow with differential strike-slip movement. Strains of $k > 1$ (prolate strains) occur in the zones of extensional flow with differential strike-slip movement. k-defines the ellipsoid shape $(X/Y - 1)/(Y/Z - 1)$ where $X \geq Y \geq Z$ are the principal axes (for details see Coward & Kim 1981).

(Allen *et al.* 1960, Ragan 1969). In three dimensions, the fault surfaces should be spoon shaped (Nye 1969, Mandl & Crans 1981). As they are zones of differential movement, extra shear strains will be set up on planes normal to the main thrust plane but with the same movement direction (Coward & Kim 1981). This can lead to folding of structures originally parallel to the main thrust plane and the orientation of the fold axes will depend on the intensity of compressional or extensional ductile flow as well as layer normal shear strains. Compressional flow with differential shear on a plane normal to the main thrust plane will produce a maximum shortening on the main shear plane almost parallel to the movement direction. However ductile extensional flow, together with the same shear strain will produce a maximum shortening of the main shear plane at a high angle to, but with fold axes almost parallel to, the movement direction. Oblique folds should form if ductile deformation accompanied movement of the surge zones, and faults climbing through these folds will lead to the production of oblique and lateral thrust ramps (Fischer & Coward, in press). Many of the oblique folds and lateral ramps in the Assynt area (Fig. 6) are probably due to differential movement of the Glencoul fault (Coward & Kim 1981).

Ductile differential movement will also lead to the production of strains whose principal axes may be oblique to the movement direction and whose shape may vary from prolate to oblate (Coward & Kim 1981). With compressional flow as well as shear on a plane normal to the main thrust plane, the resulting ellipsoid is oblate, with extensional flow the resulting ellipsoid is prolate (Fig. 18).

Surge zones, the Moine thrust and the Caledonide orogeny

At Assynt the frontal part of the surge zone is defined by the arcuate trend to the imbricate faults (Fig. 9). Similar arcuate trends occur along the length of the Moine thrust belt (Fig. 19) though the majority of these

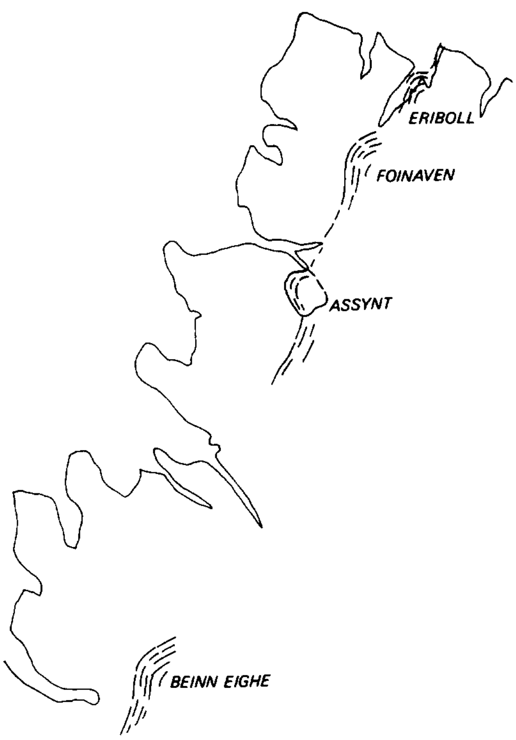

Fig. 19. Sketch map of the Moine thrust zone showing position of arcuate contractional imbricate zones.

are not part of closed systems of contractional and extensional faults as at Assynt. The real dimensions of the surge zones are not known. Those at Assynt may mark the keels of much larger eroded structures. It is not known whether the surge zones originally extended to the surface to define large-scale landslide structures or whether the extensional faults flattened to join the main movement zones, as suggested in Fig. 13, so that the surge zones represent only a downward scoop of a major fault zone.

The surge zones obviously lead to some anomalous thrust tectonic situations. Though the normal thrust sequence is from east to west, in the transport direction, low-angle extensional faults may cut back to join and reactivate earlier eastern faults. This may explain some of the controversial fault sequences proposed for the Moine thrust zone; at Eriboll for example, the Upper Arnaboll thrust has moved later than the underlying and more westerly thrusts (Soper & Wilkinson 1975, Coward 1980). Between Kishorn and Kinlochewe the Moine thrust has been reactivated by extensional flow. Similarly in southern Assynt, from evidence from igneous intrusions, Parsons (1979) has suggested that the Moine thrust has moved later than the lower Ben More and Glencoul faults. This reactivation may be one explanation for the range in textures along particular thrust planes; Christie (1960) records two distinct mylonite types in the Moine thrust zone, early ductile phyllonitic mylonites and later cataclastic brecciated mylonites.

The low-angle extensional faults also have anomalous relationships to the surrounding folds. At Assynt most of the folds formed as hanging wall or footwall ramps to thrust faults, so that the fault is parallel to bedding in the gently dipping limb but cuts sharply across bedding, to climb the stratigraphy, in the steeper limb (for discussion see Fischer & Coward, in press). However, the low-angle extensional faults cut back up through already thrust and folded strata and, hence, may slice through the earlier folds. An example of this is shown on the slopes northwest of Meall nan Caorach (Fig. 6). Sometimes care must be taken in distinguishing low-angle extensional faults from their relationship with earlier folds, as a thrust fault which develops out of sequence, or climbs from a lower structural level (Fig. 20), may slice through a previously developed fold. This may lead to apparent extensional geometry on one fold limb (Fig. 20). However, the cross-sections at Assynt show that the low-angle faults are extensional and cut down to the NW, often associated with normal faults with steeper dip (Figs. 3 and 10).

The Moine thrust is only one of a series of related movement zones which occur throughout the Caledonides. The earliest deformation appears to have been in the east of Scotland, in the Grampian region where late Cambrian–early Ordovician ages have been obtained from early orogenic intrusions (Pankhurst 1970). However movement in the Moine thrust zone took place during late Ordovician–Silurian times, as ages of ~ 430 Ma have been obtained from syntectonic intrusives in southern Assynt (van Breeman *et al.* 1979). The Grampian orogeny (~ 500 Ma) in the eastern part of Scotland may have been associated with plate collision (cf. Lambert & McKerrow 1977) but it is unlikely that the Moine thrust, which moved some 70 Ma later, could have formed from the same collision. However, the relatively abundant extensional faults in the Moine thrust zone and development of local surge zones suggest that body forces were important in driving these faults, rather than just a push from the rear. This suggests that at least during the later stages of movement, the Moines were partly driven forwards by a gravity spreading mechanism (Price 1973, Elliott 1976) probably from the thickened Caledonian mass to the east.

Acknowledgements—Field work was funded by N.E.R.C. grant GR/3/4100. Thanks are given to colleagues at Leeds for discussion and reading the manuscript. Roy Boud drew Fig. 6.

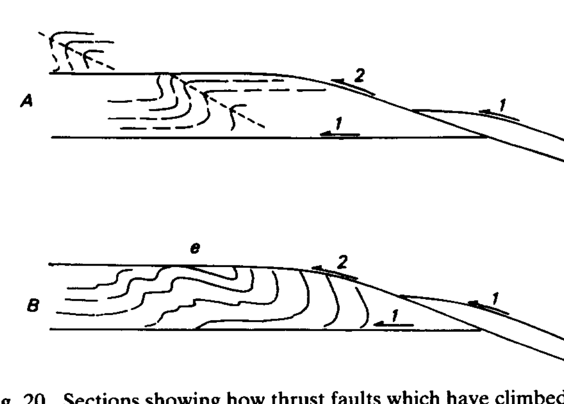

Fig. 20. Sections showing how thrust faults which have climbed from a low structural level may cut higher level structures, displacing axial planes (A) and possibly locally (at e) having apparent extensional geometry (B).

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