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The Caledonian thrust and shear zones of N.W. Scotland

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Abstract—Models of thrust tectonics derived from studies in the Rocky Mountains and the Appalachians have been applied to the deeper level Caledonian thrusts of the northern part of the Moine thrust zone at Eriboll, N.W. Scotland and also to the Caledonian thrusts as a whole. Though at the present level of erosion the thrust sequence is often from west to east, the sequence of thrust development is interpreted as from east to west, in the direction of thrust transport. The Moine thrust is only one of a series of Caledonian thrust and shear zones which should either maintain a constant dip or flatten at depth, having propagated from a flat lying decoupling zone within the crust. An interpretation of geophysical results places constraints on the shape of these thrusts at depth and suggests a position for the decoupling zone.

INTRODUCTION

ALONG the Moine thrust zone in the north-west Highlands of Scotland, Proterozoic (Moine) schists, deformed during the Caledonian orogeny, were thrust over a foreland of Lower Proterozoic (Lewisian) gneiss which was overlain by a cover of late Proterozoic (Torridonian) and Cambro-Ordovician sediments. Several large thrust sheets were stacked on top of each other. Analogies with the thrusts at the eastern margin of the Rocky Mountains and the western margin of the Appalachians, have led Elliott & Johnson (1978) and Barton (1978) to suggest that the Moine thrusts propagated westwards, in the transport direction. However Soper & Barber (1979) considered that the Moine thrust zone is different to the 'thin-skinned' tectonics of the Rockies and Appalachians and proposed a sequence in which the uppermost thrust, the Moine thrust, was the last to be emplaced.

This short paper aims to discuss the sequence of thrusts and mylonite zones:

(i) on a small scale, in the northern part of the Moine thrust zone, near Loch Eriboll (Fig. 1) where at the present erosion level, some of the easternmost thrusts are the youngest, and (ii) on a regional scale to discuss the relationships between structures in the Moines, the Moine thrust zone and a parallel thrust zone in the Outer Hebrides (Fig. 1).

THE SEQUENCE OF THRUSTS AND MYLONITES AT ERIBOLL

Beneath and to the west of the Moine thrust at Eriboll, Lewisian rocks with a cover of Cambrian sediments form the Arnaboll nappe which itself overlies imbricated Cambrian sediments (Fig. 1, after Peach *et al.* 1907, Soper & Wilkinson 1975). According to the model of

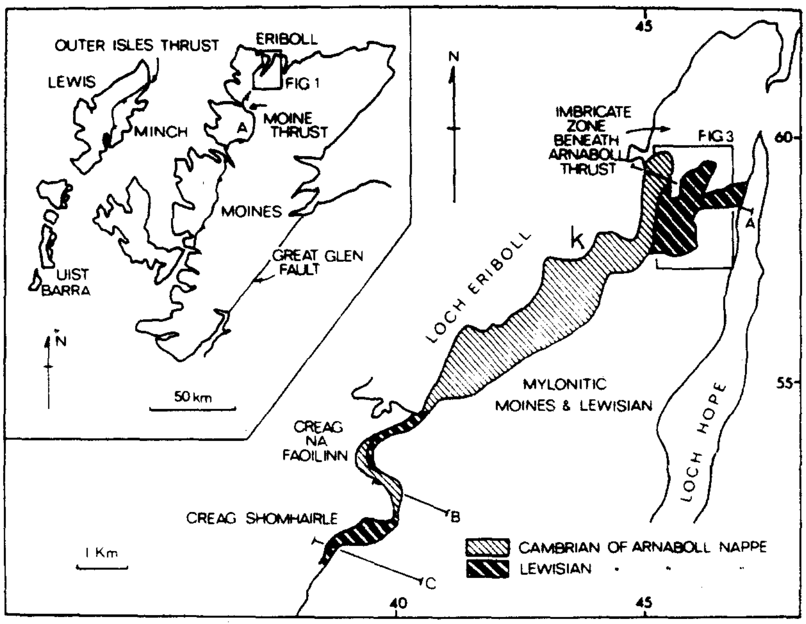

Fig. 1. Simplified map of the Moine thrust zone, Eriboll. k = Kempie Church. Inset map: The Moine and Outer Isles thrusts in N.W. Scotland. A = Assynt.

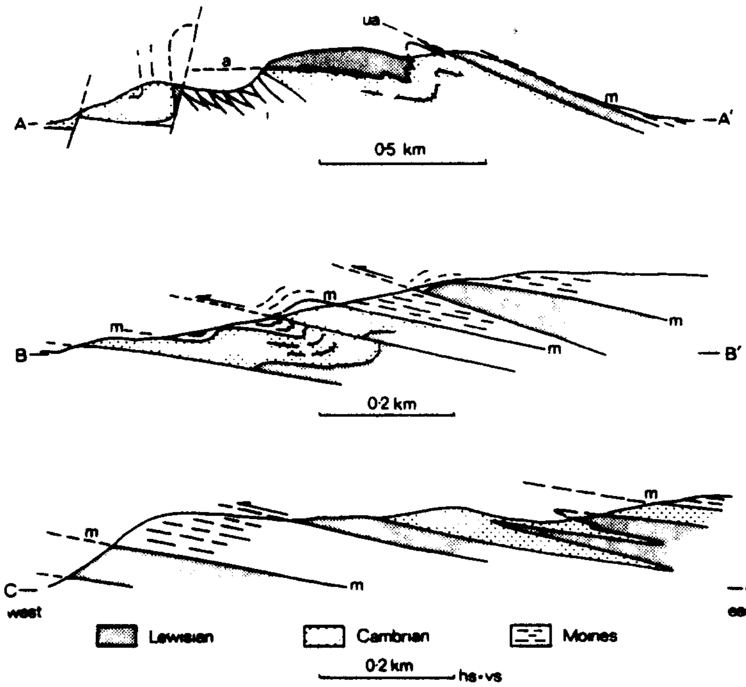

Fig. 2. Simplified sections across the Moine thrust zone, Eriboll. Section lines are shown in Fig. 1. m = Moine thrust, ua = Upper Arnaboll thrust, a = Arnaboll thrust, i = imbricate zone in Cambrian rocks.

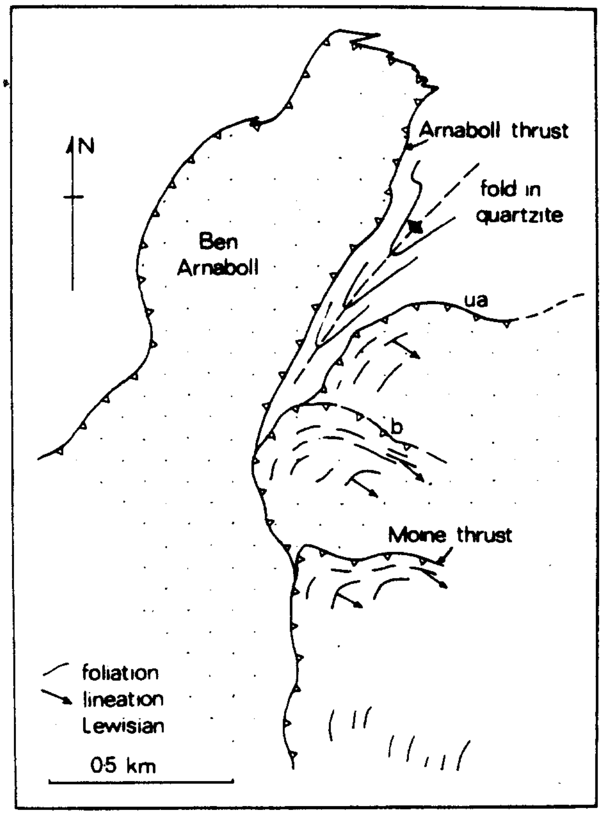

Fig. 3. Map of Ben Arnaboll showing the relationship between the Moine thrust, an un-named thrust (b), the Upper Arnaboll thrust (ua) and the Arnaboll thrust.

Elliott & Johnson (1978) the Moine thrust would have been the first to develop, the Arnaboll fault next and then the imbricate faults below. However the Arnaboll thrust slices across the imbricate sequence. There is no evidence that the imbricate faults curve into the Arnaboll thrust as they would if it was a roof thrust to a duplex zone (Dahlstrom 1970). More importantly, the Arnaboll thrust cuts through different levels of the imbricate zone. In some parts imbricated upper Cambrian dolomitic limestones underlie the Arnaboll thrust but elsewhere the thrust cuts imbricated lower Cambrian quartzite. The Arnaboll thrust is itself folded and thrust on the east side of Ben Arnaboll (Figs. 2a and 3). Thus there is an apparent sequence of thrusts from west to east, the imbricate faults having formed first, followed by the Arnaboll thrust followed by folding and faulting to the east. Similarly south of Loch Eriboll, southeast of Creag na Faoilinn (Fig. 2b) and south of Creag Shomhaile (Fig. 2c) Cambrian and Lewisian rocks are thrust over the Moines.

The model proposed for this sequence is similar to that described by Bally *et al.* (1966) for parts of the southern Canadian Rocky Mountains, in that the lower thrusts developed later than the upper thrusts. In Fig. 4, the upper thrust 1 is considered to have developed first and the lower thrust 2 second. If this lower thrust curved and climbed a ramp it could either flatten and rejoin thrust 1 to enclose a fault bounded rock 'parcel' (Bailey 1934). or it could cut through thrust 1.

South of Eriboll (Figs. 2b & c) the Moines were thrust over Cambrian and Lewisian rocks by the Moine thrust but these rocks were then thrust back over the Moines by later thrusts which developed at a lower structural level. Similarly the Arnaboll thrust has been folded and thrust by structures which developed at a lower structural level (Fig. 2a).

The model in Fig. 4b may also explain why the Arnaboll thrust cuts the imbricate faults. The Arnaboll thrust carries Lewisian gneiss and thus developed at a lower stratigraphic level than did the imbricate faults in

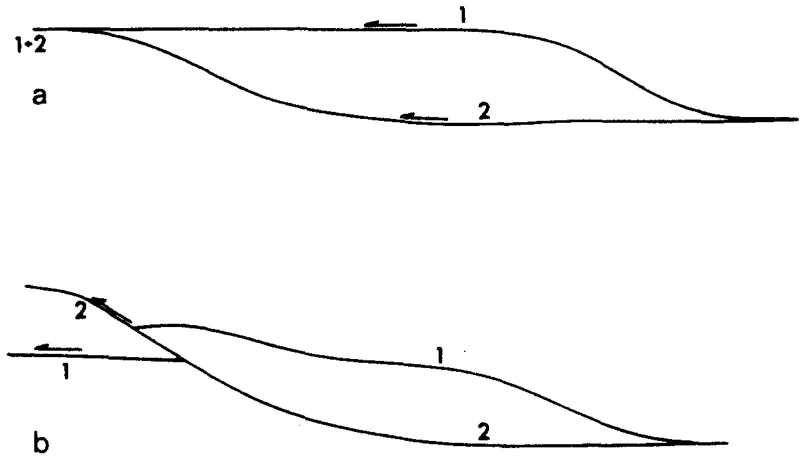

Fig. 4. Model for the sequence of thrusts, Eriboll. See text for discussion.

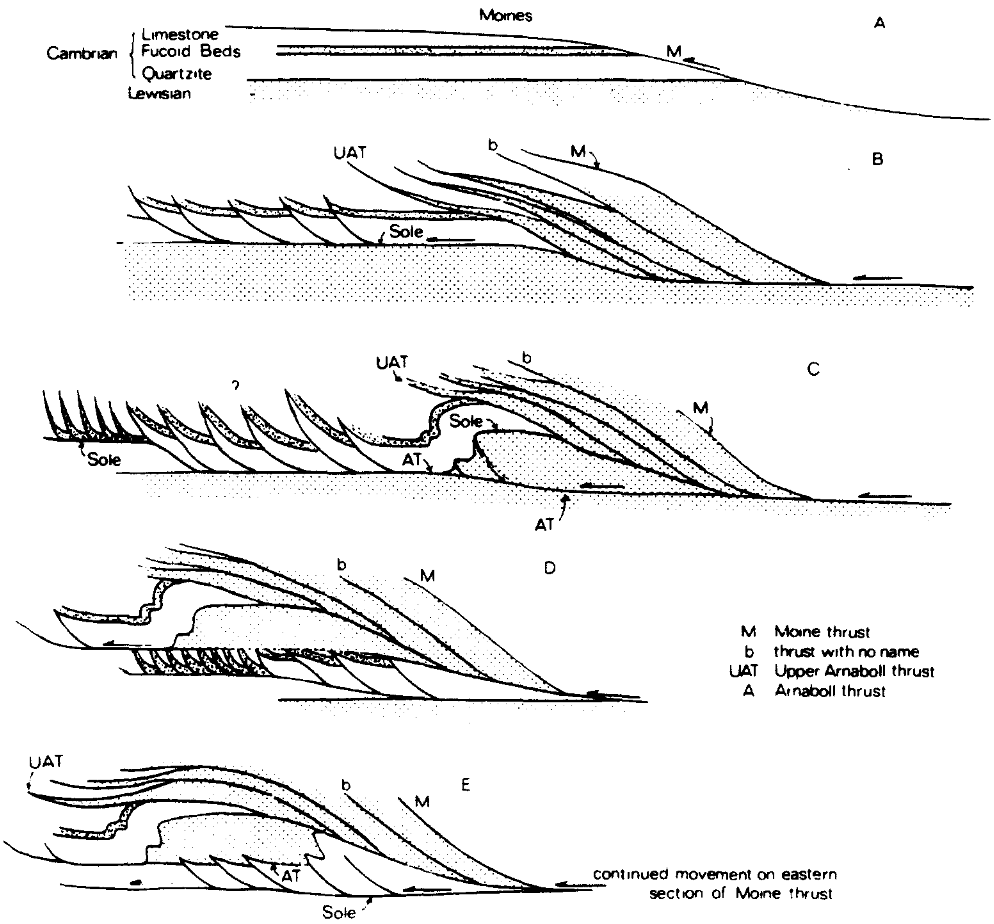

Fig. 5. Interpretation of the sequence of thrusts in the Arnaboll area (close to section line A, Figs. 1 and 2). See text for discussion.

the Cambrian rocks. The Arnaboll thrust must have climbed across the 'Sole' (Peach *et al.* 1907) or floor thrust to the imbricate faults and then flattened and sliced through these imbricates.

The relationship between the Moine thrust and the Arnaboll thrust may be seen on Arnaboll hill (Fig. 3) where the Moines were emplaced directly on to Lewisian gneiss. Presumably thérefore, the Cambrian rocks must have been removed by this thrust. To the west of Ben Arnaboll, Cambrian rocks rest unconformably on the Lewisian and so this thrust (the Moine thrust) must have climbed through the Cambrian stratigraphy. Beneath the Moine thrust other thrust zones have been mapped from the change in intensity of Caledonian fabric in the Lewisian gneiss (Fig. 3). These thrusts curve and change from a thrust sense of displacement in the south to a strike slip sense in the north. They seem to have formed in a sequence beginning with the Moine thrust, then an un-named thrust (b on Fig. 3), the Upper Arnaboll thrust and then the Arnaboll thrust. The intensity of mylonitic fabric decreases within this sequence; the Moine thrust shows the most intense deformation, the Arnaboll thrust the weakest.

Above the Upper Arnaboll thrust there are thin slices of Cambrian rock within the Lewisian gneiss. These are best seen south of Ben Arnaboll on the hillside east of Kempie (Fig. 1). The slices may be formed by either folding or faulting of the Cambrian-Lewisian unconformity.

The junction between the Arnaboll thrust and Upper Arnaboll thrust is obscured by later folding (Fig. 2a). To the west, above the Arnaboll thrust, the Cambrian-Lewisian unconformity is folded and faulted by shear zones which have developed from the Arnaboll thrust (Coward & Kim in press).

Thus the sequence of structures in the Arnaboll area was probably as follows (see Fig. 5).

(i) Displacement along the Moine thrust which carried Moines on to Lewisian gneiss. This thrust must have climbed through the Cambrian stratigraphy to the west; as on the west side of Ben Arnaboll, Cambrian rocks rest uncomfortably on the Lewisian.

(ii) Development of shear zones (thrust b and Upper Arnaboll thrust) in front of a step in the Moine thrust (Fig. 5b).

(iii) Displacement along the Sole thrust. This thrust climbed from lower Cambrian quartzites in the east to middle Cambrian dolomite shales (the Fucoid beds) in the west (Coward & Kim in press). Layer parallel shortening (Coward & Kim in press) and imbricate faults developed above this Sole thrust. Movement must have continued along the Moine thrust in the east (Fig. 5c).

(iv) Development of the Arnaboll thrust from the Upper Arnaboll thrust. The Cambrian-Lewisian unconformity, together with the Sole thrust, was folded by shears which developed above the Arnaboll thrust (Fig. 5c).

(v) Climb of the Arnaboll thrust to cut through the Sole thrust and the overlying imbricates. The Arnaboll thrust now overlay the Sole (Fig. 5d).

(vi) Folding and faulting of the Arnaboll thrust associated with displacements on an underlying fault, possibly the Sole (Fig. 5e).

To the southeast and south of Creag Shomhaile, the sequence of thrusts is similar to that of Ben Arnaboll except that the lower thrusts, comparable to thrust b and the Upper Arnaboll thrust, slice through the Moine thrust.

THE RELATIONSHIP BETWEEN THE MAJOR THRUST ZONES IN THE CALEDONIDES

Within the Moine thrust zone, the thrusts may be interpreted as having propagated from east to west in the tectonic transport direction and hence models of thrust tectonics derived from the thin-skinned thrust zones of the eastern Rocky Mountains (Bally *et al.* 1966, Dahlstrom 1970), can be applied to the deeper level thrusts of the Caledonides. However the Moine thrust is only one of a series of related thrusts which started in the Grampian region of N.E. Scotland in late Cambrian times and moved towards the foreland in end Ordovician and Silurian times (Dewey 1969). Recent geochronology by van Breeman *et al.* (1979) supports this diachroneity of thrust movements. To the east of the Moine thrust there is a major tectonic break, the Sgurr Beag slide (Tanner 1969) which occurs wholly within the Moines. To the west, from Lewis to Barra on the Outer Hebrides, the Outer Isles Thrust zone has a similar strike and transport direction as the Moine Thrust and is considered to be of Caledonian age (Francis & Sibson 1973, Sibson, in discussion of Steel & Wilson 1975). These thrusts are probably all related and part of a sequence of thrust nappes, the earliest of which occurred in the east.

Three problems arising from this sequence will be discussed below.

The original (pre-Caledonian) position of the Moines relative to the Lewisian

As the Moines have been emplaced on top of the Lewisian, using the normal rules of thrust emplacement (Dahlstrom 1970), the Moines should originally have been at a lower structural level. Thus at some stage before the development of the Moine thrust, the stratigraphy was inverted and Lewisian rocks were emplaced on top of the Moines.

The Moines show a long structural and metamorphic history including several deformation phases and the formation of granite gneisses during the mid-Proterozoic. Recently Brook *et al.* (1976, 1977) have reported Rb/Sr whole rock ages of about 1100 Ma from gneisses and metapelites in the southern Moines and this 1100 Ma event may be correlated with the Grenville event in Canada (Brook *et al.* 1977). In addition there are also whole rock ages of 550–600 and 730 Ma from granites and pematites throughout the Moines (Pidgeon & Johnson 1974 and van Breeman *et al.* 1974). These may result from a late Precambrian tectonothermal event, termed the Morarian (Lambert 1969, Johnson 1975). Powell (1974) records several deformation phases predating Morarian pegmatites and probably of Grenville age. Basement gneisses form the cores of large fold nappes in the Moines. These folds are eastward verging (Ramsay 1963, Powell 1974) but have been modified by NW verging Caledonian structures.

There is no evidence of Grenville or Morarian tectonothermal events to the west of the Moine thrust. The Lewisian gneisses give no equivalent whole rock or mineral ages and the Torridonian rocks are only gently warped by large scale folds which may be coeval with the Morarian pegmatites (Soper & Barber 1979). As the Precambrian structures in the Moines verge eastwards, the Lewisian rocks may represent an undeformed hinterland obducted eastwards over the Moines (Fig. 6). The basement gneisses to the Moines have been correlated with the Lewisian gneisses (Johnson 1975, Watson 1975) and if this correlation is correct then the present line of the Moine thrust would not represent a suture line between two Grenville-age plates. However, the western-most outcrops of basement gneiss in the Moine nappe contain high pressure granulite to eclogite facies minerals and must represent lower gneissic crust uplifted

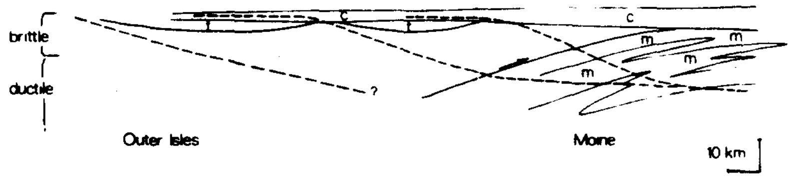

Fig. 6. Schematic section through the NW margin of the Caledonides before the development of the Moine thrust. m = Moines, t = Torridonian, c = Cambrian. Lewisian stippled. Thrusts shown by dashed lines.

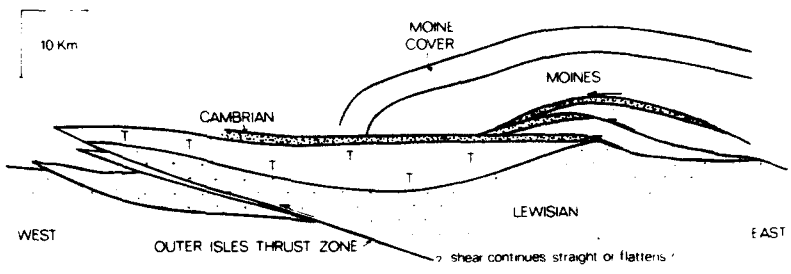

Fig. 7. Section through the NW margin of the Caledonides after the development of the Outer Isles thrust. The present erosion level of the Outer Isles thrust is considered to have been at less than 10 km depth (probably 4–5 km) during deformation (Sibson 1975, 1977).

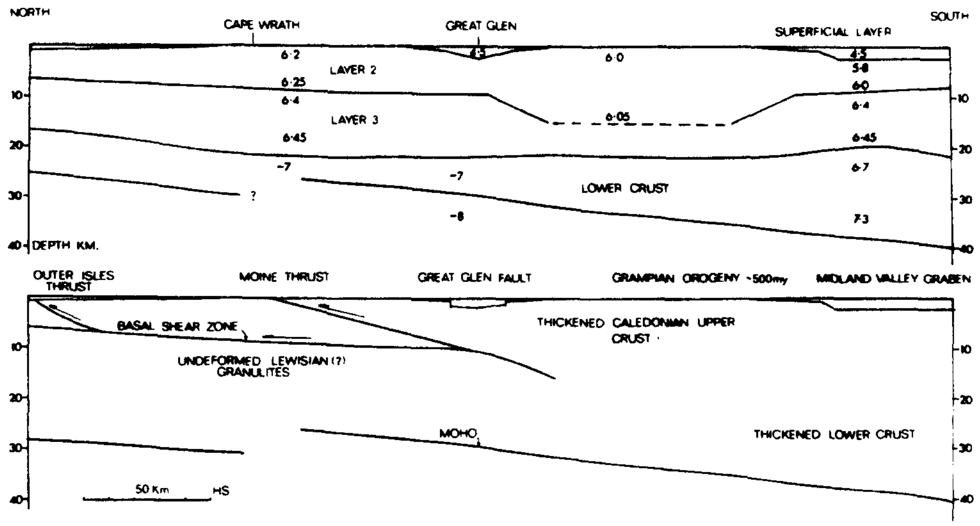

Fig. 8. Top, Crustal layers beneath the northern Caledonides interpreted from the LISPB results (Bamford *et al.* 1978). Velocities in km/sec. Bottom. Possible crustal structure of the northern Caledonides to compare with LISPB profile. NOTE, these sections are north–south (see Bamford *et al.* 1978 for details) not normal to the Caledonian structures.

during the Precambrian, possibly during the Grenville orogeny.

The position of the floor thrust to the series of Caledonian thrusts

It is interesting to speculate on the shape of the thrusts at depth and the possible position of any floor thrust or shear zone to the larger Caledonian thrusts. The Moine thrust dips at between 11 and 15° to the ESE, approximately parallel to the dip of the Cambrian sediments below the thrust zone, and presumably there has been tilting of this zone since the late Caledonian deformation. Thus during the Caledonian, the Moine thrust would have been flat lying, locally going down in steps to the east (Fig. 7). A minimum displacement of over 40 km has been estimated for thrust sheets within the Moine thrust zone (Soper & Barber 1979).

In the Outer Hebrides the thrusts dip at between 10 and 30° to the ESE. The lack of correlation of Lewisian structures across the Outer Isles thrust in South Uist (Coward 1972) suggests that there may be considerable horizontal movement and Francis & Sibson (1973) estimated a displacement of about 10 km for the main thrust on Barra. Watson (1977) considered that these thrusts steepened downwards to become vertical in the lower crust. This seems unlikely as the thrusts do not uplift rocks from the lower crustal levels. Thus the Outer Isles thrust zone either maintains a constant dip to the ESE or flattens below the Minch (Figs. 7 and 8).

High resolution explosion seismic studies across northern Britain (the LISPB project) give some indication of the crustal structure beneath the Moines (Bamford *et al.* 1977, 1978). The crust-mantle boundary is relatively shallow, at about 25–30 km, beneath the Lewisian foreland and dips gently to the southeast. The thickest crust occurs beneath the Midland Valley of Scotland. The upper crust carries a superficial layer consisting of Palaeozoic and Mesozoic sediments, thickest in the Great Glen and Midland Valley grabens (Bamford *et al.* 1977, 1978). Beneath this there is an upper crustal layer interpreted as Caledonian metamorphics, with velocities of 6.1–6.2 km/s. This is underlain by a thick layer of velocity 6.48 ± 0.06 km/s, previously recognised by Smith & Bott (1975) and identified by them as granulite facies basement gneiss, undeformed in the Caledonian. This layer extends south-east beneath the Caledonides as far as the southern part of the Midland Valley. The boundary between layers 2 and 3 is clearly identified beneath the Moines and dips gently to the ESE but becomes less clear to the southeast and layer 2 appears much thicker to the SE of the Great Glen.

Thus as there is evidence for only slightly thickened crust beneath the Moines (cf. Smith & Bott 1975), the large displacements in the Moine thrust zone cannot be taken up by shortening of the whole crust NW of the Great Glen. The Moine thrust does not bound thickened crust nor does it uplift lower crust. Thus the Moine thrust cannot steepen downwards as suggested for Himalayan structures (Dewey & Burke 1973). Furthermore, if the boundary between layers 2 and 3 represents a boundary between rocks deformed in the Caledonian orogeny and undeformed basement rocks beneath, as suggested by Bamford *et al.* (1978), then the thrust zones should shallow at depth and this boundary may mark the structural level of the sub-horizontal floor thrust to the major Caledonian thrusts (Fig. 8). Perhaps it is only to the southeast of the Great Glen that these basement rocks became involved in Caledonian tectonics, where the boundary between layers 2 and 3 is lower and more diffuse.

The driving mechanism for the thrusts

The driving mechanism for the Moine thrust is unknown. The Grampian orogeny at ~ 500 Ma in the eastern part of Scotland may have been associated with plate collision and the closing of an early Atlantic ocean (Lambert & McKerrow 1977). The Grampian metamorphism is associated with thermal re-equilibration after this collision and crustal thickening (Richardson & Powell 1976), and geophysical evidence (Bamford *et al.* 1977, 1978) suggests the presence of thick crust below this part of the Caledonides. As geochronology of igneous rocks involved in the Moine thrust suggests an age of 430 Ma (van Breemen *et al.* 1979), it is unlikely that the Moine thrust formed as a result of this collision some 70 Ma earlier, in eastern Scotland. It may have formed as a result of isostatic re-equilibrium after this collision or as a result of much later plate movements.

CONCLUSIONS

In the Moine thrust zone of Eriboll, N.W. Scotland, the thrusts are interpreted as having propagated from east to west, in the tectonic transport direction. Models of thrust tectonics derived from the thin-skinned thrust zones of the Rocky Mountains may be applied to the deeper level Caledonian thrusts. However as the younger thrusts, derived from a lower structural level, often cut through the older thrusts, at the present level of erosion, the sequence of thrusts is locally from west to east. In the Eriboll district the westernmost thrust, the Sole thrust of Peach *et al.* (1907) is not the youngest thrust.

Soper & Wilkinson (1975) and Wilkinson *et al.* (1975) suggest that the mylonites of the Moine thrust formed early in the deformation history of the thrust zone and were emplaced in their present structural position late in the thrust sequence (Soper & Barber 1979). At Arnaboll the intensity of mylonitic fabric decreases westwards along successive thrust planes but mylonitic and phyllonitic fabrics developed late in the thrust sequence along the Arnaboll thrust and on shear zones adjacent to the steep limbs of synclines in Cambrian sediments above the Arnaboll thrust. There must have been movement along the eastern part of the Moine thrust zone late in the thrust sequence (Fig. 5e) and so these mylonites may have formed over a long period.

The Moine thrust zone is only one of a series of Caledonian thrusts, the earliest of which formed in the east. The Outer Isles Thrust zone, about 60 km west of the Moine thrust may have been the last to develop. It is suggested that these thrusts propagated from an originally flat lying or gently inclined shear zone at depth. The driving force for these structures is still uncertain.

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