Moine Thrust Zone, Northern Highlands of Scotland

From Earthwise


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The Moine Thrust Zone
Balanced cross-sections through the Moine Thrust Zone.
P915469.

This zone of thrusting, associated with folding and low-grade metamorphism, forms a narrow but continuous belt stretching south-south-west from Loch Eriboll on the north coast to Skye (and probably to the Sound of Iona). Its outcrop width varies from a few hundred metres near Ullapool to 19 km in Skye. In the Assynt region north of Ullapool, the thrust zone, there 11 km wide, is particularly well exposed in a broad open antiformal culmination termed the Assynt Window. North of Assynt the thrust zone is 2 to 5 km wide. The thrust zone dips very gently ESE and delimits the Moine. East of it, all pre-Devonian rocks in the Scottish Highlands were folded and metamorphosed during the Caledonian Orogeny.

The thrusts and the ‘Zone of Complication’

Within the thrust zone there are several major individual thrust planes. Although some are continuous along the exposed length of the thrust zone (e.g. Moine Thrust), they are more generally
restricted to specific areas. The most important dislocation is the Moine Thrust itself which, with the
exception of the Sleat Peninsula of Skye, marks the western limit of rocks of the Moine assemblage.
The thrust is now commonly marked by a well defined low angle fault with local crushing and
brecciation, for example, at Creagan road, Loch Eriboll (Soper and Wilkinson, 1975), and the Sleat
Peninsula, Skye. This late fault truncates earlier folds, thrusts and mylonite zones in the thrust zone
around Knockan (between Elphin and Ullapool). North of Kinlochewe the Moine Thrust coincides
with an earlier zone of thrust movement marked by extensive mylonites at the base of the Moine
Nappe.

Below the Moine Thrust sensu stricto lies what was termed by the original surveyors (Peach and
others, 1907) a ‘Zone of Complication’ within which are several thrust-bound nappes stacked one
above another. The zone comprises a sequence of thrust, overfolded and faulted Cambrian-
Ordovician sediments, Torridonian sediments and Lewisian gneiss. The major lower thrusts in the
northern part of the zone are preferentially localised in the Fucoid Beds and Lower Cambrian
quartzites whereas south of Assynt, where Torridonian rocks are present, shales of the Diabaig
Formation have acted as planes of weakness and provided a locus for thrusting. Because each thrust
transports overlying rocks to the WNW they move generally older rocks from deeper levels to lie on
younger strata; thus inversions of stratigraphical order are common. Overturned and recumbent
folds and minor thrusts add to the complications. Later tilting has given the thrust planes a regional,
gentle easterly dip (11–15°); in detail, they may be considerably folded, locally discontinuous, and
intersect one another.

The original surveyors from the Geological Survey carefully mapped the structures of the Moine
Thrust Zone and described and documented this geometry in considerable detail (Peach and others,
1907). Because the Moine Thrust in southern Assynt prominently cuts down to the west across the
underlying Ben More Nappe, the thrust sequence was generally interpreted to imply that higher
thrusts overlap lower ones, and that the first thrust to develop was the lowest and most westerly
structure (generally the Sole Thrust). This was in contradiction to the early experimental work of
Cadell (1889), who showed that thrusts developed progressively towards the foreland carrying pre-
existing thrust slices ‘piggyback’. Work in connection with the search for oil in the foothills of the
Rocky Mountains of Canada (by Bally and others, 1966, and, more notably, by Dahlstrom, 1970) has
carefully defined the geometry of many thrust structures. This work, which incorporated both
seismic interpretation and much exploratory drilling, resulted in the establishment of a series of
tenets or ‘thrust rules’ which particularly apply to a foreland-directed thrust sequence involving
bedded units.

It has long been recognised that thrust faults are concave upwards and cut structurally up-section in
their direction of transport; in a bedded sequence they typically have a staircase trajectory. In the
less competent or weak horizons the thrust forms near horizontal flats which are separated by
steeper (typically dipping about 25°) ramps where the thrust cuts up section in a more competent
horizon. As the thrust rocks move up the ramp an antiform is formed in these overlying units. The
rocks and structures which overlie a thrust surface are said to be in the hangingwall; conversely,
those below lie in the footwall. After initial development of a thrust with a staircase trajectory,
further thrust movement is commonly taken up by the generation of a new ramp ahead of, and
below, the existing ramp. Continued thrusting movement thus takes place largely along pre-existing
flats, but with progressive footwall ramp collapse. When a new ramp forms, a lensoid thrust-bounded
mass termed a horse is created and this is then incorporated into the hangingwall of the thrust. The
development of multiple horses creates an imbricated sequence with individual slices or horses
stacked up like tiles on a roof. This structure is termed a duplex and is bounded by an upper roof
thrust and lower floor thrust. As a duplex is formed, the beds within the horses and the earlyformed
thrusts are progressively steepened (commonly to near vertical) and an antiformal culmination
develops in the units of the hangingwall.

Ramps generally have a strike near to 90° to the thrust transport direction, but may also lie oblique, or even parallel (lateral ramps), to the direction of thrusting. A lateral ramp may pass into a tear fault, such a structure providing a good indication of the direction of transport within the thrust belt. For a fuller description of the geometry of thrust zones, the reader is referred to R. W. H. Butler (1982a).

The application of these rules to the Moine Thrust Zone, even though basement gneisses are involved, seems to be validated by the observed geometry (McClay and Coward, 1981; Elliot and Johnson, 1980; R. W. H. Butler, 1982b; Coward and Kim, 1981). The thrust sequence must thus be reinterpreted with the lower and younger thrusts transporting the older and higher thrusts to the west- north-west in a piggyback fashion. The Sole Thrust is then the latest structure and in many areas the Moine Thrust is the earliest. Many of the fold structures within the thrust zone can be related to underlying ramps, and culminations are the high level manifestation of thick duplexes beneath.

P915469 gives examples of several types of structures seen within the Moine Thrust Zone. The scale of the structures is considerably smaller than those described in North America, possibly because of the relatively thinly bedded nature of the Cambro-Ordovician sequence. The sections shown are all examples of balanced cross-sections, with those in P915469b and c lying in the plane of thrust movement. The term ‘balanced’ was introduced by Dahlstrom (1969) to describe sections which can be restored to their undeformed state to give coherent stratigraphy and acceptable thrust fault trajectories, with both being compatible with adjoining data. Section balancing enables estimates of the amount of translation to be made. The average dip of the basal thrust can also be reconstructed, based on the introduction and translation of, for example, Lewisian gneiss into the imbricated Cambrian sequence. Coward (1983) estimates the true dip of the Moine Thrust Zone to be less than 3° using this method. P915469a shows a simple stacking sequence near Dundonnell, with the overlying Moine Thrust folded by accretion of underlying horses at a particular locality. It is important to realise that the Moine Thrust is the earliest structure with thrusts becoming progressively younger downwards. P915469b illustrates a classic imbricated Lower Cambrian to Ordovician sequence typical of the Sole Nappe, here seen on the east side of Loch Eriboll. The overlying Arnaboll Thrust has carried Lewisian gneiss over this sequence, with imbrication taking place as the active thrust ‘front’ migrated westward by ramp collapse. A small klippe (or outlier) of this thrust is seen adjacent to the section line. P915469c shows a more complex section in Assynt. Here recumbent folding has occurred in the deeper levels of the Moine Thrust Zone; this interfolded Lewisian gneiss and basal Torridonian sandstone and conglomerate now constitute part of the Ben More Nappe.

In Assynt and locally elsewhere evidence for low-angle extensional faulting is seen. Coward (1982) has described a section of the Glencoul and Sole Nappes within which late-stage WNW downsection movement has occurred in what he termed a ‘surge zone’. Coward (1983, Fig.7) has also illustrated the well known truncation and downsection movement of the Moine Thrust across underlying imbricated Cambrian-Ordovician rocks near Elphin (South Assynt). He suggested that such movements occurred late in the history of the Moine Thrust Zone and were a manifestation of gravitational spreading, which in turn resulted from uplift of the central part of the Caledonide Orogenic Belt and intrusion of large volumes of granitic magma.

In Cambrian and Torridonian strata of the foreland lying west of the Sole Thrust and strictly outside the Moine Thrust Zone, repetitive reverse faults may pass downwards into large open-to-tight asymmetrical folds verging to the west- north-west.
The basal or Sole Thrust is best seen in the Assynt region; further south in the Coulin Forest area and in Skye the western limit of thrusting is more poorly defined. The Sole Thrust lies within Cambrian quartzites around Loch Eriboll but climbs in Assynt to lie within the Fucoid Beds. South of Assynt the basal thrust is generally within the Diabaig Formation of the Torridonian. The Sole Nappe generally comprises imbricated Cambro-Ordovician units but, as Lewisian gneisses are also present, the basal thrust must lie in structurally lower horizons further east (see P915469c).

In northern Assynt the overlying Glencoul Thrust has also cut down into the Lewisian gneiss ‘basement’ and up to 500 m of internally little-modified gneiss and associated Cambro-Ordovician cover are thrust and imbricated over Cambro-Ordovician and Torridonian units (Frontispiece). Further north, east of Loch Eriboll, the Arnaboll Nappe occupies a similar position. There nappes wedge out along the strike of the thrust zone, with the structurally higher Moine Thrust then lying directly on the imbricated Cambrian of the Sole Nappe. The Glencoul Nappe dies out near Inchnadamph (Bailey, 1934) and the overlying Ben More Nappe (which contains Cambrian, Torridonian and Lewisian rocks) is prominent in southern Assynt.

Further south, the Kinlochewe and Kishorn thrusts translate folded Torridonian and Cambrian units and Lewisian gneiss to the west-north-west. Stratigraphical inversions are particularly notable in these more southern nappes, Moine and Outer Isles thrust zones 53 a prime example occurring around Kyle of Lochalsh where locally metamorphosed and schistose Torridonian sandstones and grits are folded into a large recumbent fold, the Lochalsh Syncline. This structure, which lies in the Kishorn Nappe, closes to the east-south-east and its upper limb is transected by the overlying Moine, Balmacara and Tarskavaig Thrusts.

Locally, small nappes occur above the Arnaboll, Ben More and Kishorn nappes (e.g. Balmacara Nappe), but in general the Moine Thrust lies structurally above. On the Sleat Peninsula of Skye a sequence of greenschist-grade schistose grits and phyllites, with affinities to both Torridonian and Moine rocks, constitute a large part of the Tarskavaig Nappe (Bailey, 1955; Cheeney and Matthews, 1965). This nappe lies on the Tarskavaig Thrust, which overlies the Kishorn Nappe and is in turn truncated by the Moine Thrust.

Within the Moine Thrust Zone north of Kinlochewe thin mylonites (see the following section) are common along the thrusts; particularly good examples are seen along the Glencoul and Arnaboll Thrusts. Considerable internal deformation and bedding-plane shearing also occur in many of the imbricated nappe sequences. In Assynt, Torridonian rocks near the Ben More Thrust are strongly deformed and lineated. Conglomerate pebbles in the basal Torridonian are flattened and stretched, and in some areas they become fractured as the thrust plane is approached. Skolithid pipes in the Lower Cambrian Pipe Rock commonly become distorted and bent over in the direction of thrust movement (McLeish, 1971) and in the mylonites themselves at the Stack of Glencoul they are reduced to white ribbons, near-parallel to the mylonitic foliations (Wilkinson and others, 1975; Coward, 1983). Lewisian gneiss, although locally sheared, fractured and even mylonitised during Caledonian deformation and metamorphism, is not generally penetratively deformed.

In contrast, south of Kinlochewe the Lewisian gneiss and Torridonian units are moderately to strongly mylonitised, and the distinction between Lewisian gneiss in the Moine Thrust Zone and mylonitic Lewisian inliers in the lowermost part of the Moines is unclear. Immediately below the Moine Thrust in Lochalsh there is a thick development of mylonitised rocks within the Balmacara and Sgurr Beag Nappes (Barber, 1965). North of Loch Carron similar rocks occur in the Kishorn Nappe (Johnson, 1960). To both the north and the south, late reactivation of the Moine Thrust causes it to overstep the rocks in the ‘Zone of Complication’. 
Mylonites were first described from the Loch Eriboll district by Lapworth (1885) who noted that they had formed by thrusting along narrow planar zones. Mylonite is a hard, very fine-grained, commonly laminated and platy rock formed by intense ductile deformation, and resulting in marked grainsize reduction and recrystallisation of the parent rock type. It forms under moderate hydrostatic pressure at depths below about 5 km in the earth’s crust in response to locally high initial strain rates, commonly associated with shearing. It should be emphasised that mylonites are dominantly a product of ductile deformation mechanisms and not a result of grinding, although recent work has suggested that brittle failure also may take place during mylonisation (White and others, 1980). Mylonites are present along the length of the Moine Thrust Zone but show their maximum development in the basal part of the Moine Nappe in the Loch Eriboll area, where they are 600–800 m thick. They are derived dominantly from Moine and Lewisian rocks in the north and from Lewisian and subsidiary Torridonian rocks in the south. The mylonites show a colour banding which in parts is extremely closely spaced, particularly where the parent rock was a banded Lewisian gneiss. The mylonites of the Moine Nappe show evidence of lower greenschist-facies metamorphism and three episodes of small-scale folding subsequent to the formation of the mylonite fabric. They are generally white, quartz-rich or dark, greygreen, chlorite-phengite-rich varieties. The dark type is termed ‘oyster-shell’ rock because of its field appearance. The mylonites grade gradually upwards into impure Moine psammites of greenschist facies.

In thin sections of mylonite, feldspars are seen to be fractured and fragmented, quartz has recrystallised to aggregates of much smaller grains (commonly with irregular grain boundaries) and biotite has been largely retrograded to chlorite. Pale-green muscovite, presumably with a high iron content (phengite), and epidote-clinozoisite are both commonly developed. Rarely, remnant yellowish biotite is found. Recrystallisation has largely obscured original mylonitic textures.

As the thrust zone is traced southwards into the Lochcarron–Lochalsh area (Johnson, 1960; Barber, 1965) the character of the mylonite changes. South of Kinlochewe the Moine rocks directly above the Moine Thrust show platy, recrystallised fabrics, but are only rarely totally reconstituted into mylonites. Lewisian rocks above the Moine Thrust are interleaved with the Moine sequence and, in part, still retain original structures and fabrics (although these are strongly modified by Caledonian deformation and metamorphism). The great development of mylonites occurs in Lewisian rocks below the Moine Thrust in the ‘Zone of Complication’ (see the previous section).

**Age of the Moine Thrust Zone**

It is difficult to date the earliest movement in the Moine Thrust Zone. At the Stack of Glencoul, Lower Cambrian Pipe Rock is strongly mylonitised and directly underlies mylonites derived from Moine and Lewisian rocks. This Pipe Rock mylonite has been interpreted by Christie (1963), and Soper and Wilkinson (1975) as being the same generation as the Moine mylonites, inferring that the main mylonisation post-dated the deposition of the Cambro-Ordovician sequence. However, Coward (1983) has recently interpreted the highly strained pipes as being a product of ductile extensional strain, possibly a product of the later stages of movement on the Moine Thrust Zone. There is abundant evidence for shear-dominated deformation in the lower parts of the Moines themselves. Ductile thrusts and slide zones are common and may relate to the mylonites and mylonitic schists which directly overlie the Moine Thrust. The Moine Thrust Zone has acted as the western margin to the Caledonian orogenic zone and has most probably been active over a considerable time period. As each phase of movement is in part superimposed on earlier phases it partly destroys evidence of such movements. The age of the earliest movements may well be linked to the overall orogenic history of the Moines; some of the mylonites may be of Precambrian age.
Work on the Loch Borralan and Loch Ailsh syenites has been summarised by Parsons (1972; 1979); he concluded that the Loch Ailsh body was emplaced prior to the main movements on the Ben More Thrust but the Borralan body was emplaced at the same time as the movements. Van Breemen and others (1979a) have dated the intrusion of the Loch Borralan complex at 430 ± 4 Ma using U-Pb methods on zircons.

The younger age limit of movement on the Moine Thrust Zone can be inferred from the occurrence of a thick lamphrophyre sill emplaced along the Moine Thrust in the central part of the Sleat Peninsula of Skye. The intrusion is commonly broken and converted to clay gouge by late fault movements probably of late-Caledonian or Tertiary age. The lamphrophyre is a member of the suites associated with the Ratagan and Ross of Mull Granites. Beckinsale and Obradovich (1973) obtained K-Ar ages of 423 ± 4 Ma from biotite and 416 ± 4 Ma from amphibole of the Ross of Mull Granite. They also obtained a single K-Ar biotite age of 406 ± 10 Ma from a minette dyke cutting the granite. Beckinsale and Obradovich also suggested that the form of the Ross of Mull Granite intrusion was controlled by a pre-existing thrust structure in the Sound of Iona which they correlated with the Moine Thrust. Thus major thrust movement along the Moine Thrust Zone appears to have terminated before 420 Ma (Mid- Silurian).

**Amount of translation across the thrust zone**

McClay and Coward (1981) infer from stretching lineations and the general trends of imbricate and tear faults that overall thrust movement across the Moine Thrust Zone is towards 290° (WNW). The occurrence of Moine rocks at Faraid Head near Durness implies that at least 11 km of movement has taken place along the Moine Thrust, and Clough (in Peach and others, 1907) and Bailey (1934) both showed that a minimum displacement of 20 km to the west-north-west has occurred along the Glencoul Thrust in Assynt. There is a complex relationship between thrusting in the ‘Zone of Complication’ and the Alkaline Complex of the Assynt area (p.103). The recent use of balanced-section techniques has shown that minimum estimates of translation may be obtained from the thickness of imbricated sequences in individual duplexes. Thus Butler (1982b) showed that the Coneamheall Duplex, 4 km SW of Loch Eriboll, had a pre-shortening width of 27 km compared with 6 km at present. Elliot and Johnson (1980) revised the values of Clough and other workers in the Loch More area of the Moine Thrust Zone; they calculated the minimum amount of translation that had taken place in the thrust zone beneath the Loch More Klippe as 43 km, and that the minimum slip across the whole Moine Thrust Zone here totalled 77 km. By analogy with other major thrust belts of the world it is likely that total translation across the Moine Thrust Zone was at least 100 km.

**Selected bibliography**

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