Geological framework of the North-west Highlands - structural units - the Moine Supergroup

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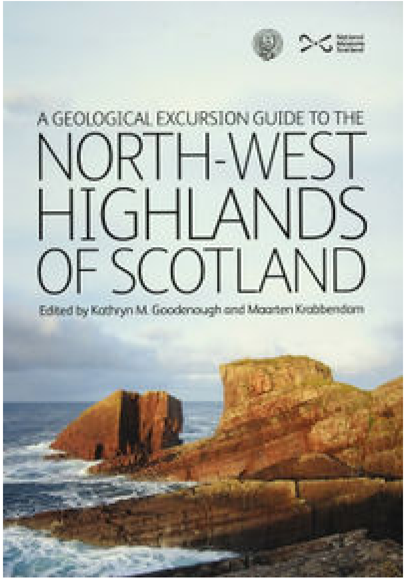

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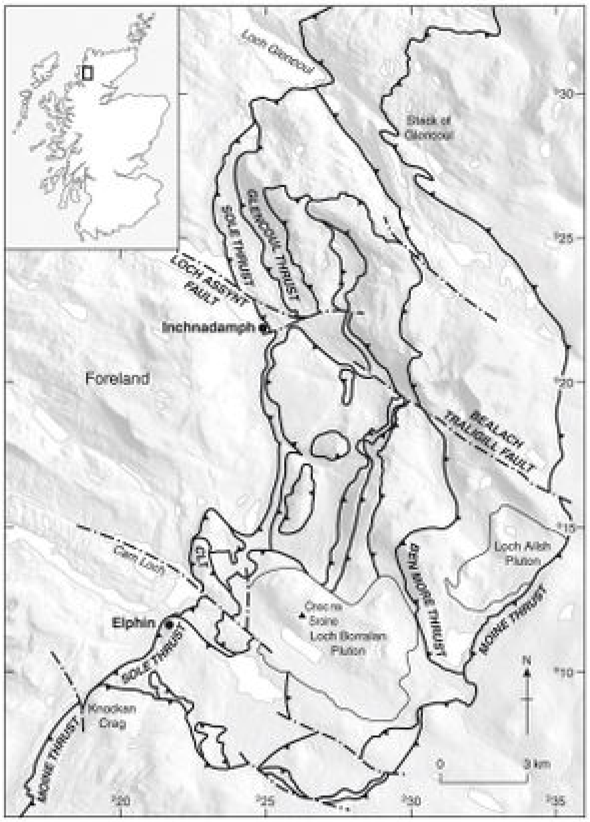


Overview map showing the main structural features, thrusts, and intrusions within the Assynt Culmination. CLT = Cam Loch Thrust.

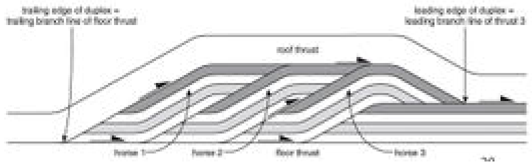
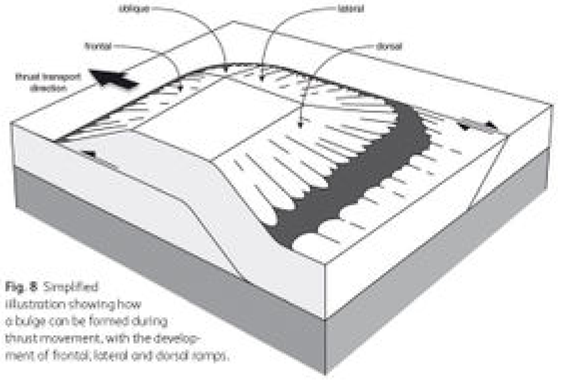
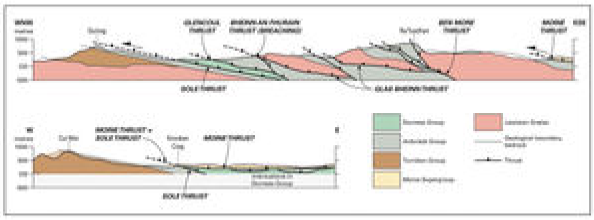


Illustration of the formation of a duplex, with thrusts propagating from left to right.



Simplified illustration showing how a bulge can be formed during thrust movement, with the development of frontal, lateral and dorsal ramps.


Schematic cross-sections through the Moine Thrust Zone. (a) Section through the Assynt Culmination, illustrating some of the complexity of this area, with numerous thrusts between the Moine and Sole thrusts. (b) Section through the Moine Thrust at Knockan Crag to the south of the Assynt Culmination, illustrating the late nature of the brittle Moine Thrust in this area.

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From: Goodenough, Kathryn M. and Krabbendam, Maartin (Editors) A geological excursion guide to the North-west Highlands of Scotland. Edinburgh : Edinburgh Geological Society in association with NMS Enterprises Limited, 2011.

Introduction

To the east of the Moine Thrust, the outcrop of the Moine Supergroup extends almost to the east coast of Scotland. The Moine Supergroup is divided into three groups (Morar, Glenfinnan and Loch Eil), of which only the Morar Group is present in the area covered by this guide. The whole of the Moine Supergroup is described in detail in *A Geological Excursion Guide to the Moine Geology of the Northern Highlands of Scotland* (Strachan *et al.*, 2010). Local inliers of 'Lewisianoid' Archaean basement occur within the Moine Supergroup, but none are present within the area described in this guide.

The rocks of the Morar Group are mainly psammitic, with subordinate beds of pelitic schist and, rarely, calc-silicates. Directly to the east of the Moine Thrust, these rocks show greenschist-facies metamorphism, with metamorphic grade increasing eastwards. The general dip of the Morar Group psammites is at low or moderate angles to the ESE, although to the east of the Assynt Culmination the strike trend varies so as to mimic the embayment of the Moine Thrust. The dominant linear structures plunge to the ESE or SE.

In the type area of Morar, Glendinning (1988) interpreted the Morar Group sediments as having been deposited in a fluvial or shallow marine environment. However, in the area to the east of Assynt, sedimentary features indicate that the Morar Group was deposited in a braided river system and can be correlated with the Torridon Group in the foreland, with both forming part of the foreland basin to the Grenville orogen (Krabbendam *et al*. 2008). The depositional environment of large parts of the Moine Supergroup, and linkages to rocks in the foreland farther south, remain unclear and would merit further study.

The age of the Moine Supergroup has long been controversial, but has largely been resolved by recent U-Pb geochronological studies. The rocks of the Morar Group were deposited after *c*.1000 Ma (the age of the youngest detrital zircon; Friend *et al*., 2003). A general constraint for the minimum age of the Moine Supergroup comes from the intrusion of granitic and gabbroic rocks (the West Highland Granite Gneiss) into the southern part of the Moine Supergroup. These intrusions have been dated, using U-Pb on zircons, at *c*.870 Ma (Friend *et al*., 1997; Millar, 1999; Rogers *et al*., 2001), and it has been suggested that intrusion occurred in an extensional setting (Millar, 1999).

The age of metamorphism of the Moine rocks is also the subject of ongoing research. Parts of the Moine succession, particularly in Knoydart and Morar, show evidence for regional metamorphism between *c*.820 and 740 Ma (the Knoydartian event). In the type area of the Morar Group, this evidence includes pegmatites that have been dated at *c*.827 and *c*.784 Ma (Rogers e*t al*., 1998), and metamorphic ages of *c*.820–790 Ma obtained by dating of garnets (Vance e*t al*., 1998), as well as U-Pb ages for titanite that suggest that the Morar Group was affected by metamorphism at *c*.737 Ma (Tanner and Evans, 2003).

In east Sutherland there is evidence for metamorphism at *c*.470 Ma (Kinny *et al*., 1999), but Caledonian regional metamorphism in the Morar Group in the area of this guide has been shown to have occurred at 435– 420 Ma (Kinny *et al*., 2003) and to be approximately coeval with movement on the Moine Thrust.

The Moine Thrust Zone

The Moine Thrust Zone is a structurally complicated belt that stretches from Loch Eriboll in the north to the Isle of Skye in the south (Excursions 5 to 10 and 14 to 15). It is defined as the zone lying below the Moine Thrust (which carries the rocks of the Moine Supergroup, with local basement inliers), but above the Sole Thrust which separates the thrust zone from the undisturbed foreland. The Moine Thrust is everywhere a distinctive structure, but the Sole Thrust is rather variable, and locally includes structures with very little displacement. The rocks within the thrust zone are derived from the foreland, but show varying states of defor-mation. In some cases, the strain and accompanying recrystallization has been so intense as to make direct correlation with specific foreland units difficult.

The thrust zone varies widely in outcrop width, from just a few metres at Knockan Crag (Excursion 6), up to about ten kilometres in the Assynt Culmination. It comprises a number of major thrust sheets, which are themselves internally deformed by thrusting and folding. It has been con-sidered as a classic example ever since the publication of the North-west Highlands memoir (Peach *et al*.,

1907) and the recognition that low-angle reverse faults (thrusts) could place older rocks on top of younger rocks. The term 'thrust' was coined by Geikie (1884), inspired by Charles Lap-worth's work in the area around Loch Eriboll (Excursion 15).

The thrusting, and associated deformation, are the result of shortening of the Laurentian continental margin during the closure of the Iapetus ocean and the collision between the continents of Laurentia and Baltica, together with the docking of Avalonia. The thrust zone, which forms the front of the Caledonian orogen in northern Scotland, developed during the Silurian, in the Scandian event which is also recognised in eastern Greenland and Scandinavia.

Elliott and Johnson (1980) presented a 'piggy-back', foreland-propa-gating model for the Moine Thrust Zone; that is, the upper thrusts moved first, and these thrust sheets were carried further by subsequent movement along lower thrusts. In this model, the earliest movement in the Moine Thrust Zone was along the Moine Thrust itself – although it should be noted that a number of important earlier thrusts (including the Naver and Sgurr Beag thrusts) occur within the rocks of the Moine Supergroup further to the east. Displacement on the thrusts was broadly towards the WNW. The thrust sheet carried by the Moine Thrust was large; on the basis of current exposure on the mainland, it was over *c*.200km in strike length and *c*.10–20km in thickness. Furthermore, the presence of a klippe (outlier) of Moine rocks at Faraid Head (Excursion 14) shows that the Moine sheet extended westwards over the foreland for a distance of at least 10km beyond its present outcrop.

Although elegant, the simple 'piggy-back' model does not account for (a) the dual nature of the Moine Thrust, which is an early ductile shear zone in some places and a late brittle fault in others; and (b) the apparent truncation of lower faults by higher ones at some localities (e.g. in the klippen to the east of Knockan, south Assynt, Excursion 6). It is clear that the Moine Thrust Zone represents a rather more complex system. A variety of models have been proposed to explain some of these features, including late-stage extensional faulting (particularly in southern Assynt; Coward, 1982, 1983); synchronous movement along imbricate thrusts and roof thrusts (Butler, 2004); and extensional collapse episodes during the largely compressional evolution of the thrust wedge (Holdsworth *et al*., 2006). Recent work has shown that detailed mapping of specific localities is essen-tial to understand the different processes that have operated in the Moine Thrust Zone (Butler, 2004; Krabbendam and Leslie, 2004; Holdsworth *et al*., 2006).

The Moine Thrust has traditionally been defined as the thrust that forms the base of the Moine Supergroup (and its Lewisianoid basement, where exposed), but this structure varies in character along its length. In places it is a ductile shear zone, represented by a thick pile of mylonites, as seen at the Stack of Glencoul and at Loch Eriboll (Excursions 11 and 15); elsewhere (e.g. at Knockan Crag, Excursion 6), it is a polyphase brittle-ductile structure, the mylonites being brecciated by late, lower-tempera-ture deformation (Coward, 1983). Mylonites are fine-grained, strongly layered rocks, formed by dynamic recrystallisation during ductile defor-mation (e.g. White, 1980), and they were first defined on the basis of examples from the Moine Thrust Zone (Lapworth, 1885).

Peach *et al*. (1907) noted that 'owing to the development of mylonites in association with the Moine Thrust, it is extremely difficult to determine everywhere its exact position', and this debate has continued to cause controversy for a century. Some workers prefer to place the Moine Thrust at the base of the Moine Supergroup (e.g. Christie, 1963; Law, 1987; Holdsworth *et al*., 2006), so that the mylonites above the Moine Thrust have a Moine protolith, whereas mylonites derived from Torridonian, Lewisian or Cambro-Ordovician protoliths lie below the Moine Thrust. Others have placed the Moine Thrust at the base of the mylonite pile (e.g. Soper and Wilkinson, 1975; Elliott and Johnson, 1980). On the east side of Loch Eriboll, the main belt of foreland-derived mylonites lies above a brittle structure that has recently been named the Lochan Riabhach Thrust by Holdsworth *et al*. (2006), but the interpretation of this structure is also controversial (Butler *et al*., 2006).

The mylonites associated with the Moine Thrust were developed largely under conditions of greenschist-facies metamorphism. Mylonites of differ-ent protoliths may be quite similar in appearance, and thus, as noted by Peach *et al*. (1907), in places it is difficult to accurately place the contact between different rock-types within the mylonite pile. An excellent place to study the mylonites is the Stack of Glencoul (Excursion 11) where a com-plex mylonite zone, reaching some 70m in thickness, has been derived from Lewisian gneiss, Cambrian quartz arenite and Moine psammites.

As ductile movement on the Moine Thrust ceased, displacement was transferred to the lower thrusts of the Moine Thrust Zone. Within the Moine Thrust Zone, numerous thrusts developed in the rocks of the foreland succession; the major thrusts are most easily studied in the Assynt Culmin-ation ((See image)). Thrusts tend to follow weak layers, as they show a prefer-ence for 'easy gliding' surfaces. In the Moine Thrust Zone, this role has typically been filled by fine-grained clastic horizons, such as the Fucoid Beds Member or the mudstones of the Diabaig Formation, and thrusts are most commonly focused along these layers. Zones where a thrust runs along one horizon are known as *flats*, with *ramps* occurring in thrust planes where they cut up or down from one 'easy gliding' horizon to another. Thrusting typically placed older rocks over younger rocks, though variations to this pattern occurred. Breaching thrusts have 'reshuffled' sequences that have already been thrusted, emplacing younger rocks over older rocks; stratigraphic inversion was also caused by the development of thrust-related folds, such as the Sgonnan Mòr Syncline (Excursion 9) and the spectacular anticline/syncline pair on Na Tuadhan in Assynt (Excursion 8).

Even a superficial examination of the geological map of Assynt (British Geological Survey, 2007) or of Loch Eriboll (British Geological Survey, 2002a) reveals the arrays of many anastomosing minor thrusts within the major thrust sheets. These were described by Peach *et al*. (1907) as imbricate structures. Elliott and Johnson (1980) and Boyer and Elliott (1982) regarded these arrays as examples of *duplex structure*, a series of curved faults asymptotically related to a higher ('roof') thrust and a lower ('floor') thrust ((See image)). Each thrust-bounded body of rock within the duplex is termed a 'horse'. Unlike an imbricate fault, a duplex must have a roof thrust that does not truncate the thrusts in its footwall. Ideally the array of faults in a duplex is a system in which slip is partitioned both along the roof thrust and along the imbricates below. A small duplex or imbri-cate structure can be observed in the Stronchrubie cliffs (Excursion 16).

In many areas 'smooth' gliding occurred, but locally 'rough' gliding led to the piling up of lenticular thrust sheets and resulted in local thickening of the hangingwall. These piled-up thrust sheets pushed up the base of the overlying Moine Thrust Sheet, folding it to create a bulge or culmination ((See image)). The most spectacular example is the Assynt Culmination ((See image)), where the cause of the local 'rough' gliding may have been the presence of large amounts of igneous rocks. However, this explanation does not apply to other culminations in the Moine Thrust, and other factors must be involved elsewhere.

Many estimates have been made for the displacement on the thrusts of the Moine Thrust Zone, but some of them are based on disputable field relationships. However, the offset of distinctive features in the Lewisian gneisses in the thrust zone relative to the foreland (Clough in Peach *et al*., 1907; Elliott and Johnson, 1980) indicates 20–25km of displacement along the Glencoul Thrust (now recognised as the northern part of the Ben More Thrust; Krabbendam and Leslie, 2004). On the basis of balanced cross-sections, Elliott and Johnson (1980) suggested a displacement of at least 77km on the Moine Thrust. Slip on the Sole Thrust is probably only a few kilometres, but in total the displacement across the Moine Thrust Zone is likely to be at least 100km. The direction of thrusting was towards what is now the WNW (290˚), as indicated by the stretching lineation in the mylonites

(Christie, 1963), the orientation of duplex and imbricate faults, and the spectacular deformation of the *Skolithos* burrows in the Pipe Rock (McLeish, 1971; Wilkinson *et al*., 1975).

Two methods have been used to date the Moine Thrust Zone: indirect dating of igneous rocks with clear relationships to the thrusting, and direct dating of micas in mylonites formed during thrusting. Constraints on the onset of thrusting are provided by U-Pb zircon dates for the Loch Ailsh Pluton and the Canisp Porphyry Sills in Assynt, both of which pre-date movement on thrusts within the Moine Thrust Zone (Excursion 9). For some years, a date of 439 ± 4 Ma has been accepted for the Loch Ailsh Pluton (Halliday *et al*., 1987), but recent high-precision dating has dated this pluton at 430.6 ± 0.3 Ma, within error of the Canisp Porphyry Sills at 430.4 ± 0.4 (Goodenough *et al*., 2011). In contrast, the later magmatic suite of the nearby Loch Borralan Pluton post-dates movement on the Ben More Thrust (Parsons and McKirdy, 1983; Excursion 10) and has now been dated at 429.2 ± 0.5 Ma (Goodenough *et al*., 2011). Movement within the Moine Thrust Zone therefore took place over a relatively short period of one to two million years. Both earlier and later periods of movement took place on the Moine Thrust itself, as shown by the second method of dating used in this area.

Direct dating of micas from mylonites along the Moine Thrust, using Rb-Sr, K-Ar, and Ar-Ar techniques, has obtained a broader spread of results. Mylonitisation of the Moine rocks was accompanied by green-schist-facies metamorphism, at a temperature of approximately 400˚C (Freeman *et al*., 1998). This ductile deformation continued until at least 430 Ma, but locally appears to extend until 408 Ma (Kelley, 1988; Freeman *et al*., 1998; Friend *et al*., 2000; Dallmeyer *et al*., 2001).

In general terms, the majority of displacement within the Moine Thrust System appears to have been confined to the interval from the middle to late Llandovery (*c*.435–428 Ma), with some displacement persisting into the early Devonian, and this timing is remarkably synchronous from Scot-land to eastern North Greenland. Although the general pattern is clear, there continues to be considerable discussion about detailed relationships within this well-preserved ancient mountain belt.

References

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