Geological framework of the North-west Highlands

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The North-west Highlands are internationally famous because they contain superb evidence for large-scale horizontal shortening of continental crust, as a result of the piling-up of thrust sheets along the Moine Thrust Zone during the Caledonian orogeny, in the early Silurian. The Moine Thrust Zone extends for around 200 km, from Loch Eriboll to the Isle of Skye, and the total displacement along its component thrusts was at least 100 km. This guide describes the northern part of the Moine Thrust Zone (Figure 1). The thrust relationships are clearly displayed on the mountainsides, in one of the few parts of Britain in which the visitor can enjoy geological vistas that can truly be compared with the Alps. However, the thrust zone is just one of the important geological features of the North-west Highlands; the foreland succession, comprising an Archaean–Palaeoproterozoic gneiss complex overlain by Proterozoic and early Palaeozoic sedimentary rocks, has also been studied in significant detail. The area additionally contains a suite of alkaline igneous intrusions, which includes some of the most potassic igneous rocks in Britain.

The geology of the area was first extensively studied during the nineteenth century, and sparked some major scientific arguments, which have been described in detail elsewhere (e.g. Oldroyd, 1990). Although that period of debate concluded with the publication of the North-west Highlands memoir (Peach *et al*., 1907), research into the rocks and structure of the region has continued throughout much of the last century (Butler, 2007; Law *et al.*, 2010a). Modern overviews of the geology are provided by Mendum *et al*. (2009), Trewin (2002), and Woodcock and Strachan (2000).

The stratigraphical succession in the North-west Highlands extends from the Archaean through to the Ordovician. The Archaean to Palaeoproterozoic tectonic history of Scotland is complex, but is steadily being unravelled with the application of modern geochronological techniques.

During much of the Proterozoic era, Scotland lay within a major super-continent called Rodinia. This continent broke up towards the end of the Neoproterozoic, and Scotland, together with Greenland and parts of North America, was then part of the continent of Laurentia, which existed for much of the Palaeozoic. Palaeomagnetic data show that Laurentia drifted from close to the South Pole in the late Neoproterozoic, to close to the equator in the Ordovician, thus experiencing a range of different climatic belts. During the Silurian, closure of an ocean called Iapetus led to the collision of Laurentia with the continents of Baltica and Avalonia, and the formation of the Moine Thrust Zone.

The rock units of the North-west Highlands record almost 3000 million years of this remarkable and diverse geological history, including two major Proterozoic unconformities. The area can be broadly divided into three distinct structural domains, each characterised by its different structures and lithologies (Figure 1). These are:

1. The unmoved region or foreland lying to the west of the lowest thrust (the Sole Thrust). The complete foreland stratigraphical succession is shown in (Table A).
2. The Moine Thrust Zone, which includes the Moine Thrust and the subsidiary thrusts occurring structurally below and to the west of it.
3. The rocks of the Moine Supergroup lying to the east of, and structurally above, the Moine Thrust.

A variety of post-Cambrian igneous rocks occur within all three of these domains. They include two alkaline plutons, one of which represents the only silica-undersaturated major intrusion in the British Isles, and a suite of dykes and sills ranging from calc-alkaline to peralkaline in composition. Emplacement of these intrusions spanned the development of the Moine Thrust Zone, and therefore provides upper and lower age limits for thrusting.

A: The structural units

(1) The Foreland

The rocks of the foreland include the Archaean basement of the Lewisian Gneiss Complex, the overlying Meso- to Neoproterozoic sandstone-dominated Stoer and Torridon groups, the Cambrian clastic sedimentary rocks of the Ardvreck Group, and the Cambro-Ordovician dolostones and limestones of the Durness Group. Each of these major lithological units gives rise to a distinctive type of scenery. A particularly spectacular feature of the area is the 'double unconformity', where the planar base-Cambrian unconformity cuts across the more irregular unconformity between the Torridon Group and the underlying Lewisian Gneiss Complex (Figure 2). On many of the hills in the area, it is easy to pick out the distinct lithological changes across the unconformities at the base of the Torridon Group, and at the base of the Cambrian succession. The basal Cambrian unconformity, which must have been horizontal when it formed, is now tilted gently towards the south-east.

The Lewisian gneisses form a rocky plateau with a succession of ridges and low hills of bare rock, among which lie many lochs (cnoc-and-lochan scenery). Above this plateau rises a thick pile of nearly horizontal beds of Torridon Group sandstone, which forms many of the spectacular mountains of the North-west Highlands (Figure 3). Characteristic features of these spectacular relic mountains are the terraced slopes and precipitous cliffs, with giant buttresses and pinnacles that have been sculpted by erosion.

The white Cambrian quartz arenites of the Ardvreck Group produce gleaming escarpments and long dip slopes, such as on the eastern faces of Quinag, Canisp and Foinaven. In contrast, the dolostones and limestones of the Durness Group form lower-lying valleys, typically with swards of green grass punctuated by outcrops of grey carbonate rocks, representing the largest area of karst landscape in Scotland.

Lewisian Gneiss Complex

The basement of the North-west Highlands is formed by the Lewisian Gneiss Complex. The early detailed surveys of this area (Peach *et al*., 1907) recognised that the Lewisian Gneiss Complex could be separated into three districts (northern, southern and central), with the central district containing pyroxene-bearing gneisses (granulite facies) and the northern and southern districts being composed of hornblende-bearing gneisses (amphibolite facies). A simple chronology (Peach *et al*., 1907; Sutton and Watson, 1951) was established, with a 'fundamental' complex that was metamorphosed prior to intrusion of a swarm of dykes, known as the Scourie Dyke Swarm. Following dyke intrusion, the northern and southern districts of the complex were reworked at high temperatures (the Laxfordian orogeny).

More recent research, notably aided by advances in radiometric dating, has recognised that the evolution of the Lewisian gneisses was rather more complex. A large body of work (summarised by Kinny *et al*., 2005) has shown that the different districts have different protolith ages, as well as different metamorphic histories, and it has been suggested that they represent different crustal blocks or terranes. Two of these terranes lie within the area covered by this guide: the northern, 'Rhiconich' Terrane; and the central, 'Assynt' Terrane.

Most of the Archaean gneisses of the Assynt Terrane had a tonalitic or leucotonalitic protolith, formed at 3030–2960 Ma (Kinny and Friend, 1997). These rocks were metamorphosed in an early granulite-facies metamorphic event (the 'Badcallian'). The age of this event is currently unresolved; whilst many authors have obtained ages around 2700 Ma for the granulite-facies metamorphism (Pidgeon and Bowes, 1972; Corfu *et al*., 1994; Zhu *et al*., 1997), others have suggested that the main high-grade metamorphism occurred at *c*.2490 Ma (Friend and Kinny, 1995). The gneisses were later locally reworked by an amphibolite-facies event known as the Inverian, which formed a series of major shear zones (Evans, 1965; Attfield, 1987). This was followed by the intrusion of the Scourie Dyke Swarm, in the period 2400 to 2000 Ma (Heaman and Tarney, 1989). Further local reworking occurred during the Palaeoproterozoic, in the Laxfordian event, which has been dated at *c*.1740–1670 Ma (Corfu *et al.*, 1994; Kinny and Friend, 1997).

The Assynt Terrane is typified by grey pyroxene-bearing felsic gneisses, commonly having a marked gneissic banding, and consisting largely of quartz, locally bluish or opalescent, and plagioclase feldspar. These have been named the 'Eddrachillis gneisses' by Kinny *et al*. (2005). Away from zones of Inverian reworking, hypersthene is the principal ferromagnesian mineral; where the gneisses have been retrogressed, hornblende is common and biotite may be present. The felsic gneisses enclose bands and lenses of more mafic meta-igneous rock, of widely varying scales from a few centimetres to a few kilometres across. Unretrogressed mafic bodies contain clino-and orthopyroxene, locally with garnet;

where retrogressed, they are dominated by hornblende. Examples of typical felsic and mafic gneisses of the Assynt Terrane can be seen in Excursion 12.

In a few areas, particularly just south of Loch Laxford (Davies, 1974; Excursion 13) and near Stoer (Cartwright and Barnicoat, 1987), the mafic bodies are associated with garnet-biotite-quartz schists and rare calc-silicate rocks (the Claisfearn supracrustals), which are considered to have had a sedimentary protolith. It has been suggested that this association of mafic and ultramafic rocks with metasedimentary rocks could represent an ocean-floor assemblage, tectonically accreted to the continental margin (Park and Tarney, 1987).

In contrast, the protoliths of the Rhiconich Terrane gneisses were mostly granodioritic, and have been dated at 2800–2840 Ma (Kinny and Friend, 1997). They show no evidence of early, granulite-facies metamorphism, but were affected by an undated metamorphic event prior to the intrusion of the Scourie Dyke Swarm (Chowdhary and Bowes, 1972). They were pervasively reworked during the Laxfordian event (1740–1670 Ma; Corfu *et al*., 1994, Kinny and Friend, 1997). The amphibolite-facies gneisses of the Rhiconich Terrane are pink to grey in colour, with a strong gneissic banding, and commonly also show evidence of migmatisation. They contain both plagioclase and alkali feldspar, plus quartz, hornblende and biotite. Older mafic bodies are much less common in the Rhiconich than in the Assynt Terrane.

Both terranes are cut by a major swarm of NW–SE- to WNW–ESE-trending dykes, known as the Scourie Dykes (Excursion 12). The Scourie Dykes vary in width from a few centimetres up to tens of metres and are remarkably laterally persistent. In Assynt, the dykes fall into two main classes: an earlier and widely distributed NW–SE-trending set that includes olivine-gabbros, norites and, most commonly, quartz-dolerite; and a later, less abundant, set of east-west-trending picrites and NW–SE-trending dolerites (Tarney, 1973). Both sets clearly cross-cut the gneissic banding. Although some dykes in the Assynt Terrane still retain their primary igneous mineralogy and textures, most have undergone metamorphism at amphibolite facies. In the Rhiconich Terrane, all the Scourie Dykes have been metamorphosed to coarse-grained amphibolites, and they are typically pervasively deformed, with their margins broadly parallel to the foliation in the host gneisses. Their period of intrusion may have spanned a long time, but the main dyke swarm was probably intruded at about 2400 Ma during a period of crustal extension (Heaman and Tarney, 1989).

The Assynt Terrane is cut by a number of broadly NW–SE-trending shear zones, marked by intensely deformed and retrogressed gneisses with a steeply-dipping foliation. Some of the major shear zones (such as the Canisp Shear Zone; Excursion 2) were initiated during the Inverian event, prior to the intrusion of the Scourie Dykes, and reactivated during the Laxfordian at about 1740 Ma (Attfield, 1987; Kinny and Friend, 1997). From Kylesku, narrow shear zones increase in abundance northwards, culminating in the major Laxford Shear Zone (Beach e*t al*., 1974; Goodenough e*t al*., 2010) at the margin of the Assynt and Rhiconich terranes (Excursion 13). This shear zone is considered to represent the boundary along which the two terranes were accreted, and it has been suggested that this occurred prior to Scourie Dyke emplacement, during the Inverian event (Goodenough e*t al*., 2010). Further north, in the Rhiconich Terrane, Laxfordian deformation is pervasive. Laxfordian deformation in this terrane was associated with the intrusion of a large number of sheets of granite and pegmatitic granite, some of which are strongly foliated, whilst others are relatively undeformed.

The Lewisian gneisses within the Moine Thrust Zone typically show the same features as those in the foreland. The transition from granulite-facies gneisses of the Assynt Terrane to amphibolite-facies gneisses of the Rhiconich Terrane occurs in the thrust belt in the vicinity of Loch Glencoul, several kilometres to the south of the same boundary in the foreland.

Stoer Group

The Stoer Group includes some of the oldest undeformed sedimentary rocks and the oldest life forms in Europe, with Pb-Pb ages on samples of limestone indicating deposition at around 1200 Ma (Turnbull *et al*., 1996). The rocks of the Stoer Group are well-exposed on the Stoer peninsula (Excursion 3) and south of Enard Bay (Excursion 4), and at both localities the base of the group lies unconformably on rocks of the Lewisian Gneiss Complex.

The Stoer Group is divided into three formations (Stewart, 2002). The lowest Clachtoll Formation comprises basal conglomerate overlain by massive muddy sandstone with further conglomerates, suggesting deposition in lakes fringed by debris fans (Stewart, 2002). The overlying Bay of Stoer Formation contains fluviatile sandstone. Within this formation is the Stac Fada Member, which can be traced for over 100 km; it is generally considered to represent a volcaniclastic deposit (Sanders and Johnston, 1989), but has also been explained as a meteorite impact layer (Amor e*t al*., 2008). Above the Stac Fada Member is the Poll a'Mhuilt Member, comprising layered and massive mudstone, probably of lacustrine origin, with some indications of evaporitic activity (Stewart, 2002). This is followed by the sandstones of the Meall Dearg Formation, deposited in a fluviatile (or possibly aeolian) environment.

A glacial origin for the basal part of the Stoer Group was proposed by Davison and Hambrey (1996, 1997), but Young (1999) and Stewart (1997, 2002) showed that the conglomerates and breccias could be interpreted as locally derived fan head material or debris fans, formed in a tectonically active environment with no need for glacial activity. The critical exposures are described in Excursions 3 and 4.

Detrital zircons from the Stoer Group show a cluster of late Archaean ages, although the youngest zircon is dated at *c*.1740 Ma (Rainbird *et al*. 2001; Kinnaird *et al*., 2007). The adjacent Lewisian gneiss is therefore considered as the most likely source for the sediments. It is generally agreed that the Stoer Group was deposited in a rift basin (Stewart, 1982, 2002; Beacom *et al*., 1999; Rainbird *et al*., 2001), on the basis of a number of features. These include: abundant vertical and lateral facies changes, with a mixture of fluviatile, debris-fan, lacustrine, volcanic and evaporitic deposits; the local source for the sediments; the presence of syn-depositional extensional (transtensional) faulting within the sequence; and the existence of opposing palaeocurrents in different units, suggesting alternating fault displacement along bounding faults.

The Stoer Group is separated from the overlying Torridon Group by a distinct angular unconformity, which can be seen at Bay of Culkein near Stoer (Excursion 3), Enard Bay (Excursion 4) and Achiltibuie. Palaeomagnetic studies indicate that Scotland had drifted southwards by some 40 degrees between the deposition of the Stoer and Torridon groups, and thus that this angular unconformity represents a considerable time gap (Stewart and Irving, 1974; Smith *et al*., 1983; Torsvik and Sturt, 1987).

Torridon Group

The Torridon Group is divided into four formations, of which three are seen in the area described in this guide: the basal Diabaig Formation and the overlying Applecross and Aultbea formations. The lower two formations can be easily studied on the shores of Loch Assynt (Excursion 1). A comprehensive overview of the Torridon Group is provided by Stewart (2002).

The unconformity at the base of the Diabaig Formation preserves a 'fossil' Proterozoic landscape, which shows spectacular relief; for example, a Lewisian 'hill' about 200 m high forms the lower slopes on the north side of Quinag. The Diabaig Formation, which typically infills this topography, varies in thickness from a few metres to about a hundred metres. The formation includes breccias, conglomerates, and tabular-bedded sandstones and mudstones. Clasts in the breccias and conglomerates include locally-derived Lewisian gneiss and Stoer Group sandstone (Excursion 4).

The Applecross Formation is up to about 1 km thick in the area of this guide, and forms many of the distinctive mountains, such as Suilven and Quinag. The formation chiefly consists of dark red or purplish-red, cross-bedded, arkosic sandstones with conglomerate beds. Trough and planar cross-bedding is common (Figure 4); over most of the Assynt area, palaeocurrents are towards the south-east, but around Cape Wrath they are more easterly-directed. Soft sediment contortions such as oversteepened cross-bedding, slump folds and water escape structures are common. Pebbles in the Applecross Formation conglomerates include vein quartz and quartzite (some with tourmaline), jasper, chert, and porphyritic rhyolite (Williams, 1969).

Deposition of the Torridon Group, in rivers flowing across the Rodinian supercontinent, occurred at around 1000 Ma (Turnbull *et al*., 1996; Rainbird *et al*., 2001). The depositional setting of this group is the source of continuing debate; some authors suggest that it was formed from large-scale alluvial fans and braided river systems in a rift valley of the order of 100 km wide (Stewart, 1982; Williams, 2001), but evidence from sedimentary structures suggests a much larger river system (Nicholson, 1993) and detrital zircon ages suggest a more distal source area, possibly the contemporaneous

Grenville orogenic belt (Rainbird *et al*., 2001; Kinnaird *et al*., 2007; Krabbendam *et al*., 2008). This would imply that the Torridon Group was deposited in a large-scale, orogen-parallel foreland basin to the Grenville orogen.

The Cambro-Ordovician succession

Following late Neoproterozoic rifting and the opening of the Iapetus Ocean, northern Scotland formed part of the eastern margin of Laurentia. The oldest undeformed sediments deposited on the continental margin are of early Cambrian age and record only the later phases of margin development, not the initial rifting. Evidence of rifting is preserved elsewhere in Scotland, in the Dalradian Supergroup of the Grampian Highlands. Subsidence and deposition on the Laurentian margin was continuous from south-eastern USA, through maritime Canada and Newfoundland to North Greenland, a distance of several thousand kilometres. The subsidence history and stratigraphical record in the Newfoundland–Scotland–East Greenland sector of the margin show remarkable similarities that have been recognised since the early days of plate tectonic research (Swett and Smit 1972; Wright and Knight 1995; Higgins *et al*. 2001).

Within the North-west Highlands, rocks of Cambro-Ordovician age crop out in a narrow, almost continuous belt, rarely more than 10 km wide, which stretches 170 km from Loch Eriboll south-westwards to the Isle of Skye. The initial phase of Early Cambrian deposition comprised quartz-rich siliciclastic sediments, assigned to the Eriboll Formation (Ardvreck Group). These unconformably overlie both the Torridon Group and, where the Torridon Group rocks were eroded prior to Cambrian deposition, the Lewisian Gneiss Complex (Table A). This 'double unconformity' is spectacularly displayed in the Assynt area, particularly on the slopes of Canisp and Beinn Garbh to the south of Loch Assynt ((Figure 2), Excursion 1). The foreland succession in the Assynt area is shown in (Figure 4).

The Eriboll Formation is divided into two members: the older, pervasively cross-bedded Basal Quartzite Member (75–125 m thick); and the overlying Pipe Rock Member (75–100 m , which is also cross-bedded but extensively bioturbated by pipe-like, vertical *Skolithos* burrows. Despite the term 'Basal Quartzite', the rocks of the formation are actually sandstones and range from sub-arkoses to quartz arenites in composition.

The top few metres of the Eriboll Formation become more clay-rich and there is an abrupt change to the distinctive yellow-brown dolomitic siltstones of the Fucoid Beds Member (An t-Sròn Formation; 12–27 m . These iron-and phosphate-rich rocks contain a diverse trace fossil assemblage that includes the ichnogenera *Palaeophycus*, *Skolithos* and *Cruziana*, together with a number of other fossils, particularly the trilobite *Olenellus*. The siltstone layers are punctuated by cross-bedded dolomitic grainstones, which represent storm events.

The succession from the base of the Eriboll Formation to the top of the Fucoid Beds Member represents an overall trend of sea-level rise, from tidally dominated shelf sedimentation in the Eriboll Formation, to background sedimentation below fair weather wave-base in the Fucoid Beds Member (McKie, 1990). The Fucoid Beds Member is conformably overlain by the arenaceous Salterella Grit Member (An t-Sròn Formation), which is typified by round millet-seed quartz grains and conical Salterell*a* (commonly weathered out). This member is considered to be the product of relative sea-level fall and a return to tidally dominated shelf sedimentation (McKie, 1990); the round grain shapes probably indicate aeolian trans-port prior to deposition.

At the top of the An t-Sròn Formation, there is an abrupt change to carbonates of the Durness Group, and this shift from siliciclastic-dominated to carbonate-dominated sedimentation is seen along most of the Iapetus margin of Laurentia. The Durness Group comprises at least 935 m of peritidal and shallow subtidal limestones and dolostones, which record deposition within a tropical setting – stromatolites and thrombolites (the products of microbially mediated sedimentation) are common, ooids are locally abundant, and evidence of former evaporites and early dolomite formation is found in parts of the succession. The lowest two units of the Durness Group, the Ghrudaidh and Eilean Dubh formations, are widely exposed along the Moine Thrust Zone; but only at the northern and southern ends of the thrust zone, in the Durness area and on the Isle of Skye, is a more complete succession represented (Figure 5). Even here, the stratigraphic succession is truncated by thrusting (Excursion 14).

The Ghrudaidh Formation (65 m comprises lead-grey burrow-mottled or massive dolostones, of predominantly subtidal origin. The base of the formation contains *Salterella* and the trilobite *Olenellus*, indicative of the late Lower to earliest

Middle Cambrian. The Ghrudaidh Formation is conformably overlain by the Eilean Dubh Formation (minimum thickness 135 m , a unit of pale-weathering, laminated, very shallow subtidal and peritidal dolostones. Metre-scale shallowing upward parasequences (sea-level related cycles) are frequently seen in the lower and middle part of the formation, but tend to be absent in the upper part. The Eilean Dubh Formation contains stromatolites, but is otherwise unfossiliferous except for the uppermost few metres, where conodonts are recorded (Huselbee and Thomas, 1998) and provide evidence that the Cambrian–Ordovician boundary occurs in the upper few metres of the formation.

The overlying Sailmhor Formation (115 m constitutes a marked change to dark carbonates with conspicuous parasequences, and represents an earliest Tremadocian sea-level rise that has been documented globally (Nielsen, 2004). Burrow mottling and conspicuous chert concretions are common. Palmer *et al*. (1980) described a substantial unconformity surface

at the top of the Sailmhor Formation, with deep fissures and a significant time interval absent. However, these are now recognised to be Holocene erosion surfaces which expose Cenozoic fault breccias, and data from conodonts indicate that there is no significant temporal discontinuity in the succession.

Continuing up-sequence, the Sangomore Formation (55 m comprises generally light grey and buff finely laminated dolostones with some mid-grey thrombolitic limestones and stromatolites. The unit contains a reasonably diverse micro- and macrofauna that includes conodonts, gastropods and cephalopods. A significant sequence boundary, marked by a distinctive pebble bed, occurs at the top of the formation and may correlate with a similar 'megasequence' boundary in western Newfoundland (Knight and James, 1987). The overlying Balnakeil Formation (minimum thickness 85 m remains rich in microbialitic sediments, but with a conspicuous change to darker grey carbonates and a more subtidally dominated succession. The succeeding Croisaphuill Formation (minimum 350 m marks a shift from microbial-dominated carbonates to burrow-mottled limestones with dolomitised burrow systems. This shift represents the maximum flooding surface of the megasequence — a surface that can be correlated across most of Laurentia and is close to coincident with the Tremadoc–Arenig boundary (Haq and Schutter, 2009). The lower part of the Croisaphuill Formation is richly fossiliferous, yielding diverse and abundant cephalopod, gastropod and conodont faunas.

The youngest unit of the Durness Group, the Durine Formation (minimum 130 m , records the abrupt, eustatic fall in sea-level at the Lower–Middle Ordovician boundary, which begins in the upper Croisaphuill Formation but is most pronounced at the boundary with the Durine Formation. This formation consists chiefly of lighter grey, fine-grained peritidal dolostones. The macrofauna is sparse, but conodonts are present and indicate that the youngest part of the formation is of early Middle Ordovician age (*c*.470 Ma). The top of the formation is everywhere truncated by faulting, and in Sango Bay the Moine Thrust juxtaposes mylonitised Eriboll Formation and Lewisian gneiss (Excursion 14).

(2) The Moine Supergroup

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 *et 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.

(3) 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 deformation. 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 considered 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 Lapworth'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-propagating 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*.200 km in strike length and *c*.10–20 km 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 10 km 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 essential 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-temperature deformation (Coward, 1983). Mylonites are fine-grained, strongly layered rocks, formed by dynamic recrystallisation during ductile deformation (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 different 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 complex mylonite zone, reaching some 70 m 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 Culmination (Figure 6). Thrusts tend to follow weak layers, as they show a preference 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 (Figure 7). 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 imbricate 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 (Figure 8). The most spectacular example is the Assynt Culmination (Figure 9), 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 20–25 km 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 77 km 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 100 km. 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 greenschist-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 Scotland 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.

B: Igneous rocks

The Assynt district contains a considerable range of igneous rocks, some of extreme composition and many unique in the British Isles, which were emplaced during the Caledonian orogeny and provide both relative and absolute chronology of displacements in the Moine Thrust Zone. The literature is complicated by archaic terminology as well as great mineralogical variety, summarised in (Table B). A comprehensive overview has been provided by Parsons (1999).

The Loch Borralan Pluton (Excursion 10) is the only alkaline pluton in the British Isles that includes nepheline syenites. It also contains exotic, strongly ultrapotassic units and is associated with a small body of carbonatite. The smaller Loch Ailsh Pluton (Excursion 9) is composed mainly of silica-saturated syenite. Abundant dykes and sills, ranging from calc-alkaline lamprophyres to peralkaline rhyolites, are found throughout the thrust sheets. In the foreland to the west, the Canisp Porphyry forms a large sill complex of quartz-microsyenite; and two mafic phonolite dykes, focussed on the Loch

Borralan intrusion, reach the coast NW of Achiltibuie and near Achmelvich. Deformed sills of quartz-microsyenite ('nordmarkite') occur close to the Moine Thrust, and extend eastwards into the Moine psammites. It must be borne in mind that crustal shortening of several tens of kilometres may have occurred between the intrusions near the Moine Thrust and the compositionally similar Canisp Porphyry Sills in the foreland.

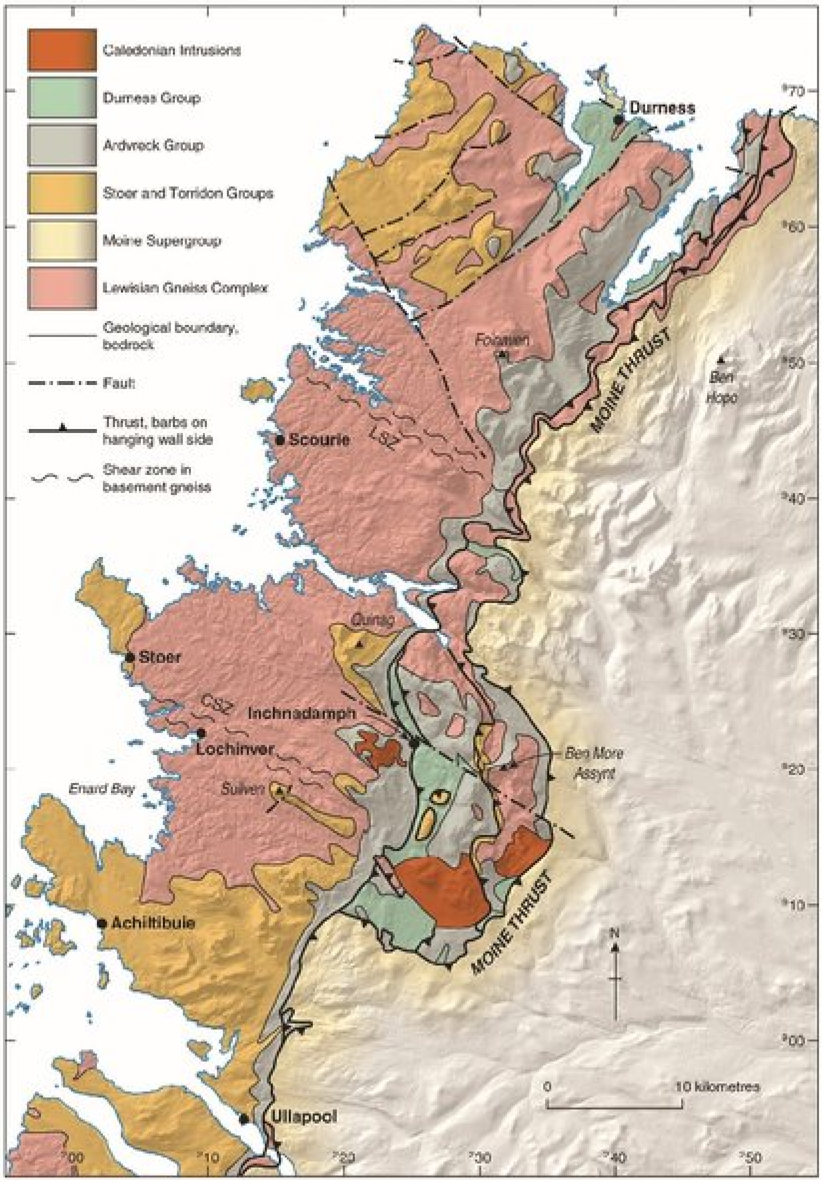
The alkaline plutons are part of a strip of late Caledonian intrusions that occur along, and slightly to the east of, the Moine Thrust Zone, extending from Loch Loyal in the north to Glen Dessary in the south. The alkaline igneous activity represents the north-west edge of the slightly younger, calc-alkaline granitic magmatism that dominates the remainder of the Highlands and Southern Uplands. Like alkaline magmatism elsewhere it extended over a long period of time, from 448 ± 2 Ma at Glen Dessary (van Breemen *et al*., 1979b; Goodenough *et al*., 2011) to 425 ± 3 Ma at Ratagain (Rogers and Dunning, 1991). Alkaline magmatism is most commonly associated with extension of the crust, as in the rift-valleys of present-day East Africa, but the North-west Highlands are a region of marked crustal shortening. A westward-dipping subduction zone has been postulated to exist beneath the Scottish Caledonides and many of the alkaline igneous rocks in the North-west Highlands have affinities with shoshonites, subduction-related basaltic rocks unusually rich in potassium (Thompson and Fowler, 1986; Thirlwall and Burnard, 1990). The source of ultrapotassic magmas and carbonatites is usually placed in the mantle. It is possible that the alkaline magmas arose by partial melting, during subduction, of mantle enriched in alkalis during an earlier phase of carbonatitic metasomatism, as has been postulated for subduction-related ultra-potassic rocks in Italy. However, this does not explain the localisation of alkaline magmatism to a narrow band near the Moine Thrust Zone.

The Loch Borralan Pluton, in southern Assynt, is divided into early and late suites (Woolley, 1970), the former being dominated by silica-undersaturated rocks that include pyroxenites and nepheline syenites (see (Table B)). Ultrapotassic rocks ('pseudoleucite syenites'), containing white spots made of nepheline and potassium-rich feldspar replacing the potassium-rich feldspathoid leucite, are mainly confined to the eastern end of the outcrop of the early suite. A carbonatite, which contains xenoliths of nepheline syenite, is emplaced in Durness Group dolostones 400 m outside the main Loch Borralan Pluton, but is most probably related to the early suite (Young *et al*., 1994). The late suite cuts through the undersaturated units and is composed of silica-saturated or quartz-bearing alkali feldspar syenites. The relationships between the multiplicity of rock types in the early suite are difficult to establish because of poor exposure, but strong crystal fractionation, much of it in magma chambers below the present level, is likely to have been involved. The quartz-bearing late suite cannot, however, have been derived directly from the early suite by crystal fractionation; no amount of fractionation can change a magma from being silica undersaturated to silica saturated.

The Loch Ailsh Pluton is less diverse and composed largely of very leucocratic alkali feldspar syenites, some with small amounts of quartz, formed in three magmatic pulses termed S1, S2 and S3 (Parsons, 1965a). As at Loch Borralan, ultramafic pyroxenites occur only where the magmas were in contact with Durness Group dolostone. In places there is clear evidence that some pyroxenites have been produced by reactions between silicate magma and dolomite, but at Loch Borralan there is good evidence that the main mass of biotite pyroxenite is intrusive. The reason for the association with dolostone is not understood. It would require extremely high temperatures to produce magmas of the composition of the diopside-biotite pyroxenites and emplacement as a cumulate mush is probable.

Dykes and sills of the North-west Highlands Minor Intrusion Suite are abundant throughout the Assynt Culmination, but are rare elsewhere (Sabine, 1953; Goodenough *et al*., 2004). The main suite of minor intrusions varies in composition from lamprophyres, through hornblende diorites to per-alkaline rhyolites, all of which have been deformed and were clearly intruded prior to thrusting. These intrusions are unevenly distributed through the thrust sheets. The most basic type comprises dark grey-weathering vogesites (hornblende-bearing lamprophyres) that occur predominantly in the Durness Group dolostones in the Sole Thrust Sheet. In contrast the most evolved type, the brick-red peralkaline rhyolites, mainly occur above the Ben More Thrust, and cut the slightly earlier Loch Ailsh Pluton. There is therefore a hint of regional variation in magmatism prior to crustal shortening. The various types of minor intrusive include both calc-alkaline and alkaline compositions, and are thought to have formed by fractionation from a common parental magma, formed in a mantle source modified by subduction-related components (Goodenough *et al*., 2004).

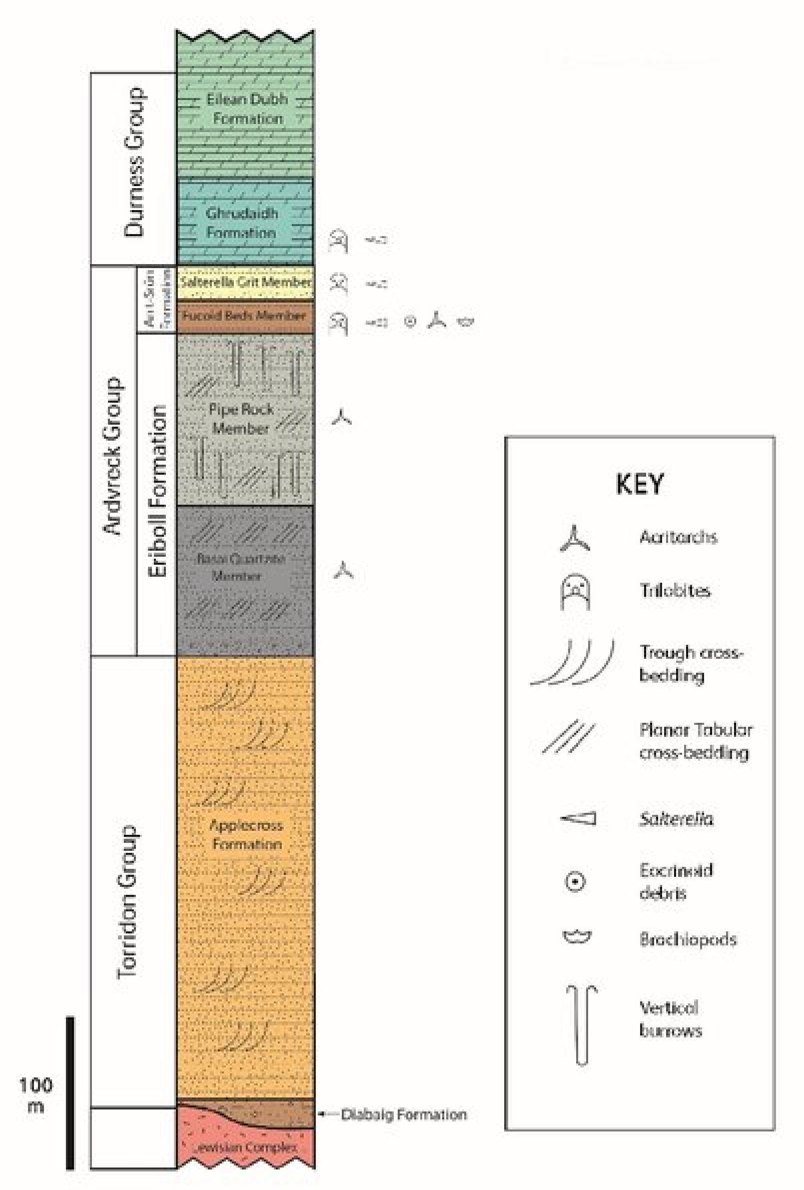
References



(Figure 1) Simplified geological map of the area covered by this excursion guide. CSZ = Canisp Shear Zone; LSZ = Laxford Shear Zone.

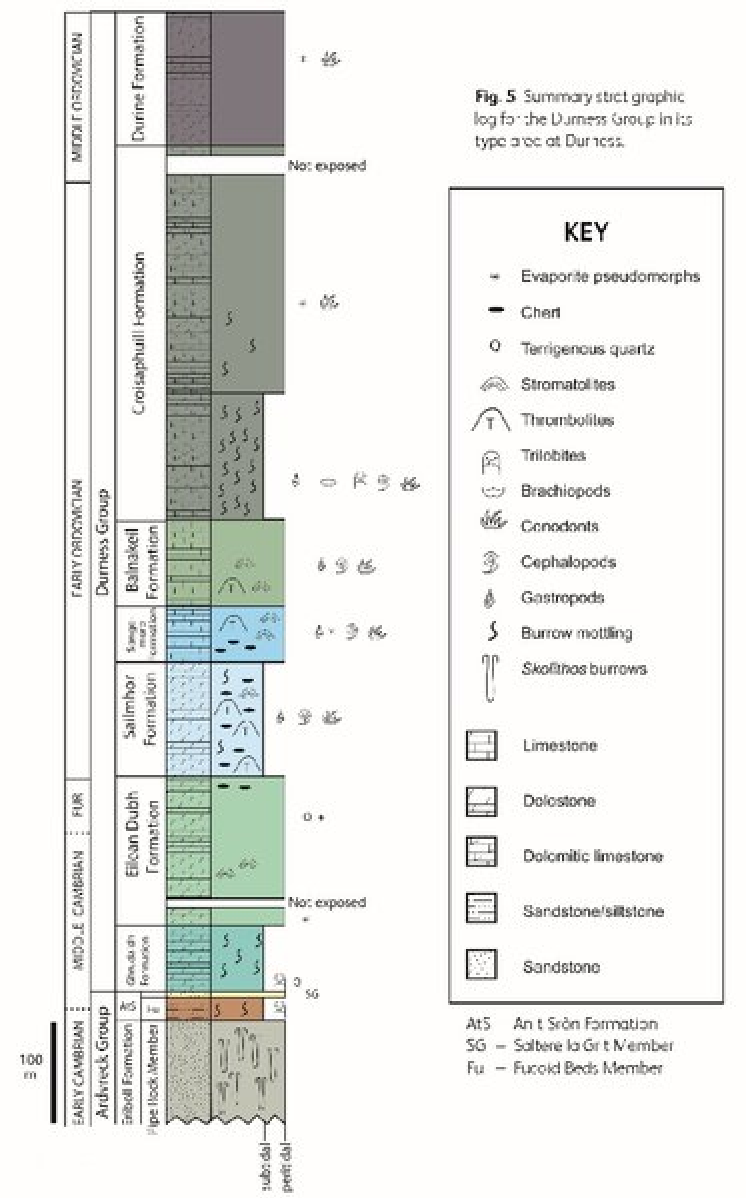
(Figure 2) The 'double unconformity' of Loch Assynt, looking south towards Beinn Gharbh (539m). Arkosic rocks of the Torridon Group (To) unconformably overlie the Lewisian Gneiss Complex (Le); the unconformity is of buried landscape type, with relief of several hundred metres on top of the Lewisian gneisses. The Torridon Group is in turn overlain by quartz arenites of the Lower Cambrian Ardvreck Group (Ar) at a planar, marine unconformity. The two unconformities *intersect to the east (left), such that the Ardvreck Group directly overlies the Lewisian Gneiss Complex. (Photograph: © M. P. Smith).*

(Figure 3) The peaks of Quinag, with quartz arenites which form the Torridon Group sandstones over-highest summits. (BGS Photograph: P670756, © NERC).

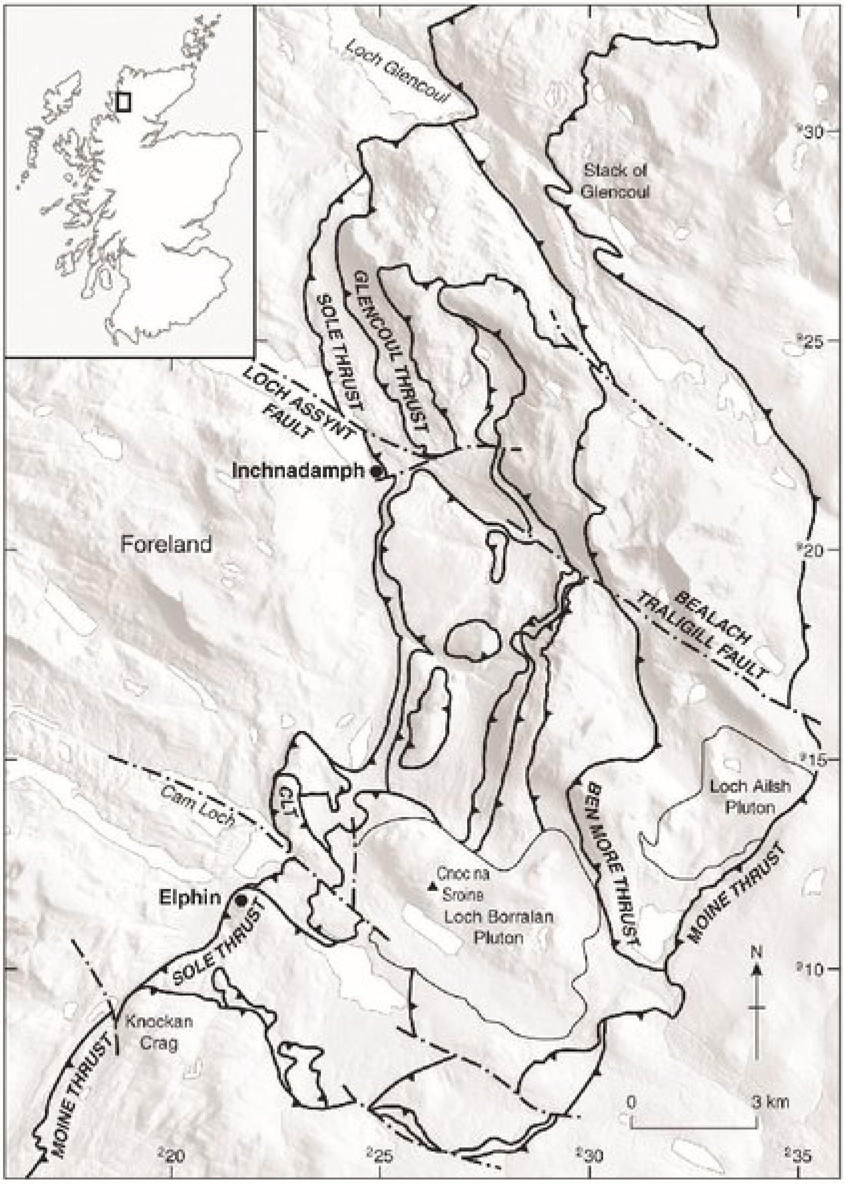


(Figure 4) Summary stratigraphic log for the Torridon, Ardvreck and basal Durness groups as seen in Assynt.

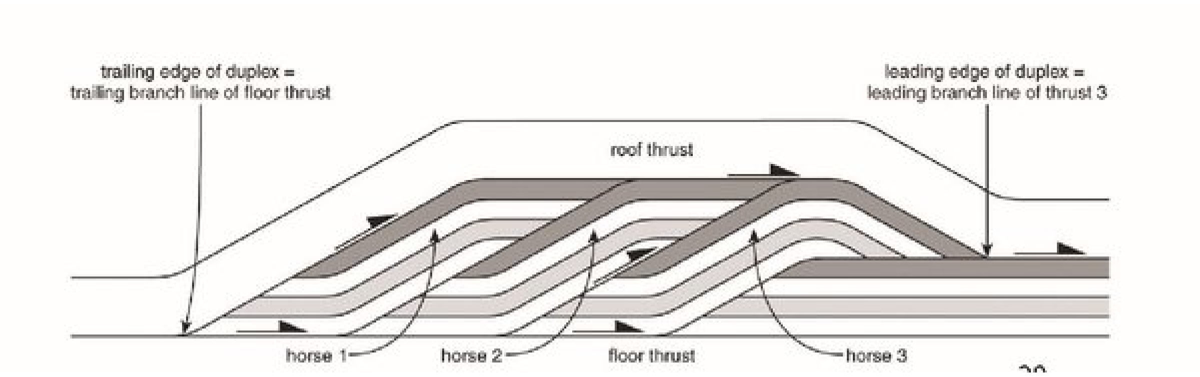
(Table A) Foreland stratigraphical succession



(Figure 5) Summary stratigraphic log for the Durness Group in its type area at Durness.



(Figure 6) Overview map showing the main structural features, thrusts, and intrusions within the Assynt Culmination. CLT = Cam Loch Thrust.



(Figure 7) Illustration of the formation of a duplex, with thrusts propagating from left to right.

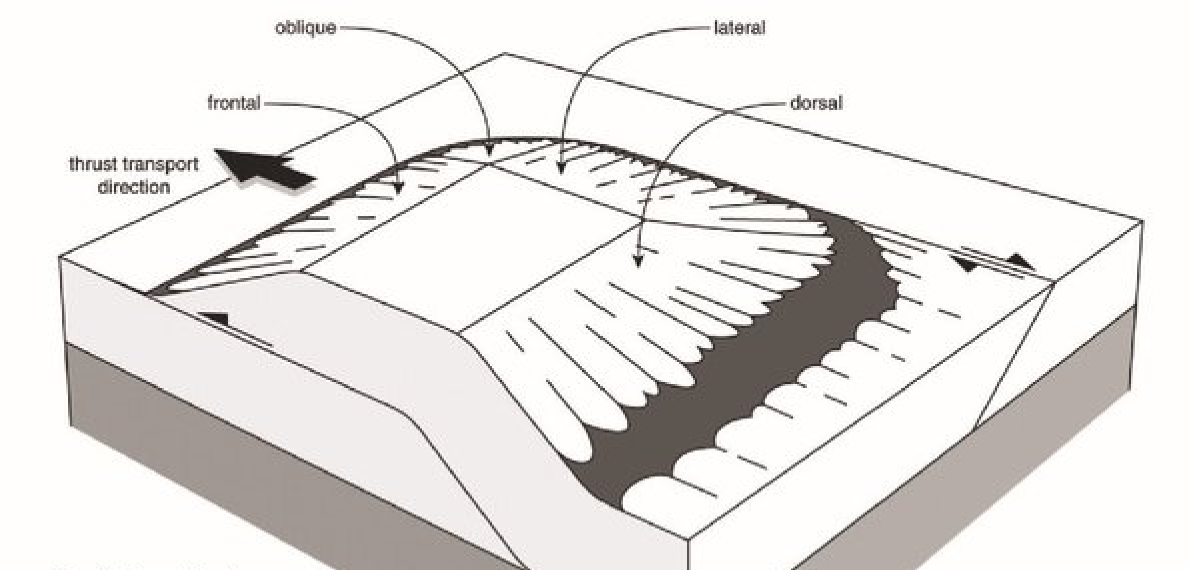
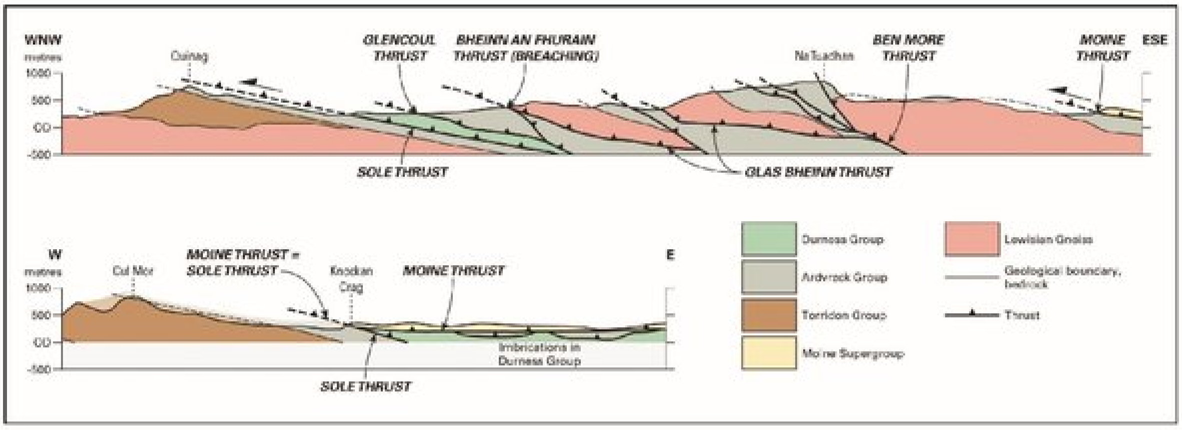


Fig. 8 Simplified illustration showing how a bulge can be formed during thrust movement, with the development of frontal, lateral and dorsal ramps.

(Figure 8) Simplified illustration showing how a bulge can be formed during thrust movement, with the development of frontal, lateral and dorsal ramps.



(Figure 9) 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.