Geological framework of the North-west Highlands - structural units - The Foreland

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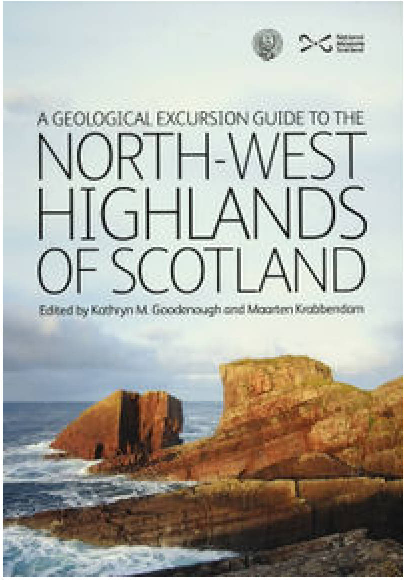

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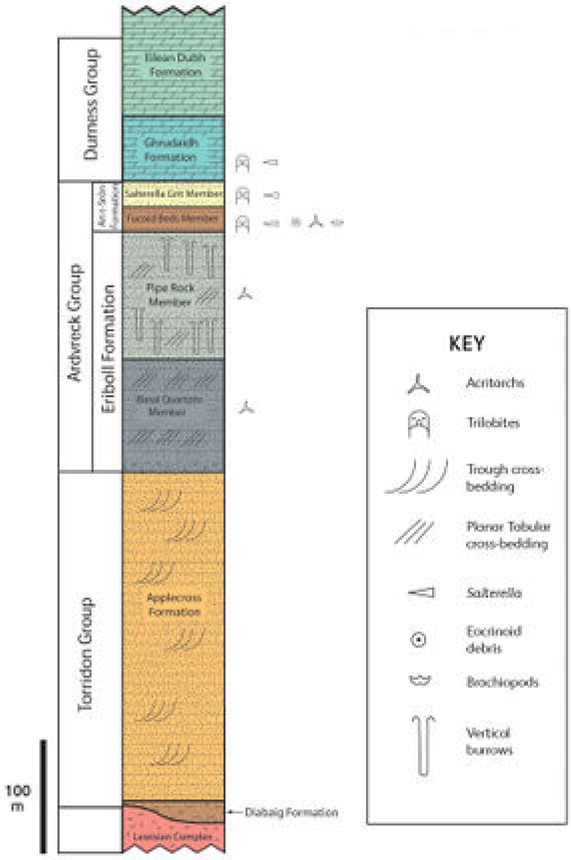
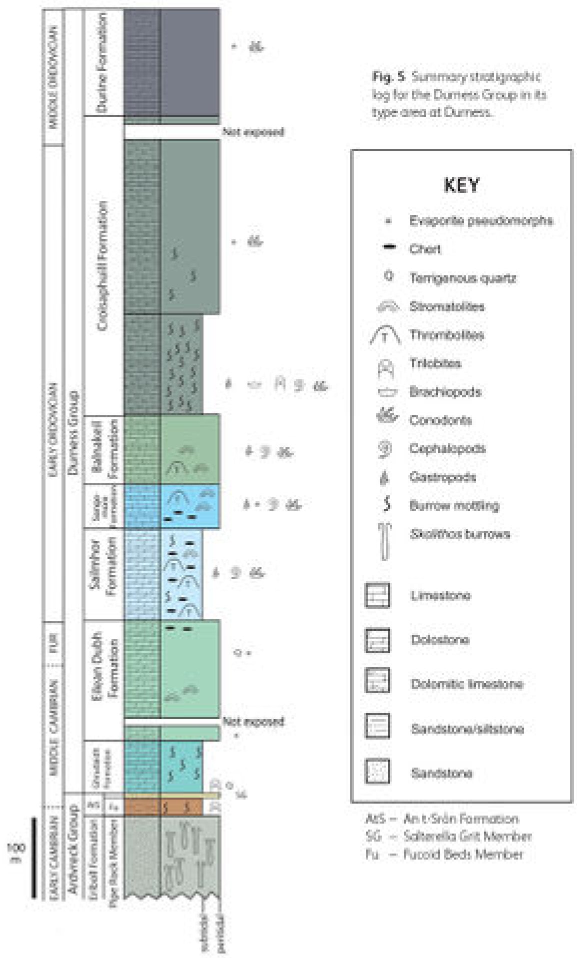
The 'double unconformity' of Loch Assynt, looking south towards Beinn Gharbh (539m). Arkosic rocks of the Torridon Group (To) unconformably overlie the Lewisian Gneiss Complex (Le); the unconformity is of buried landscape type, with relief of several hundred metres on top of the Lewisian gneisses. The 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).

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



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



Summary stratigraphic log for the Durness Group in its type area at Durness.

By Michael Johnson, Ian Parsons, Paul Smith, Robert Raine and Kathryn Goodenough

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Contents

Introduction

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 uncon-formity cuts across the more irregular unconformity between the Torridon Group and the underlying Lewisian Gneiss Complex ((See image)). 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 ((P670756)). 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.

DURNESS GROUP	Durine Formation	Light grey, fine-grained peritidal dolostones	≥ 130	ORDOVICIAN
	Croisaphuill Formation	Mid-grey, burrow-mottled limestones	≥ 350	
	Balnakeil Formation	Mid- to dark-grey dolostone and limestone	≥ 85	
	Sangomore Formation	Light grey and buff finely laminated dolostones and limestones	55	
	Sailmhor Formation	Dark grey mottled dolostones with cherts	115	
	Eilean Dubh Formation	Very light grey dolostones, locally laminated, with stromatolites	≥ 135	
	Ghrudaidh Formation	Lead grey burrow-mottled or massive dolostones	65	CAMBRIAN
ARDVRECK GROUP	An t-Sròn Formation	Salterella Grit Member; quartz arenite and thin siltstones	< 20	
		Fucoid Beds Member; dolomitic shales	12–27	
	Eriboll Formation	Pipe Rock Member; quartz arenite with vertical Skolithos worm-burrows	75–100	
		Basal Quartzite Member; cross-bedded quartz arenite with pebbly base	75–125	

Unconformity: plane of marine erosion				
TORRIDON GROUP	Aultbea Formation	Fine–medium-grained red sandstones, lacking pebbles, commonly with contorted bedding	~ 2000	NEOPROTEROZOIC
	Applecross Formation	Red, trough cross-bedded coarse-grained sandstones and conglomerates showing soft-sediment deformation	~ 3000	
	Diabaig Formation	Breccias, conglomerates, tabular sandstones and mudstones	< 100	
Angular unconformity				
STOER GROUP		Red sandstones and mudstoneswith a volcaniclastic member	< 2000	MESOPROTEROZOIC
Unconformity: old land-surface				
LEWISIAN GNEISS COMPLEX	Rubha Ruadh (Laxfordian) granites Scourie Dyke Swarm			PALAEOPROTEROZOIC
	Mafic and felsic orthogneisses and paragneisses			ARCHAEAN

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) recog-nised 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 (amphi-bolite 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 repre-sent 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 centi-metres to a few kilometres across. Unretrogressed mafic bodies contain clino-and ortho-pyroxene, 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 con-tain 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 amphi-bolite 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 *et al*., 1974; Goodenough *et 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 defor-mation 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 deposi-tion 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 100km; 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-deposi-tional extensional (transtensional) faulting within the sequence; and the existence of opposing palaeocurrents in different units, suggesting alter-nating 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. Palaeo-magnetic 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 forma-tions 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 200m 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 for-mation 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 1km 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 ((See image)); over most of the Assynt area, palaeo-currents 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 100km wide (Stewart, 1982; Williams, 2001), but evidence from sedimen-tary structures suggests a much larger river system (Nicholson, 1993) and detrital zircon ages suggest a more distal source area, possibly the contem-poraneous 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. Sub-sidence 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 10km wide, which stretches 170km 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 uncon-formity' is spectacularly displayed in the Assynt area, particularly on the slopes of Canisp and Beinn Garbh to the south of Loch Assynt ((See image), Excursion 1). The foreland succession in the Assynt area is shown in (See image).

The Eriboll Formation is divided into two members: the older, perva-sively cross-bedded Basal Quartzite Member (75–125m thick); and the overlying Pipe Rock Member (75–100m), 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 sand-stones 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; 12–27m). These iron-and phosphate-rich rocks contain a diverse trace fossil assem-blage 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 back-ground 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* (com-monly 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 935m of peri-tidal and shallow subtidal limestones and dolostones, which record deposi-tion 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 forma-tion 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 ((See image)). Even here, the stratigraphic succession is truncated by thrusting (Excursion 14).

The Ghrudaidh Formation (65m) 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 135m), 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 (115m) 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 con-odonts indicate that there is no significant temporal discontinuity in the succession.

Continuing up-sequence, the Sangomore Formation (55m) comprises generally light grey and buff finely laminated dolostones with some mid-grey thrombolitic limestones and stromatolites. The unit contains a reason-ably 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 85m) 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 350m) 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 boun-dary (Haq and Schutter, 2009). The lower part of the Croisaphuill Forma-tion is richly fossiliferous, yielding diverse and abundant cephalopod, gastropod and conodont faunas.

The youngest unit of the Durness Group, the Durine Formation (mini-mum 130m), 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).

References

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