British Cambrian to Ordovician Stratigraphy

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Chapter 12

Scotland: Cambrian and Ordovician of the Hebridean Terrane

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INTRODUCTION

The Hebridean Terrane is a fragment of the Laurentian craton and is made up of Archean and early Proterozoic gneiss (Lewisian Gneiss), overlain unconformably by thick unmetamorphosed Torridonian sedimentary rocks of later Proterozoic age. These rocks were peneplaned and formed a broad but shallow marine shelf, upon which a thick Cambrian–Ordovician succession was deposited. In places this succession was later involved in the movements of the Moine thrust zone, probably during later parts of the Ordovician.

The Cambrian rocks form a narrow outcrop, mainly of arenaceous rocks, extending with uniform stratigraphy for nearly 200 km, from Eriboll in the north to Skye in the south (Figure 12.1). Overlying these conformably are Durness Group carbonates of Cambrian to Ordovician age; their outcrop is less continuous than that of the arenaceous beds, partly through erosion and partly because in many places they have been scraped off by the Moine Thrust complex. The Durness Group is most completely preserved in a half-graben at Durness.

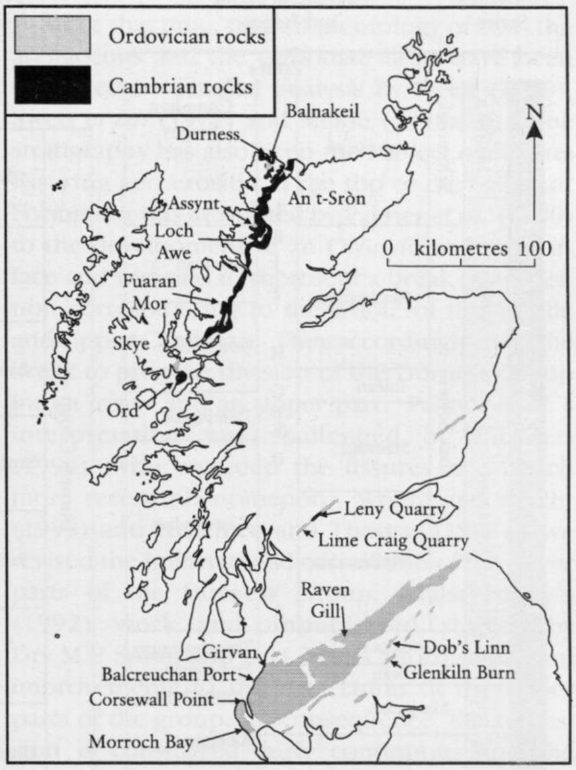

Figure 12.1 Distribution of Cambrian and Ordovician rocks in Scotland, showing the general location of key sites.

There is a long history of research in the region: the complications of the structure defied ready interpretation and led to acrimonious debates during the 19th century. Oldroyd (1990) has given a fascinating account of these, their resolution and the aftermath, together with a list of relevant literature.

The Geological Survey's detailed mapping of the north-west Scottish Highlands, described by Oldroyd (1990, p. 265) as 'one of the outstanding pieces of geological work accomplished in the nineteenth century', formed the basis of all subsequent work. A full account is given in Peach *et al.* (1907), a work that proved so comprehensive that for many years little new research was undertaken on the Cambrian and Ordovician rocks. Pioneer sedimentological studies (e.g. by Swett and Smit, 1972) have been revised and extended by McKie (1990a, 1993). There have been important new studies of the lower parts of the Durness Group (Nicholas, 1994; Wright and Knight, 1995; Huselbee and Thomas, 1998), whilst new work on faunas from the upper parts of the group is valuable for correlation. Fortey (1992) wrote on the trilobites, but much other work is still unpublished; however, Drs D.H. Evans and M.P. Smith have kindly made the results of their work available in advance of publication. Geological guides to various sections have been published, e.g. by Macgregor and Phemister (1972) and Bell and Harris (1986).

The Cambrian–Ordovician succession is of great importance. The uniform and recognizable stratigraphy formed a basis for the mapping and interpretation of what is in general a very complicated and intractable region. The rocks furnish evidence that enables palaeogeographical and environmental interpretations and yield fossils that provide constraints on the geological history of the craton margin and on the timing of movements on the Moine Thrust belt. The faunas are exclusively of warm-water Laurentian type and, having nothing in common with coeval cooler-water faunas in England and Wales, gave some of the first-described and best evidence for the former existence of the barrier to migration known as the Iapetus Ocean.

The stratigraphical succession adopted here is shown in Figure 12.2. It follows McKie (1990a), except that his 'Lower Member' is replaced by the old name 'False Bedded Quartzite', treated as a member. The principal divisions of the

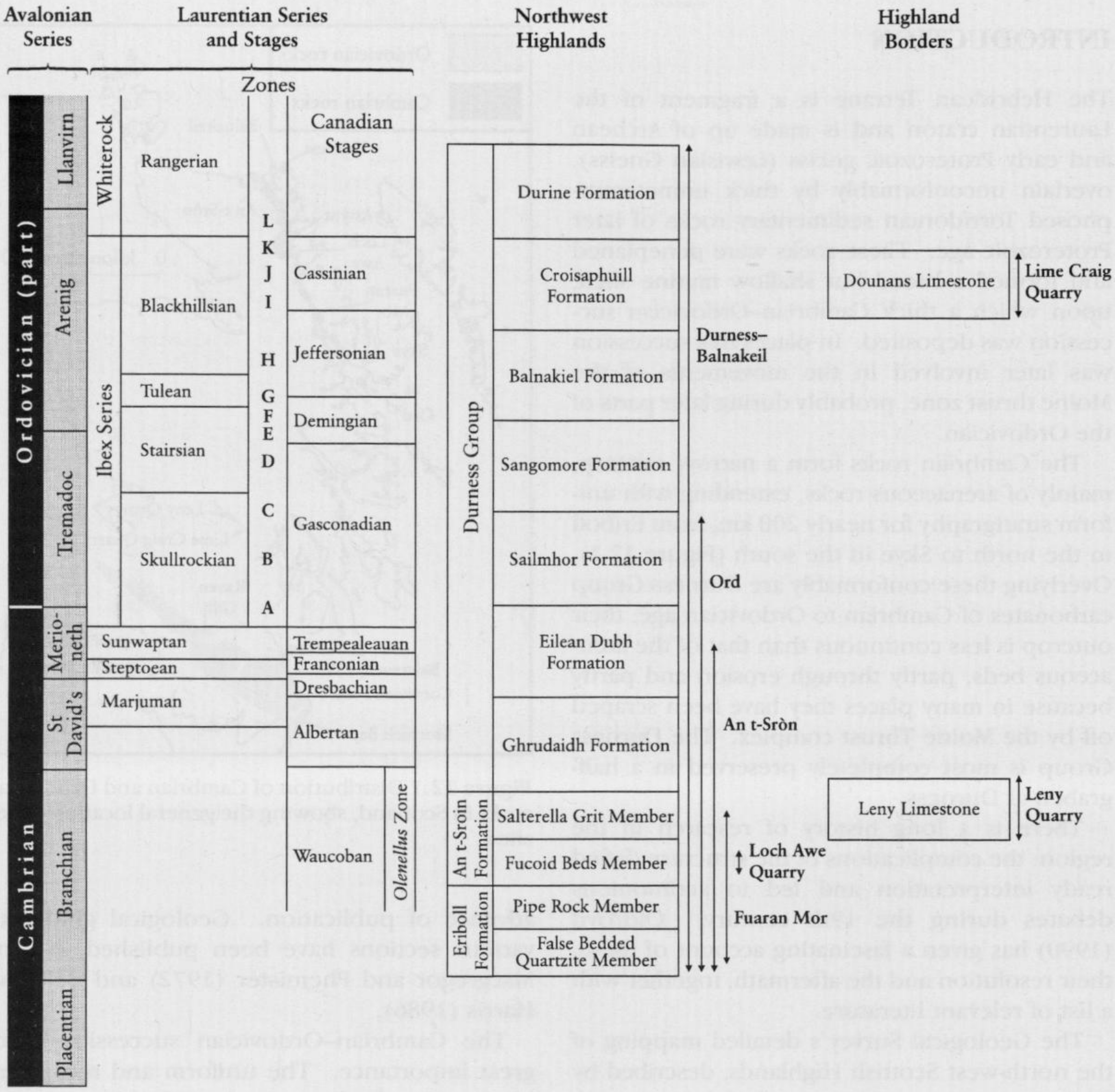

Figure 12.2 Stratigraphical succession in the north-west Highlands of Scotland, correlated with Laurentian (North American) chronostratigraphy; the scheme for the Ibex and Whiterock follows Ross *et al.* (1997), the older stages of the Canadian Series being retained for reference to the succession of cephalopod faunas. The Avalonian standard is also shown for comparison. The Leny and Dounans limestones occur along the Highland Boundary fault complex, and their stratigraphical settings are discussed in the text.

Durness Group (which have been individually mapped) are treated as formations, following Cowie *et al.* (1972), not members.

The fullest stratigraphical succession is seen at Durness and Balnakeil, but the arenaceous basal part is better exposed and interpreted at the historic site at An t-Sròn. The most important fossil localities in the Fucoid Beds are at Fuaran Mor, where the trilobites are the most complete and varied, and at Loch Awe, where they are the most numerous, if fragmentary. The site at Ord is of special interest because it shows the lateral persistence of the stratigraphical sequence to the south-westerly limit of its exposure.

DURNESS AND BALNAKEIL (NC 358 687, NC 361 630, NC 389 657 AND NC 372 676–NC 425 668)

Introduction

The Durness area is much the most important site for the Cambrian–Ordovician stratigraphy of the Hebridean Terrane in north-west Scotland. It shows the most complete representation of the Laurentian foreland sequence and is the type area for the Durness Group.

The site is extensive, covering parts of the shore of the Kyle of Durness, Balnakeil Bay (the older spelling was 'Balnakiel') and the areas to the south and east of Durness (Figure 12.3). The rocks range from the unconformity at the base of the arenaceous Eriboll Sandstone Formation, through the An t-Sròn Formation to the carbonates that make up the entire known thickness of the Durness Group, all seven formations of which are exposed in the area. A Cambrian age is accepted for the lower units, from the basal unconformity to very near the top of the Eilean Dubh Formation. The overlying Sailmhor and Sangomore formations are of Tremadoc age, and the Balnakiel, Croisaphuill and Durine formations are of Arenig and possibly early Llanvirn age.

For 140 years geologists have recognized the close resemblance of the Durness carbonate rocks and their fossils to those of eastern Canada (e.g. north-west Newfoundland), whereas equivalent rocks in Wales bear no resemblance and the faunas have no species in common. These contrasts provided key evidence for the concept of a proto-Atlantic (or Iapetus) Ocean and led ultimately to the modern understanding of Cambrian–Ordovician palaeogeography in the North Atlantic region, in which it is postulated that the sequences in Scotland and Wales were deposited on opposite sides of a wide oceanic barrier. Thus Durness is a key site, both for the excellent exposures of the stratigraphy and for the international implications for correlation and palaeogeography.

Macculloch (1836), Cunningham (1841) and Nicol (1857) had worked on the Durness area, but it was Murchison who first made a detailed study of the Durness Group (Murchison, 1859), whilst the fossils that Charles Peach had collected from the area were described by Salter (1859) as 'lower Silurian' (rather than Devonian or Carboniferous, as had earlier been supposed). The region was visited by many of the combatants, notably Lapworth, during the years of the Highlands controversy (Oldroyd, 1990), but only after the controversy had been resolved was the stratigraphical succession described in detail by Peach *et al.* (1907); their work remains the most comprehensive summary of the stratigraphy and structure of the area.

Since that time, the sedimentology of both the arenaceous and the carbonate units have been subjected to detailed analysis by Swett (1969), Swett *et al.* (1971) and McKie (1990a, b). The stratigraphy has also been the subject of debate: fissuring and erosion at the top of the Sailmhor Formation was attributed by Palmer *et al.* (1980) to the development of an Ordovician karst surface and was said to represent a break in deposition corresponding to the whole of the Middle and Upper Cambrian. They accordingly used the break to propose division of the Durness Group into a lower and an upper part. Palmer *et al.*'s interpretation was challenged by Nicholas (1994), who regarded the fissures as a much more recent phenomenon. Wright and Knight (1995) and Huselbee and Thomas (1998) have revised the international correlation of the lower parts of the Durness Group, whilst Fortey's (1992) work and unpublished studies by Drs M.P. Smith and D.H. Evans afford significant improvements to the correlation of the upper parts of the group. In consequence, the succession is considered fairly continuous and the Durness Group does not fall naturally into lower and upper parts.

Description

The Cambrian strata of Durness form a triangular area about 14 km long and up to 5 km wide, known as the Durness Basin (Figure 12.3). The strata were once continuous with those at Eriboll (see the An t-Sròn site report) but have been isolated from that outcrop by the action of two sets of normal faults, one extending NNE–SSW and the other trending almost perpendicularly. These faults have brought the Cambrian–Ordovician strata down to sea level. The structure of the Durness Basin contrasts sharply with that elsewhere in the Highlands, with normal faulting rather than thrust-faulting controlling the outcrop pattern.

The oldest strata lie on the western shore of the Kyle of Durness, north of Daill (358 687), where there is evidence for a double unconformity – the basal Cambrian quartzites rest on the Precambrian Torridonian Sandstone, which in turn rests on Lewisian Gneiss. Red Torridonian sandstones and conglomerates dip gently south and form a scarp, whereas 100 m to the east there are quartzites of the Eriboll Sandstone Formation dipping ESE at about 15°, giving clear evidence of angular unconformity between the

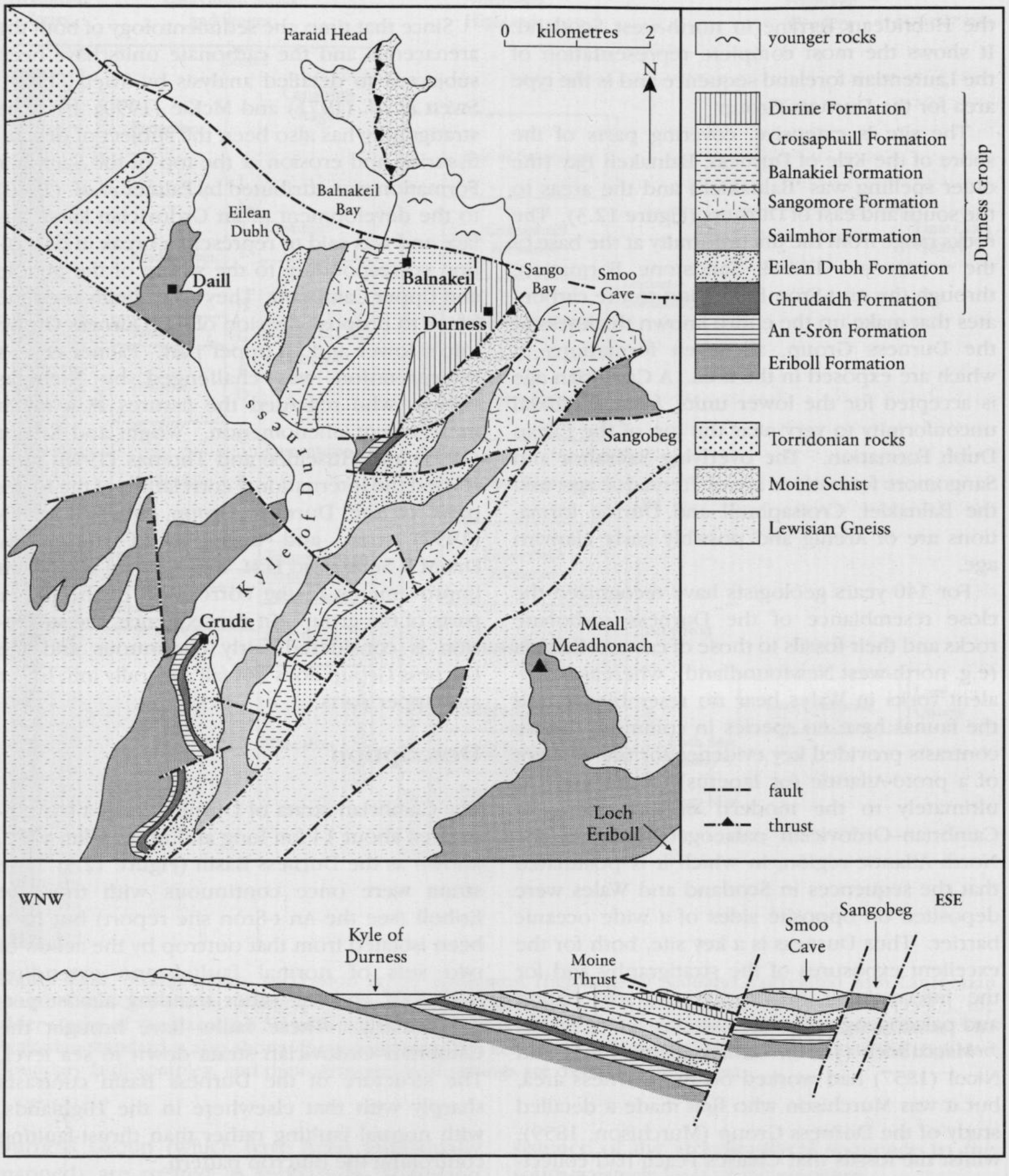

Figure 12.3 Geological sketch-map of the Durness area, after Geological Survey of Scotland (1893), and schematic section from near Daill to Sangobeg (about 10 km), after Peach *et al.* (1907, fig. 20).

Torridonian Sandstone and the Cambrian (Figure 12.3). Farther north, the Cambrian sediments overstep the Torridonian Sandstone to lie directly on the Lewisian gneissose rocks. There is marked discordance between the planes of foliation in the gneiss and the plane of unconformity.

The False Bedded Quartzite and Pipe Rock members are not very well exposed around Durness, and they are described in more detail in the An t-Sròn site report, though the Pipe Rock can be examined between Smoo House and Sangobeg (4245 6672), where it forms a faulted outlier.

The Fucoid Beds and Salterella Grit members of the An t-Sròn Formation are poorly exposed in the Durness area (partly because the sections are interrupted by the waters of the Kyle of Durness), so both divisions are considered in detail in the reports for other sites (An t-Sròn, Loch Awe and Fuaran Mor), at which they are better exposed. In contrast, the formations of the Durness Group are very well exposed in the Durness area.

The lowest division, the Ghrudaidh Formation, generally consists of about 60 m of lead-grey dolomites that are occasionally mottled. The formation takes its name from the house 'Grudie' (361 632), at the head of the Kyle of Durness (on the Geological Survey map, Scottish sheet 114 west, of 1889, the formation name was spelt 'Grudaidh', but the 1893 re-issue spelt it 'Grudie', and later Peach *et al.* (1907) used 'Grudhaidh' or 'Ghrudaidh', the last of which seems the most generally used). The formation is exposed by the shore of the Kyle and on the hill slopes around Grudie, where it shows scarp and slack topography. The beds dip ESE at about 15° and strike up the side of Sithean Mor to the south. Some beds are massive, thickly bedded and coarsely crystalline; others are more thinly bedded and fine-grained. Oolitic limestones are found in the middle of the sequence, a typical example being 30 cm thick and occurring within well-bedded dolomites. The oolites are dark-grey in a paler matrix. The base of the Ghrudaidh Formation is not exposed at Durness but is described at An t-Sròn (see site report).

The Eilean Dubh Formation is composed of thinly bedded flaggy dolomites with an abundance of sedimentary structures. East of Grudie the contact with the Ghrudaidh Formation is not seen, but the paler-coloured, sometimes red-stained rocks of the Eilean Dubh Formation can be seen overlying it on Sithean Mor and form the rest of the exposures on the shores of the Kyle. Farther east, the Sailmhor Formation, dark-grey limestones with abundant prominent chert nodules, extends southwards from the mouth of the River Dionard (3643 6250) to the bridge. These beds are described in more detail below.

The lower divisions of the Durness Group are exposed on the hillside between the road and Cnoc na Mòine 2 km south-west of Durness (389 657). The Ghrudaidh Formation occurs as both massive, coarsely crystalline units and finely crystalline, thinly bedded units, dipping ESE at 12°. *Planolites* burrows occur in places, giving the rock a mottled appearance. *Salterella* is recorded hereabouts (loc. 9a of Peach *et al.*, 1907, p. 626). Higher up the hillside, thinly bedded flaggy dolomites of the Eilean Dubh Formation occur as pale grey and occasionally pink beds, whose bases may be irregular and show load structures. Flaggy units between more massive beds show ripple cross-lamination and parallel lamination. These beds crop out with a scarp and slack topography. Near the hilltop are laminated, domal stromatolitic structures.

The best exposures of the beds above the Ghrudaidh Formation are on the shore of Balnakeil Bay (372 676–389 688), where there is a continuous succession from the Eilean Dubh Formation into the Balnakiel Formation (Figure 12.3). The Eilean Dubh Formation is called after the island of Eilean Dubh, and at the headland opposite this island are thinly bedded pale-grey dolomites, dipping south-east at 25° and estimated at 120–200 m in thickness. Large dome-like structures (Figure 12.4) with algal layers of *Cryptozoon* type characterize a stromalitic horizon that can be traced down the cliffs to the sea. Between the more massive algal horizons, fine-grained beds a few centimetres thick show parallel and cross-lamination, with scoured and loaded bases. Beds of lenticular mud-flake conglomerate occur. Apart from algae, macrofossils are not recorded from the Durness area, but the Cambrian age of most of the formation is constrained by conodonts, which indicate that the Cambrian–Ordovician boundary lies a few tens of centimetres below the top of the Eilean Dubh Formation (Huselbee, 1997; Huselbee and Thomas, 1998).

Strata of the Eilean Dubh Formation, which are easily eroded, extend along the foreshore and in the low cliff face for about 200 m, beyond which a 10–15 m high cliff (378 688) shows the best known contact with the more resistant dark-grey dolomites of the Sailmhor Formation (Figure 12.5). This formation, about 150 m thick, consists of massive granular dolomites, with the spectacular dark-grey and white mottling that led to local use of the term 'leopard stone' (or 'leopard rock') for the formation. This mottling is due to differential dolomitization of branching burrow systems (cf. Palmer *et al.*, 1980). Chert is extensively developed, both as nodules up to 30 cm across and as finely laminated layers, commonly associated with

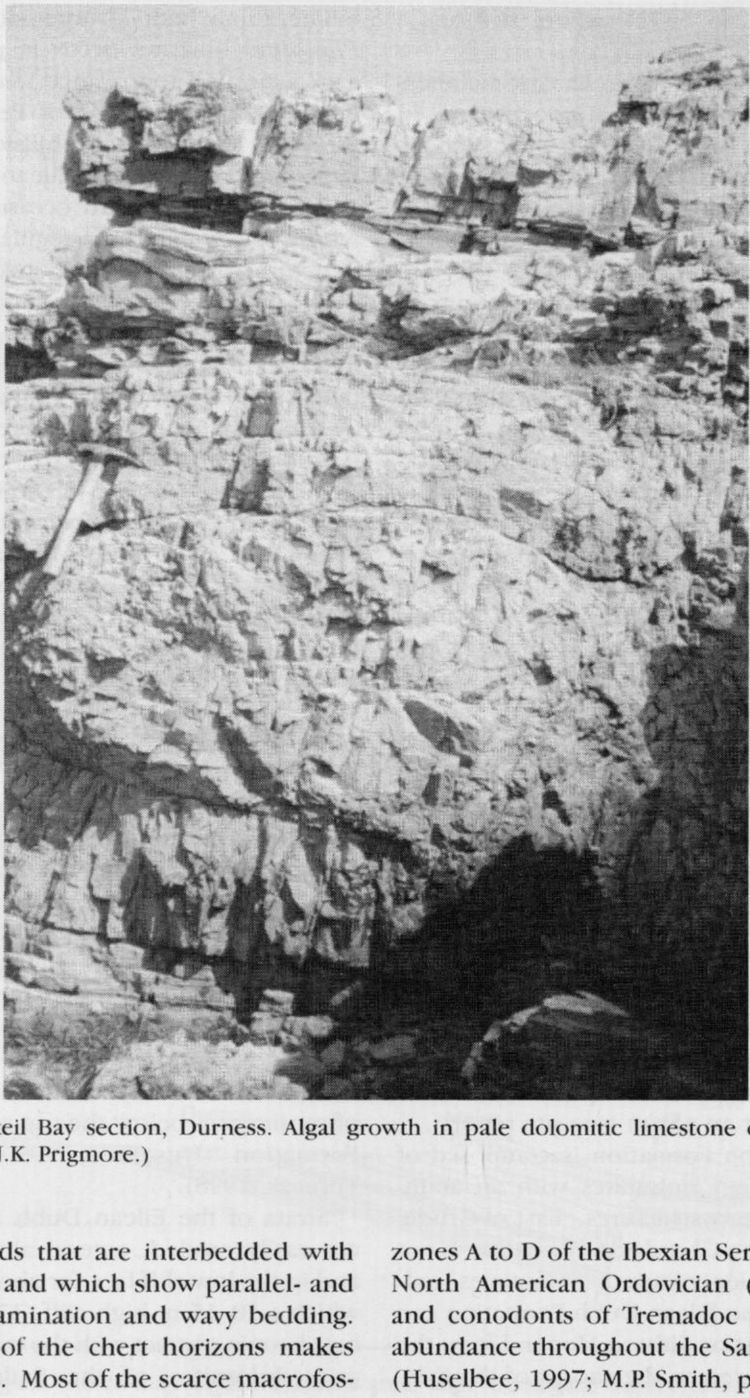

Figure 12.4 Balnakeil Bay section, Durness. Algal growth in pale dolomitic limestone of the Eilean Dubh Formation. (Photo: J.K. Prigmore.)

paler-coloured beds that are interbedded with the leopard stone and which show parallel- and occasional cross-lamination and wavy bedding. The light colour of the chert horizons makes them conspicuous. Most of the scarce macrofossils recorded are Mollusca (Peach *et al.*, 1907). The gastropods *Euconia etna* (Billings) and *E. ramsayi* (Billings) are also both recorded from the Croisaphuill Formation, but the single trilobite recorded is not available for reassessment (Fortey, 1992). However, Dr D.H. Evans (pers. comm., 1997) has noted species of the cephalopods *Ellesmeroceras* and *Walcottoceras*?, indicative of the Gasconadian stage of the Canadian Series (cf. Flower (1978); roughly zones A to D of the Ibexian Series of the western North American Ordovician (see Figure 12.2) and conodonts of Tremadoc age occur in low abundance throughout the Sailmhor Formation (Huselbee, 1997; M.P. Smith, pers. comm.).

The breccias described by Palmer *et al.* (1980) consist of angular fragments of dolomite, often showing the characteristic mottling of the Sailmhor Formation, with subordinate fragments of chert. They are poorly sorted, with clasts from 1 mm to 20 cm across set at all angles in a finer-grained matrix. Most of the material forming these breccias appears to be locally derived from the Sailmhor Formation. The breccias are perpendicular to bedding and appear to repre-

Figure 12.5 Balnakeil Bay section, looking north. Resistant carbonates of the Sangomore Formation forming a cliff above an eroded platform of the Sailmhor Formation. (Photo: J.K. Prigmore.)

sent fillings of fissures, some of which have been traced down to the top of the Eilean Dubh Formation (Palmer *et al.*, 1980). The upper surface of the Sailmhor Formation, which occurs at the base of a low cliff (3841 6887–3837 6886), is extensively brecciated and was considered by Palmer *et al.* (1980) to represent a karst surface, marking a considerable break in deposition. However, this interpretation was challenged by Nicholas (1994), who regarded the brecciation as a phenomenon of Tertiary or Recent age. Furthermore, evidence from fossils now indicates a relatively continuous succession.

The low cliff above this brecciated surface exposes the basal beds of the Sangomore Formation (up to about 180 m thick), which consists generally of fine granular dolomites. The basal few metres show much chert, occurring as large nodules and laminated layers up to 2 m thick. There is no sign of brecciation in these beds. Access to the overlying exposures is difficult, as they form steep cliffs, consisting of well-bedded, massive, fine-grained, pale-cream-coloured dolomites, with some laminated beds and rare massive units showing burrow-mottling resembling the 'leopard stone' lithology of the Sailmhor Formation. Towards the top of the formation there are bands of pink and cream limestone. An anticlinal fold repeats these beds, along with the basal beds of the Balnakiel Formation. Although no fossils have yet been described from the Sangomore Formation, a fossil locality mentioned by Palmer *et al.* (1980) has yielded a probable *Ellesmeroceras* (Dr D.H. Evans, pers. comm., 1997), which supports evidence from conodont faunas for a Tremadoc age (M.P. Smith, pers. comm., 1997).

At the eastern end of the shore section in Balnakeil Bay, the Sangomore Formation is succeeded by the Balnakiel Formation. This, estimated at over 300 m thick, consists of alternations of dark- and light-grey dolomitic limestones, interbedded in units 5–20 cm thick. Irregular diagenetic nodules of white or pink chert are common. Towards the base of the formation, large *Cryptozoon*-like domal stromatolitic structures occur, resembling those in the Eilean Dubh Formation. Relatively rich shelly faunas are reported from scattered localities, some of which are within the present site. Many genera of gastropods – *Oriostoma, Holopea, Maclurea, Ceratopea*, *Ectomaria*, *Euconia*, *Hormotoma, Lecanospira, Trochonema* – are recorded from both this formation and the

Figure 12.6 Smoo Cave, east of Durness. Cliffs of flat-lying Sailmhor Formation overlain in conformable succession by the lower beds of the Sangomore Formation. The height of the cliffs is about 30 m. (Photo: British Geological Survey photographic collection.)

Croisaphuill; of them a few, such as *Hormotoma dubium* Donald, are known only from the Balnakiel Formation. Flower (1978) commented briefly on some of the cephalopods. One, *Dyscritoceras*, occurs in the lowest beds of the Balnakiel Formation and indicates a mid-Ibexian age (zones E–G), which correlates around the Tremadoc–Arenig boundary. Dr D.H. Evans (pers. comm., 1997) reports that higher in the formation there are pilocerids and proterocameroceratids, the latter including *Platysiphon*, which appears to be confined to the Jeffersonian (or Ibexian Zone H) (Figure 12.2). One trilobite, *Jeffersonia timon* (Billings), is known from the Balnakiel Formation SSW of Durness (Fortey, 1992, fig. 1d) and also indicates Zone H.

The overlying Croisaphuill Formation is well exposed in scarp and slack topography south of the Balnakeil to Durness road (around 396 680). It consists of mid- and dark-grey dolomitic limestones, estimated as 145 m thick, partly thinly bedded in units 1–5 cm thick and partly thickly bedded (up to 30 cm thick) and massive, and sometimes burrow-mottled. Abundant chert nodules are developed along bedding planes and exploit the mottling. The shelly fauna has gastropods in common with that of the Balnakiel Formation but also includes the gastropod operculum *Ceratopea billingsi* Yochelson and the trilobite *Petigurus nero* (Billings), neither of which is recorded from lower in the succession. Dr D.H. Evans (pers. comm.) has noted a varied cephalopod fauna: pilocerids include *Cassinoceras*, protocycloceratids include *Protocycloceras mendax* (Salter), tarphycerids are represented by *Aphetoceras* and *Clytoceras,* and the troedssonellid *Buttsoceras* occurs in the upper part of the formation. These cephalopods indicate the Cassinian or high Ibexian zones I to K (Figure 12.2). Higgins (in Higgins and Austin, 1985, p. 44) recorded conodont faunas from near the base of the Croisaphuill Formation.

Exposures of the Durine Formation south of the road lie east of the Balnakiel Formation (400 680) and extend beneath Durness itself. It consists of fairly uniform light grey fine-grained dolomitic limestones, not well-bedded and generally lacking silicification and mottling, and approaches 200 m in thickness. Some beds show a fracture-cleavage, and the highest beds (around 404 675) are overthrust by a mass of Moine Schist. Shelly fossils are rare, but the gastropod *Hormotoma gracile* (Hall) is present, ranging up from the underlying formations. Higgins (1967, in Higgins and Austin, 1985, p. 43) recorded several species of conodonts from various levels in this formation.

East of Durness, a high-angle fault has uplifted the Durness Group such that further exposures of the Sailmhor and Sangomore Formations are seen in the cliffs around the inlet that leads to Smoo Cave (415 679–425 668). The rocks dip to the south-east at 10° or less, and individual beds can be traced right around the headlands. The lower beds, referred to the Sailmhor Formation, are massive fine- to medium-grained dolomites, in beds 10–50 cm thick. Many beds show 'leopard stone' lithology, and chert horizons are common. The contact of the Sailmhor Formation with the overlying Sangomore Formation occurs in the sheer cliffs of the inlet (Figure 12.6). Nicholas (1994) reported that there is little evidence for brecciation, or for an undulating and weathered karstic surface, in the lower part of these cliffs; the outcrops suggest rather that the succession is straightforward, and there is no evidence for a significant break in deposition. The Sangomore Formation in and around Smoo Cave itself consists of cream, white and pink, massive, finely crystalline dolomites and limestones, well bedded in units up to 50 cm thick. Some thinner flaggy beds with parallel lamination also occur.

At Sangobeg, at the eastern end of the site, another fault introduces an outcrop of the Eriboll Sandstone Formation. A small cliff on the eastern side of the bay exposes 7–8 m of massive, thinly bedded, pink-stained quartzites, generally 5–10 cm thick, with thinner sandstones intercalated that pinch and swell laterally and show cross-lamination. To the west, beds with densely packed vertical burrows (which characterize the Pipe Rock Member) include simple pipes (*Skolithos* burrows) and trumpet pipes (*Monocraterion*).

Interpretation

The significance of the Eriboll and An t-Sròn formations is considered under the An t-Sròn site. Swett (1969) studied the carbonates of the Durness Group and considered that they were mainly of biochemical origin, forming in a warm, continuously subsiding shallow sea where the accumulation rate matched the subsidence rate. He proposed the following diagenetic sequence: 1, recrystallization; 2, dolomitization; 3, silicification; 4, calcitization; 5, dolomitization; this suffices to account for the structures, textures and compositions to be seen in the sediments and algal structures. He suggested an original aragonitic or calcitic composition for all the Durness carbonate rocks and considered the chert to be of secondary origin. Swett *et al.* (1971) judged the deposition of all these rocks to be under intertidal to supratidal conditions. The upward changes in texture and mineralogical composition were taken to indicate increasing maturity, reflecting isolation from clastic sources rather than increasing depth of water. However, the presence of burrow-mottling, which tends to occur in conditions interpreted as subtidal, suggests that a substantial part of the succession is of deeper, subtidal origin.

The Laurentian affinities of the faunas of the Durness Group were recognized when they were first described (Salter, 1859) and have been accepted ever since, as discussed by Fortey (1992), who gave a quantified estimate of the affinities of the trilobites. This area provides one particularly striking example of the faunal distributions discussed by Wilson (1966) when he argued for the existence of a proto-Atlantic ocean, now generally accepted and referred to as the Iapetus Ocean. In a wider context, the Cambrian evidence was reviewed by Conway Morris and Rushton (1988) and that for the Ordovician by Fortey and Cocks (1988), all of whom accepted the equatorial position of Laurentia (Figure 1.2).

The age and correlation of the formations of the Durness Group have frequently been discussed, much of the evidence being reviewed by Wright and Knight (1995) and Huselbee and Thomas (1998). The latter authors confirmed the long-held view that the Ghrudaidh Formation is Lower Cambrian, at least in its lower part, by finding *Olenellus* in a thrust horse of the formation in the Assynt district (Figure 12.1). The age of the Eilean Dubh Formation is more contentious (Wright and Knight, 1995, p. 13), on account of the paucity of fossils. Brasier (1977) assigned a late Early Cambrian age to a chert biota collected from near the base of the division in a fault-block near Inchnadamph, Assynt, whilst Nicholas' (1994) study of strontium isotopes suggested that the higher Eilean Dubh is Middle Cambrian or younger. Huselbee and Thomas (1998) collected conodonts from the uppermost parts of the Eilean Dubh, notably the basal Tremadoc taxon *Cordylodus lindstromi* Druce and Jones from the upper 10 cm of the formation. This shows that the base of the Ordovician lies just below the Eilean Dubh–Sailmhor boundary; the appearance of conodonts in the Durness Group at this level may be related to the world-wide earliest Ordovician transgression. A correlation of the barren intervening strata was proposed by Wright and Knight (1995), who made a close lithological comparison between Cambrian–Ordovician successions of Scotland with the succession of western Newfoundland, which is better constrained biostratigraphically. They place the Ghrudaidh–Eilean Dubh boundary close to the Middle–Upper Cambrian boundary, which is in agreement with most other evidence, apart from that of Brasier (1977). Their contention that the Durness and Newfoundland succession is 'largely continuous' is, however, debatable, since the faunas that control the latter sequence are far from being a complete representation of the Cambrian faunal succession in Laurentia; a number of breaks, whilst smaller than those proposed hitherto, may well be present.

Evidence for an early Ordovician age for the Sailmhor and Sangomore formations has been cited, but no details are yet published: Wright and Knight (1995, p. 12) mention a basal Sailmhor fauna with cephalopods that Dr D.H. Evans (pers. comm., 1997) interprets as equivalent to the Gasconadian (approximately Tremadoc), and M.P. Smith (pers. comm., 1997) has recovered Tremadoc conodonts of North American mid-continent provincial affinity throughout both the Sailmhor and the Sangomore formations.

The correlation of the more fossiliferous Balnakiel and Croisaphuill formations with the higher Ibex (or Canadian) Series is better established, and Fortey (1992) has shown that the trilobites from both the Balnakiel and Croisaphuill formations are species known from Zone H of the western North American succession (equivalent to the earlier Arenig). Details of the cephalopods have yet to be published, but Dr D.H. Evans' work suggests that the Balnakiel corresponds to Zone H and the Croisaphuill to Zones I to K: that is, a slightly higher horizon than is suggested by the trilobite *Petigurus,* redescribed by Fortey. The conodonts from the Durine Formation (Higgins, in Higgins and Austin, 1985, p. 43) are typically North American mid-continent forms and are of early Whiterock (about late Arenig or early Llanvirn) age (Bergström in Higgins and Austin, 1985, p. 50).

Conclusions

The Durness area is a site of international significance. It shows most completely the Cambrian and Ordovician strata of a fragment of the Laurentian Plate, formerly a part of North America and now attached to Scotland, and was historically one of the first examples of such a displaced fragment to be recognized on faunal grounds. The Durness area provides the fullest stratigraphical standard by which to interpret the complexities of the Moine Thrust belt in the north-west Highlands of Scotland.

AN T-SRÒN (NC 443 576)

Introduction

The headland An t-Sròn, on the east side of Loch Eriboll, shows the succession of the lower arenaceous units of the Cambrian sequence in northern Scotland, including some important stratigraphical contacts. Evidence at this site proved central to the resolution of the controversy over the stratigraphy and structure of the northern Highlands of Scotland. The Eriboll and An t-Sròn formations (each with two members), are well displayed in the area and are relatively undisturbed by folding or faulting, and the upward transition to the Ghrudaidh and Eilean Dubh formations of the Durness Group is also exposed.

The site at An t-Sròn played a vital part during the Highlands controversy (Oldroyd, 1990, 1996). At that time, Murchison (Murchison, 1860; Murchison and Geikie, 1861) recognized an upward passage from 'quartz-rock' (now termed the 'Eriboll' and 'An t-Sròn' formations) and 'limestone' (of the Durness Group) into 'upper quartz-rock', overlain by 'upper (or 'eastern') gneiss' (Moine Schist). However, the part of Murchison's interpretation involving the 'upper quartz-rock' was based partly on sections inland (east) of An t-Sròn and near Eriboll House, at which he failed to take account of structural complications. Nicol (1861), who had detected evidence locally for stratigraphical inversion, believed that the upper quartzite was a repetition of the lower quartzite, which had been brought up to the east by folding. Oldroyd (1990) described the background to the clash between these workers and the consequences thereof. Nicol's conclusions were partially vindicated by the work of Callaway (1883), but

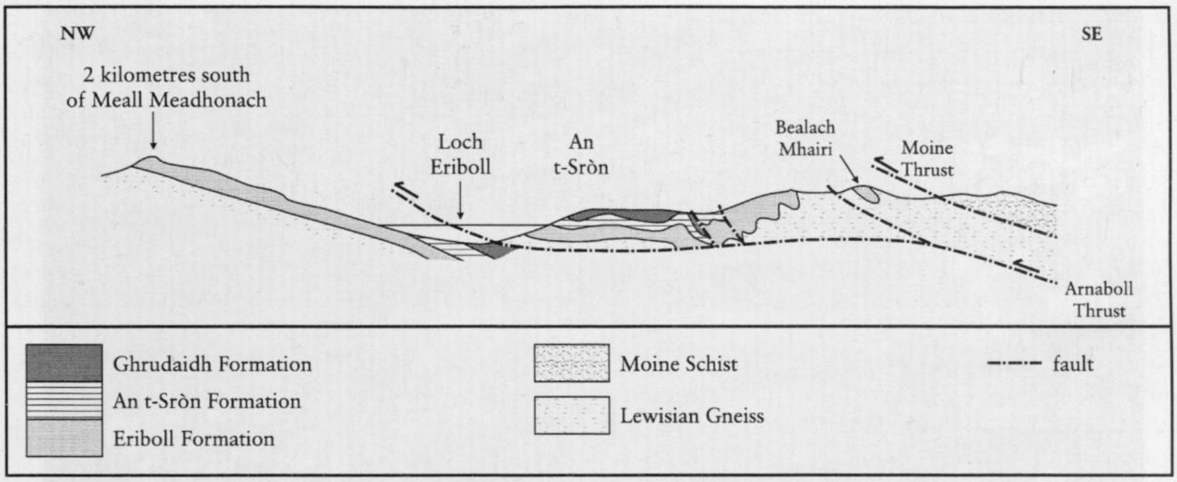

Figure 12.7 Simplified section across Loch Eriboll at An t-Sròn, from Peach *et al.* (1907, figs 20, 21). The length of the section is about 7 km.

more far-reaching were the results of Lapworth's (1883) detailed mapping. He used the succession at An t-Sròn as a stratigraphical standard and, having mapped the surrounding area in great detail, was able to elucidate the structure and show that the upper quartzite was an isoclinal repetition of the lower quartzite; more importantly, he demonstrated the significance of overthrusting along the Moine Thrust belt. The Geological Survey adopted the same ideas and extended the mapping regionally (Peach *et al.*, 1888) and subsequently gave a detailed description of this area (Peach *et al.*, 1907, pp. 481–486).

Description

The coastal sections around the An t-Sròn headland and to the south show a complete sequence from the Pipe Rock Member of the Eriboll Sandstone Formation to the Eilean Dubh Formation of the Durness Group. The strata are arranged in a gentle, open anticline (Figure 12.7). On the most northerly point of the headland (4425 5820), the Pipe Rock Member dips at about 12° to the south-west and consists of medium- to coarse-grained quartzites. Beds vary from 5–50 cm thick and are often well jointed. The vertical *Skolithos* burrows (or 'pipes') that give the formation its name can be seen in plan view on many bedding planes, where they are closely packed and weather out as prominent knobs. Peach *et al.* (1907) divided this member into several units based on the differing character of the 'pipes', but these have not been substantiated in practice.

About 60 m southwards from the headland is a low cliff, the base of which shows white quartzites of the Pipe Rock Member but the higher parts of which expose brown-weathering, thinly bedded shales and dolomites characteristic of the Fucoid Beds Member of the An t-Sròn Formation (Figure 12.8). There is a deeply weathered unit at the base of the Fucoid Beds that exhibits bi-directional cross-lamination, above which is a massive sandstone 50 cm thick. Upwards, there are thinly bedded mudstones and siltstones and more massive dolomites about 5 cm thick, weathering to a buff-brown colour; these contain numerous flattened *Planolites* burrows ('fucoids'). The section along the coast from this point was described by Peach *et al.* (1907).

Higher in the sequence, the Fucoid Beds show flaggy, dolomitic sandstones with thin intercalations of dolomitic mudstone. These sandstones are generally 10–15 cm thick but can reach 30–50 cm; they commonly show parallel lamination and occasionally cross-lamination and extend to a small headland (4400 5805). Towards the top of the promontory are the massive quartzites of the Salterella Grit Member, which slope down to meet the shoreline at the southern end of the small bay beyond it. In the slopes at the back of the bay the highest part of

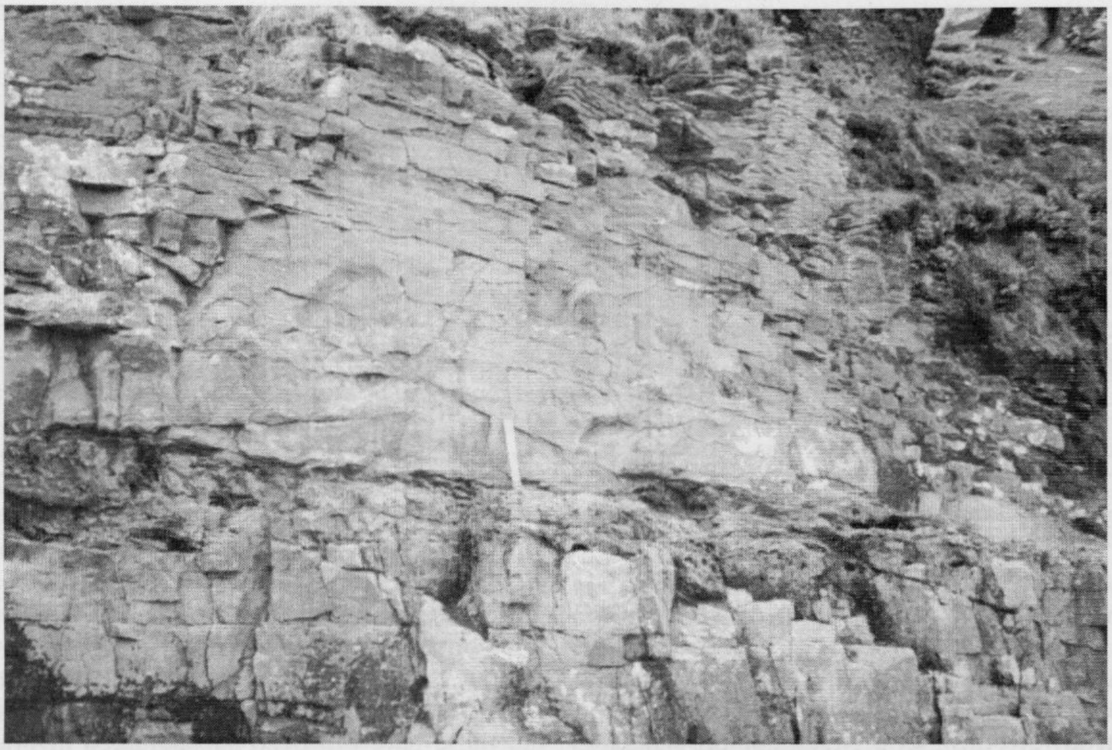

Figure 12.8 An t-Sròn. Pipe Rock Member of the Eriboll Formation overlain by the Fucoid Beds Member of the An t-Sròn Formation. The contact lies at the base of the thinly-bedded weathered unit a little below the hammer-head. (Photo: J.K. Prigmore.)

the Fucoid Beds Member underlies the Salterella Grit Member (Figure 12.9). The highest Fucoid Beds consist of fine-grained, cleaved, fissile shales, which weather to a cream-buff colour but are grey-blue when fresh; a bed a few centimetres thick within them has yielded fragments of *Olenellus* (identified as *O. reticulatus* in Peach *et al.*, 1907, p. 628). This bed closely resembles the *Olenellus* layer in the section exposed at Fuaran Mor (see site report).

The Salterella Grit Member consists mainly of thickly bedded quartzites that show large-scale cross-stratification, defined by darker layers. The highest 2 m of these beds consist of pink dolomitic sandstones that are deeply weathered with very distinct surfaces and are pierced by large, vertical burrows and crowded with tubes of *Salterella maccullochi* (Salter). This distinctive horizon marks the top of the arenaceous units of the Lower Cambrian; and the rocks pass upwards into the dolomitic Ghrudaidh Formation of the Durness Group. The actual boundary forms a slack feature in the cliff. Dolomitic limestones characteristic of the Ghrudaidh Formation, thinly bedded, dark-grey and sometimes mottled, occur for some distance along the coast, dipping south-west at about 40°. The sequence is punctuated at intervals in its upper part by white flaggy dolomites, with layers that show fine parallel lamination and some silicification, and also by a deeply weathered dolomitic horizon (Peach *et al.*, 1907). Folding may cause some repetition of these strata before they pass upwards into the fine-grained, flaggy argillaceous dolomites and limestones of the Eilean Dubh Formation that form the remainder of the exposures southwards along the coast.

Representatives of the various divisions described in the coast section can also be seen on the low hillside above and in the road cutting. The roadside above Kempie House shows the Pipe Rock in the core of an anticline, with Fucoid Beds on either side. Northwards up the road and round the corner, the Salterella Grit and Ghrudaidh formations occur in sequence, although the outcrops become complicated by folding. A good view of the outcrops on the headland of An t-Sròn can be obtained from the roadside to the north. The Pipe Rock quartzites form a prominent feature, and their upper contact with the Fucoid Beds can easily be discerned striking up the hillside.

Figure 12.9 An t-Sròn Formation at An t-Sròn. Thinly-bedded unit at the top of the Fucoid Beds Member overlain by massive arenites of the Salterella Grit Member. (Photo: J.K. Prigmore.)

Eastwards from the broad anticline exposed at An t-Sròn, the Ghrudaidh dolomites are truncated by a reverse fault that brings the Fucoid Beds back to the surface, arranged in two synclines, each fold containing an outlier of Salterella Grit (Peach *et al*., 1907, p. 482, fig. 21; NC 448 579). The beds exposed in one of these folded structures are exposed on the southern side of the road above Kempie House, where the Fucoid Beds and overlying Salterella Grit are almost vertical. Eastwards, the Salterella Grit is brought into contact with the Pipe Rock by a small thrust (Peach *et al*., 1907). At the corner in the road, white quartzites with vertical *Skolithos* burrows of the Pipe Rock dip steeply towards the ESE; however, the pipe structures occur on the *lower* surfaces of these beds, indicating that the strata here are overturned.

The hillside 1 km east of An t-Sròn, towards Bealach Mhairi, presents an important descending sequence, from the Pipe Rock Member through the False Bedded Quartzite Member to the basal conglomerate, which lies unconformably on Lewisian Gneiss (Figure 12.7). Ascending the hill, the crags are mainly white quartzites of the Pipe Rock Formation. They are isoclinally folded, such that some beds show the pipes on the upper surfaces, while others are inverted and show the openings on the lower surfaces. Towards the top of the hill, quartzites of the False Bedded Quartzite predominate. They dip steeply towards the ESE and are thickly bedded, with large-scale tabular cross-bedding in many beds, having set thicknesses of 8 cm to 1 m. Bi-directional cross-bedding can be seen in adjacent units in places.

Above the prominent ridge formed by the quartzitic rocks, the junction of False Bedded Quartzite with the Lewisian Gneiss can be seen. The thin basal conglomerate that is developed locally at the base of the arenaceous beds can be observed in places on Bealach Mhairi, notably in an outlier of isoclinally folded False Bedded Quartzite (Figure 12.7), measuring approximately 140 m by 650 m (Peach *et al.*, 1907, p. 483). The conglomerate is usually 30 cm to 1 m thick, and pebbles consist of well-rounded quartzite, feldspar and felsite in a cream or greenish matrix. Peach *et al.* (1907) also record fragments of coloured shales. At the junction with the Lewisian, the quartzites and basal conglomerate dip to the ESE at 80° and occur in inverted order, as the beds are overturned; the relationships across this junction suggest a distinct unconformity.

Interpretation

The rocks exposed in the area of An t-Sròn provide historically important sequences through the Cambrian rocks of the north-west Highlands of Scotland. At the coast, the succession through the arenaceous members of the Cambrian, namely the Pipe Rock, Fucoid Beds, Salterella Grit and up into the dolomitic Ghrudaidh Formation, is clear and undisturbed structurally, whereas complicated folding and faulting occurs to the east, considerably affecting the sequence.

The basal conglomerate of the Eriboll Sandstone Formation is well seen to the west of Loch Eriboll (around 400 607), about 6 km north-west of An t-Sròn (Peach *et al.*, 1907, p. 391), resting on the Lewisian and signifying a major unconformity (Figure 12.7), with marine planation of the underlying rocks succeeded by marine transgression (McKie, 1993). At An t-Sròn the basal conglomerate is seen in the isoclinally folded outliers east of An t-Sròn, where it was first detected by Lapworth.

Features of the sandstones of the False Bedded Quartzite indicate deposition on a shallow shelf, under the influence of tidal currents (McKie, 1990a), and the overlying Pipe Rock Formation is taken to represent similar environments. McKie (1993) thought that the dense burrowing was related to intervals with a slower rate of sedimentation, and recognized erosive intervals that signify shallowing. Hallam and Swett (1966) considered that the *Skolithos* and occasional *Monocraterion* burrows characteristic of the Pipe Rock were made by the same organisms, which changed their burrowing habit in response to the rate of sedimentation: slower sedimentation allowed the formation of simple *Skolithos*-type burrows, while rapid sedimentation led to rapid upward movement of the organisms, with the generation of escape structures. Absence of these burrows in some beds may be due to inappropriate thixotropic conditions or to complete bioturbation. The uniform thickness of the Eriboll Sandstone Formation along its entire outcrop suggests that it is tabular, as would be expected of a transgressive deposit, or that the outcrop parallels the strandline of a wedge-shaped deposit (Swett, 1969).

The occurrence at the present locality of an *Olenellus*-bearing horizon in the Fucoid Beds Member allows comparison with other sections, notably that exposed at Fuaran Mor (see site report). Based on detailed studies along the whole outcrop, McKie (1990b, 1993) concluded that the Fucoid Beds represent deposition on a shallow, but deepening, storm-dominated shelf. Coarse-grained, tabular cross-bedded and parallel-laminated sandstones, often seen at the base, represent proximal transport of tractional deposits, possibly under tidal influence. The parallel- and cross-laminated silts and finer sands have erosive bases, indicating shelf erosion during storms, and were deposited from suspension as the storm waned. Palaeocurrents from the cross-laminated divisions suggest north to north-west transport, and this may indicate the dominant direction of transport by storms on the shelf. During fair-weather intervals, which were quiescent, the storm beds became burrowed and echinoderm grainstones, found throughout these beds, accumulated. Coarse sandstones that appear towards the top of the Fucoid Beds, though not exposed in Loch Awe Quarry (see site report), are interpreted as a condensed sequence (McKie, 1990b).

The Salterella Grit, with quartzitic sandstones showing cross-bedding and an increase in grain size, represents a brief marine regression (McKie, 1990c) during which conditions were similar to those in which the Eriboll Sandstone Formation was deposited. Subsequently the transgressive trend continued, with deposition of the carbonates of the Durness Group (see the Durness and Balnakeil site reports). McKie (1993) showed that sedimentation on the Hebridean foreland shelf was sensitive to relative changes of sea level, but his suggestion that the Salterella Grit represents the Hawke Bay regressive event (Palmer and James, 1980) is disproved by the discovery of *Olenellus* in the Ghrudaidh Formation (Huselbee and Thomas, 1998), because it indicates that the deepening that accommodated the Ghrudaidh was already effective at or before the time that the Hawke Bay event commenced. The Ghrudaidh and other formations of the Durness Group are discussed in the Durness and Balnakeil site reports. Huselbee and Thomas (1998) discussed the wider correlation of the Lower Cambrian of the Hebridean Foreland and concluded that the whole sequence lies high in the Lower Cambrian, equivalent to the Branchian Series of Landing (1994), and that the lower and greater part of the Lower Cambrian, equivalent to the Placentian Series, is not represented.

Conclusions

An t-Sròn is important because it exposes sections at which the succession of sandy Lower Cambrian rocks can be demonstrated. It furnishes a stratigraphical standard for the Cambrian rocks of the whole north-west Highlands region of Scotland. Historically, it is the location that provided a vital key to unravelling the structure of the Highlands and where low-angle thrust tectonics were first invoked to interpret British geology.

FUARAN MOR (NG 980 653)

Introduction

The site at Fuaran Mor exposes the most important trilobite locality in the Fucoid Beds Member of the An t-Sròn Formation. Olenellid trilobites there show affinities with species from Greenland, Spitsbergen and Arctic Canada and indicate the *Bonnia–Olenellus* Zone of Lower Cambrian age. This gives the best indication of the age of the Cambrian sequence in the north-west Highlands of Scotland. Fuaran Mor is the type locality for several species.

In 1891 Macconochie collected the first Scottish example of the trilobite *Olenellus* in the Fucoid Beds near Loch an Nid, Dundonnell Forest, and this led to the discovery of the same form at several Fucoid Beds localities, of which Fuaran Mor is the most notable. The trilobites were described by Peach and Horne (1892) and Peach (1894) and have been revised by Lake (1906–1946) and Cowie and McNamara (1978) (see also the Loch Awe Quarry site report, below).

Description

The site Fuaran Mor is named after a shoulder on the northern slopes of Meall a'Ghiubhais, north-west of Kinlochewe and on the south side of Loch Maree. An undisturbed sequence is exposed, ascending from the Precambrian Torridonian Sandstone Group, across the basal Cambrian unconformity and into the arenaceous parts of the Cambrian succession up to the Salterella Grit. The Cambrian succession is truncated by the Kinlochewe Thrust Plane, which brings in the Torridonian Sandstones, the unit that forms the summit of Meall a'Ghiubhais. The thrust plane is almost horizontal and can be traced right around the hilltop (Figure 12.10).

The lower parts of the hill-slopes are formed of red Torridonian sandstones and conglomerates that dip south-east at about 3°. Higher up, the False Bedded Quartzite forms a white escarpment consisting of coarse-grained, thick- to medium-bedded quartzites, with a few pebbly beds dipping to the east at 25°. Many units show cross-stratification, especially in the lower part of the sequence. Above this escarpment, the Pipe Rock Member is exposed as flat bedding planes showing *Skolithos* burrows. Uphill these quartzites form a series of waterfalls in a large stream and show the vertical burrows of both *Skolithos* and *Monocraterion* ('trumpet pipes').

Above the stream another escarpment shows white quartzites at its base and the Fucoid Beds at the top. These consist of brown, earthy-weathering dolomitic siltstones, sandstones and shales. The sandstones form beds up to 10 cm thick (although usually less), are medium- to coarse-grained and often show cross- and parallel lamination, with muddy drapes and shaly partings (Figure 12.11). The mudstones are darker-grey and generally structureless. Further outcrops of these beds can be found in other stream sections nearby. Above these exposures is the Kinlochewe Thrust Plane, which introduces the Torridonian Sandstone that caps the

Figure 12.10 Summit of Meall a' Ghiubhais viewed from the south-west, showing the Kinlochewe thrust plane (K–K). Above the thrust is a nappe of deformed Lewisian, Torridonian and Cambrian rocks. Below it, Torridonian rocks are overlain unconformably by the Eriboll and An t-Sròn formations. (Photo: British Geological Survey photographic collection, C30.)

hill (Figure 12.10). In places, white quartzites of the Salterella Grit occur above the Fucoid Beds and below the thrust, although elsewhere it cuts them out.

A stream section at about 9795 6515 is the most important fossil locality within the Fucoid Beds. It is 7 m in extent; Macconochie (in Peach *et al*., 1907, p. 414) described the several subdivisions. Despite the proximity of the thrust plane, the fossils are barely distorted. They include lingulate brachiopods and hyolithids, but most significant are the olenellid trilobites. These were recorded from several levels, but most interesting are those from the lowest unit, the '*Olenellus* Layer', in which some species are represented by complete dorsal shields – otherwise almost unknown in the Cambrian of Scotland. *Olenellus lapworthi* Peach and Horne is the commonest form, with slightly fewer *O. reticulatus* Peach and rare *O. intermedius* Peach; all these were revised by Cowie and McNamara (1978). This is the type locality for the latter two taxa, as well as for two others, *O. lapworthi elongatus* Peach and *O. gigas* Peach, which are respectively regarded as synonyms of *O. lapworthi* and *O. reticulatus* (Cowie and McNamara, 1978). The remarkable *O. (Olenelloides) armatus* Peach, originally described from the basal layer at this locality, was revised by McNamara (1978).

Interpretation

The Fucoid Beds are interpreted as storm deposits laid down in a shallow shelf sea (McKie, 1990b; see the site report for An t-Sròn). Although the biota of the Fucoid Beds is assembled from material from several localities (Peach *et al*., 1907, p. 628), that found at Fuaran Mor typifies the development of the trilobite-bearing horizons. The trilobites are of Laurentian type and indicate the *Bonnia–Olenellus* Zone of the Lower Cambrian (Cowie and McNamara, 1978), allowing correlation with sequences in the North American 'Pacific Province' in areas such as Greenland, Spitsbergen and Arctic Canada. The absence of similar faunas in England and Wales signifies a palaeobiogeographical barrier between Scotland and southern Britain and implies the existence of the Iapetus Ocean dur-

Figure 12.11 Fucoid Beds Member in the stream section at Fuaran Mor, Meall a' Ghiubhais. (Photo: J.K. Prigmore.)

ing the Early Cambrian (Conway Morris and Rushton, 1988).

McNamara (1978) suggested that *O. lapworthi* was adapted to benthic life in relatively deep, poorly oxygenated water. His morphological study of the other *Olenellus* in the Fucoid Beds led him to postulate that they might all be paedomorphic developments from the *lapworthi* stock (McNamara, 1978, p. 652), variously adapted to different conditions of depth, temperature and oxygen, and that *Olenelloides armatus* was the smallest, possibly planktonic, offshoot.

Conclusions

This site exposes an internationally important fossiliferous horizon, with the greatest variety of Cambrian trilobites and almost all the complete examples known in Scotland. The trilobites are closely related to forms found in the Lower Cambrian of Greenland, Spitsbergen and Arctic Canada but are unknown from equivalent strata in England and Wales, indicating that a barrier to migration existed, i.e. the Iapetus (proto-Atlantic) Ocean.

LOCH AWE QUARRY (NC 250 158)

Introduction

The quarry at Loch Awe has yielded the most prolific trilobite fauna of the Fucoid Beds Member of the An t-Sròn Formation and is the type locality for one species, *Olenellus hamoculus*, which has been made the type species of the subgenus *Olenellus (Angustolenellus)* Palmer and Repina.

The sequence of rocks from quartzites to limestones has long been recognized in the Assynt area (e.g. Macculloch, 1836), although the first recognition of the Fucoid Beds as a separate unit was by Cunningham (1841). Nicol (1857), who examined the strata in the Loch Assynt region, recorded brown shale-like beds, with what appeared to be fucoid (seaweed) impressions, though today these are considered to be *Planolites* burrows. These, the Fucoid Beds Member of the An t-Sròn Formation, provide an important marker band in the stratigraphical sequence in the north-west Highlands of Scotland and are invaluable for mapping purposes. The biostratigraphically vital *Olenellus* fauna, indicative of a Lower Cambrian age, was

Figure 12.12 Loch Awe Quarry, showing the Fucoid Beds Member. The lower beds, massive dolomitic sandstones, are overlain by thinly bedded units which include fossiliferous beds with *Olenellus* (Photo: British Geological Survey photographic collection, D1284.)

detected by the Geological Survey at several localities (Peach *et al*., 1907, p. 628). Generally trilobites are rare and difficult to collect; however, while Bowie *et al*. (1966) were conducting research on the potash content of the Fucoid Beds, Brand (1965) found that beds at Loch Awe Quarry yield large numbers of *Olenellus*, which were described by Cowie and McNamara (1978).

Description

Loch Awe Quarry, situated by the road south of Inchnadamph, exposes about 7–8 m of the Fucoid Beds Member dipping WSW at about 30° (Figure 12.12). The Fucoid Beds generally consist of dolomitic siltstones, with some dolomitic sandstones and shales, carbonates and rare pisolitic ironstones. The lower part of the face at the back of the quarry shows 3–5 m of relatively massive strata, consisting of dolomitic siltstones and sandstones that are thickly bedded and weather brown. Calcite veins are common on joint surfaces. The sandstones and siltstones are generally a few centimetres thick and show sedimentary structures such as parallel lamination, cross-lamination and occasional wave ripples. Structureless, unlaminated mudstones are intercalated. Bioturbation is common, and both vertical burrows and horizontal *Planolites* burrows occur throughout. A few coarser sandstones show sharp erosive bases. Above the massive beds are 2–3 m of shalier strata, consisting of dark-grey dolomitic siltstones and shales with little internal structure. They break with a conchoidal fracture and contain occasional thin laminae of siltstone and fine sandstone.

This site has yielded a large number of trilobites from various horizons, the best-preserved specimens coming from an unbedded mudstone unit some 1.5 m above the top of the calcareous portion of the Fucoid Beds that forms the main mass of the quarry. The dominant species is *Olenellus reticulatus* Peach (Cowie and McNamara, 1978, p. 625), with rarer *O. lapworthi* Peach and Horne and a few specimens of *O. hamoculus* Cowie and McNamara, for which this is the type and only known locality. The trilobites indicate the *Bonnia–Olenellus* Zone of late Lower Cambrian age, as discussed under Fuaran Mor (see site report). Hyolithids, echinoderm fragments (McKie and Donovan, 1992) and inarticulate brachiopods also occur. Faunal details can be found in Brand (1965), Cowie (1974) and Cowie and McNamara (1978).

Interpretation

The conditions of deposition of the Fucoid Beds are discussed under Fuaran Mor (see site report). The species of *Olenellus* described by Peach and Horne (1892) and Peach (1894) were based on few specimens, and it is evident from the discussion in Lake (1906–1946, pp. 238–44) that distinction among them was a matter of uncertainty. The large number of cranidia obtained from Loch Awe Quarry (more than 100 specimens of *O. reticulatus*) enabled Cowie and McNamara (1978) to describe the variation within the species of *Olenellus* and hence to delimit the species, including their new species *O. hamoculus*, with greater clarity.

Potash-rich beds are widespread on the western margin of the Iapetus Ocean. Bowie *et al.* (1966) suggested that the potash in the Fucoid Beds originated from a volcanic source in the underlying Precambrian rocks. However, Swett (1969) pointed to a general lack of volcanic sources in both the Lewisian and the Torridonian and suggested instead that potassium was released during dolomitization from illite, which is present in the overlying limestones.

Conclusions

Loch Awe Quarry is important palaeontologically, in that it exposes a fossiliferous bed that yields the trilobite *Olenellus* in exceptional abundance, enabling the study of populations of this genus. They are much the most useful fossils for dating the lower part of the north-west Highlands of Scotland as of Early Cambrian age and enable correlation with areas in Greenland, Canada and Spitsbergen.

ORD (NG 618 124, NG 615 132–NG 625 142)

Introduction

This site, situated in the Sleat Peninsula, southern Skye, demonstrates the remarkable lateral consistency of the Hebridean Foreland succession. It covers part of the area of the Ord Window, which includes the coastal section from Rubha Dubh Ard to the hamlet of Ord, and an area of hillside to the south of Ord. Despite structural complications, successions are exposed through the Eriboll and An t-Sròn formations, up into the Ghrudaidh, Eilean Dubh and Sailmhor formations of the Durness Group, all of which show features typical of their development nearly 200 km to the north, at Durness and An t-Sròn (see site reports).

The Sleat Peninsula is made up mainly of thrust sheets of Precambrian rocks, but around Ord, where the Torridonian rocks of the Kishorn Thrust Sheet are eroded, the 'Ord Window' reveals an area of the foreland succession. The area was investigated by early workers, such as Macculloch (Peach *et al.*, 1907, p. 420) and Geikie (Oldroyd, 1990, p. 116), but the complications of the thrust tectonics in the area were only fully dealt with by the Geological Survey (Clough, in Peach *et al.*, 1907, p. 417). Much of the present site is described in Excursion 2 of the field guide by Bell and Harris (1986, p. 159). Farther north, near Broadford, there are further outcrops of the Durness Group. These are fragmentary successions associated with the Kishorn Thrust, and are not considered in the present account.

Description

The coastal section north-east of Ord and the hillside south of Ord together expose examples of all the Cambrian and Tremadoc strata represented on Skye. In the coastal section (Figure 12.13) the oldest rocks, occurring on the eastern side of the headland Rubha Dubh Ard (NG 625 142), consist of white quartzites of the False Bedded Quartzite, dipping west at about 60°. Cross-bedding is accentuated by pink staining. Although the basal conglomerate of the unit is not exposed at this locality, Peach *et al.* (1907) described such a conglomerate about 2 km to the south, on the east of Sgaith-bheinn Chrossavaig.

On the western side of Rubha Dubh Ard, the rocks exposed at low tide show the Pipe Rock Member. In the lowest beds, again dipping west at 60°, the *Skolithos* burrows are 1–3 mm across and densely packed. This is the least disturbed section through the Pipe Rock in the area, and Peach *et al.* (1907, p. 418) described the 'zonal' subdivisions of the Pipe Rock there. In the bay, to the southern end of the outcrop of the Pipe Rock, thinly bedded quartzites 5–10 cm thick give way upwards to 10–30 cm thick beds, then

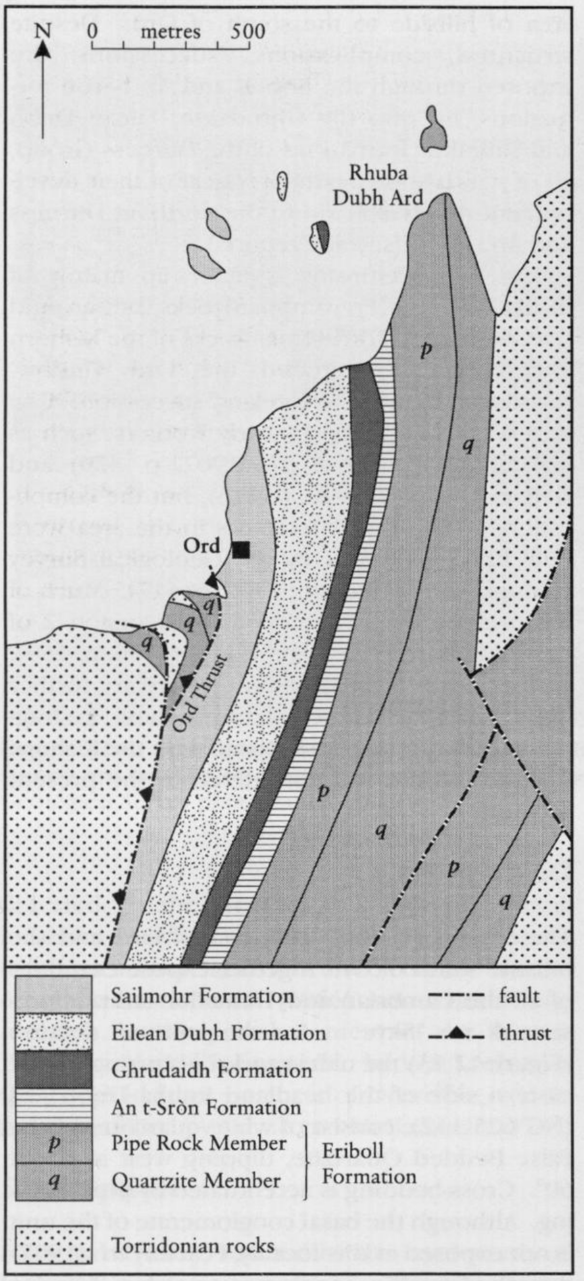

Figure 12.13 Simplified sketch-map of the area of Ord, southern Skye, after Bell and Harris (1986, fig. 16a).

finally to massive, 50–80 cm thick units. These beds are stained pink and the pipes stand out in white.

The Pipe Rock quartzites are followed immediately by the Fucoid Beds. These are brown-weathering sandy shales with thin, yellow calcareous flags, overlain by variegated grey shales with thin, brown sandstone beds. Near the base are beds of dolomitic limestone. *Olenellus* has been found in these beds near Ord but not in the present shore-section. To the south of the house situated on the bay (622 138) is a quartzite that represents the Salterella Grit. A break in exposure where the section is faulted conceals a disturbed repetition of the Fucoid Beds (Peach *et al.*, 1907, p. 419), followed by Salterella Grit.

The beds west of the house consist of a continuation of the Salterella Grit overlain by brown-weathered sandy dolomites that are referred to the Ghrudaidh Formation. These beds are affected by thrusting and are closely followed above by flaggy dolomites of the Eilean Dubh Formation, which are exposed in the headland at the west of the bay, where they are folded. They generally dip south-west at 75° and consist of colour-banded and finely laminated limestones and dolomites, the layers being cream, white, yellow, pink and red. Some layers are coarser-grained and contain clastic grains of quartz. Chert horizons and nodules are common at the base and top of the sequence. The Sailmhor Formation, consisting of massive, granular, dark-grey dolomites with extensive chert development, is exposed in the cliffs and on the foreshore towards Ord. On the foreshore at Ord there are thrust repetitions of inverted Torridonian and basal Cambrian, and on the south-west side of Ord Bay a major fault introduces Torridonian sandstones.

The same general sequence of strata can be seen on the hillside 1.3 km SSE of Ord. The rocks dip NNW at 80°, such that the lowest units occur at the top of the hill (619 121) and successively younger strata are crossed on descent. At the top of the hill, the False Bedded Quartzite occurs as medium to thickly bedded massive quartzites, with few sedimentary structures apart from occasional cross-bedding. To the north-west, the Pipe Rock shows typical *Skolithos* burrows and forms prominent crags at the hilltop. The Fucoid Beds tend to be concealed by gently sloping boggy ground, but farther down the hillside the Salterella Grit forms a prominent ridge of pink-stained massive quartzite. Within a few metres, the Ghrudaidh Formation forms another ridge consisting of dark-grey coarsely crystalline dolomites. Downhill, exposure is sporadic, but the Ghrudaidh Formation gives way up-dip to the cream-coloured, fine-grained limestones of the Eilean Dubh Formation. Finally, the Sailmhor Formation crops out, composed of massive dark-coloured dolomites with chert nodules and layers and with burrow-mottling at some levels.

Interpretation

Despite the tectonic disruption of the Cambrian rocks of southern Skye, it is possible to recognize many of the features that characterize each of the units of the Eriboll and An t-Sròn formations and the lower formations of the Durness Group. From Eriboll in the NNE to Skye in the SSW, the thickness and sedimentological features of the Eriboll and An t-Sròn formations remain remarkably constant. McKie (1993, p. 253) gave a schematic section indicating relative deepening of the shelf to the SSW. Minor lithological changes include a southward increase in the proportion of micaceous shale interbeds in the Eriboll Sandstone Formation (Peach *et al.*, 1907, p. 369) and a southward increase in the proportion of the mudrock component of the Fucoid Beds (McKie, 1993). Likewise, the Ghrudaidh, Eilean Dubh and Sailmhor formations retain such features as their colour and the chert beds, which characterize their development in the Durness-Balnakeil area (see site report).

Conclusions

The site at Ord together with the sites nearly 200 km away on the north Scottish coast, demonstrates the uniformity of the shallow-water Lower Cambrian strata deposited on the edge of the fragment of the Laurentian continent known as the Hebridean Terrane. This uniformity indicates that during the Cambrian the continental margin lay nearly parallel to the present NNE–SSW trend of the Cambrian outcrop.