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Stratigraphy and faunas of the Durness Group (Cambrian–Middle Ordovician) of Northwest Scotland: constraints on tectonic models and the development of the Great American Carbonate Bank

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Abstract

The Durness Group of NW Scotland records deposition on the Laurentian margin from the basal Miaolingian (Cambrian, 509 Ma) to the Dapingian–Darriwilian boundary interval (Middle Ordovician, 470.3–468.9 Ma). The 930 m thick succession of peritidal and subtidal carbonates was deposited on the Scottish promontory, a nearly 120° deflection in the Palaeozoic continental margin between the Appalachian and Greenland sectors. These sediments were deposited as part of the Great American Carbonate Bank, a non-uniformitarian, continent-scale carbonate platform developed on the peneplaned craton. Measurement and description of a bed-by-bed composite section through the Durness Group provide a high-resolution reference framework that integrates conodont biostratigraphy, chemostratigraphy and sequence stratigraphy, including correlation with the Sauk megasequence and its subdivisions. The Sauk II–Sauk III sequence boundary marks the base of the group. The top of the group is faulted against rocks of the Moine thrust zone, generated by the Scandian orogeny, but sedimentation was probably terminated by the earlier Grampian arc–continent collision at 470–469 Ma. The highly mature quartz arenites of the underlying Ardvreck Group (Cambrian Series 2) indicate that there was no source-to-sink depositional continuity from the Hebridean foreland to the Dalradian Supergroup, which has coeval clastic sedimentary rocks of contrasting composition.

1. Introduction

The limestones and dolostones of the Durness Group are the youngest preserved pre-Caledonian sedimentary rocks in Scotland north of the Highland Boundary Fault and were deposited on the Laurentian passive margin. In consequence, the component units inform an understanding of both the development of the passive margin itself and the orogenic activity that terminated sedimentation. Palaeogeographically, the Durness Group was located in an intermediate position between the relatively attenuated carbonate succession of western Newfoundland and the thick, subtidally dominated carbonate succession preserved in the allochthon of North-East Greenland (Swett and Smit 1972a, b; Swett 1981; Smith and Rasmussen 2008). Across much of Laurentia, Cambrian to Ordovician sedimentation can be divided into a lower siliciclastic unit and an overlying carbonate succession. In NW Scotland, this couplet corresponds, respectively, to the Ardvreck and Durness groups, and they crop out in a narrow, almost continuous belt, rarely more than 10 km wide that stretches 180 km southwestwards from Loch Eriboll to the Isle of Skye (Fig. 1). In Scotland, the Ardvreck Group (British Geological Survey 2007) predominantly comprises cross-bedded subarkoses and quartz arenites of the Eriboll Formation (McKie 1990a, 1993) (Fig. 2), conformably overlain by rippled dolomitic siltstones and subordinate thin crinoidal grainstones of the Fucoid Member (McKie 1990b), which are in turn overlain by a thin (up to 15 m thick) quartz arenite sheet, the Salterella Grit Member (McKie 1990c; Smith and Raine 2011). Together, these two units comprise the An t-Sròn Formation (Fig. 2). The overlying Durness Group comprises dolostones, limestones and dolomitic limestones, with cherts, evaporite pseudomorphs and collapse breccias in some intervals, deposited in peritidal and subtidal environments (Raine *et al.* 2011; Raine and Smith 2012). The divisions of the Ardvreck and Durness groups show remarkable consistency along strike, both in terms of their thickness and sedimentological nature along the whole outcrop length (probably indicating that the outcrop belt is sub-parallel to the Laurentian margin).

The Durness Group was first recognized by Lapworth (1883), and the internal lithostratigraphy that was established by Peach and Horne (1884) and refined by Peach

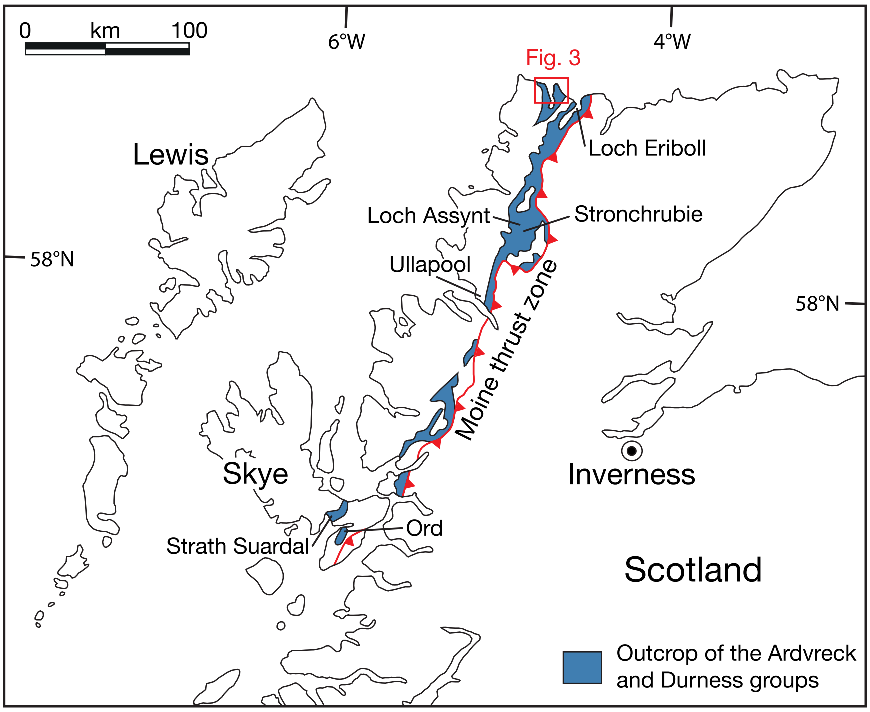

Figure 1. Map of NW Scotland showing the outcrop of Cambrian–Ordovician rocks of the Ardvreck Group and the Durness Group on the foreland to the west of the Moine thrust and in duplexes of the thrust zone. The Ardvreck Group (Cambrian Series 2) predominantly comprises siliciclastic sedimentary rocks, whereas the Durness Group is composed of carbonate lithologies. Cambrian units of the Durness Group extend along the outcrop belt, but Ordovician rocks crop out in the type area around Durness (Fig. 3), in the vicinity of Stronchrubie at the eastern end of Loch Assynt and in the Ord and Strath districts of the Isle of Skye.

et al. (1907) remains the basis for subdivision. The best exposed and preserved sections are those in the type area around the village of Durness, Highland, particularly the readily accessible coastal exposures along the southern edge of Balnakeil Bay (Fig. 3). This section, together with nearby inland sections and exposures, provides the main data used in this study. Supplementary sections were also examined at An t-Sròn in Loch Eriboll, Stronchrubie and Loch Assynt (Fig. 1). In the Ord and Strath Suardal areas of Skye (Fig. 1), all but the uppermost formation of the Durness Group crop out, but there is a lack of continuous section for detailed study, and the rocks are significantly affected by contact metamorphism (Strath Suardal) and faulting (Ord).

The aim of this paper is to provide the first comprehensive overview of the Durness Group since the initial documentation by Peach *et al.* (1907). Bed-by-bed sedimentary logging through the entire Durness Group has enabled a revision of the lithostratigraphy, together with the establishment of a sequence stratigraphic framework (Raine and Smith 2012, 2017). Sampling through the group using a measured composite section (Fig. 2) has also allowed the application of detailed conodont biostratigraphy for the first time. Together, these approaches provide constraints on correlation of the Durness Group along the Laurentian passive margin and on tectonic models for NW Scotland.

2. Methods

Bed-by-bed sedimentary logging through the entire group for this paper provided the opportunity to determine accurate thicknesses for the constituent formations of the Durness Group and for a revision of the lithostratigraphy and to use these to re-appraise the depositional context of the group. Marker beds and packages of beds were traced across many of the faults that are present along the southern edge of Balnakeil Bay in order to eliminate structural displacements. Gaps in sections were measured, and the true vertical thickness of units was calculated from bed dips. Despite this, the largest extensional faults excise too much stratigraphy to permit correlation across them, so the thickness estimates provided are minimum values. Nevertheless, they are the most accurate thickness measurements available for the Durness Group.

Reconnaissance studies of conodonts were first recorded from the Durness Group by Higgins (1967, 1971, 1985). Detailed sampling was undertaken for this study, with 88 stratigraphically constrained, productive samples collected from 12 different measured sections supplemented by 17 spot samples from three transects across poorly exposed areas (locality details are provided in Supplementary File 1). Together, these allowed a single detailed composite section through the Durness Group to be constructed (Fig. 2). The transects through the Croisaphuill and Durine formations (locations in Fig. 3) were the only source of samples until detailed mapping and logging allowed a composite section to be constructed and new samples to be collected and placed stratigraphically. Transect samples were located by GPS with an accuracy of around 10 m^2. Of the 88 productive samples, 33 were collected at high resolution across the Cambrian–Ordovician boundary, spanning the upper 25 m of the Eilean Dubh Formation and the lower 35 m of the Sailmhor Formation (Fig. 4, Supplementary File 2).

Limestone samples were digested in buffered acetic acid following the method of Jeppsson *et al.* (1999), and dolostone samples were in a buffered solution of formic acid (Jeppsson and Anehus 1995). Samples were buffered with precipitated calcium carbonate powder or with crushed chalk. Acid solutions were changed every seven days, and the residue was wet sieved with 1 mm and 63 μm meshes to sort the residues. The fine fraction was subject to heavy-liquid separation using bromoform or lithium heteropolytungstate.

Yields of conodont elements were very low, particularly in the Eilean Dubh Formation, where 64% of samples were barren and the average yield in productive samples was only 0.6 elements/kg. The yields in the Sailmhor Formation were higher, at 1.28 elements/processed kg, and only 36% of samples were barren. For these reasons, large samples were collected where possible during

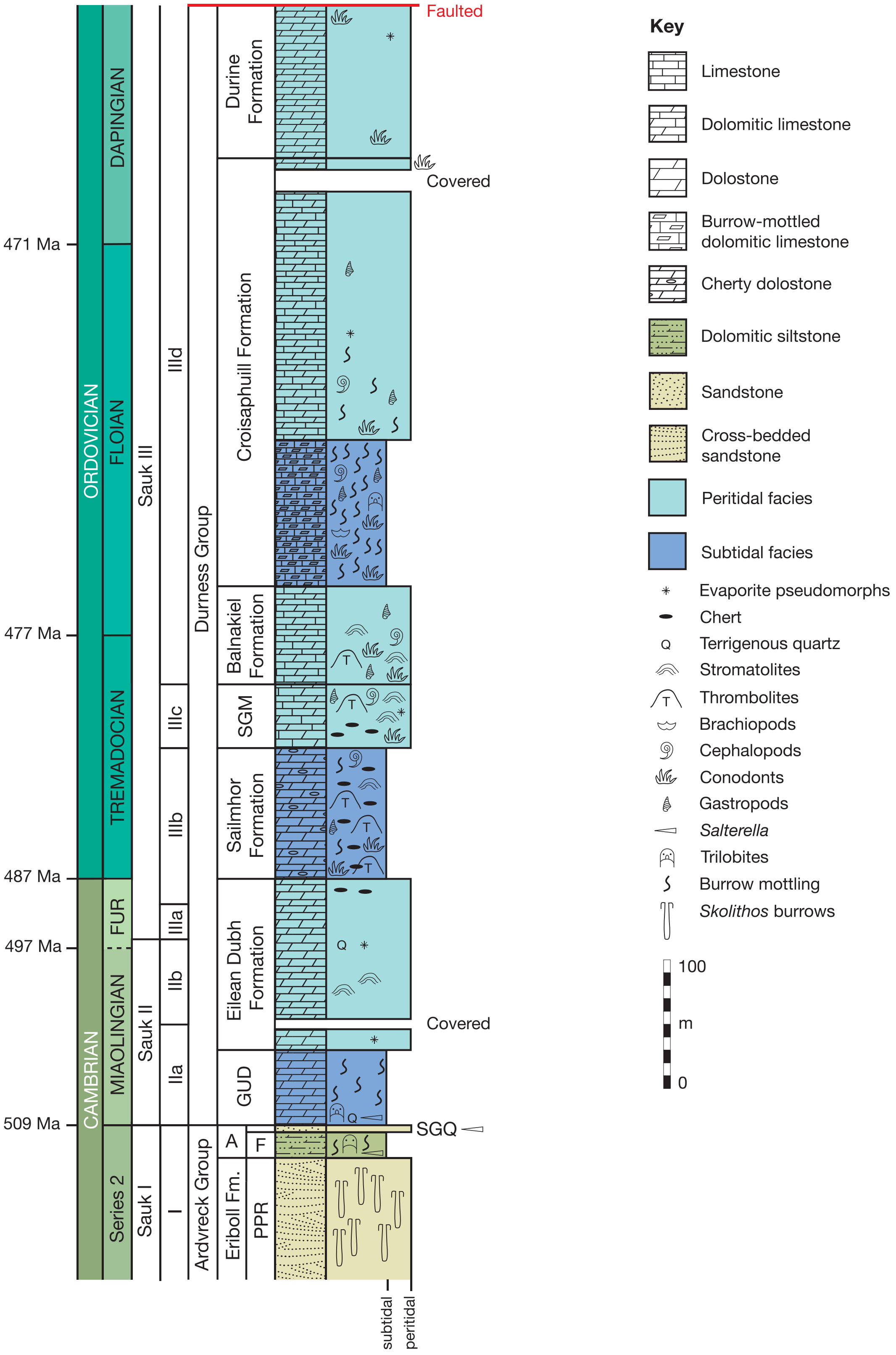

Figure 2. Summary composite sedimentary log of the upper Ardvreck Group (Cambrian Series 2) and Durness Group (Miaolingian–Dapingian) in the Durness (Fig. 3) and Loch Eriboll (Fig. 1) areas of NW Scotland. Correlation with Sauk sequences from Raine and Smith (2012). Absolute ages from Goldman *et al.* (2020) and Peng *et al.* (2020). A, An t-Sròn Formation; GUD, Ghrudaidh Formation; F, Fucoid Member; FUR, Furongian; PPR, Pipe Rock Member; SGQ, Salterella Grit Member; SGM, Sangomore Formation.

successive sampling trips, with sample weights up to 6.7 kg. Conodont samples, mainly in the range of 3–5 kg, were also taken at approximately 10 m intervals along the composite section measured through the Durness Group above the Sailmhor Formation. Yields ranged from an average of 0.1 elements per kilogram of sample processed in the Eilean Dubh Formation to an average of 30.3 in the Croisaphuill Formation. Peak abundances in the Croisaphuill Formation reached 1231 elements recovered from 3789 g of dissolved rock (325 elements/kg), 17.9 m above the formation base). A combination of diagenesis and tectonism has

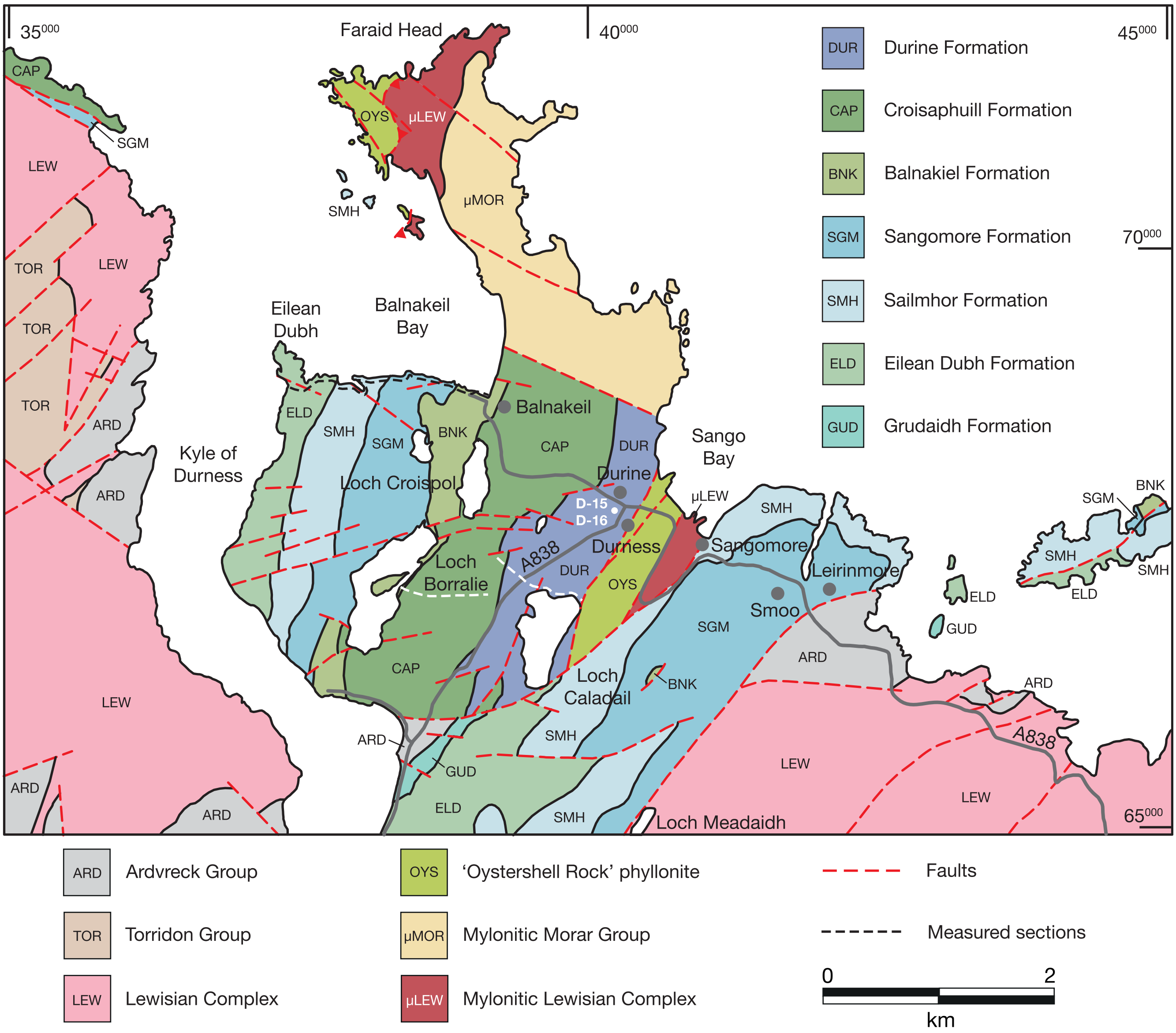

Figure 3. Geological map of the Durness area, showing the formations of the Durness Group, measured sections and the location of Higgin's (1967, 1971, 1985) spot samples in the uppermost Durine Formation (D-15, D-16). Location of map indicated in Fig. 1. Linework based on the British Geological Survey (2002) 1:50k sheet and fieldwork by the authors. Map coordinates relate to UK National Grid 100 km-square NC.

resulted in a poor level of preservation, and a significant number of taxa are described in open nomenclature. It must be noted that this is mainly a consequence of taphonomy and sample processing rather than species diversity at the time of deposition.

The colour alteration index (CAI) of conodonts in the Durness area is 5 to 6, indicating minimum temperatures of 300–350°C, although material from Stronchrubie, 50 km to the SSW adjacent to Loch Assynt (Fig. 1), is CAI 7 indicating a minimum temperature of 550°C (Epstein *et al.* 1977; Rejebian *et al.* 1987).

For biostratigraphic correlation of the conodont faunas, the composite sections of Sweet and Tolbert (1997) and Sweet *et al.* (2005) are used as a reference framework. Conodont ranges in 14 individual measured sections ranging from latest Cambrian to earliest Whiterockian (early Darriwilian) age were composited using Shaw's method of graphical correlation by Sweet and Tolbert (1997). An additional five sections included by Sweet *et al.* (2005) extended the composite section into the Darriwilian and improved coverage and resolution. The Midcontinent biozonal scheme of Goldman *et al.* (2020) is used for this study, which is developed from those of Ross *et al.* (1997) and Sweet & Tolbert (1997) and in turn from Ethington & Clark (1982).

All conodont collections, including figured specimens, are deposited at the Lapworth Museum of Geology, University of Birmingham (prefix BIRUG).

3. Lithostratigraphy of the Durness Group

Although the individual formation names have been stable since they were erected by Peach *et al.* (1907), published thicknesses for the Durness Group have been highly variable, ranging from a total of 460 m (Peach *et al.* 1907) to almost 1600 m (Phemister 1948). Swett (1965, 1969) recorded 1250 m, and Wright (1985) gave a thickness of around 770 m for the group. These variable estimates are, in part, because the Durness area is transected by multiple

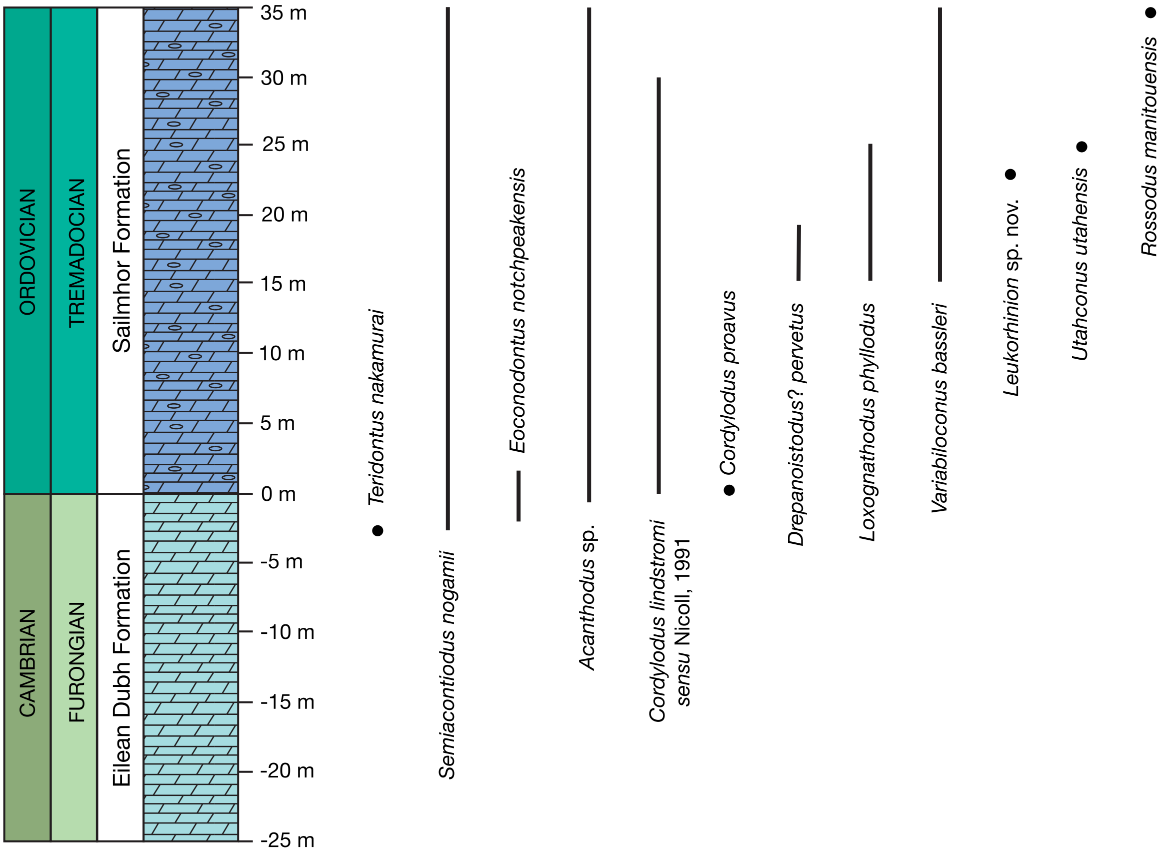

Figure 4. Range chart of conodonts across the Cambrian–Ordovician boundary interval, which spans the Eilean Dubh–Sailmhor formation boundary. The Cambrian–Ordovician boundary lies within a few metres below the formation boundary, and the base of the *manitouensis* conodont biozone is no higher than 35.0 m in the Sailmhor Formation. For details of the sedimentary log, see Fig. 2, Raine *et al.* (2011) and Raine and Smith (2012). After Huselbee (1998).

NE–SW and ESE–WNW-trending faults related to the Permo-Triassic and Jurassic opening of the West Orkney basin (Elmore *et al.* 2010; Wilson *et al.* 2010) that have downfaulted rocks of the Moine thrust zone and Durness Group to form the Faraid Head and Durness outliers, respectively (Fig. 3).

Peach *et al.* (1907) divided their 'Calcareous Series' into seven 'groups' – Ghrudaidh, Eilean Dubh, Sailmhor, Sangomore, Balnakiel (note the original spelling used for the formation name), Croisaphuill and Durine. Swett (1969) reduced these groups to member status, but this was further amended by Cowie *et al.* (1972) and Whittington (1972) to the current usage of the Durness Group (Molyneux *et al.* 2023) with seven constituent formations using the original names of Peach *et al.* (1907) (Figs. 2 and 3).

Although the standard divisions of the Durness Group seen in the type area can also be recognized on Skye, the nature of the outcrop and the presence of contact metamorphism associated with Palaeogene igneous intrusions have led to alternative stratigraphic nomenclatures being erected there (e.g. British Geological Survey 2005). From the current work, it is clear that equivalents of all but the Durine Formation occur on Skye. The Ghrudaidh Formation, Eilean Dubh, Sailmhor and Sangomore formations are all present in sections around Ord (Fig. 1), and it is here recommended that the members erected in the Strath Suardal area of Skye (Fig. 1) by Holdroyd (1994) and used on recent maps (British Geological Survey 2005) are abandoned. The units lack lithostratigraphical consistency and integrity and, in part, represent different grades of contact metamorphism. With care, the units of the type area can be correlated and used on Skye where chert abundance and bioturbation styles are preserved, and this is confirmed by the biostratigraphy of gastropod operculae and cephalopods (Evans 2011).

The revised measured thickness of the Durness Group is 930 m, and the lithologies within the group represent a spectrum of subtidal to supratidal limestones, dolostones and dolomitic limestones with associated cherts and minor evaporite pseudomorphs (Fig. 2). Microbialites are both abundant and diverse, and a variety of morphological forms of stromatolites and thrombolites are present. The type area for the Durness Group is the peninsula at Durness, with the most complete section at Balnakeil Bay (OS grid reference NC 3738 6858–3918 6851) (Fig. 3) where the Eilean Dubh, Sailmhor, Sangomore and Balnakiel formations are all well exposed. The lower boundary of the group is conformable with the Salterella Grit Member (An t-Sròn Formation, Ardvreck Group) and marks a shift from siliciclastic- to carbonate-dominated sedimentation that occurred across Laurentia, coincident with a sea-level rise that drowned siliciclastic sources (Runkel *et al.* 1998). This boundary is a major sequence boundary that also correlates with the Redlichiid–Olenellid Extinction Carbon Isotope Excursion (ROECE), the Sauk I–II supersequence boundary and the Cambrian Series 2–Miaolingian boundary (Faggetter *et al.* 2018). The upper boundary of the Durness Group is typically faulted against mylonites of the Moine thrust zone (Fig. 3). This fault is oriented NE–SW and is part of the post-Caledonian Permian–Triassic brittle faulting related to West Orkney Basin development (Wilson *et al.* 2010), but in Sango Bay (Fig. 3), the original thrusted relationship with tectonically overlying mylonites is preserved (Raine *et al.* 2011).

3.a. Ghrudaidh Formation

The lower boundary of the formation is marked by a change from quartz arenites of the Salterella Grit Member (An t-Sròn Formation) to carbonates (Fig. 2). The boundary is placed at the lowest dolomitic siltstone or dolostone and represents a deepening of facies. Well-rounded quartz sand grains continue into the Ghrudaidh Formation for a few metres, and around Loch Assynt (Fig. 1) thin quartz arenites (<50 cm) are present in the lower part of the formation. The remainder of the formation is composed of mottled dolostones, oolites, local mud-flake breccias and calcite pseudomorphed evaporites.

Although the Ghrudaidh Formation has a large outcrop area, and it is often seen in thrust slices in Loch Eriboll and Assynt, the uniform nature of the unit makes internal correlation difficult. The formation is also exposed in the tectonic window near Ord, Skye, and the base is well exposed at Skiag Bridge, Loch Assynt and in nearby streams (Fig. 1; Smith and Raine 2011).

The base of the Ghrudaidh Formation represents the Sauk I–II supersequence boundary (Sloss 1963; Raine and Smith 2012) and also correlates with ROECE and the Series 2–Miaolingian boundary (Faggetter *et al.* 2018). The formation constitutes the transgressive systems tract (TST) of a depositional sequence that extends into the overlying Eilean Dubh Formation and which forms the lower sequence (Sauk IIa) within the Sauk II Supersequence (Fig. 2; Raine and Smith 2012). Faggetter *et al.* (2018) also identified the Drumian negative carbon isotope excursion (DICE) 30 m above the base of the Ghrudaidh Formation, corresponding to the Wuliuan–Drumian stage boundary (Peng *et al.* 2020).

3.b. Eilean Dubh Formation

The lower boundary is exposed at An t-Sròn and Grudie (see Supplementary File 1 for section locations), where pale grey and cream-weathering dolostones overlie pale grey dolostones and sucrosic, mottled, dark grey dolostones of the Ghrudaidh Formation (although some fine-grained, cream coloured dolomite beds are present in the upper part of the formation). The upper boundary is seen at Stronchrubie (Fig. 1), Balnakeil Bay and on the shores of the Kyle of Durness (Fig. 3), but at Ord, it is faulted. At all these localities, the nature of the boundary is remarkably consistent. Wright (1993) divided the formation into three members (Kyle, Stromatolite and Solmar), but these were not fully defined, and the bases of the lowest two members were placed above intervals of non-exposure. Although Wright (1993) documented the lower and upper members in the Assynt area, he did not recognize the stromatolite member. The three members of the Eilean Dubh Formation are, at best, subtly developed in Assynt, and this may be a result of the high density of thrust faults or the higher metamorphic grade and recrystallisation. The three members within the Eilean Dubh Formation (Wright 1993, Wright and Knight 1995, Park *et al.* 2002) are here abandoned based upon recent logging and the lack of application for correlation.

In Balnakeil Bay, 121 m are exposed and lithologically the formation comprises stromatolites, fine-grained ripple-laminated dolostone, mud-flake breccias, minor amounts of clastic sediment and evaporite pseudomorphs. The basal 12 m of the unit exposed at An t-Sròn shows no overlap with the lowest part of the logged section at Balnakeil Bay, and hence a minimum thickness for the formation is 133 m. The thickness of the Eilean Dubh Formation in the Assynt area is difficult to ascertain due to poor outcrop and thrust repetition.

The Sauk IIa sequence extends into the lowermost Eilean Dubh Formation, where fine-grained, cream-weathering dolostones with pseudomorphed evaporites and collapse breccias represent the upper highstand systems tract (HST) (Fig. 2; Raine and Smith 2012). The overlying Sauk IIb sequence (67 m) is incompletely exposed, particularly the TST (Raine and Smith 2012). Lithologically, the sequence comprises dolostones with spar-filled vugs, stratiform intraclast breccias and locally abundant stromatolites. Immediately below the Sauk II–III boundary, approximately 86 m above the base of the formation, well-rounded ('millet seed') grains become abundant and cap thin parasequences. This 5 m interval, which contains ten parasequences, represents sabkha deposits preserved in a falling stage systems tract (FSST) and was described in detail by Raine and Smith (2017). The top of the FSST is marked by a pronounced palaeokarst surface with sandstone-filled fissures. The maximum regression at the Sauk II–III boundary correlates elsewhere with the global Steptoean positive carbon isotope excursion (SPICE) in the early Furongian (Saltzman *et al.* 1998, 2004), but the excursion recognized in Scotland (Pruss *et al.* 2019) is c. 23 m below the sequence boundary identified here, lying just below the first influx of quartz sand to the succession. This suggests diachroneity or an expanded stratigraphic thickness in Scotland as proposed by Raine and Smith (2017). Although the causal relationship between the sequence boundary and the carbon isotope excursion is unclear, the identification of the Sauk II–III boundary does provide a stratigraphic tie point in the almost unfossiliferous Eilean Dubh Formation. An additional chemostratigraphic marker in this unfossiliferous section is provided by the strontium isotope stratigraphy of Nicholas (1994), who recorded an $^{87}Sr/^{86}Sr$ peak of 0.7103 in the upper part of the Eilean Dubh Formation that represents the Cambrian maximum value correlative with the end of the SPICE excursion (Peng *et al.* 2020, fig. 19.12).

The upper 46 m of the Eilean Dubh Formation contains a third-order sequence, 28 m thick, which is correlated with Sauk IIIa (Raine and Smith 2012), and thin, 6–10 cm, beds of breccia within peritidal dolostones marks the erosive surface at the upper sequence boundary. The uppermost 18 m of the Eilean Dubh Formation probably represents the TST of the overlying Sauk IIIb sequence (Raine and Smith 2012).

3.c. Sailmhor Formation

The formation comprises a 113 m succession of mostly dark grey, mottled thrombolitic dolostones arranged in metre-scale parasequences with pale grey weathering tops containing stromatolites (Fig. 2). The formation is well exposed in its type section along the shores of Balnakeil Bay (Fig. 3), although there are numerous small-scale faults, and the upper parts are well exposed around Smoo. Distinctive white cherts are particularly abundant in the lower half of the formation. At Stronchrubie, near Loch Assynt (Fig. 1), the basal 23 m are exposed in a thrust horse, and at Ord, on the Isle of Skye, the formation is partly exposed along the shore.

The base of the formation is placed at a sharp colour and lithological change from pale grey weathering, peritidal, finely crystalline dolostones of the underlying Eilean Dubh Formation to dark grey dolostones exhibiting locally common cherts. In Balnakeil Bay, the basal boundary is exposed low in the cliff (Fig. 4; Raine and Smith 2012, fig. 7). The distinctive colour change and distribution of cherts are also recognizable along the shores of the Kyle of Durness, 1.1 km to the southwest. The subtidal parasequence bases commonly contain oolite beds in the lower half of the formation; thrombolites (responsible for most of the distinctive mottling) become more common up-section, and the parasequences are often capped by ripple- and parallel-laminated, pale grey weathering, peritidal dolostones containing stromatolites (Raine *et al.* 2011; Raine and Smith 2012).

The TST of Sauk IIIb comprises the lower part of the Sailmhor Formation and part of the underlying Eilean Dubh Formation (Fig. 2), and the distinctively cyclic parasequences increase in overall thickness up-section in the Sailmhor Formation, with the proportion of subtidal facies also increasing. They have a maximum thickness of 6 m with thin, peritidal caps of pale grey dolostone. The maximum flooding zone (MFZ) is not exposed, but in the lower HST, microbial biostromes fill the accommodation space. In the upper HST, towards the top of the Sailmhor Formation, the parasequences thin upwards, which is particularly well seen in Smoo inlet (Fig. 3; Raine and Smith 2012, fig. 8).

3.d. Sangomore Formation

The 55 m unit is exposed in its entirety along the type section in Balnakeil Bay and is distinguished by its buff-weathering, finely laminated dolostones, with some mid-grey, interbedded thrombolitic limestones, stromatolites and bioclastic, peloidal and ooidal wackestones or packstones occurring locally. The Sangomore Formation also crops out on Skye, where a small outcrop of buff-weathering, finely crystalline dolostone is seen at Ord.

The Sangomore Formation is separated from the underlying Sailmhor Formation by beds of chert breccias and allogenic dolomite sand. The boundary between the two formations is placed at the top of a 60 cm thick dolomite sand, which forms a distinctive notch in the cliff in Balnakeil Bay. Above this, the dolostones become paler, and the cherts are dominantly orange in colour.

The chert breccias and dolomite sands at the base are taken to mark the Sauk IIIb–IIIc sequence boundary, and Sauk IIIc is confined to the Sangomore Formation (Fig. 2; Raine and Smith 2012). The upper sequence boundary is marked by a distinctive 20 cm thick oncoidal pebble bed with clasts up to 3 cm that passes upwards into angular carbonate breccias that infill karstic depressions.

3.e. Balnakiel Formation

The Balnakiel Formation has a minimum thickness of 86 m at the type locality in Balnakeil Bay and is also exposed inland where around 28 m have been recorded, but it is fairly certain that this is a repetition of the basal interval. Wright (1985) cited a thickness of 140 m for the formation, but this was based on the assumption that the inland exposure recorded an unrepeated, upper part of the formation. The lower boundary is marked by the distinctive oncoidal pebble bed in Balnakeil Bay but is seen nowhere else. Lithologies defining the Balnakiel Formation include mid- to dark grey weathering, stromatolitic and thrombolitic dolostones and limestones, with ribbon carbonates and bioclastic wackestones and packstones.

The Balnakiel Formation represents the TST of the 568 m thick Sauk IIId sequence that spans the upper three formations of the Durness Group (Fig. 2). The difference in scale, in terms of both time and rock thickness, between the lower Sauk III sequences and Sauk IIId, has led some authors to propose that it is a second- rather than third-order sequence and therefore a separate supersequence, Sauk IV (Golonka and Kiessling 2002). For consistency in correlation, the usage of Sauk IIId in the Derby *et al.* (2012a) Great American Carbonate Bank volume is retained here.

The TST parasequences in the Balnakiel Formation comprise peloidal and bioclastic wackestones and thrombolites, overlain by peritidal carbonate facies with microbial laminites and stromatolites. Ribbon carbonates (distinctive wavy and lenticular bedded facies) become abundant in the upper part of the formation (Raine and Smith 2012), and the parasequences become thicker and less well-defined as peritidal caps thin and then disappear up-section.

3.f. Croisaphuill Formation

The unit comprises an informal lower member of monotonous, subtidal, burrow-mottled, dolomitic limestones and an upper member composed of conspicuous, shallowing-upward, primarily dolomitic, parasequences. In its type section, a cliff above the eastern shore of Loch Borralie (Fig. 3), a composite measured section provides a minimum thickness of 350 m. However, many recent published thicknesses have been based upon the work of Wright (1985), who apparently logged to the top of the cliff at Loch Borralie but did not include the large tract of poorly exposed ground to the east. The lithologies of the Croisaphuill Formation mark a distinct change from those observed within the Balnakiel Formation, although the boundary is everywhere faulted or unexposed.

The lower informal member of the formation comprises around 125 m of strongly burrow-mottled, purplish-grey dolomitic limestones. Fossils are commonly found within brownish black cherts in the basal 30 m and include rostroconchs, cephalopods, gastropods, brachiopods and sponges. Most of the fossils are poorly preserved, with some replaced by dolomite but the majority by chert (beekite).

The upper member is exposed on the hillside to the SSE of Loch Croispol (Fig. 3), where 225 m were logged, but the outcrop width suggests it may be thicker. The upper part is distinct from the underlying succession and marks a unit in which dolostone is more abundant. Several pale grey weathering, structureless, dolomitic limestone beds up to 3 m thick are present at various levels, and burrow-mottled, dolomitic limestone beds persist.

The MFZ for Sauk IIId (and for the higher order Sauk III supersequence) occurs low in the lower member and is characterized by thickly bedded and burrow-mottled dolomitic limestones with an increase in chert volume (Fig. 2; Raine and Smith 2012). Parasequences are not visible, suggesting rapid aggradation due to increased accommodation space. The late HST is represented by the poorly exposed 215 m thick upper member, with a progressive filling of available accommodation space and the re-appearance of recognizable parasequences that are commonly capped by peritidal, parallel-laminated dolostones containing evaporite pseudomorphs.

3.g. Durine Formation

The formation is not exposed in any one complete section, but a composite of inland sections (Fig. 3) provides a minimum thickness of 132 m. The basal boundary is gradational, with pale grey weathering, fine-grained dolostones becoming more abundant above the uppermost part of the Croisaphuill Formation (NC 3927 6749). The basal part of the Durine Formation contains some beds of burrow-mottled carbonate, but there is a higher proportion of dolostone, a change in the colour of the cherts from black to orange-pink and an increasing proportion of parallel- and ripple-laminated, dolostones. Evaporite pseudomorphs are preserved as chert nodules. The formation represents a sustained HST through to the highest preserved sediments in the Durness Group, at the top of the Durine Formation (Fig. 2).

4. Macrofaunas

In 1854–55, fossils were discovered in the Durness Group by Charles Peach, a coastguard and amateur naturalist (and father of geologist Benjamin Peach, who would later play a key role in mapping the Moine thrust zone) (Peach 1855). Murchison originally identified the fossils as Devonian in age (Oldroyd 1990) but later concluded that they were 'lower Silurian' based on the descriptions of Salter (1859). It has long been established that the faunas from the Durness Group bear a close similarity to those recorded from other parts of Laurentia, and comparisons of the faunas by Salter (1859), Peach (1913), Peach and Horne (1930) and Grabau (1916) with the Cambrian–Ordovician of the USA and western Newfoundland allowed determination of some of the formation ages for the first time.

Previous biostratigraphical studies have been limited, and this is mostly due to the scarcity and poor preservation of the fauna. Only the Balnakiel and Croisaphuill formations are comparatively rich in macrofossils. Peach *et al.* (1907) recorded around 100 species in the Balnakiel–Croisaphuill interval, 66 of which are present within the Balnakiel Formation (15 being restricted to the Balnakiel Formation).

Cephalopods were first described from the Durness Group by Salter (1859) and were also examined by Foord (1887, 1888). Species lists were published by Peach *et al.* (1907) based on material recovered during mapping by the Geological Survey. A recent revision of the cephalopod fauna has shown that although cephalopods are scarce and poorly preserved, they are present within the Sailmhor, Sangomore, Balnakiel and Croisaphuill formations. Thirty-four species have been recorded representing 6 orders and 15 families (Evans 2011).

Salterella is an enigmatic small shell of uncertain, but possible stem-molluscan, affinity (Yochelson 1983). The fossil was first mentioned by Macculloch (1814) and later described and named by Salter (1859). Peach *et al.* (1907) recorded *Salterella* from the middle part of the Pipe Rock Member and the overlying Fucoid Member, Salterella Grit Member and Ghrudaidh Formation. Yochelson (1983) reviewed the taxonomy of *Salterella* and concluded that it was of use as a biostratigraphic indicator, due to having a short range, being widespread across Laurentia and often present in large numbers. Fritz and Yochelson (1988) concluded that *Salterella maccullochi* (Salter) is diagnostic of the middle *Olenellus* trilobite biozone of Laurentia (equating to mid-Stage 4, Cambrian Series 2), but the distribution in the Ardvreck and Durness groups indicates that the range extends into the basal Miaolingian as its occurrence postdates the Sauk I–II boundary and the ROECE isotope excursion.

Trilobites are rare within the Cambrian–Ordovician of NW Scotland and, although most common within the An t-Sròn Formation (Ardvreck Group), the Durness Group has yielded a handful of specimens. The North American biozonal trilobite *Olenellus* was first recovered from the Scottish succession during systematic collecting of potential fossiliferous horizons (identified by the Geological Survey's mapping), by the survey fossil collector Arthur Macconochie in 1891, and provided the first evidence of Cambrian-aged strata in this succession (Peach *et al.* 1907). A single *Olenellus* has since been discovered within the lower 1 m of the Ghrudaidh Formation at Loch Assynt (Huselbee and Thomas 1998) giving a maximum age of the *Olenellus* trilobite biozone for the base of the Durness Group and confirming stratigraphic continuity with the underlying Ardvreck Group.

Trilobites recorded from the Sailmhor and Croisaphuill formations (Peach *et al.* 1907) include a single species from the Sailmhor Formation, ascribed to *Asaphus canalis* Conrad. The specimen was not figured in their monograph and is now lost (Cowie *et al.* 1972; Fortey 1992). Provided Peach *et al.* identified the trilobite correctly, the genus would now be assignable to *Isoteloides* according to Fortey (1992). *Petigurus nero* (Billings) was also recorded by Peach *et al.* (1907) from the Croisaphuill Formation and later figured by Fortey (1992) who also recorded the occurrence of *Jeffersonia timon* (Billings) and *Cybelopsis* sp. nov. from the Croisaphuill Formation. *P. nero* is age diagnostic of the *Strigigenalis caudata* trilobite biozone (Boyce and Stouge 1997) of the Laurentian upper Ibexian, which equates with the mid-Floian in global terms. The species also occurs in the lower part of the Catoche Formation of western Newfoundland (Fortey 1979), North Greenland (Fortey 1986) and NE Spitsbergen (Fortey and Bruton 2013).

Elements of the macrofauna of less biostratigraphical potential have been briefly studied or only mentioned in passing. Hinde (1889) recorded the sponges *Archeoscyphia minganensis* and *Calathium* sp. from the Durness Group, and Palmer *et al.* (1980) were the first to record fossils from the Sangomore Formation, the only unit in which Peach et al. (1907) recovered no fossil remains. Palmer *et al.* recorded the gastropods *Murchisonia* sp. and *Pleurotomaria* sp. together with the cephalopod *Orthoceras* sp. More recently, Herringshaw and Raine (2007) recorded a machaeridian sclerite from the middle part of the Sangomore Formation, and this is currently the earliest recorded machaeridian.

Brachiopods have been recovered from the Croisaphuill Formation (= Ben Suardal Formation) on Skye (Curry and Williams 1984). The silicified brachiopod fauna was recovered by the acid digestion of limestone blocks. Seven known genera and one species, assignable to a new genus along with several new species were recorded. Sixty-two per cent of the brachiopod fauna from Skye can be recognized within the Arbuckle Group of Oklahoma (Curry and Williams 1984).

A single species of rostroconch, *Euchasma blumenbachi* (Billings), has been recorded from the Croisaphuill Formation (Peach *et al.* 1907), and it is also present in equivalent strata in western Newfoundland, where it has been shown to have a short-range spanning the lower half of the *Oepikodus communis* conodont biozone within the Catoche Formation (Rohr *et al.* 2008).

Silicified gastropod opercula, now attributable to the genera *Maclurites* Le Sueur and *Ceratopea* Ulrich, are common within the Croisaphuill Formation. The operculum figured by Salter (1859) as *Maclurea peachii* was subsequently assigned to a new species, *Ceratopea billingsi*, by Yochelson (1964). Peach *et al.* (1907) made reference to four opercula of '*Maclurea*' in their species list but did not figure the specimens.

All available macrofossil material, from both museum and new field collections, was examined whilst developing a biostratigraphy

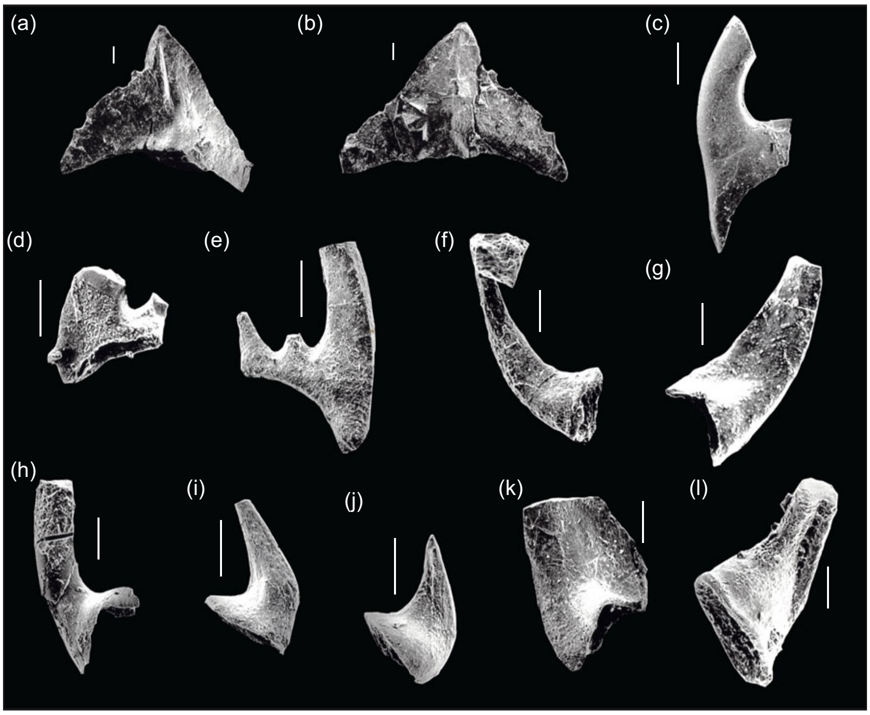

Figure 5. Conodonts of the Sailmhor Formation, Durness Group, spanning the *fluctivagus*, *angulatus* and *manitouensis* conodont biozones. (a, b) *Loxognathodus phyllodus* Ji and Barnes; Sailmhor Formation, 25.0 m; BIRUG: BU5500. (c) *Cordylodus proavus* Müller; Sailmhor Formation, 0.3 m; BIRUG: BU5501. (d, e) *Cordylodus lindstromi* Druce and Jones *sensu* Nicoll (1991); Sailmhor Formation, 25.0 m; BIRUG: BU5502, BU5503. (f, g) *Utahconus utahensis* (Miller); Sailmhor Formation 25.0 m; BIRUG: BU5504, BU5505. (h) *Acanthodus* sp.; Sailmhor Formation, 0.3 m; BIRUG: BU5506. (i, j) *Leukorhinion* sp. nov.; Sailmhor Formation, 22.4 m; BIRUG: BU5507, BU5508. (k) *Rossodus manitouensis* Repetski and Ethington; Sailmhor Formation, 35.0 m; Sb element; BIRUG: BU5509. (l) *Semiacontiodus nogamii* (Miller); base of Sailmhor Formation (0 m); BIRUG: BU5510. All specimens are from the Balnakeil Bay section near Durness, NW Scotland; all scale bars are 100 μm. After Huselbee (1998).

for the Durness Group. For the most part, however, the macrofauna was too scarce and zonally undiagnostic, so the only means of producing a high-resolution biostratigraphic framework was through the use of conodonts.

5. Conodont faunas

5.a. Cambrian–Ordovician boundary interval

The conodonts of the Cambrian–Ordovician boundary interval were studied by Huselbee (1998), and the oldest productive sample in the very low-yielding Eilean Dubh Formation is 2.8 m below the upper formation boundary. The conodont taxon used to define the base of the Ordovician (*Iapetognathus fluctivagus* Nicoll *et al.*) was not recovered, as is commonly the case in shallow water settings, and the only conodonts recovered in the Eilean Dubh Formation were *Acanthodus* sp., *Eoconodontus notchpeakensis* (Miller), *Semiacontiodus nogamii* (Miller) and *Teridontus nakamurai* (Nogami) (Fig. 4), of which *Acanthodus* sp. (Fig. 5h) and *S. nogamii* (Fig. 5l) extend through the lower 35 m of the Sailmhor Formation. *Cordylodus lindstromi* Druce and Jones (Fig. 5d, e) has a first appearance at the base of that formation and ranges to +30 m, and *Cordylodus proavus* Müller (Fig. 5c) has a single occurrence at +0.3 m (Fig. 4; see also the conodont abundance table in Supplementary File 2).

In the global stratotype for the base of the Ordovician at Green Point, Newfoundland (R. A. Cooper *et al.* 2001; Goldman *et al.* 2020), *C. lindstromi sensu* Nicoll (1991) has a first appearance datum (FAD) at the Cambrian–Ordovician boundary, and in the graphically correlated composite section for the Furongian–Darriwilian of Laurentia (Sweet and Tolbert 1997), the FAD of *C. lindstromi* abuts but does not overlap with the last appearance datum (LAD) of *E. notchpeakensis* at 202 composite standard units (csu). The genus *Acanthodus* also has an FAD at 202 csu.

The very poor abundance of conodonts in the shallow water carbonates of the uppermost Eilean Dubh Formation means that the Cambrian–Ordovician boundary cannot be located with high precision. In the Durness section, *E. notchpeakensis* has an LAD 1.6 m above the base of the Sailmhor Formation. It may therefore be concluded that, within the limitations imposed by facies restriction and low levels of conodont element recovery, the Cambrian–Ordovician boundary in the Balnakeil Bay section lies 1 m or 2 m below the Eilean Dubh–Sailmhor formation boundary, which in turn is approximately 196 m above the base of the Durness Group.

5.b. Cordylodus angulatus biozone

The low diversity and abundance of conodonts in the Sailmhor Formation mean that the *angulatus* conodont biozone cannot be precisely recognized in the Durness Group, but it must be confined to the lowest 35 m of the formation, below the appearance of the next zonal taxon, *Rossodus manitouensis* Repetski and Ethington (Figs. 4 and 5k). The only other first appearances present in the putative interval of the *angulatus* biozone are *Drepanoistodus*? *pervetus* Nowlan, a new species of *Leukorhinion* (Fig. 5i, j), *Loxognathodus phyllodus* Ji and Barnes (Fig. 5 a, b), a single occurrence of *Utahconus utahensis* (Miller) (Fig. 5f, g) and *Variabiloconus bassleri* (Furnish) (from 15.6 m) (Fig. 6). *L. phyllodus* is a rare Laurentian species from the *angulatus* biozone that was first described from western Newfoundland (Ji and Barnes 1994) and has also been recorded from the Johansen Land Formation of North Greenland (Bryant and Smith 1990).

5.c. Rossodus manitouensis biozone

The *manitouensis* biozone extends from 35 m above the base of the Sailmhor Formation to 5.4 m into the overlying Sangomore Formation, equating to 83 m of strata (Fig. 6). A typical *manitouensis* biozone assemblage occurs at the base of the Sangomore Formation, comprising *Acanthodus* sp. (Fig. 7e), *Clavohamulus densus* Furnish (Fig. 7d), *Utahconus longipinnatus* Ji and Barnes (Fig. 7a) and *Variabiloconus bassleri* (Furnish)

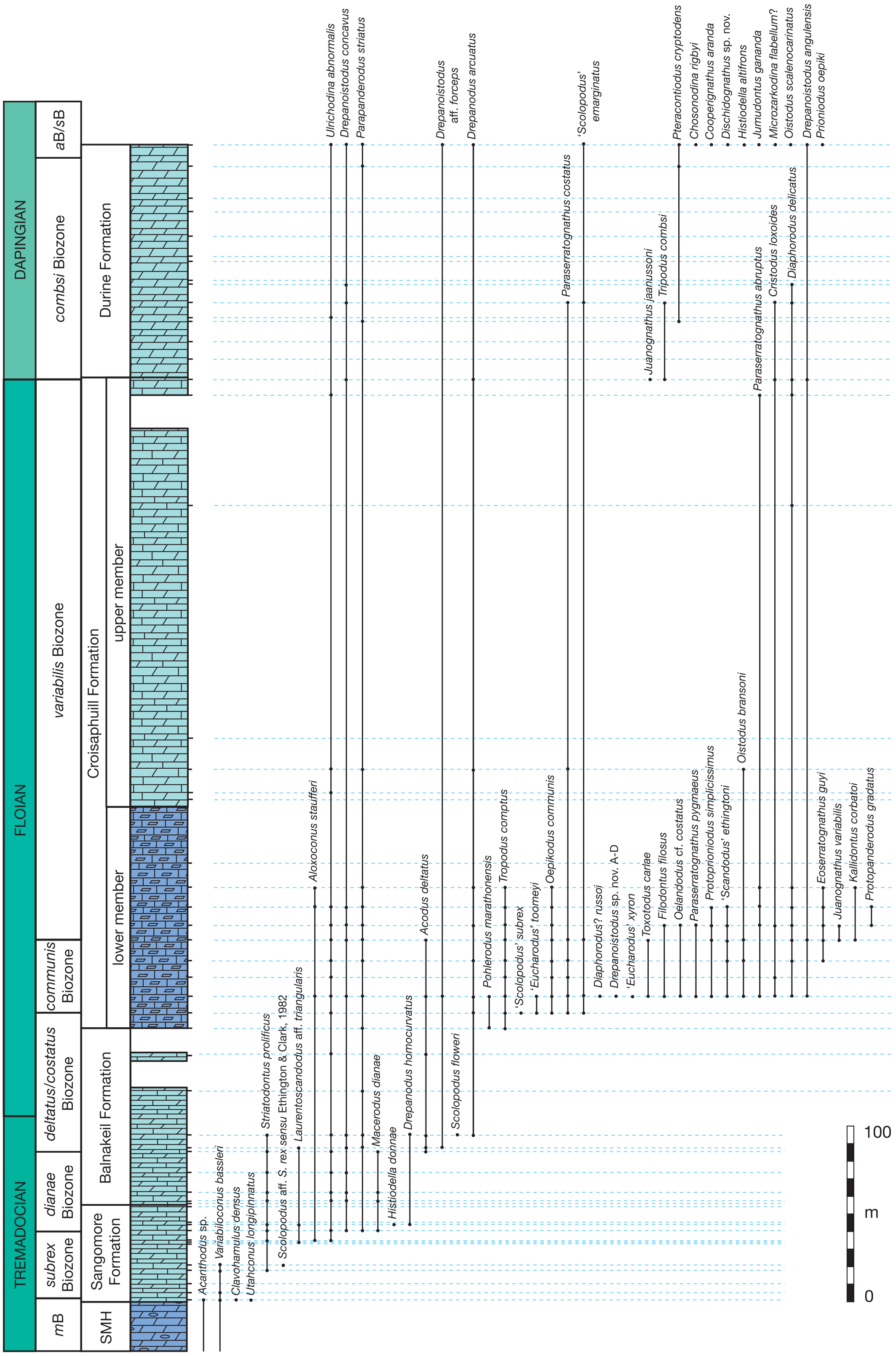

Figure 6. Range chart of selected conodont taxa in the upper Durness Group (Sangomore–Durine formations), spanning the upper Tremadocian to Dapingian and correlated with the standard Midcontinent conodont zonation (Ethington and Clark 1982; Ross *et al.* 1997). The distribution of all conodonts recovered, together with sample heights, is available in Supplementary File 2. In the lithological column, predominantly subtidal intervals are indicated in dark blue and peritidal intervals in pale blue. Horizontal dashed lines indicate sample horizons, and solid dots within range bars indicate species occurrences within samples. For lithological key, see Fig. 2. *a*B/*s*B, *altifrons* and *sinuosa* biozones; *m*B, *manitouensis* biozone; SMH, Sailmhor Formation.

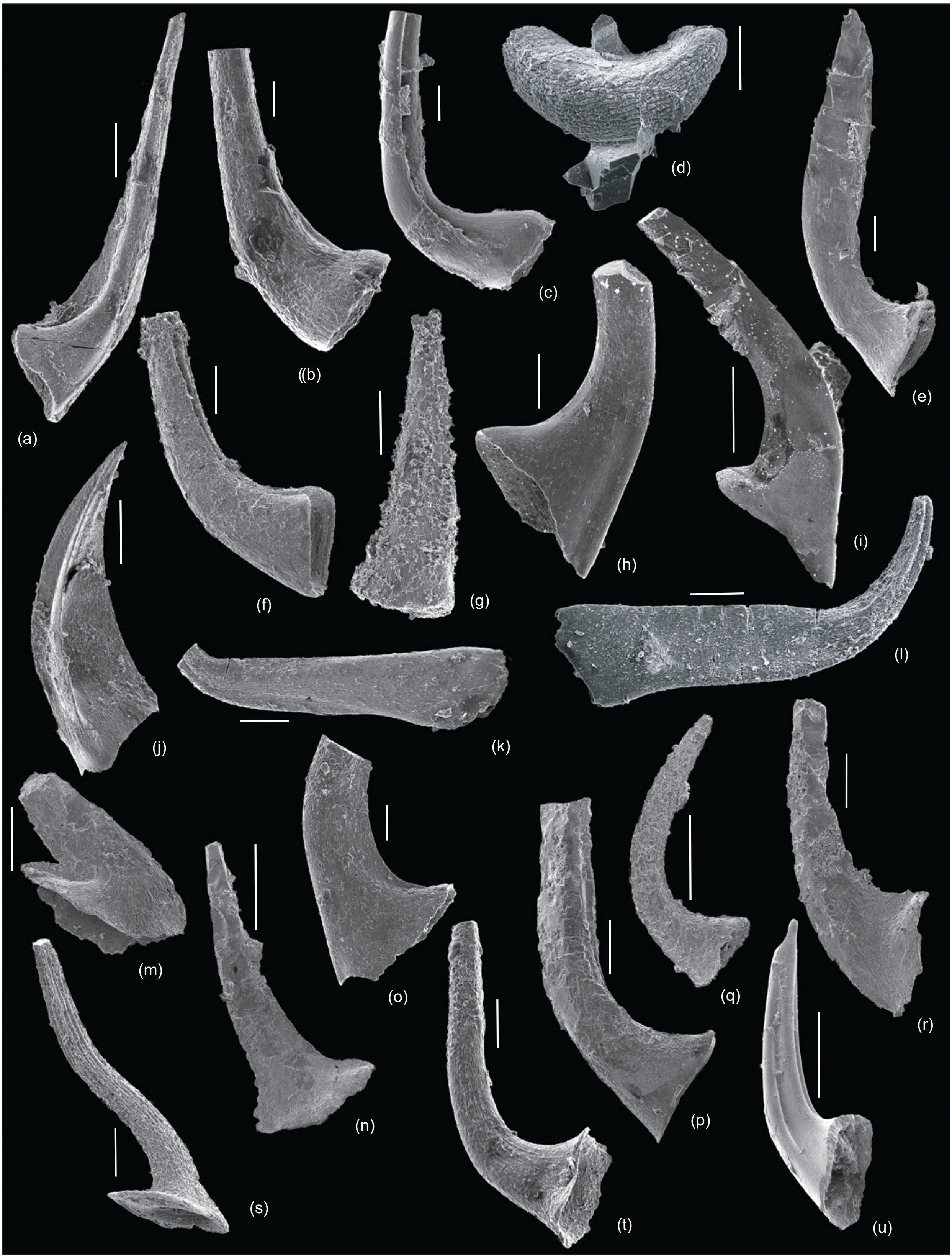

Figure 7. Conodonts from the Sangomore and Balnakiel formations, Durness Group, spanning the upper *manitouensis*, *subrex*, *dianae* and *deltatus/costatus* biozones (Fig. 6). (a) *Utahconus longipinnatus* Ji and Barnes; Sangomore Formation, 1.5 m; BIRUG: BU5511. (b, c) *Variabiloconus bassleri* (Furnish); Sangomore Formation, 1.5 m; BIRUG: BU5512, BU5513. (d) *Clavohamulus densus* Furnish; Sangomore Formation, 1.5 m; BIRUG: BU5514. (e) *Acanthodus lineatus* (Furnish); Sangomore Formation, 1.5 m; BIRUG: BU5515. (f) *Striatodontus prolificus* Ji and Barnes; Balnakiel Formation, 30.4 m; BIRUG: BU5516. (g) *Striatodontus prolificus* Ji and Barnes; Sangomore Formation, 44.0 m; BIRUG: BU5517. (h) *Laurentoscandodus* aff. *triangularis* (Furnish); Sangomore Formation, 44.0 m; BIRUG: BU5518. (i) *Drepanodus* sp.; Sangomore Formation, 33.9 m; BIRUG: BU5519. (j) *Histiodella donnae*? Repetski; Sangomore Formation, 44.0 m; BIRUG: BU5520. (k) *Macerodus dianae* Fåhræus and Nowlan; Balnakiel Formation, 30.4 m; BIRUG: BU5521. (l) *Macerodus dianae* Fåhræus and Nowlan; Balnakiel Formation, 7.3 m; BIRUG: BU5522. (m, n) *Drepanoistodus* sp. A Stouge and Boyce; Balnakiel Formation, 39.8 m; BIRUG: BU5523, BU5524. (o) *Drepanoistodus*? *concavus* (Branson and Mehl); Balnakiel Formation, 2.5 m; BIRUG: BU5525. (p) *Drepanodus homocurvatus* Lindström; Balnakiel Formation, 39.8 m; BIRUG: BU5526. (q) *Drepanodus arcuatus* Pander; Balnakiel Formation, 39.8 m; BIRUG: BU5527. (r) *Drepanoistodus* aff. *nowlani* Ji and Barnes; Balnakiel Formation, 39.8 m; BIRUG: BU5528. (s) Gen. nov.; Balnakiel Formation, 30.4 m; BIRUG: BU5529. (t) ‘*Eucharodus*’ sp. nov.; Balnakiel Formation, 2.5 m; BIRUG: BU 5530. (u) *Ulrichodina abnormalis* (Branson and Mehl); Balnakiel Formation top; BIRUG: BU5531. All scale bars are 100 µm.

(Fig. 7b, c). This assemblage can be recognized in many widespread localities in Laurentia and confirms an upper *manitouensis* biozone position (Sweet and Tolbert 1997) for the base of the Sangomore Formation.

5.d. ‘*Scolopodus*’ *subrex* biozone

The *subrex* biozone (Goldman *et al.* 2020) was referred to as the ‘Low Diversity Interval’ by Ethington and Clark (1982) and is characterized by sparse, low diversity conodont faunas across much of North America. It corresponds to 336–391 csu (composite standard units) in the composite reference section for the Midcontinent Lower Ordovician (Sweet and Tolbert 1997). In the Durness Group, the overall low yields mean that the interval is not conspicuously developed, but diversity is low in the lower part of the Sangomore Formation, and zonally diagnostic taxa are absent for the most part. Only *V. bassleri* persists from the *manitouensis* biozone, and it has an LAD 21 m above the formation base (Fig. 6). Other taxa recorded include *Scolopodus* aff. *S. rex* Lindström *sensu* (Ethington and Clark 1982), *Ulrichodina abnormalis* (Branson and Mehl) (*sensu* Landing in Landing and Westrop 2006), *Striatodontus prolificus* Ji and Barnes (Fig. 7f, g), *Laurentoscandodus* aff. *triangularis* (Furnish) (Fig. 7h), *Drepanodus* sp. (Fig. 7i) and *Aloxoconus staufferi* Furnish. The faunal succession compares closely with western Newfoundland, where samples from the uppermost Watts Bight Formation have barren or low diversity yields, with *V. bassleri* the only taxon present (Ji and Barnes 1994, Stouge and Boyce 1997).

5.e. *Macerodus dianae* biozone

The FAD of *Macerodus dianae* Fåhræus and Nowlan (Fig. 7k, l) lies 40.9 m above the base of the Sangomore Formation and defines the base of the *dianae* biozone, which has a total thickness of 44.4 m and encompasses the upper 14.0 m of the Sangomore and the lowest 30.4 m of the Balnakiel Formation. Other taxa recorded from this zone include an element assigned to *Histiodella donnae* Repetski (Fig. 7j), ‘*Eucharodus*’? sp. nov. (Fig. 7t), *Oneotodus* sp. nov. A, *Macerodus* sp. nov., *Drepanodus homocurvatus* Lindström, *S. prolificus*, *L.* aff. *triangularis*, *Drepanoistodus concavus* (Branson and Mehl) and *Parapanderodus striatus* (Graves and Ellison).

In the Durness Group, the range of *M. dianae* extends beyond a sequence boundary interpreted as correlating with the Sauk IIIC–IIID sequence boundary of Laurentia and with the Boat Harbour disconformity that marks that sequence boundary in western Newfoundland (Raine and Smith 2012). In Newfoundland, the strata beneath this sequence boundary are of *dianae* biozone age (Ji and Barnes 1994, Stouge and Boyce 1997). *M. dianae* has an FAD 16.5 m above the base of the Boat Harbour Formation and this species and many others have their LAD at the disconformity (Stouge 1982). The occurrence of *M. dianae* above, as well as below, the sequence boundary in NW Scotland suggests either that the succession is more expanded compared with that in western Newfoundland or that the range of this species is incompletely known.

5.f. *Acodus deltatus*/*Paraserratognathus costatus* biozone

Acodus deltatus Lindström, which we consider to be distinct from *Diaphorodus delicatus* Branson and Mehl, has an FAD 30.4 m above the base of the Balnakiel Formation and the biozone is 64 m thick, extending through the remaining Balnakiel Formation into the lowermost beds of the Croisaphuill Formation (Fig. 6). The zone contains a notably more diverse conodont fauna than the underlying Durness Group that includes *Parapanderodus striatus* (Graves and Ellison), *Scolopodus floweri* (Repetski), *Juanognathus* sp. nov. (= *Juanognathus* sp. A *sensu* Stouge 1982), *Laurentoscandodus* aff. *triangularis*, *Striatodontus prolificus*, *Drepanodus arcuatus* Pander (Fig. 7q), *D. homocurvatus* (Fig. 7p), *D. concavus* (Fig. 7o), *Drepanoistodus* aff. *nowlani* (*sensu* Ji and Barnes) (Fig. 7r), *M. dianae*, *Drepanoistodus* sp. A Stouge and Boyce (Fig. 7m, n), *Oneotodus* sp. A and a new genus (Fig. 7s).

In western Newfoundland, *M. dianae*, *S. floweri* and *D.* aff. *nowlani* are present with *Juanognathus* sp. A *sensu* Stouge in the Boat Harbour Formation below the Boat Harbour disconformity/Sauk IIIC–IIID sequence boundary (Stouge 1982; Stouge and Boyce 1997), but none of these taxa extend above it. The occurrence of these taxa within the *deltatus/costatus* biozone in Scotland suggests that the lower part of the zone is missing at the sequence boundary in Newfoundland or that the ranges are longer in NW Scotland.

The Tremadocian–Floian boundary is defined by the FAD of the graptolite *Paratetragraptus approximatus* Nicholson and corresponds to an absolute age of 477.1 Ma (Goldman *et al.* 2020). Although there has been some debate about the position of the Tremadocian–Floian boundary within the *deltatus/costatus* biozone, there is now some agreement that it lies around three-quarters of the way through the biozone (Goldman *et al.* 2020, 2023). On this basis, the stage boundary would lie within the middle to upper part of the Balnakiel Formation (c. 440 m above the base of the Durness Group and approximately 245 m above the base of the Ordovician), though this carries the caveat that correlation of the GSSP for the base of the Floian Stage with shallow water Scottish and other Laurentian reference sections remains problematic (Bergström *et al.* 2004).

5.g. *Oepikodus communis* biozone

The base of the *communis* biozone is marked by the FAD of *Oepikodus communis* (Ethington and Clark) (Fig. 8a, b), 8.5 m above the base of the Croisaphuill Formation. The zone is 41.5 m thick in the Durness Group (Fig. 6) and represents peak conodont and macrofaunal diversity in the succession, with the base also corresponding to the maximum flooding event of the whole Durness Group succession (Raine and Smith 2012). Based upon the recovery of *O. communis* and other zonally diagnostic taxa, the Croisaphuill Formation is significantly younger than the *deltatus/costatus* biozone age previously suggested by Higgins (1985). Many of the species recorded from the Durness Group have their FADs within 10 m above the base of the zone (and within 20 m of the formation base). Excluding long-ranging taxa, species recovered include ‘*Scolopodus*’ *subrex* Ji and Barnes (Fig. 10a), ‘*Eucharodus*’ *toomeyi* (Ethington and Clark) (Fig. 10d–f), ‘*Scandodus*’ *ethingtoni* Smith (Fig. 8r), *Oelandodus* cf. *costatus* van Wamel (Fig. 8v), *Toxotodus carlae* (Repetski) (Fig. 9t), *Protoprioniodus simplicissimus* McTavish (Fig. 8f–h), *Filodontus filosus* (Ethington and Clark) (Fig. 10k), *Tropodus comptus* (Branson and Mehl) (Fig. 8n–p), *Oneotodus* sp. A *sensu* Smith (1991) (Fig. 9q), *Oneotodus* sp. B (this study), *Pohlerodus marathonensis* (Bradshaw) and several species of *Drepanoistodus* (Fig. 9f, h, i, l). The base of the *communis* biozone also represents the FAD of a group of form species that may represent apparatus components of a single species – *Paraserratognathus abruptus* (Repetski), *Paraserratognathus*

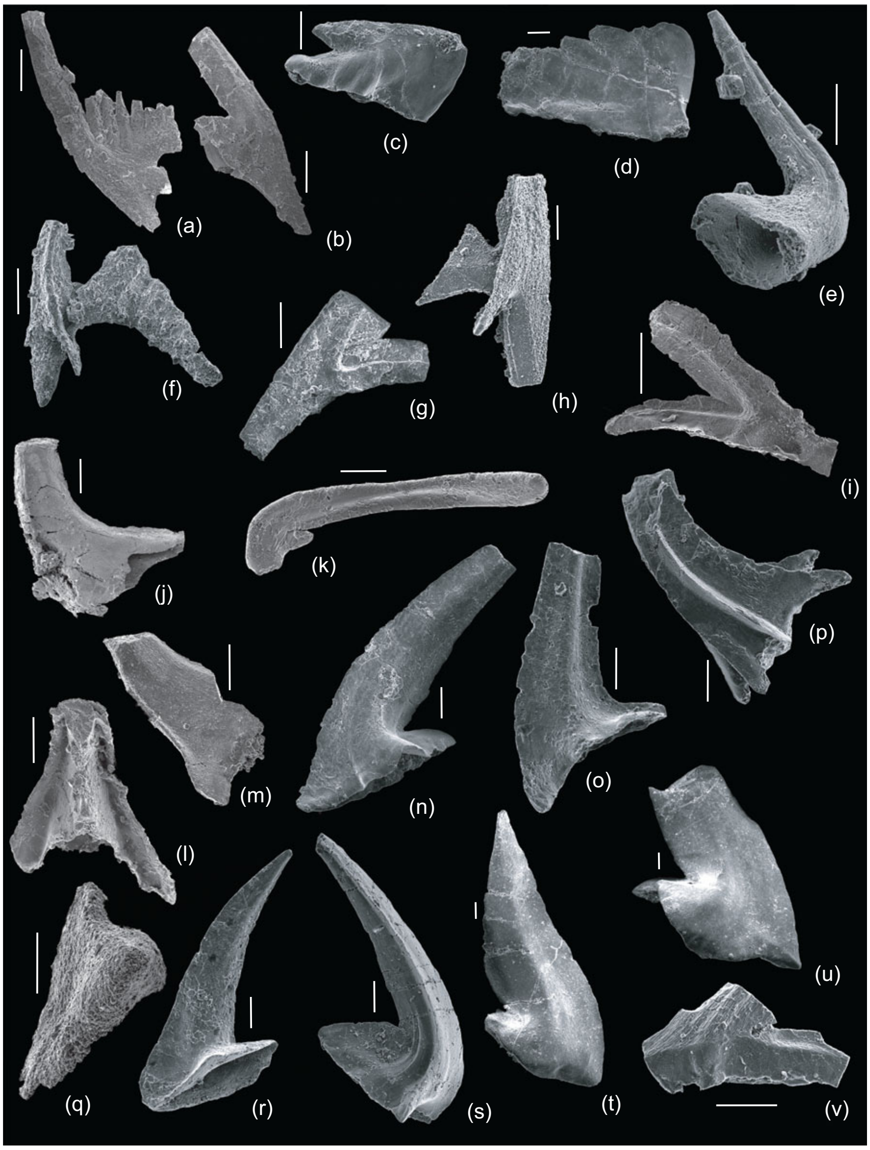

Figure 8. Conodonts from the Croisaphuill Formation (*communis* and *andinus* biozones). (a, b) *Oepikodus communis* (Ethington and Clark); spot sample 2003-10; BIRUG: BU5532, BU5533. (c, d) *Cristodus loxoides* Repetski; 17.9 m; BIRUG: BU5534, 5535. (e) aff. *Semiacontiodus* sp. Albanesi and Vaccari; 17.9 m; BIRUG: BU5536. (f, g) *Protoprioniodus simplicissimus* McTavish; 50.1 m; BIRUG: BU5537, BU5538. (h) *Protoprioniodus simplicissimus* McTavish; 58.6 m; BIRUG: BU5539. (i) *Protoprioniodus simplicissimus* McTavish; 17.9 m; BIRUG: BU5540. (j) *Diaphorodus delicatus* (Branson and Mehl); 297.0 m; BIRUG: BU5541. (k) '*Oistodus*' *ectyphus* Smith; spot sample, middle Croisaphuill Formation; BIRUG: BU5542. (l) *Diaphorodus delicatus* (Branson and Mehl); 297.0 m; BIRUG: BU5543. (m) *Triangulodus*? sp.; 297.0 m; BIRUG: BU5544. (n–p) *Tropodus comptus* (Branson and Mehl); 17.9 m; BIRUG: BU5545, BU5546, BU5547. (q) *Kallidontus corbatoi* (Serpagli); 78.9 m; BIRUG: BU5548. (r) '*Scandodus*' *ethingtoni* Smith; 17.9 m; BIRUG: BU5549. (s) *Oistodus* aff. *lanceolatus* Pander; spot sample; BIRUG: BU5550. (t, u) *Oistodus bransoni* (Ethington and Clark); 38.3 m; BIRUG: BU5551, BU5552. (v) *Oelandodus* cf. *costatus* van Wamel; 17.9 m; BIRUG: BU5553. All scale bars are 100 µm.

pygmaeus (Ji and Barnes) and possibly *Eoserratognathus* guyi (Smith) (Fig. 9m, n, o, r, s).

The long-ranging taxa *U. abnormalis* (Fig 10c, i), *P. striatus* (Fig.10h, l, m), *A. deltatus* (Fig. 9k), *D. arcuatus* (Fig. 9b), *D. concavus* and *Drepanoistodus* aff. *forceps* (Lindström) (Fig. 9j) persist into the Croisaphuill Formation, whilst other long-ranging taxa have their local FAD at or near the base of the *communis* biozone. The latter include *Paraserratognathus costatus* (Ethington and Brand) (Fig. 9p), '*Scolopodus*' *emarginatus* Barnes and Tuke (Fig. 10o), *Aloxoconus* sp. A *sensu* Smith, *Drepanoistodus angulensis* (Harris) (Fig. 9c, d), *Cristodus loxoides* Repetski (Fig. 8c, d), *Oistodus bransoni* (Ethington and Clark) (Fig. 8t, u) and *Diaphorodus delicatus* (Branson and Mehl) (Fig. 8j).

Although *Aloxoconus staufferi* (Furnish) (Fig. 9w) represents a single-element morphotype in an unknown apparatus, it is not placed in the reconstructed apparatus of *Ulrichodina abnormalis*, as suggested by Ji and Barnes (1994). Instead, the apparatus reconstruction of Landing (in Landing and Westrop 2006) is followed (incorporating *Eucharodus parallelus*, *Ulrichodina abnormalis* and *Colaptoconus quadraplicatus*). A new species of *Aloxoconus* was also recovered from 17.9 m above the base of the Croisaphuill Formation (Fig. 9v), which is very similar to the one figured as scolopodiform C by Ethington and Clark (1982), and an element resembling '*Scolopodus*' *subrex* Ji and Barnes was recovered from the Croisaphuill Formation (Fig. 10a).

In western Newfoundland *O. communis* and *E. guyi* first appear within 3 m of the top of the Boat Harbour Formation, and *T. comptus* and *Paraserratognathus costatus* become abundant. In the lower Catoche Formation, conodonts become increasingly abundant and the fauna more diverse. The conodonts *C. loxoides* and *Protoprioniodus* sp. A (*sensu* Stouge 1982) are present, and then *Toxotodus carlae* (Repetski) and finally *Bergstroemognathus extensus* (Graves and Ellison), *Kallidontus corbatoi* (Serpagli) and '*Reutterodus andinus*' Serpagli have their first appearances successively higher in the Catoche Formation (Stouge and Boyce 1997). This pattern closely mirrors the succession observed in the Durness Group (Fig. 6). *E. guyi* also first appears within the

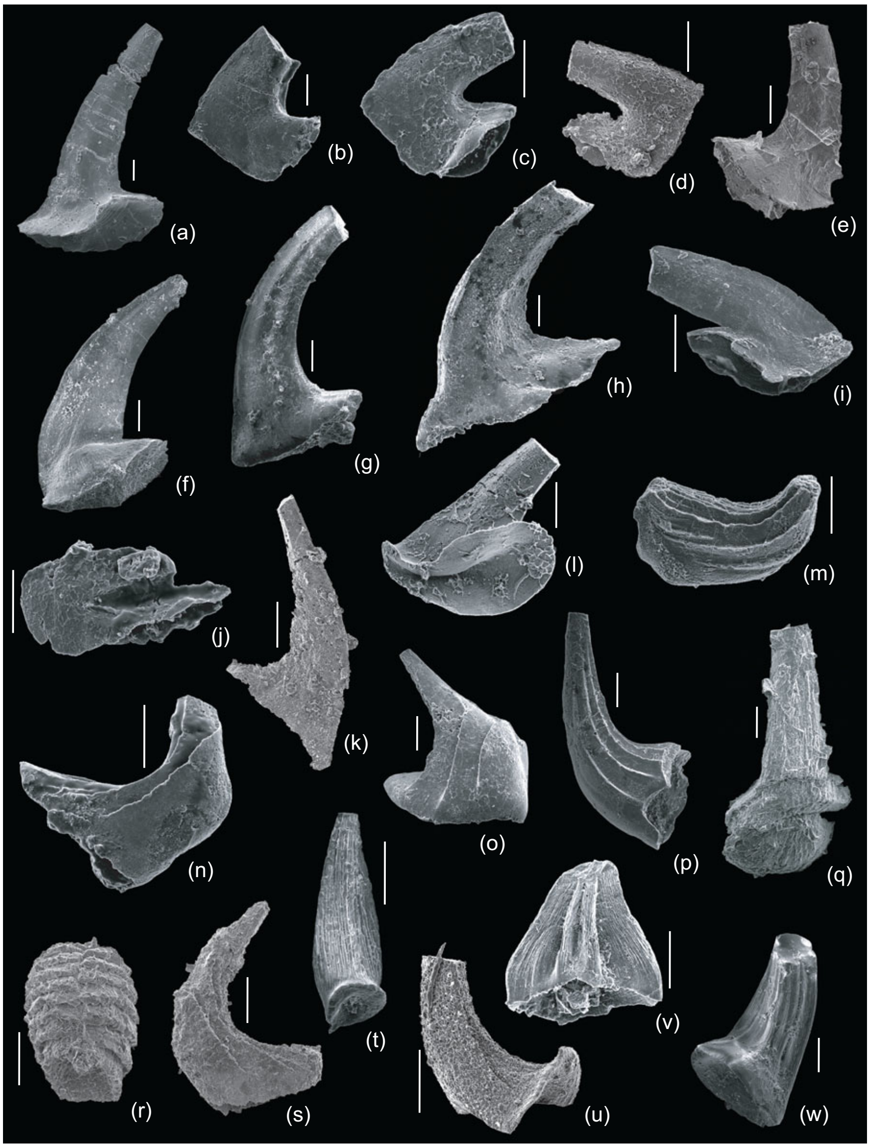

Figure 9. Conodonts from the Croisaphuill Formation (*communis* and *andinus* biozones). (a) *Drepanoistodus* sp.; 17.9 m; BIRUG: BU5554. (b) *Drepanodus arcuatus* Pander; 17.9 m; BIRUG: BU5555. (c) *Drepanoistodus angulensis* (Harris); 17.9 m; BIRUG: BU5556. (d) *Drepanoistodus angulensis* (Harris); spot sample, mid Croisaphuill Formation; BIRUG: BU5557. (e) *Drepanodus* sp.; spot sample; BIRUG: BU5558. (f) *Drepanoistodus* sp. A; 17.9 m; BIRUG: BU5559. (g) *Drepanoistodus* sp.; 17.9 m; BIRUG: BU5560. (h) *Drepanoistodus* sp. B; 17.9 m; BIRUG: BU5561. (i) *Drepanoistodus* sp. C; 17.9 m; BIRUG: BU5562. (j) *Drepanoistodus* aff. *forceps* (Lindström); 17.9 m; BIRUG: BU5563. (k) *Acodus deltatus* Lindström; 50.1 m; BIRUG: BU5564. (l) *Drepanoistodus* sp. D; 17.9 m; BIRUG: BU5565. (m) *Paraserratognathus pygmaeus* (Ji and Barnes); 17.9 m; BIRUG: BU5566. (n, o) *Paraserratognathus abruptus* (Repetski); 17.9 m; BIRUG: BU5567, BU5568. (p) *Paraserratognathus costatus* (Ethington and Brand); 17.9 m; BIRUG: BU5569. (q) *Oneotodus* sp. A *sensu* Smith (1991); spot sample, lower Croisaphuill Formation; BIRUG: BU5570. (r) *Eoserratognathus guyi* (Smith); spot sample, lower Croisaphuill Formation; BIRUG: BU5571. (s) *Paraserratognathus abruptus* (Repetski); spot sample; BIRUG: BU5572. (t) *Toxotodus carlae* (Repetski); 17.9 m; BIRUG: BU5573. (u) *Protopanderodus gradatus* Serpagli; 58.55 m; BIRUG: BU5574. (v) *Aloxoconus* sp. nov. (= scolopodiform C of Ethington and Clark); 17.9 m; BIRUG: BU5575. (w) *Aloxoconus staufferi* (Furnish); 17.9 m; BIRUG: BU5576. All scale bars are 100 µm.

communis biozone in Ny Friesland, NE Spitsbergen (Lehnert *et al.* 2013), and extends into the succeeding *variabilis* biozone.

5.i. *Juanognathus variabilis* biozone

Reutterodus andinus was first described by Serpagli (1974) as a trimembrate apparatus comprising 'unibranched', 'bibranched' and 'cone-like' morphotypes, with the unibranched element as the holotype. Many studies of Laurentian faunas have recovered the coniform element but not the other morphotypes, and this has resulted in this element generally being described in some form of open nomenclature (e.g. Ethington and Clark, 1982; Repetski 1982; Smith 1991), despite it being a zonal taxon in the Midcontinent (Ross *et al.* 1997) and Argentinean Precordillera (Albanesi and Ortega, 2016). Pyle and Barnes (2002) recognized the overall morphological similarity and co-occurrence of the coniform element with elements of *Juanognathus variabilis* Serpagli and included it in that apparatus as the M element. This synonymy is followed here, although it is here interpreted as a P element on the basis of the morphological similarity with P elements of coniform prioniodontid apparatuses such as *Tropodus*.

The taxonomic revision of *R. andinus* has implications for the standard Midcontinent zonation of Ross *et al.* (1997; see also Goldman *et al.* 2020, 2023) and the ?*R. andinus* biozone in particular. In the composite reference section of Sweet and Tolbert (1997), the S elements of *J. variabilis* have a lower FAD (660 csu) than the element now interpreted as the P element (758 csu), which is unsurprising given their greater abundance in the apparatus. However, it has the effect of compressing the *communis* biozone, since the FAD of *Oepikodus communis* is also at 660 csu. In this study, the taxonomic name of the *andinus* biozone is simply changed to the *variabilis* biozone, but in the long term, it may prove more practicable to select the FAD of an alternative taxon to divide the interval between the range-base of *Oepikodus communis* and that of *Tripodus combsi*.

In the Durness Group, *Juanognathus variabilis* occurs in just two samples, with a range from 50.1 to 58.6 m above the base of the Croisaphuill Formation. The P elements (= '?*Reutterodus andinus*') occur in both samples and S elements in just the upper one, so in this instance, there is no compression of the *communis* biozone, which is 41.6 m thick. The *variabilis* biozone is 300 m

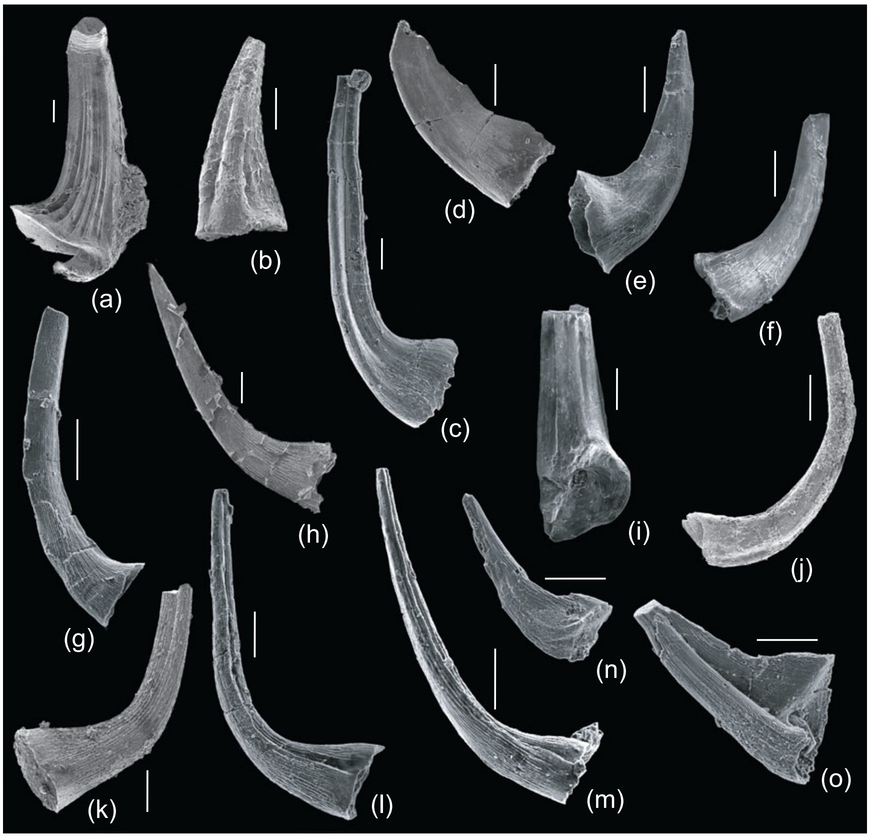

Figure 10. Conodonts from the Croisaphuill Formation. (a) *'Scolopodus' subrex* Ji and Barnes; 8.5 m; BIRUG: BU5577. (b) *Ulrichodina* sp. nov. A; spot sample, mid Croisaphuill Formation; BIRUG: BU5578. (c) *Ulrichodina abnormalis* (Branson and Mehl); 17.9 m; BIRUG: BU5579. (d) *'Eucharodus' toomeyi* (Ethington and Clark); 8.5 m; BIRUG: BU5580. (e) *'Eucharodus' toomeyi* (Ethington and Clark); 17.9 m; BIRUG: BU5581. (f) *'Eucharodus'* cf. *toomeyi* (Ethington and Clark); 17.9 m; BIRUG: BU5582. (g) *'Eucharodus'* xyron (Repetski); 17.9 m; BIRUG: BU5583. (h) *Parapanderodus striatus* (Graves and Ellison); spot sample, lower Croisaphuill Formation; BIRUG: BU5584. (i) *Ulrichodina abnormalis* (Branson and Mehl); 17.9 m; BIRUG: BU5585. (j) *Parapanderodus striatus* (Graves and Ellison) spot sample; BIRUG: BU5586. (k) *'Scolopodus' filosus* Ethington and Clark; 58.6 m; BIRUG: BU5587. (l, m) *Parapanderodus striatus* (Graves and Ellison); 17.9 m; BIRUG: BU5588, BU5589. (n, o) *'Scolopodus' emarginatus* Barnes and Tuke; 17.9 m; BIRUG: BU5590, BU5591. All scale bars are 100 µm.

thick within the Durness Group and includes much of the Croisaphuill Formation (upper 75 m of the informal lower member and 225 m of the upper member). The conodonts *Kallidontus corbatoi* (Serpagli) (Fig. 8q), *Juanognathus variabilis* Serpagli, *Protopanderodus gradatus* Serpagli (Fig. 9u), *Scolopodus* aff. *cornutiformis* Branson and Mehl and *Juanognathus* sp. A sensu Smith (1991) all have their FAD within the lower parts of the *variabilis* biozone (Fig. 6) and characterize the fauna of this zone.

Long-ranging taxa recovered include *A. deltatus* (Fig. 9k), *C. loxoides*, *D. delicatus* (Fig. 8j), *D. arcuatus*, *D. concavus*, *D. angulensis*, *P. costatus*, *P. striatus*, *P. abruptus*, *S. emarginatus*, *U. abnormalis*, *Aloxoconus* sp. A sensu Smith (1991) and *Drepanoistodus* aff. *forceps* (Lindström) (Fig. 9j), and all persist through the zone. *Aloxoconus staufferi* (Furnish) (Fig. 9w), *F. filosus*, *O. communis*, *P. pygmaeus*, *Protoprioniodus simplicissimus* McTavish (Fig. 8i), '*S*'. *ethingtoni* and *T. comptus* extend from the underlying *communis* biozone but have their LADs within the lower parts of the *variabilis* biozone (Fig. 6).

Spot samples in poorly exposed intervals of the Croisaphuill Formation revealed more detail of the faunas in the formation, with the additional presence of '*Oistodus*' *ectyphus* (Smith) (Fig. 8k) and *Bergstroemognathus extensus* confirming the presence of the *variabilis* biozone within the middle of the Croisaphuill Formation.

5.j. Tripodus combsi biozone

Ross *et al.* (1997) selected the FAD of *Tripodus laevis* Bradshaw as the zonal index for the youngest conodont biozone in the Laurentian Lower Ordovician. Although the name *T. laevis* continues to be used as the biozonal name in some stratigraphic schemes (e.g. Albanesi & Ortega 2016; Goldman *et al.* 2020), Sweet *et al.* (2005) accepted the recommendation of Stouge (1984) as the first revisor that *Acodus combsi* Bradshaw is the available name, whilst retaining the generic assignment to *Tripodus* (see Loch and Ethington, 2017, for a taxonomic summary).

T. combsi has a FAD in the uppermost sample of the Croisaphuill Formation, 350 m above the formation base and 800 m above the base of the Durness Group. The *combsi* biozone is less than 130 m thick and extends from the top few centimetres of the Croisaphuill Formation through most of the overlying Durine Formation. Conodont species recorded from this zone include many long-ranging taxa, some of which have their LAD within the zone (Fig. 6). *Tripodus combsi*, for example, has an LAD 43 m above the base of the Durine Formation (Fig. 11n). A possible new species of *Ulrichodina* (Fig. 11k) is recorded from 20.7 m above the base of the Durine Formation.

Biostratigraphical resolution within the Durine Formation is hampered by the increasingly poor preservation of elements up-section, by the discontinuous nature of the sections and by the increased number of barren samples in the peritidal dolostones that make up the unit.

The base of the Dapingian stage and the Middle Ordovician series are defined at the FAD of the conodont *Baltoniodus triangularis* (Lindström) in the Huanghuachang section GSSP, northeast of Yichang, China (Wang *et al.* 2005; Goldman *et al.* 2020, 2023). *Microzarkodina flabellum* (Lindström) has an FAD 20 cm higher in that section, and the base of the *B. triangularis*–*M. flabellum* biozone in the GSSP section was correlated by Wang *et al.* (2005) with the base of the *T. laevis*–*M. flabellum* interval in Laurentia (Ethington and Clark 1982; Ross and Ethington 1992), formalized as the *T. laevis* biozone by Ross *et al.* (1997) (now the *T.*

Figure 11. Conodonts from the Durine Formation. (a) *Drepanoistodus*? sp.; 42.9 m; BIRUG: BU5592. (b) *Diaphorodus*? sp.; 42.9 m; BIRUG: BU5593. (c) *Juanognathus*? sp. P element; 42.9 m; BIRUG: BU5594. (d) *Ulrichodina abnormalis* (Branson and Mehl) spot sample 2003-30, top of Durine Formation; BIRUG: BU5595. (e) *Dischidognathus* sp. nov. *sensu* Ethington and Clark (1982); spot sample, 2003-30, top of Durine Formation; BIRUG: BU5596. (f) *Pteracontiodus cryptodens* (Mound); spot sample 2004-06, lower Durine Formation; BIRUG: BU5597. (g, h) *Pteracontiodus cryptodens* (Mound); spot sample 2003-08, top of Durine Formation; BIRUG: BU5598, BU5599. (i) *Pteracontiodus cryptodens* (Mound); 32.2 m; BIRUG: BU5600. (j) '*Oistodus*' aff. *akpatokensis* Barnes *in* Workum *et al.*; spot sample 2004-06, lower Durine Formation; BIRUG: BU5601. (k) *Ulrichodina* sp. nov.; 20.7 m; BIRUG: BU5602. (l) *Paraserratognathus costatus* (Ethington and Brand); 42.9 m; BIRUG: BU5603. (m) Gen. nov. B; 120.5 m; BIRUG: BU5604. (n) *Tripodus combsi* Bradshaw; 42.9 m; BIRUG: BU5605. (o) prioniodontid M element; spot sample 2003-08, top of Durine Formation; BIRUG: BU5606. (p) *Chosonodina rigbyi* Ethington and Clark; spot sample 2003-30, top of Durine Formation; BIRUG: BU5607. All scale bars are 100 µm.

combsi biozone as outlined above). The base of the Dapingian, and the Lower–Middle Ordovician boundary, is therefore placed 350 m above the base of the Croisaphuill Formation (800 m above the base of the Durness Group) and the Lower Ordovician interval within the group is 604 m thick.

5.k. Histiodella altifrons and Histiodella sinuosa biozones

A spot sample (2003-30) at the top of the Durine Formation, collected as close to faulted Moine thrust zone rocks as possible, yielded a reasonably diverse fauna that included *P. cryptodens*, (Fig. 11f–i), *Chosonodina rigbyi* Ethington and Clark (Fig. 11e), *Microzarkodina flabellum*? (Lindström) and *Dischidognathus* sp. nov. *sensu* Ethington and Clark (1982) (Fig. 11p). Higgins (1967) also collected samples from isolated outcrops close to the faulted upper limit of the Durine Formation and recorded a diverse and relatively well-preserved conodont fauna. Recollecting of Higgins' localities (D-15 and D-16, Fig. 3) in the uppermost Durine Formation produced diverse and relatively well-preserved faunas that include *Histiodella altifrons* (Harris) (Fig. 12h–j) together with *Jumudontus gananda* Cooper (Fig. 12l–n), *Cooperignathus aranda* (Cooper) (Fig. 12p, q), *Chosonodina rigbyi*, *Dischidognathus* sp. nov. (Fig. 12y), *Pteracontiodus cryptodens* (Mound) (Fig. 12 a–c, w, x), *Scolopodus paracornutiformis*, *Oistodus scalenocarinatus* Mound (Fig. 12d), *Prioniodus oepiki* (McTavish) (Fig. 12o), *Drepanodus arcuatus* Pander (Fig. 12v), *Parapanderodus striatus* (Graves and Ellison) (Fig. 12f, g), *Drepanoistodus concavus* Branson and Mehl) (Fig. 12r), *Drepanoistodus angulensis* (Harris) (Fig. 12s), *Drepanoistodus* aff. *forceps* Lindström (Fig. 12t), *Ulrichodina abnormalis* (Branson and Mehl) (Fig. 12k) and '*Scolopodus*' *emarginatus* (Barnes and Tuke) (Fig. 12u).

The age of the top of the Durine Formation and the top of preserved carbonates in the Durness Group was for many years assumed to be the latest Arenig or early Llanvirn (Higgins 1967) but was more precisely referred to the *Pteracontiodus cryptodens*–*Histiodella altifrons*–*Multioistodus auritus* interval of Ethington and Clark (1982) by Bergström (1985).

In the Laurentian Middle Ordovician composite reference section of Sweet *et al.* (2005), the zonal taxon *H. altifrons* has a short range from 598 to 658 csu and has a limited overlap with the upper ranges of *C. aranda* (554–614 csu) and *J. ganada* (487–618 csu). The co-occurrence of these three taxa in samples from the uppermost Durine Formation confirms that the top of the Durine Formation corresponds to the *altifrons* biozone or lower *sinuosa* biozone. The presence of *Chosonodina rigbyi* in other samples from the uppermost Durine Formation provides support for the presence of the *sinuosa* biozone within the unit because in the composite reference section of Sweet *et al.* (2005) *C. rigbyi* has a range of 665–806 csu, with an FAD within the *sinuosa* biozone (606–702 csu).

The *altifrons* biozone has a short span of around 0.7 million years in the late Dapingian, from 470.3 to 469.6 Ma (Goldman *et al.* 2020) and the *sinuosa* biozone from 469.6 to 468.9 Ma, spanning the Dapingian–Darriwilian boundary. The Durine Formation conodont faunas provide a high precision estimate for the age of the youngest preserved carbonates within the Durness Group, and based on the current geological timescale for the Ordovician (Goldman *et al.* 2020), this corresponds to 470.3–468.9 Ma.

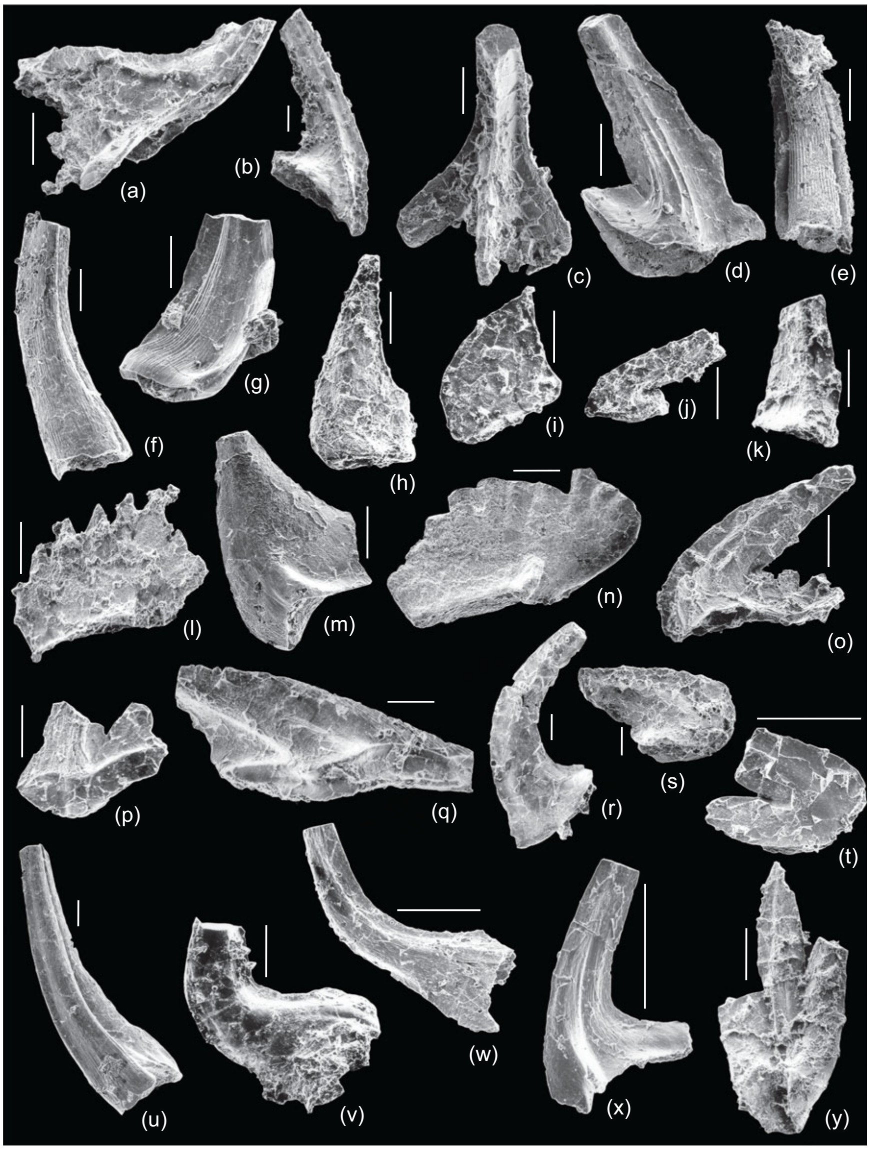

Figure 12. Conodonts from the uppermost Durine Formation (*altifrons* and *sinuosa* biozones) collected from localities D-15 and D-16 of Higgins (1967, 1971, 1985). (a–c) *Pteracontiodus cryptodens* (Mound); D-16; BIRUG: BU5608, BU5609, BU5610. (d) *Oistodus scalenocarinatus* Mound, D-15; BIRUG: BU5611. (e) '*Scolopodus*' sp.; D-15; BIRUG: BU5612. (f, g) *Parapanderodus striatus* (Graves and Ellison); D-15; BIRUG: BU5613, BU5614. (h–j) *Histiodella altifrons* Harris; D-16; BIRUG: BU5615, BU5616, BU5617. (k) *Ulrichodina abnormalis* (Branson and Mehl); D-16; BIRUG: BU5618. (l) *Jumudontus gananda* Cooper; D-16; BIRUG: BU5619. (m, n) *Jumudontus gananda* Cooper; D-15; BIRUG: BU5620, BU5621. (o) *Prioniodus oepiki* (McTavish); D-16; BIRUG: BU5622. (p, q) *Cooperignathus aranda* (Cooper); D-15; BIRUG: BU5623, BU5624. (r) *Drepanoistodus concavus* (Branson and Mehl); D-15; BIRUG: BU5625. (s) *Drepanoistodus angulensis* (Harris); D-16; BIRUG: BU5626. (t) *Drepanoistodus* aff. *forceps* (Lindström); D-15; BIRUG: BU5627. (u) '*Scolopodus*' *emarginatus* Barnes and Tuke; D-15; BIRUG: BU5628. (v) *Drepanodus arcuatus* Pander; D-16; BIRUG: BU5629. (w, x) *Pteracontiodus cryptodens* (Mound); D-15; BIRUG: BU5630, BU5631. (y) *Dischidognathus* sp. nov. *sensu* Ethington and Clark (1982); D-16; BIRUG: BU5632. All scale bars are 100 µm.

6. The Durness Group and the Great American Carbonate Bank

In the Cambrian and Ordovician, NW Scotland was a constituent part of Laurentia (Derby *et al.* 2012b), a craton that was roughly oblong in shape and bisected along its long axis by the palaeo-equator (Golonka 2002) (Fig. 13). Partly in response to this geographical position, a large-scale, non-uniformitarian environmental setting developed, which has been termed the Great American Carbonate Bank (GACB; Derby *et al.* 2012a). The GACB was an area of almost continuous carbonate deposition that extended for over 8,000 km from New Mexico in the palaeo-west to Greenland and Svalbard in the palaeo-east, with NW Scotland constituting the palaeo-south-eastern extremity of this continent-scale depositional belt (Fig. 13). The geological history of NW Scotland may thus be interpreted in the context of deposition on an east- and south-facing, low latitude, passively subsiding cratonic margin, and it has long been recognized that there are depositional similarities, and a facility of correlation, with both Greenland to the north and Newfoundland to the west (e.g. Swett and Smit 1972a, b; Swett 1981; Smith and Rasmussen 2008). The Durness Group preserves an important record of almost continuous carbonate sedimentation on the eastern Laurentian margin from the base of the Miaolingian (mid-Cambrian; 509 Ma) to the Dapingian (Middle Ordovician; 470 Ma), as part of GACB.

This distinctive position of NW Scotland within Laurentia has been referred to as the 'Scottish promontory' (Soper 1994; Dalziel and Soper 2001), which constituted the easternmost of a series of promontories and embayments that extended along the palaeo-southern margin of Laurentia from Scotland, through maritime Canada and the Appalachians as far as Alabama and Texas (Thomas 1977; Lavoie *et al.* 2003, 2012). It has been suggested that these palaeogeographical features on the Iapetus margin (Fig. 13) reflect the interplay of rifting and oceanic transform faults during Iapetus opening and the formation of the Laurentian passive margin at 540–535 Ma (Williams and Max 1980; Soper 1994; Cawood *et al.* 2001; Lavoie *et al.* 2003).

In palinspastic terms, the nearest preserved Cambrian–Ordovician sediments to the Durness Group are probably some poorly known metamorphosed rocks within the ultrapotassic Batbjerg intrusive complex, at the head of Kangerlussuaq, south-

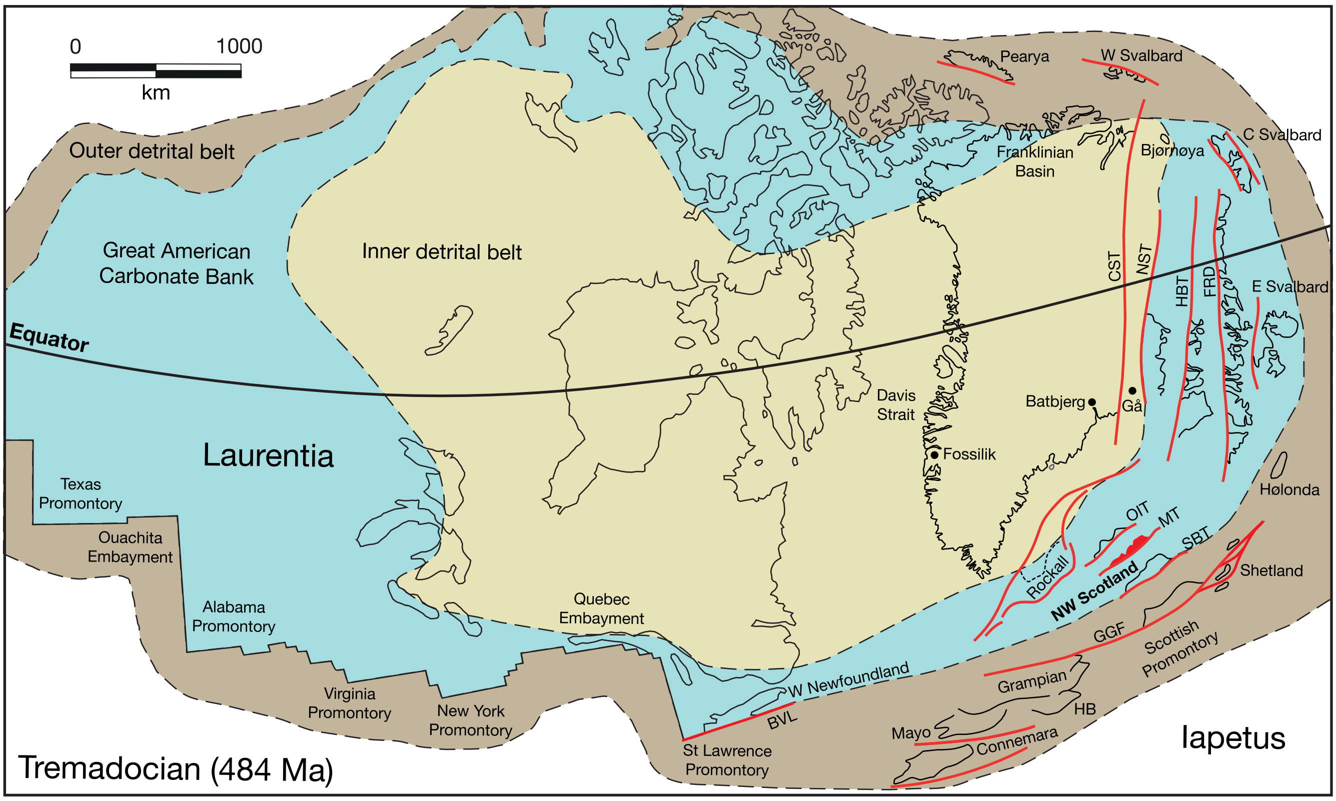

Figure 13. Palinspastic reconstruction of Laurentia during Tremadocian (Early Ordovician) time, *c.* 484 Ma, showing the depositional context of the Durness Group in NW Scotland and the extent of the Great American Carbonate Bank (GACB) and inner detrital belt. During maximum Ordovician sea-level highstands, such as the basal Floian, the inner detrital belt would have been considerably smaller and the GACB correspondingly expanded; Fossilik in western Greenland, for example, was a site of active carbonate deposition during only maximum sea-level highstands. Map compiled from Derby *et al.* (2012b); Lavoie *et al.* (2003, 2012) and Smith and Rasmussen (2008), with additional data from Leslie *et al.* (2008), Ryan and Dewey (2019) and Smith (2000). The position of the palaeo-equator is based on Golonka (2002), and red lines indicate post-depositional fault movements; offshore terranes and arcs are not depicted. Modern coastlines and lake outlines are provided for reference and, for clarity, internal Caledonian deformation within allochthonous blocks is not depicted. BVL, Baie Verte Line; CST, Caledonian Sole Thrust; FRD, Fjord Region Detachment; Gå, Gåseland window; GGF, Great Glen Fault; HB, Highland Border; HBT, Hagar Bjerg Thrust; MT, Moine Thrust; NST, Niggli Spids Thrust; OIT, Outer Isles Thrust; SBT, Sgurr Beag Thrust.

eastern Greenland (68°40′N; Fig. 13). The Batbjerg complex has a cooling age of 445 Ma and is dominated by alkaline pyroxenite; the complex has similarities to the Assynt alkaline suite of NW Scotland (Brooks *et al.* 1981). The complex also preserves a 3–20 m wide screen of contact metamorphosed dolostones with associated quartzites that Brooks *et al.* (1981) interpreted as a cauldron-subsided remnant of former Lower Palaeozoic sedimentary cover. The couplet of a thin quartz arenite sheet overlain by thin carbonates is a distinctive feature of the foreland/parautochthon of the Greenland Caledonides and is present both as the Slottet and Målebjerg formations of the nunatak zone (71°50′N–74°30′N) and the 'Zebra series' of Dronning Louise Land (76°2′N–77°27′N) (Smith *et al.* 2004; Smith and Rasmussen 2008). Probable equivalents of the Målebjerg Formation occur as far south as the Gåseland window (70°10′N) (Fig. 13; Smith and Rasmussen 2008). This couplet comprising Cambrian Series 2 clastic sediments overlain by Cambrian or Ordovician carbonates is characteristic of the most inboard deposition on the Laurentian margin in Greenland, where subsidence and available accommodation space were comparatively low.

During Ordovician sea-level highstands, carbonate sedimentation extended much farther onto the Laurentian craton due to the high degree of peneplanation. Evidence is preserved at Fossilik, 50 km east of Maniitsoq in southern West Greenland (Fig. 13), where Ordovician limestone clasts are preserved in a Jurassic volcanic breccia (Steenfelt *et al.* 2006; Secher *et al.* 2009). Conodonts from these blocks fall into three tightly constrained faunules of the *communis* biozone, *aculeata* biozone and *velicuspis* biozone (Smith and Bjerreskov 1994), corresponding, respectively, to middle Floian (Lower Ordovician), Sandbian (Late Ordovician) and early Katian (Late Ordovician) sea-level highstands. Scattered evidence for these highstand deposits occurs elsewhere onshore in West Greenland, and remnants of Ordovician successions are widespread offshore in the Davis Strait, although relatively poorly known (Peel 2019, with references).

Together, Batbjerg, the nunatak zone of North-East Greenland and Fossilik provide the context for Ordovician deposition in the hinterland of the Durness Group and its response to sea-level change. Of the three highstands recorded at Fossilik, only the oldest overlaps in age with the Durness Group, and it corresponds to the maximum flooding zone of Sauk IIId (and for the higher order Sauk III supersequence) low in the Croisaphuill Formation (Fig. 2). This implies that the Floian sea-level highstand is one of the absolute highest in the Cambrian–Ordovician interval and perhaps in the Phanerozoic (Simmons *et al.* 2020).

Comparison has more usually been made between the Durness Group and the Cambrian–Ordovician of the fjord region of North-East Greenland (Swett and Smit 1972a, b; Swett 1981). This sedimentary succession is assigned to the Kong Oscar Fjord Group (Smith *et al.* 2004) and is situated within the Franz Joseph

Allochthon (Higgins *et al.* 2004), structurally above and outboard of the Fjord Region Detachment, a major structure on which the most recent movement is extensional and top-down-to-the-east, related to orogenic collapse (Andresen *et al.* 1998; Higgins and Leslie 2008). Nevertheless, there was considerable telescoping of the Laurentian margin during the Caledonian collision with Baltica, with a minimum shortening of 200–400 km (40–60%) that juxtaposed the carbonates of the Franz Joseph Allochthon with the strandline represented on the parautochthon and foreland (Higgins and Leslie 2000; Higgins *et al.* 2004; Smith and Rasmussen 2008).

The Cambrian–Ordovician carbonates within the Kong Oscar Fjord Group that are the equivalent of the Durness Group exceed 3500 m in thickness, in comparison with 930 m for the Durness Group, and subtidal facies (including abundant microbialites) make up a higher proportion of the succession (Smith and Rasmussen 2008; Stouge *et al.* 2001, 2002, 2012). The contrast in thickness between the two areas reflects the more outboard position of the Greenland succession and consequently the higher subsidence on the margin and the greater accommodation space. This is reflected in the decompacted and backstripped subsidence curves of Smith and Rasmussen (2008, fig. 13) where, using the revised timescale of Goldman *et al.* (2020) and a duration for the Early Ordovician of 16 million years (m.y.), the tectonic subsidence rate for the Durness Group is 10.4 m m.y.$^{-1}$ and that for the Kong Oscar Fjord Group in the Franz Joseph Allochthon is 17.2–21.6 m m.y.$^{-1}$ depending upon location. Sedimentation in the Heimbjerge Formation, the youngest unit, extended into the late Darriwilian or earliest Sandbian (459–457 Ma) with no major hiatus in the Middle Ordovician, unlike Newfoundland (Smith and Bjerreskov 1994; Smith and Rasmussen 2008).

Stouge *et al.* (2001, 2002, 2012) did, however, propose a disconformity in the basal Ordovician of NE Greenland on the basis of macrofossils, spanning the equivalent of the *subrex* and *dianae* conodont biozones, although the age of the limestones above the putative disconformity remains poorly constrained (McCobb *et al.* 2014).

In contrast to the Greenland successions, western Newfoundland was situated on the palaeo-southern margin of Laurentia during the Cambrian and Ordovician (Fig. 13). The Durness Group is equivalent to the Port au Port and St George groups of western Newfoundland (James *et al.* 1989; Knight *et al.* 2007, 2008; Lavoie *et al.* 2012), but the latter region preserves the outer detrital belt in the allochthonous Cow Head and Northern Head groups, which represent shelf margin and slope deposits (James and Stevens 1986; M. Cooper *et al.* 2001) and preserve lowstand systems tracts that are represented by disconformities in the carbonate successions. The Port Au Port–St George group boundary is equivalent to the Eilean Dubh–Sailmhor formation boundary in the Durness Group and represents the shift from predominantly peritidal to predominantly subtidal deposition. The Port au Port Group is 450–500 m thick, and the St George Group is 500 m (Lavoie *et al.* 2012), so the thicknesses are comparable with those of the Durness Group, and this is reflected in the similar subsidence curves derived from backstripping (Smith and Rasmussen 2008).

Differences become apparent between Durness and western Newfoundland towards the top of Sauk IIId where, in Newfoundland, a major unconformity is present in the St George Group with significant palaeo-relief and the development of both exo- and endokarst (Knight *et al.* 1991; M. Cooper *et al.* 2001). Although the unconformity marks the Sauk–Tippecanoe megasequence boundary in Newfoundland, it is interpreted as having a tectonic origin and to be related to the migration of a peripheral bulge that was generated by Taconic loading (Knight *et al.* 1991; Lavoie *et al.* 2012). The unconformity is contained within the *altifrons* and *sinuosa* conodont biozones (= Faunas 2 and 3 of Knight *et al.* 1991), corresponding to a late Dapingian–earliest Darriwilian age (470.4–468.8 Ma in the timescale of Goldman *et al.*, 2020). The tectonic unconformity within the St George Group in western Newfoundland is thus closely correlative with the youngest preserved strata of the Durness Group. In western Newfoundland, the development of a foreland basin led to renewed deposition in the *holodentata* biozone with the deposition of the Table Head Group (Knight *et al.* 1991; Lavoie *et al.* 2012) as part of a 'flexural bulge megasequence' (M. Cooper *et al.* 2001). The tectonic event is also reflected in the deep-water slope succession of the Cow Head Group, where there was synchronous platform margin collapse and deep erosion leading to the formation of large-scale debrites (James and Stevens 1986; Lavoie *et al.* 2012).

7. The Durness Group and the Grampian/Taconic orogeny

The Caledonian orogeny is an amalgam of Cambrian–Devonian collisional events around the modern North Atlantic, and of these, the two that are most relevant to the post-depositional history of the Durness Group are the Grampian/Taconic and Scandian orogenies. The Grampian/Taconic orogeny was a Middle Ordovician event caused by the collision of an oceanic arc terrane with the palaeo-southern margin of Laurentia (Dewey and Shackleton 1984; Ryan and Dewey 2019), whereas the Scandian orogeny relates to the Silurian continent–continent collision of Baltica with the palaeo-eastern margin (Chew and Strachan 2014). The Scottish promontory (Fig. 13) experienced both events, and in each case, the Durness Group represents the youngest preserved pre-orogenic sedimentation.

The Scandian orogeny in Scotland led to extensive regional deformation and metamorphism resulting in reworking of the Neoproterozoic Loch Ness and Wester Ross supergroups (*sensu* Krabbendam *et al.* 2022) and the development of the Moine thrust zone in the final stages of the event (Strachan and Evans 2008). Syn- and post-thrust intrusions in the Assynt area (Fig. 1) are dated at 430 Ma (Goodenough *et al.* 2011, and Rb–Sr and K–Ar ages of associated mylonites provide ages of 435–430 Ma (Freeman *et al.* 1998). The older units of the Durness Group, the Ghrudaidh and Eilean Dubh formations, are commonly incorporated in the basal thrust sheets of the Moine thrust zone, and the lowest thrust of the Moine thrust zone truncates the Durine Formation in Sango Bay (Fig. 3; Raine *et al.* 2011), although in the Durness area, the Durness Group is more commonly juxtaposed against rocks of the thrust zone on younger structures (Wilson *et al.* 2010).

In the Greenland sector of the Laurentian margin, the Scandian event is remarkably synchronous with dates obtained from Scotland and also along the 1300 km length of the eastern Greenland margin. Kalsbeek *et al.* (2008) recorded sensitive high-resolution ion microprobe (SHRIMP) U-Pb analyses of zircons of 432 Ma on I-type calc-alkaline granodiorites and quartz diorites in the Hagar Bjerg thrust sheet (Fig. 13) of the Scoresby Sund region, and S-type granites derived from crustal thickening are dated 435–425 Ma. In the far north of Greenland, turbidites derived from emergent Scandian thrust sheets were deposited in deep water during the late Llandovery (Higgins *et al.* 1991). The carbonate shelf foundered due to loading shortly after, in the latest

Llandovery, and clastic deposition commenced. Mudstones of the middle Wenlock Profilfjeldet Member (Lauge Koch Land Formation) on the shelf were overridden by Caledonian thrusts, and this provides a maximum age for these frontal thrusts of *c.* 430 Ma.

Although the youngest rocks of the Durness Group are truncated by a Scandian thrust, the age difference of over 50 million years between the Scandian collision and the cessation of deposition means that there is not necessarily a causal relationship. The Durine Formation is, however, synchronous with Grampian peak metamorphism. Furthermore, the top of the Durine Formation is time correlative with the St George unconformity that resulted from Taconic tectonic activity farther along the Laurentian margin and interrupts deposition on the passive margin in western Newfoundland (Knight *et al.* 1991; M. Cooper *et al.* 2001; Lavoie *et al.* 2012). Did the same event result in the termination of deposition in the Durness Group? Based on the new conodont data, the Durine Formation is no younger than 469 Ma, and this compares closely with the timing of Grampian peak metamorphism and associated magmatism. For example, in Connemara (Fig. 13), syn-D2 to early D3 basic intrusions have yielded U–Pb zircon ages of 474.5 ± 1 Ma and 470.1 ± 1 Ma (Friedrich *et al.* 1999), and in Scotland, syn-D2 equivalents have been dated at 471 ± 0.6 Ma (Carty *et al.* 2012). Similarly, Sm–Nd garnet ages constrain peak metamorphism in the Scottish Highlands to 473–465 Ma (Baxter *et al.* 2002) and S-type granites in NE Scotland derived from crustal melting at peak metamorphism cluster at 470 Ma (Oliver *et al.* 2008; see Chew and Strachan 2014 for a review).

Grampian peak metamorphism at around 470 Ma is thus exactly coeval with the youngest Durness Group carbonates and the St George unconformity in western Newfoundland, and it is likely that associated uplift terminated deposition. In turn, the Durness Group places additional constraints on tectonic models. Carbonate systems are extremely sensitive both to base-level change and clastic input, and uplift of even a few decimetres would be recorded in the carbonate record. The backstripped subsidence curves do not record an interval of relative uplift, unlike in western Newfoundland (Smith and Rasmussen 2008), and the sequence stratigraphy does not record one either (Raine and Smith 2012). Therefore, the earlier recorded Grampian activity, pre-470 Ma, either occurred outboard of the Laurentian margin, prior to the collision, or it occurred elsewhere on the margin and the Grampian and Northern Highlands/foreland components were juxtaposed at a later date through sinistral strike-slip movement on the Great Glen Fault (Fig. 13; Soper *et al.* 1992; Dewey and Strachan 2003; Dewey and Ryan 2022).

Depositional continuity across the Laurentian margin, between the Ardvreck and Durness groups of the NW Highlands foreland and uppermost Dalradian Supergroup rocks to the south-east, has been proposed on the basis of zircon profiles and structural considerations (Cawood *et al.* 2007, 2012; Leslie *et al.* 2008; Searle 2022), but few of these studies have considered sediment composition. Sand-grade clastic sediment within the Ardvreck and Durness groups is supermature with >99% quartz, very well-rounded, high-sphericity grains (commonly with ‘millet-seed’ texture) and little clay, indicative of a continental interior provenance (Dickinson *et al.* 1983). In contrast, the Cambrian Series 2–Miaolingian Keltie Water Grit Formation (Trossachs Group) of the Highland border, interpreted as being in the uppermost Dalradian Supergroup (Tanner and Sutherland 2007), has a less mature composition, with sub-rounded to sub-angular clasts of quartz, variable proportions of feldspar and lesser amounts of lithic fragments with a matrix of ubiquitous detrital muscovite, sometimes with biotite, and differing proportions of sericite, carbonate and chlorite (Tanner and Pringle 1999). These lithic arkoses and subarkoses have compositions more characteristic of the quartz–feldspar–lithic profile for recycled orogen, uplifted basement or transitional continental provenance than of continental interior sediment with long residence times in the hinterland (Dickinson *et al.* 1983). There is also a contrast in the detrital zircon age spectra, with 1.2–1.0 Ga detritus entirely absent in the Ardvreck Group (Cawood *et al.* 2012). The Trossachs Group cannot have had the same provenance and sediment transport pathway as the Ardvreck and Durness groups, particularly since the least mature sediment would be outboard, and this lends support to strike-slip emplacement of the Grampian terrane as proposed, for example, by Ryan and Dewey (2019) (Fig. 13).

8. Conclusions

The 930 m thick Durness Group represents the youngest preserved pre-orogenic sedimentation in the Scottish Caledonides, ranging in age from basal Miaolingian (Cambrian, 509 Ma) to the Dapingian–Darriwilian boundary interval (Middle Ordovician, 469.4–468.9 Ma). Bed-by-bed logging at 10 cm resolution of sections in NW Scotland has enabled the construction of a detailed stratigraphic framework for the group (Figs. 2, 4 and 6). The Miaolingian age of the base of the oldest formation, the Ghrudaidh Formation, is well-constrained by the macrofauna and the presence of ROECE, and it correlates with the Sauk I–II supersequence boundary (Faggetter *et al.* 2018). The remainder of the Cambrian, corresponding to the Ghrudaidh and Eilean Dubh formations, contains no macro- or microfossil biotas except for the uppermost few metres, but the Sauk IIa–IIb, IIb–IIIa and IIIa–IIIb boundaries are all identifiable on the basis of sequence stratigraphy within the 133 m thick Eilean Dubh Formation at 20 m, 87 m and 115 m, respectively, above the unit base and provide some stratigraphic control (Fig. 2; Raine and Smith 2012). The Eilean Dubh Formation is unfossiliferous except for conodonts in the top 3 m (Fig. 4), but the identification of the Sauk II–III supersequence boundary, and its temporal proximity with the SPICE isotope event, provides a stratigraphic tie point at two-thirds height in the formation (Fig. 2), corresponding to the early Furongian (Peng *et al.* 2020).

Although conodont faunas are very sparse, there is sufficient control to indicate that the Cambrian–Ordovician boundary lies 1 m or 2 m below the Eilean Dubh–Sailmhor formation boundary (Figs. 4 and 5). In the overlying Ordovician, conodont faunas are generally sparse but sufficient to recognize most zonal intervals, and individual formations and events are now well-constrained by conodont biostratigraphy (Fig. 6). The Sauk IIIb–IIIc boundary is coincident with the base of the Sangomore Formation (Raine and Smith 2012), corresponding to the uppermost *manitounesis* biozone. Sauk IIIc is entirely contained with the Sangomore Formation, with the Sauk IIIc–IIId boundary coincident with the Sangomore–Balnakiel Formation boundary (Raine and Smith 2012) within the *dianae* biozone. Sauk IIId was termed Sauk IV by Golonka and Kiessling (2002) because of its long duration but correlation across Laurentia is problematic (Raine and Smith 2012). Nevertheless, the remainder of the Durness Group, including the entirety of the Balnakeil, Croisaphuill and Durine formations is contained within Sauk IIId.

The Tremadocian–Floian boundary, within the *deltatus*/*costatus* biozone, lies in the middle to upper Balnakiel Formation (Fig. 6), and towards the MFS in the lower Croisaphuill Formation conodonts become both abundant and diverse. The Floian–Dapingian boundary, corresponding to the base of the *combsi* biozone is located 350 m above the base of the Croisaphuill Formation (800 m above the base of the Durness Group), just below the boundary with the Durine Formation (Fig. 6), and the Lower Ordovician interval within the group is therefore 604 m thick. Diverse conodont samples from the uppermost Durine Formation provide good constraint on the age of the uppermost part of the Durness Group and of the youngest pre-orogenic sediments in NW Scotland, providing more precision than has hitherto been available. The youngest conodont faunas in the Durine Formation, within 20 m of the faulted contact with rocks of the Moine thrust zone, belong to the *altifrons* or early *sinuosa* biozones, corresponding to a depositional age of 470.3–468.9 Ma in the timescale of Goldman *et al.* (2020).

The Durness Group was deposited on the Scottish promontory, occupying a distinctive flexure in the Laurentian margin between the palaeo-south sector occupied by western Newfoundland, maritime Canada and the Appalachians and the palaeo-east facing Greenland sector. From this position, sedimentation on the Great American Carbonate Bank was continuous during sea-level highstands for over 7,000 km from Durness to modern New Mexico, USA, and for a further 2,500 km to North-East Greenland and Bjørnøya (Fig. 13).

The presence of near continuous deposition within the Durness Group from 509 Ma (Miaolingian) to 469 Ma (Dapingian–Darriwilian boundary interval), confirmed by high-resolution conodont biostratigraphy in the Ordovician units, means that Grampian orogenesis must have had no effect on the carbonate shelf system, which was highly sensitive to base-level change, until 469 Ma. Although depositional continuity across an intact Laurentian margin has been proposed, from the Durness Group on the foreland across the Scottish Highlands to the Trossachs Group on the Highland border, considerations of sediment composition suggest that they are not part of a single source-to-sink sediment pathway. The supermature quartz arenites of the proximal Ardvreck and Durness groups on the foreland cannot have had the same source as the feldspar- and lithoclast-rich sandstones of the coeval and more distal Trossachs Group (uppermost Dalradian Supergroup). Instead, it is probable that these terranes were juxtaposed by post-Scandian sinistral strike-slip faulting (Fig. 13).

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0016756824000372.

Data accessibility. Details of measured section locations (Supplementary File 1) and conodont sampling, together with abundance tables (Supplementary File 2), are available.

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