Uppermost Triassic to Lower Jurassic stratigraphy in the Lough Foyle Basin of County Londonderry, Northern Ireland.

Robert Raine[1], James P.G. Fenton[2], Ian Boomer[3], Azrin Azmi[3,4], Philip Copestake[5]

[1] Geological Survey of Northern Ireland, Dundonald House, Upper Newtownards Road, Belfast, Northern Ireland, BT4 3SB
[2]CGG Robertson, Tyn y Coed, Llanrhos, Llandudno, Wales LL30 1SA,
[3] Geosciences Research Group, GEES, University of Birmingham, England, B15 2TT,
[4] School of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.
[5] Merlin Energy Resources Ltd., Newberry House, Ledbury, Herefordshire, England, HR8 2EJ.

Abstract

The Lough Foyle Basin is a half-graben that straddles the border between Northern Ireland and the Republic of Ireland and contains sediments that range in age from Lower Carboniferous to Holocene. The basin's post-rift succession is represented by sediments of the Penarth Group and Lias Group. The lithostratigraphy and biostratigraphy of that interval are revised using new borehole material and existing outcrop. Palaeontological data provide a chronostratigraphic framework and aid palaeoenvironmental interpretations. Foraminifera, ostracods, palynomorphs indicate a nearshore, marginal marine depositional setting throughout much of the Rhaetian with a more marine, shelf and nearshore depositional setting for the Lias Group. The Penarth Group succession is similar to that elsewhere in Northern Ireland but the Lias Group (Waterloo Mudstone Formation) differs in that five distinct members can be recognised (Clooney Mudstone, Drummans Siltstone, Gortmore Mudstone, Tircreven Sandstone and Ballyleighery Mudstone), four of which are newly described. The deltaic and shelf sandstones of the Tircreven Sandstone Member are the only such examples preserved in the Jurassic strata of Northern Ireland and are some of the oldest in the Jurassic of the UK and Ireland, providing evidence of the proximity of the nearby Irish Landmass and representing a useful comparison for Early Jurassic sandstone reservoirs in offshore basins.

1. Geological setting and basin history

The Lough Foyle Basin (Lough Foyle Trough of Evans and Evans, 1987; Bazley et al., 1997) broadly corresponds to the present-day Lough Foyle between Co. Donegal and Co. Londonderry (Fig. 1). In some papers, this area has been included in the Rathlin Basin or Rathlin Trough (Fitzsimons and Parnell, 1995; Warrington, 1997). However, the basin constitutes a distinct half-graben, with a gravity low against the Foyle Fault, sediment forming a wedge that thickens north-westwards towards the fault (Fig. 1). The Lough Foyle Basin is separated from the Rathlin Basin to the east by an area of higher gravity (Evans and Evans, 1987). Gravity modelling suggests that the maximum depth of sediment in the basin is two kilometres (Evans and Evans, 1987; Bazley et al., 1997).

The Lough Foyle Basin is approximately 30 km long in a SW–NE direction (Evans and Evans, 1987; Bazley et al., 1997) reflecting the Caledonian structural grain of the Dalradian Supergroup basement in the Grampian terrane (Anderson et al., 1995) and of a similar orientation and style to the offshore Lough Indaal Basin as seen on the WINCH seismic profile (Hall et al., 1984).

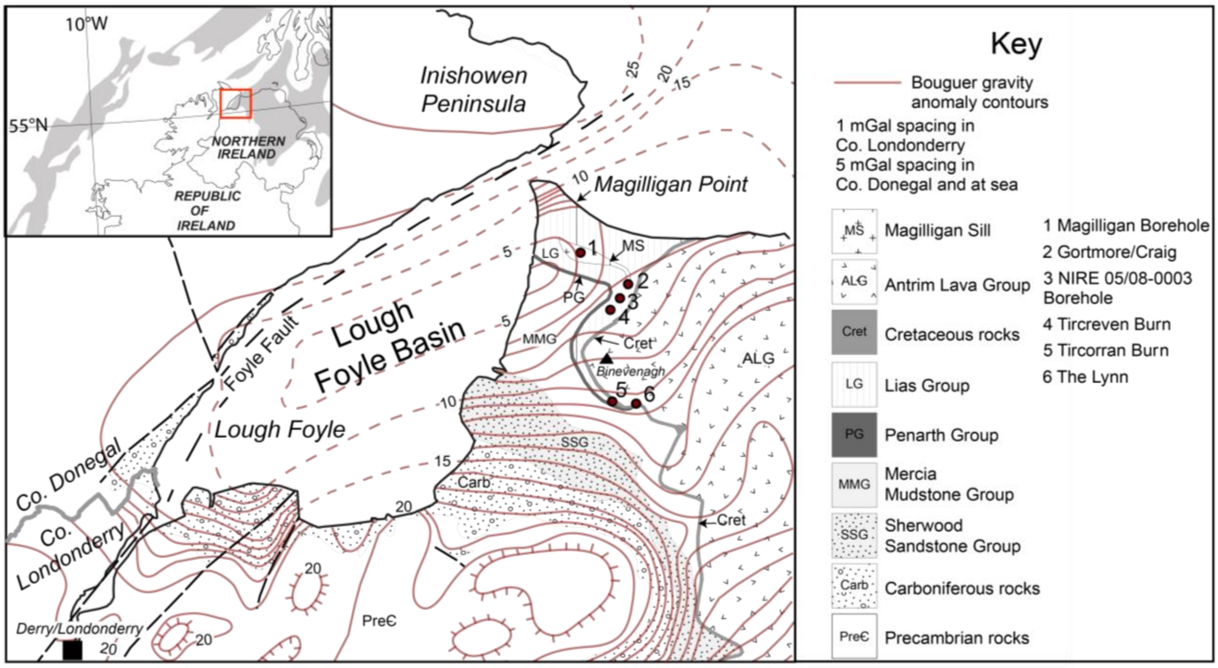


Figure 1. Location map of the Lough Foyle Basin covering the area marked by the box in the inset map. Geology is based on GSNI 1:250 000 scale geological map and GSI 1:500 000 geological map. Gravity data are reproduced from Bazley et al. (1997). Inset map (modified after Raine et al., 2020a) depicts the location of the study basin and surrounding basins.

Although the Lough Foyle Basin is still poorly understood and not well explored in the subsurface (being only partly located onshore) the cuspate foreland of Magilligan Point extends to only a few kilometres from the basin bounding fault and the gravity low underneath this area was drilled in 1962 by the GSNI (Geological Survey of Northern Ireland) as the Magilligan Borehole (Figs. 1, 2 and 3) in the search for buried coal fields. Although only three thin coal seams were encountered, the borehole has been of great scientific value in understanding the basin history.

2. Basin stratigraphy

The Lough Foyle Basin contains four main stratigraphic sequences separated by major unconformities.
1) Pre-rift sediments comprise the Carboniferous sandstones and conglomerates at outcrop and the correlative sandstones within the Magilligan Borehole (Fig. 3). At outcrop these are seen to lie unconformably on Precambrian metasediments of the Dalradian Supergroup (Bazley et al., 1997) and they are truncated by a regional unconformity marking Variscan orogenic uplift (Fig. 2). The Carboniferous sediments result from a pre-existing, extensive basin, the full extent of which is not known. The initiation of the Lough Foyle Basin proper began with rifting that possibly took place during the Early Triassic.
2) The second sequence comprises synrift to post-rift sediments that comprise Lower Triassic to Lower Jurassic strata and are truncated by a regional, angular unconformity (Fig. 2).
3) Following uplift of the basin, a series of smaller sequences of Upper Cretaceous rocks were also deposited in the area.
4) Later thermal uplift created a further unconformity over which Paleogene lavas were extruded (Mitchell, 2004).

The pre-rift Carboniferous strata and the syn-rift Lower to Mid-Triassic basin-fill are briefly discussed in the following sections, but the principal focus of this study is the post-rift uppermost Triassic to Lower Jurassic succession. The post-rift section is a poorly documented part of the basin-fill, but one that spans the Triassic–Jurassic boundary interval, a period of major sea-level, climatic, and faunal change. Only selected samples remain from the original Magilligan Borehole and for this particular interval there is no core remaining. Outcrops of this interval are limited to a few poorly-exposed stream sections, but a borehole drilled in 2013 (NIRE 05/08-0003) has allowed core from this interval to be re-examined in detail.

The Lough Foyle Basin is distinct from other basins across Northern Ireland in the absence of Lower Permian Enler Group and Upper Permian Belfast Group strata that are present elsewhere across Northern Ireland (although based on other localities, parts of the Sherwood Sandstone Group are likely to be of Late Permian age, see Warrington et al., 1980). Rifting in the Lough Foyle Basin probably began during the latest Permian to earliest Triassic, somewhat later than in the Rathlin, Larne and Lough Neagh basins.

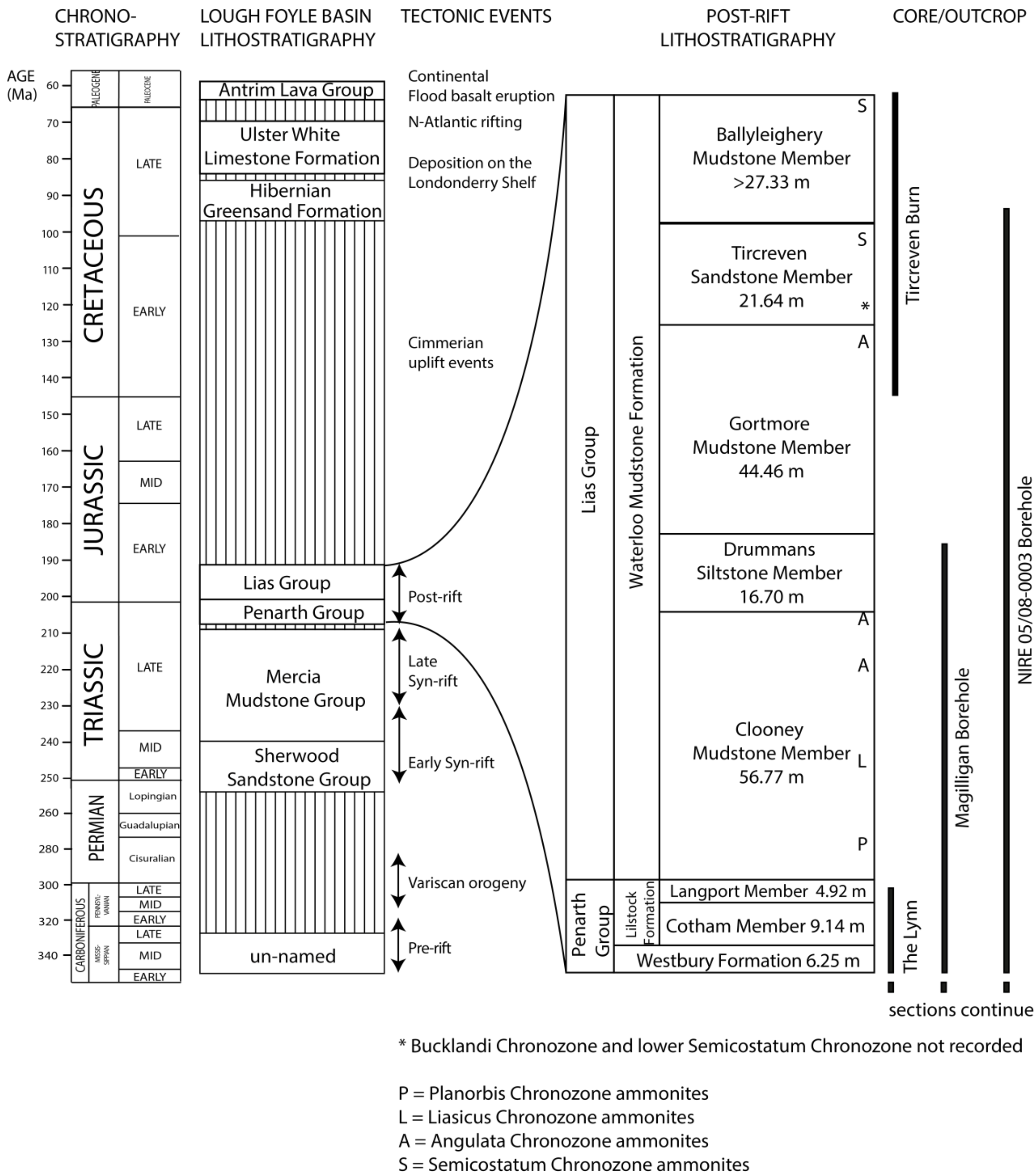
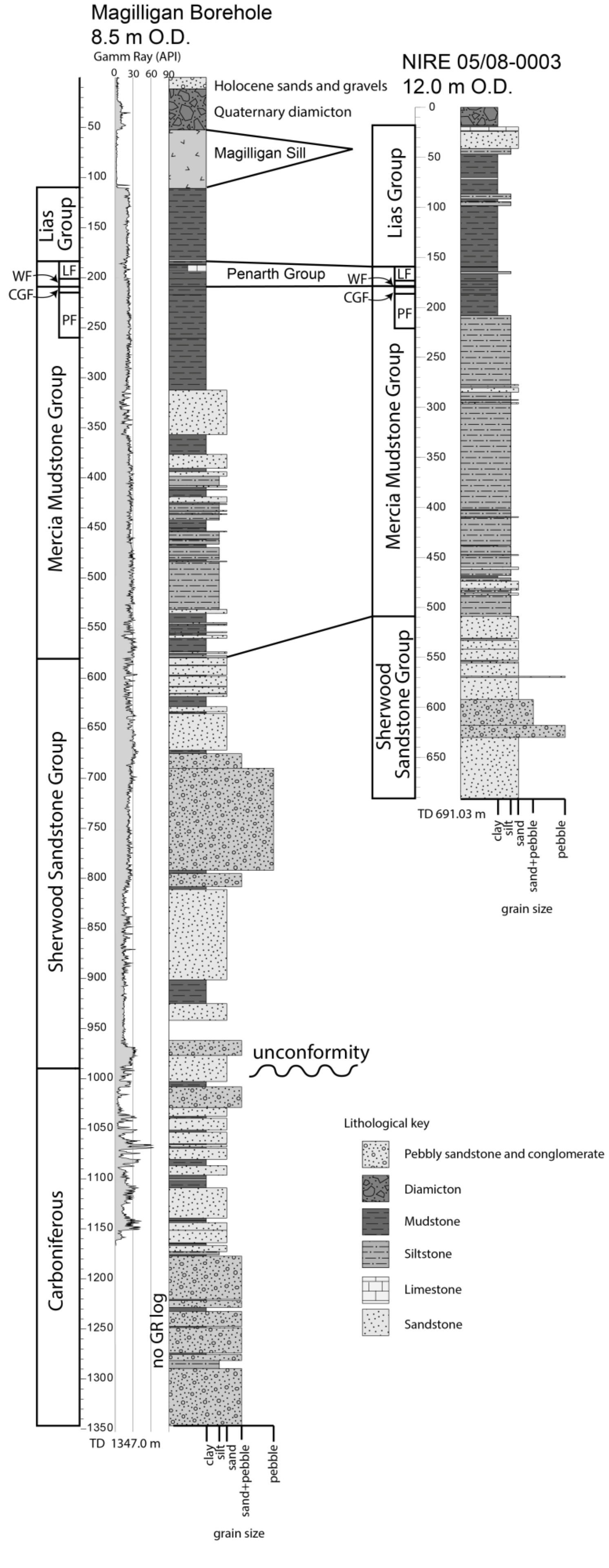


Figure 2. Lithostratigraphy and tectonic history of the Lough Foyle Basin with indications of the stratigraphical intervals discussed in this paper. Thicknesses of the post-rift stratigraphic units are taken from the NIRE 05/08-0003 Borehole, with the exception of the Ballyleighery Mudstone Member, which is from the Tircreven Burn section, as measured by Bazley et al. (1997).



Magilligan Borehole
8.5 m O.D.
Gamm Ray (API)
0 30 60 90
Holocene sands and gravels
Quaternary diamicton
Magilligan Sill
Lias Group
WF
LF
CGF
PF
Penarth Group
Mercia Mudstone Group
Sherwood Sandstone Group
Carboniferous
unconformity
no GR log
TD 1347.0 m
clay
silt
sand
sand+pebble
pebble
grain size
NIRE 05/08-0003
12.0 m O.D.
Sherwood Sandstone Group
TD 691.03 m
Lithological key
Pebbly sandstone and conglomerate
Diamicton
Mudstone
Siltstone
Limestone
Sandstone

Figure 3. Borehole records for the Lough Foyle Basin. The Magilligan Borehole summary has been drawn from GSNI unpublished borehole records and data in Bazley et al. (1997). In the lithostratigraphic column PF=Portmore Formation, CGF=Collin Glen Formation, WF=Westbury Formation and LF=Lilstock Formation.

2.1 Syn-rift basin sedimentary sequence (uppermost Permian? to Upper Triassic)

The syn-rift sedimentary fill of the basin includes the Sherwood Sandstone and Mercia Mudstone groups which total up to 780 m (recorded in the Magilligan Borehole) (Fig. 3 this paper). The Sherwood Sandstone Group (SSG) in Northern Ireland is of Late Permian to Mid Triassic (Anisian) age (Warrington et al., 1980) and comprises a thick succession dominated by red, cross-stratified, feldspathic sandstones. In the Lough Foyle Basin it is up to 409 m thick and is characterised by being coarser-grained and containing 78 m of pebbly sandstones and conglomerates in the middle part of the group (Fig. 3). The overlying mudrock-dominated succession of the Mercia Mudstone Group (MMG) is 371 m thick and comprises red and occasionally green siltstones, claystones and sandstones, which locally contain abundant gypsum/anhydrite. The MMG in this basin contains more sandstone than other basins across Northern Ireland (Wilson and Manning, 1978; Penn et al., 1983). Elsewhere in Northern Ireland only the basal Lagavarra Formation contains appreciable quantities of sandstone, but in the Lough Foyle Basin approximately the lowest 270 m are characterised by siltstones, with beds of sandstone and in the Magilligan Borehole thick sandstone intervals up to 44 m are recorded (Bazley et al., 1997) (Fig. 3 this paper).

Subdivisions of the MMG recorded in the Larne No 2 (Penn et al., 1983) and the Port More (Wilson and Manning, 1978) boreholes cannot be recognised in this basin with the exception of the upper two thin units (Port More and Collin Glen formations). There is a greater thickness variation in the MMG across these basins than there is within the SSG and this difference led Ruffell and Shelton (1999) to propose that most extension took place during the Mid–Late Triassic and that the MMG rather than the SSG was deposited syn-rift with the underlying SSG filling pre-existing, sediment-starved basins and eroded remnants of the Variscan uplands. Whilst this may be the case in the Larne Basin, which experienced earlier rifting during the Permian, the Lough Foyle Basin was probably not in existence until the latest Permian and the coarse-grained facies of the SSG may support deposition during more active basin bounding fault movement. The MMG is thinner in the Lough Foyle Basin (372 m) compared to 652–673 m in the Rathlin Basin. This thickness variation may suggest a certain amount of diachroneity of the boundary between the SSG and the MMG in the two basins and possibly differences in accommodation space created through extension in the Mid- to Late Triassic as suggested by Ruffell and Shelton (1999) for the Larne Basin.

2.2 Post-rift sedimentation (latest Triassic to Early Jurassic) and the Late Cimmerian unconformity

The Penarth Group is remarkable in that the Westbury and Lilstock formations (both generally less than 15 m thick) can be recognised across the whole of the UK with similar lithologies (Warrington et al., 1980; Swift, 1999; Gallois, 2008, 2009) and the Late Triassic (Rhaetian) has been identified as a period when basin margin faults in other basins seem to show little indication of movement (Woodland, 1971; Broughan et al., 1989) which could possibly explain the uniform nature of the Penarth Group. The upper two formations of the MMG (Colin Glen & Port More) may additionally represent part of the post-rift succession as they are widely recognised across Northern Ireland, but the Penarth and Lias groups together represent a clear post-rift part of the sequence within the Lough Foyle Basin and are relatively uniform in thickness (although the top is variably truncated). Later strata of Cretaceous and Paleogene age each unconformably overlie the Triassic and Jurassic strata (Fig. 2). The initial unconformity progressively oversteps the Waterloo Mudstone Formation, Penarth Group and MMG towards the southern part of the basin (Fig. 1). It is evident that these were uplifted and tilted northward at some point during the mid-Jurassic to Early Cretaceous, a period during which mid- and late Cimmerian tectonic events have been identified across the UK (Ziegler, 1981; Underhill and Partington, 1993; Naylor et al., 2003, Green et al., 2000; Hillis et al., 2008; Johnson et al., 2005).

3. Lithostratigraphic revision of the uppermost Triassic to Lower Jurassic post-rift sequence in the Lough Foyle Basin

A significant extent of uppermost Triassic to Lower Jurassic strata are concealed beneath the Holocene sediments of the Magilligan Peninsula and were recorded in the Magilligan Borehole (Bazley et al., 1997), but they are also partly exposed further inland on the lower slopes of Binevenagh (Fig. 1) where they are subject to landslip (Bazley et al., 1997). Despite this, some relatively undisturbed sections occur, such as along the Tircreven Burn section, described herein. That section, together with new borehole material which is described, constitute the best record of this interval in the Lough Foyle Basin. Additional outcrops are located in other stream sections around Binevenagh (Fig. 1), for example, The Lynn (55° 5′ 36.0′′ N; 6° 53′ 20.0′′ W), Tircorran Burn (55° 5′ 31.1′′ N; 6° 55′ 0.5′′ W), Tircreven Burn (55° 7′ 49.6′′ N; 6° 53′ 54.7′ W) and Gortmore/Craig stream (55° 8′ 47.8′′N; 6° 53′ 29.6′′W) (Bazley et al., 1997). Early work on these strata include a geological memoir by Portlock (1843) and research by Tate (1867), with a much later survey report by Bazley et al. (1997), little other research having been undertaken. The strata recorded at the above-mentioned outcrops compare well with records from the Magilligan Borehole, but no core samples remain from this interval.

However, in 2013 a new borehole (NIRE 05/08-0003) was drilled at (55° 8′ 30.17′′ N, 6° 54′ 8.29′′ W) that continuously cored the Waterloo Mudstone Formation (Lias Group, total 141.52 m) as well as the underlying Penarth Group (20.31 m), the MMG (329.27 m) and part of the Sherwood Sandstone Group (182.08 m) down to a depth of 691.03 m (Fig. 3). The recovery of the new borehole material together with a studies of some key outcrops has permitted a re-evaluation of the lithostratigraphy, biostratigraphy and palaeoenvironments of the Late Triassic to Early Jurassic interval of the Lough Foyle Basin. Details of the late Triassic and Early Jurassic palynology and micropalaeontology in the basin are outlined here for the first time based on samples from the NIRE 05/08-0003 Borehole and the Tircreven Burn section.

3.1. Penarth Group

The Penarth Group, similar to other basins in Northern Ireland and across the UK, can be divided into a lower Westbury Formation and an upper Lilstock Formation, the latter comprising the Cotham Member and the overlying Langport Member. These subdivisions are well established and have been described in Northern Ireland by other authors (Bazley et al. 1997; Warrington 1997; Raine et al., 2020a; Boomer et al., 2020a), so are not considered in detail here.

3.1.1. Westbury Formation

The Westbury Formation is well-exposed at The Lynn and poorly in the Tircorran Burn. It was from the Tircorran Burn that the holotype of *Rhaetavicula contorta* was described by Portlock (1843) and the interval was for many years referred to as the contorta Zone. The base of the Westbury Formation is locally erosive and fissured in the Magilligan Borehole with a thin siltstone recorded just above the boundary (Bazley et al., 1997). Fractures containing very dark grey claystone extending down into the underlying claystone of the Collin Glen Formation were observed in the NIRE 05/08-0003 Borehole. In the Magilligan Borehole the Westbury Formation is 7.92 m thick (209.09–201.17 m depth) and comprises very dark grey shales with thin micaceous siltstones. In the NIRE 05/08-0003 Borehole it is 6.25 m (179.68–173.43 m depth) (revised from the thickness of 6.38 m in Raine et al., 2020) and also contains some ripple-laminated sandstone beds and laminae toward the base of the unit (Fig. 4). Numerous shell beds containing either *Protocardia* or *Rhaetavicula* are present and there are metre-scale intervals with common siltstone, pinstripe laminae that display limited bivalve burrows, general burrow mottling, small muddy *Arenicolites* and silt-filled *Planolites*. A moderately-rich assemblage of bivalves, along with gastropods and fish teeth were recorded from the Magilligan Borehole by Bazley et al. (1997).

3.1.2. Lilstock Formation

Above the very dark grey, laminated mudrocks of the Westbury Formation there is a poorly-laminated greenish grey mudstone (201.17 to 202.10 m in the Magilligan Borehole) marking the basal bed of the Cotham Member (Fig. 4). This bed contains a fauna that would be considered typical of the Westbury Formation, with *R. contorta* as shallow as 201.8 m depth, but on the basis of lithology it is included in the Lilstock Formation. Correspondingly, at The Lynn *R. contorta* is also found in a calcareous light grey, laminated mudstone above the Westbury Formation (Bazley et al., 1997) and both of these sections compare well with records from Colin Glen (the place name is now spelt differently from the lithostratigraphic unit after which it was originally named) near Belfast (Manning et al., 1970) and in East Antrim (Jeram et al., this volume). The Cotham Member in the Foyle Basin comprises claystones that are light- to mid-grey in colour at the base and top, but a red-brown colour in the middle of the unit (Fig. 4). Soft sediment deformation is particularly obvious within this red-brown interval and has previously been recorded and discussed (Bazley et al., 1997; Simms, 2003, 2007; Laborde-Casadaban et al., 2021 this volume). The Cotham Member has not yet yielded macrofossil remains in this basin (although palynomorphs are recorded below) but in the Larne Basin it contains a limited fauna of bivalves (Simms and Jeram, 2007; Opazo Mele and Page, 2021; Wignall and Atkinson, 2020). The Cotham Member is 8.28 m thick (201.17–192.89 m) in the Magilligan Borehole (Bazley et al., 1997) and 9.14 m in the NIRE 05/08-0003 Borehole (173.43–164.29 m depth).

The overlying Langport Member (Fig. 4) differs from that seen at other sections in Northern Ireland. In the Larne Basin it is more typically composed of siltstones and silty mudstones with numerous bivalves, common bioturbation and limestones, which are largely restricted to the basal part of the member. In the Lough Foyle Basin, limestones and very fine-grained claystones or calcareous claystones dominate much of the unit. The upper part of the NIRE 05/08-0003 Borehole contains a series of cross-stratified, oolitic and bioclastic grainstones, a facies that is represented by a single bed at The Lynn (Bazley et al., 1997). The Langport Member is 5.44 m thick (192.89–187.45 m) in the Magilligan Borehole (Bazley et al., 1997) and it is 4.92 m in the NIRE 05/08-0003 Borehole (164.29–159.37 m), with the upper part possibly condensed, it is only partly exposed at The Lynn (Bazley et al., 1997). The fauna recorded from the Langport Member of the Lough Foyle Basin is dominated by bivalves (Bazley et al. 1997), with the assemblage being fairly diagnostic of equivalent strata in the Langport Member elsewhere in Great Britain (Ivimey-Cook et al., 1999).

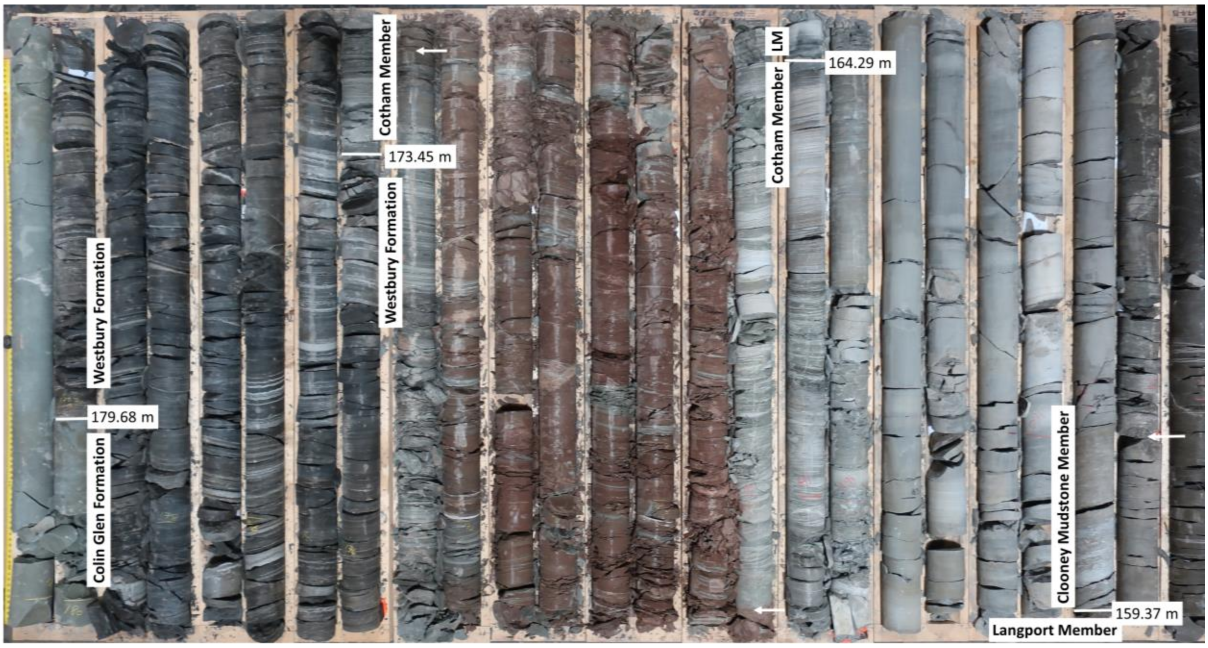


Figure 4. The interval spanning the top of the MMG (Collin Glen Formation) to the base of the Lias Group (Clooney Mudstone Member of the Waterloo Mudstone Formation) in the NIRE 05/08-0003 Borehole. Each section of core is approximately 1 m long. The arrow just above the base of the Cotham Member marks a flooding event picked up by a facies change at 158.09 m and marked increase in calcareous microfossil abundance data from 158.00 m.

3.2. Lias Group

3.2.1. Waterloo Mudstone Formation

The Lias Group is represented in the area by the Waterloo Mudstone Formation. This is a mudstone-dominated unit that is recognised across Northern Ireland (Raine et al. 2020a) and broadly equates to the Blue Lias Formation in Great Britain. The Waterloo Mudstone Formation was encountered in the Magilligan Borehole (74 m), but the upper parts were intruded by Paleogene dolerite of the Magilligan Sill and the mudstones were locally hornfelsed, making further study of those horizons difficult (Bazley et al. 1997). A total of 52 m of strata were measured in the Tircreven Burn section by Bazley et al., 1997, representing a stratigraphically younger interval than the Magilligan Borehole. At the time no section existed that covered the break in stratigraphy between the two successions. A thermally unaltered and more complete succession of the formation has now been cored in the NIRE 05/08-0003 Borehole (141.52 m thick) and the stratigraphy can now be resolved more clearly. Based on these records the Waterloo Mudstone Formation in this basin can be divided into five distinct members (four of which are newly named and described herein).

During the GSNI's geological mapping of the area, unpublished work on the Magilligan Borehole by A. Brandon informally divided the section underlying the Magilligan Sill into an upper shale/siltstone member and a lower mudstone member. Although not formalised at the time, these are clearly observed in the new NIRE 05/08-0003 Borehole 2.6 km southeast from the original Magilligan Borehole site and are therefore more widely recognisable. At outcrop and stratigraphically above the position of the Magilligan Borehole, a sandstone unit (the Tircreven Sandstone Member) was formally described by Bazley et al. (1997), but the mudstone successions below and above this were never named. In a letter (in GSNI records archive) from H.E. Wilson to H. Ivimey-Cook it was suggested that the two fine-grained units in the Magilligan Borehole could be named after the nearby Clooney and Drummans townlands and the mudstones above the Tircreven Sandstone Member, named after the nearby Ballyleighery townland. Based on new material, a five-fold subdivision of the Waterloo Mudstone Formation, with four new members is here proposed.

Proposed subdivisions of the Waterloo Mudstone Formation
Ballyleighery Mudstone Member (defined herein)
Tircreven Sandstone Member (Bazley et al., 1997)
Gortmore Mudstone Member (defined herein)
Drummans Siltstone Member (defined herein)
Clooney Mudstone Member (defined herein)

Table 1. Revised Lithostratigraphy of the Waterloo Mudstone Formation within the Lough Foyle Basin.

3.2.1.1. Clooney Mudstone Member

Name. Named after the townland of Clooney, located approximately 10 km south of the Magilligan Borehole.

Type section. Core in the NIRE 05/08-0003 Borehole 102.60–159.37 m (56.77 m thick). This member is not exposed at surface in the area. Only the lowest and highest parts are figured here (Figs 4 and 5) and are representative of the lithology.

Reference section(s). Magilligan Borehole core description 127.41–187.45 m (60.04 m) (Bazley et al., 1997).

Lithology. Comprised of largely un-bioturbated (except for the basal few metres), laminated claystones, with some tabular and nodular bioclastic limestones, particularly toward the base. The limestones in the lower part locally display bedding-parallel, fibrous calcite veins. Toward the base, in the Magilligan Borehole, Bazley et al. (1997) recorded a conglomerate containing large, rounded pebbles of grey limestone. This bed was not seen in the NIRE 05/08-0003 Borehole and so its significance is not known, but it may relate to the relatively thin Planorbis Chronozone recorded in the borehole (4.24 m), suggesting a period of either condensation or erosion at the base. In the core material from NIRE 05/08-0003, the lowest beds comprise bioclastic limestones (14 cm) containing *Liostrea* that then grade upward into bioclastic claystones with *Thalassinoides* and *Teichichnus* burrows. At 158.09 m there is a distinctive, intensely-bioturbated claystone with crinoid debris that passes upward into mid- to dark grey, laminated, slightly silty claystones. This change seems to mark a flooding surface above which the mudrocks are finer-grained and more organic-rich.

Definition of lower boundary. The lower boundary with the Lilstock Formation is taken at the change from mid-grey porcelaneous and ooidal limestones with blocky claystones to bioturbated and fossiliferous claystones that are commonly laminated and dark grey in colour (Fig. 4). The base is marked by a 2 cm claystone overlain by bioclastic limestones and then by bioclastic and bioturbated claystones.

Age. Latest Rhaetian to Early Hettangian based on microfossil records and palynology (see later sections). Ammonites are rare, but *Psiloceras planorbis* (Sowerby) is recorded in the Magilligan Borehole core (Bazley et al., 1997) and a *Psiloceras* sp. occurs at 155.17 m depth in the NIRE 05/08-0003 Borehole. The youngest strata are devoid of ammonites in the Magilligan Borehole, the stratigraphically highest ammonites proving the Liasicus Chronozone (*Waehneroceras portlocki* (Wright) at 158.44 m and *Waehneroceras* sp. up to 132.66 m). Ammonite records from Tircreven Burn (Bazley et al., 1997) indicate the upper part of the member is most likely early Angulata Chronozone, supported by the discovery of *Schlotheimia* sp. at 103.50 m depth in the NIRE 05/08-0003 Borehole during this study.

Depositional setting. Open marine, mudstones with shell beds representing sporadic storm activity.

3.2.1.2. Drummans Siltstone Member

Name. Taken from the Upper Drummans townland in which the Magilligan Borehole was situated.

Type section. The member is cored in the NIRE 05/08-0003 Borehole from 85.90-102.60 m (16.70 m) (Fig. 5).

Reference section(s). The siltstones were recorded in the Magilligan Borehole (unpublished GSNI borehole record) from 111.00 m depth to 127.41 m (16.41 m), where the upper part is absent and the unit is in contact with the lower boundary of the Magilligan Sill.

Lithology. The unit comprises siltstone and claystone, which are dominated by ripple-laminated or normally-graded event beds that commonly have scoured bases. The facies are strongly bioturbated by *Teichichnus*, *Phycosiphon* and *Chondrites* (Fig. 6). Beds are cm-scale and are arranged into two coarsening upward successions with increasing numbers of siltstone beds upwards, towards 40% of the facies, culminating in a few decimetre-thick beds of carbonate-cemented siltstone to very fine sandstone.

Definition of lower boundary. Although somewhat gradational, the lower boundary, seen in core is taken at an erosive-based, carbonate-cemented siltstone, above which siltstone pinstripe laminations, ripples and silt-filled scours with burrows become common. Below the boundary, similar siltstone beds and pinstripe laminae account for less than 5% of the sediment and, in general, the claystones are darker and more laminated.

Age. The member is assigned a Hettangian age (Angulata Chronozone) based on ammonite records and confirmed by microfossil and palynological analysis (see below). *Schlotheimia* sp. was recovered from 90 cm below the base of the member in the NIRE 05/08-0003 Borehole at 103.50 m depth and the overlying member contains *Schlotheimia* sp. in the Tircreven Burn section (Bazley et al., 1997) indicating that the Drummans Siltstone Member lies entirely within the Angulata Chronozone.

Depositional setting. The facies suggest a marine subtidal environment with episodic but sustained supply of coarser-grained material (silt and sand grade) that may represent small tempestite deposits that are intermittently colonised. The dominantly clay-grade background suggests an environment between storms that was characterised by suspension fallout sedimentation with an annelid dominated infauna (based on the trace fossil assemblage).

Figure 5. Drummans Siltstone Member in the NIRE 05/08-0003 Borehole showing the distribution of siltstone and sandstone (light grey) interspersed with claystone (dark grey). Two coarsening up cycles occur in the Drummans Siltstone Member (boundary is labelled). Each core box is approximately one metre in length.

3.2.1.3. Gortmore Mudstone Member

Name. The unit is named after the nearby townland of Gortmore, which lies 130 m to the north of the NIRE 05/08-0003 Borehole.

Type section. Cored in full in the NIRE 05/08-0003 Borehole 41.14–85.90 m depth (44.46 m). Only the lowest and highest parts of the member are figured here but are representative of the lithology (Figs 5 and 10).

Reference section(s). It is absent from the Magilligan Borehole, being cut out by a dolerite sill. The member is intermittently exposed in the Tircreven Burn section.

Lithology. Bazley et al. (1997) recorded mudstones, with local siltstones and limestones in the Tircreven Burn section that contained bivalves, brachiopods and the ammonite *Schlotheimia.* Layers of carbonate nodules bearing plant remains were also recorded. Towards the top of the member, the stream section contains a black carbonaceous claystone, overlain by a grey, organic-rich, claystone containing abundant woody material (Fig. 7).

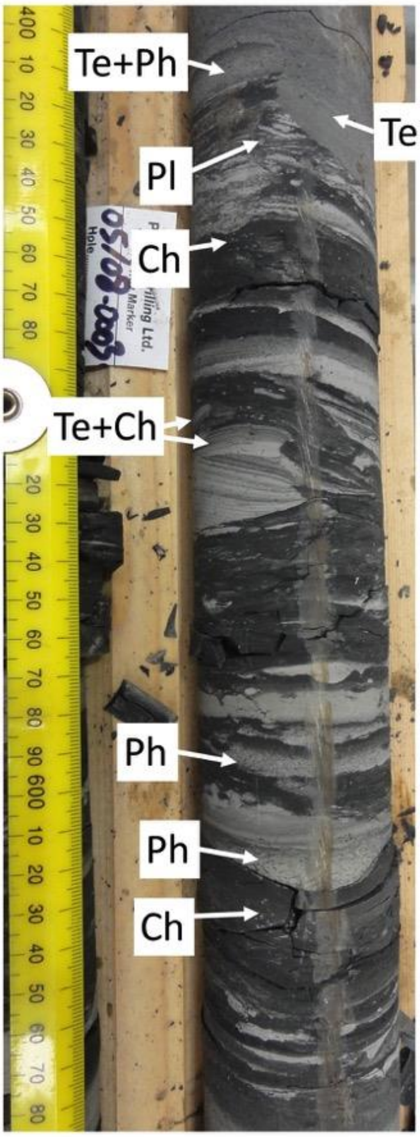


Figure 6. Part of the core from NIRE 05/08-0003 from the Drummans Siltstone Member displaying characteristic bioturbation of *Teichichnus* (Te), *Phycosiphon* (Ph) and *Chondrites* (Ch). There are some isolated *Planolites* burrows (Pl).

Vitrinite Reflectance values from just above the black claystone yielded good amounts of vitrinite with a Ro of 0.2 suggesting low thermal maturity. The bed may be that which was recorded by Portlock (1843) who considered a similar organic rock in the vicinity to be the coal sunk for by Lord Bristol and referred to by Sampson (1802). This black claystone was not present in the NIRE 05/08-0003 Borehole, where the member is largely represented by dark grey, laminated claystones and mid-grey, calcareous claystones, with limestone and bioclastic limestone beds. Limestone beds are particularly common between 76 and 71 m core depth. The claystones in the member contain sparse pinstripe laminae of silt that become more common in the upper 7 m, where the facies and bioturbation are similar to the underlying Drummans Siltstone Member. This siltstone unit at the top of the member is not observed in the Tircreven Burn section and it may be that it is either cut out by the overlying sandstones, or it is a lateral equivalent of the coarsening-up *Diplocraterion*-burrowed section near the base of the Tircreven Sandstone Member.

Definition of lower boundary. The lower boundary with the underlying Drummans Siltstone Member (Fig. 5) is sharp and comprises laminated dark grey claystones that overlie an irregular surface of a nodular limestone containing *Thalassinoides* burrows.

Age. In the Tircreven Burn section a *Schlotheimia* sp. specimen was recovered 3.06 m below the base of the Tircreven Sandstone Member, suggesting that the whole of the Gortmore Mudstone Member lies within the Angulata Chronozone. The Hettangian age is further supported by the calcareous microfossils and the palynomorphs recovered from the unit (see below).

Depositional setting. The claystones are interpreted as representing an offshore setting, due to the fine-grained nature and the fauna recorded. Towards the top there is an increasing terrestrial influx, indicated by coarser sediment with plant material.

Figure 7. Black carbonaceous claystone (marked by the trowel) at the top of the Gortmore Mudstone Member, the location of TCB-P2 sample in the Tircreven Burn section.

3.2.1.4 Tircreven Sandstone Member

Name. Named by Bazley et al. (1997) after the Tircreven Burn where the member is well-exposed (Figs 8 and 9).

Type section. The Tircreven Burn section where it is exposed in cut-banks and in the bed of the stream (Bazley et al. 1997). The measured section in the stream is 14 metres, but this includes two concealed intervals (Fig. 9).

Reference section(s). Gortmore/Craig Stream (Portlock, 1843; Bazley et al. 1997) and has been cored in the NIRE 05/08-0003 Borehole (21.64 m thickness, from 19.50–41.14 m depth) (Fig. 10 this paper).

Lithology. At the type locality, this member comprises sandstones, siltstones and subordinate, carbonaceous claystones. The lowest part of the continuously-exposed section comprises beds of siltstone and silty sandstone that have diffuse bed boundaries and are intensely bioturbated by *Diplocraterion parallelum* Torell (Fig. 8A and B). Beds comprise light grey, bioturbated, very fine sandstone, overlain by light brown, fine-grained stratified sandstones with small scale ripple cross-lamination and clay drapes. Overlying this are more bioturbated, sandy siltstones that are mid-grey, weathering to orange, cleaner (decreasing clay fraction) and coarsening upward to upper very fine, well-sorted, bioturbated sandstone (Fig. 8A). The burrows are locally filled by white sand. Locally, fallen blocks have also yielded root structures (Fig. 8C).

Overlying the silty sandstones are a series of decimetre-scale beds of quartz arenite sandstone that are fine-grained, locally very-fine, and well-sorted to very well-sorted (Figs 8D and 9), woody fragments are not uncommon. These sandstones are separated by mid-grey, pinstriped and bioturbated siltstones with some black carbonaceous claystones. The section can then be traced upstream where the beds comprise light orange-brown and yellow weathering fine-grained sandstones, moderately well-sorted sandstones that are arranged into dm-scale beds of alternating carbonate rich layers, with some less well-cemented (Fig. 8E). The boundaries appear gradational, but there are some well-defined, siltier beds that are ripple cross-laminated and well-sorted very fine-grained sandstones. These beds yielded *Gryphaea* in the present study, but Bazley et al. (1997) also recorded the bivalves *Plagiostoma, Plicatula*, *Pleuromya*, *Pinna*, *Cardinia* and *Antiquilima*, the nautiloid *Cenoceras* sp., the gastropod *Ptycomphalus*, and burrows similar to *Zoophycos* on bedding surfaces.

In the NIRE 05/08-0003 Borehole (Fig. 10), the succession is somewhat different and the *Diplocraterion*-burrowed interval was not observed. Sandstones in the lower part of the member display cross-stratification and are variably cemented, some are friable and appear structureless. The upper part of the member is marked by bioturbated, calcareous sandstones with bivalve burrows (Fig. 10). The upper part corresponds to the Tircreven Burn section that is carbonate-cemented (Fig. 9).

Definition of lower boundary. The base of the unit comprises a sharp change from a dominantly mudstone to a dominantly sandstone lithology and lies above siltstones and claystones that comprise the upper part of the Gortmore Mudstone Member. The base of the Tircreven Sandstone Member is taken at the base of the lowest sandstone bed. This boundary is observed in the NIRE 05/08-0003 Borehole (Fig. 10), but is poorly exposed in the Tircreven Burn, where a sharp boundary between a claystone bed and an overlying sandstone bed, is immediately overlain by a 2 m non-exposed interval.

Age. The lower part of the member, of largely un-cemented sandstones, has been dated as Hettangian based on palynological data (see later section). The upper part is carbonate-cemented and contains marine macrofossils, including ammonites, that give a Sinemurian age (upper Semicostatum Chronozone). The boundary between the uncemented and cemented sandstones may represent an intra-member hiatus.

Depositional setting. In the lower part of the member, the sandstones represent coastal marine sediments with the clean, cross-stratified sandstones in core probably representing a fine-grained distributary channel sandstone. The root traces observed at outcrop along with *Diplocraterion* suggest that conditions became shallow enough for vegetation to colonise the substrate although there is no evidence of palaeosol formation and the facies may represent channel margin deposits. The marine fossils recorded from the upper part of the member represent more open marine, shelf conditions.

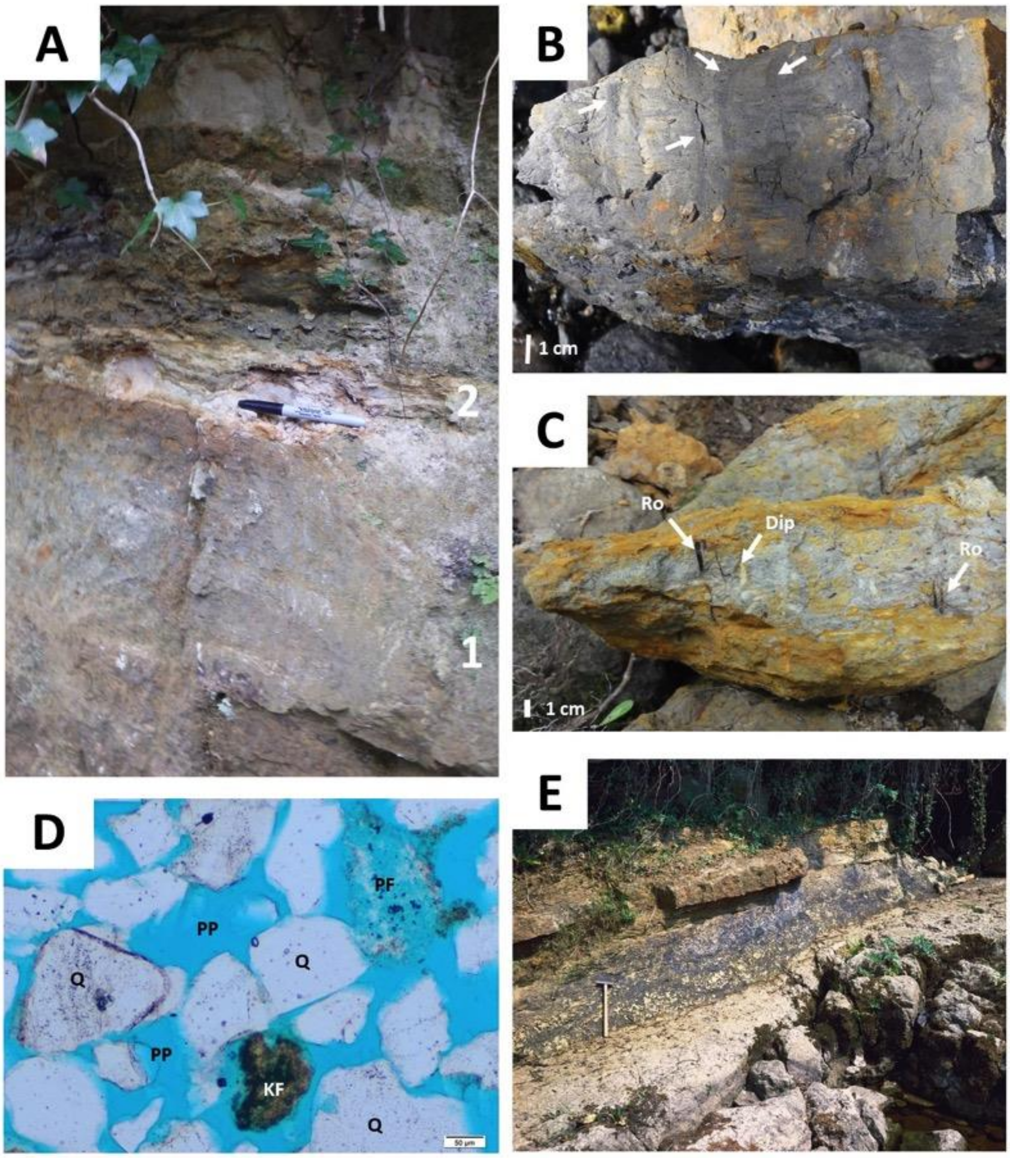


Figure 8. Tircreven Sandstone Member in Tircreven Burn. A) The lower Tircreven Sandstone Member is seen at the base of the river cliff and comprises bioturbated highly silty sandstones (1) and interbedded clean sandstones and siltstones (2). Pen is 14 cm in length. B) Fallen block from the highly silty sandstone interval containing abundant *Diplocraterion* (marked by arrows). C) Fallen block of silty sandstone with sand-filled *Diplocraterion* (Dip) and roots (Ro). D) Thin section photomicrograph of sample from the lowest clean sandstone. The sample is a moderately well-sorted, fine-grained quartz arenite, with detrital grains of quartz (Q), degraded plagioclase feldspar (PF), potassium feldspar (KF) and open and well-connected primary pores (PP). E) Light brown tabular calcareous sandstones in the upper part of the Tircreven Sandstone Member. The dark colour of the more recessive bed (at the level of the hammer) is a result of surface algae rather than organic content (© UKRI, BGS Photo P225399).

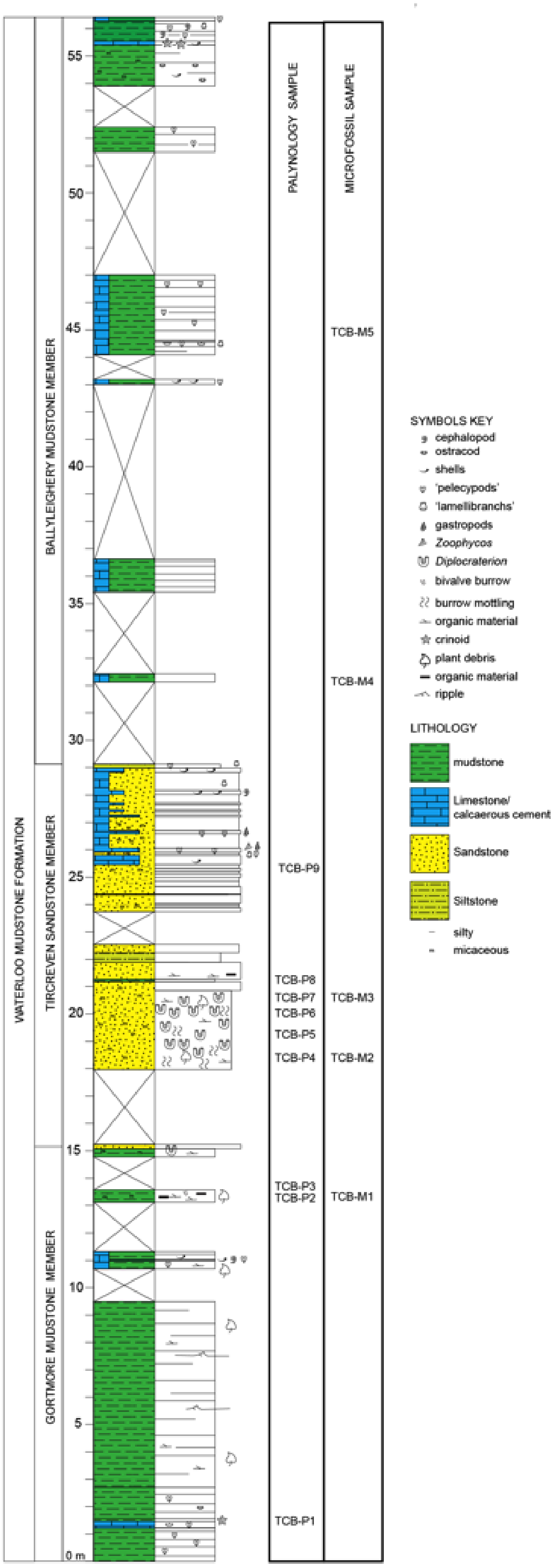


Figure 9. Graphic log of the Tircreven Burn section, showing the location of the microfossil and palynological samples. The log is based on records in Bazley et al., (1997) and amended with recent observations.

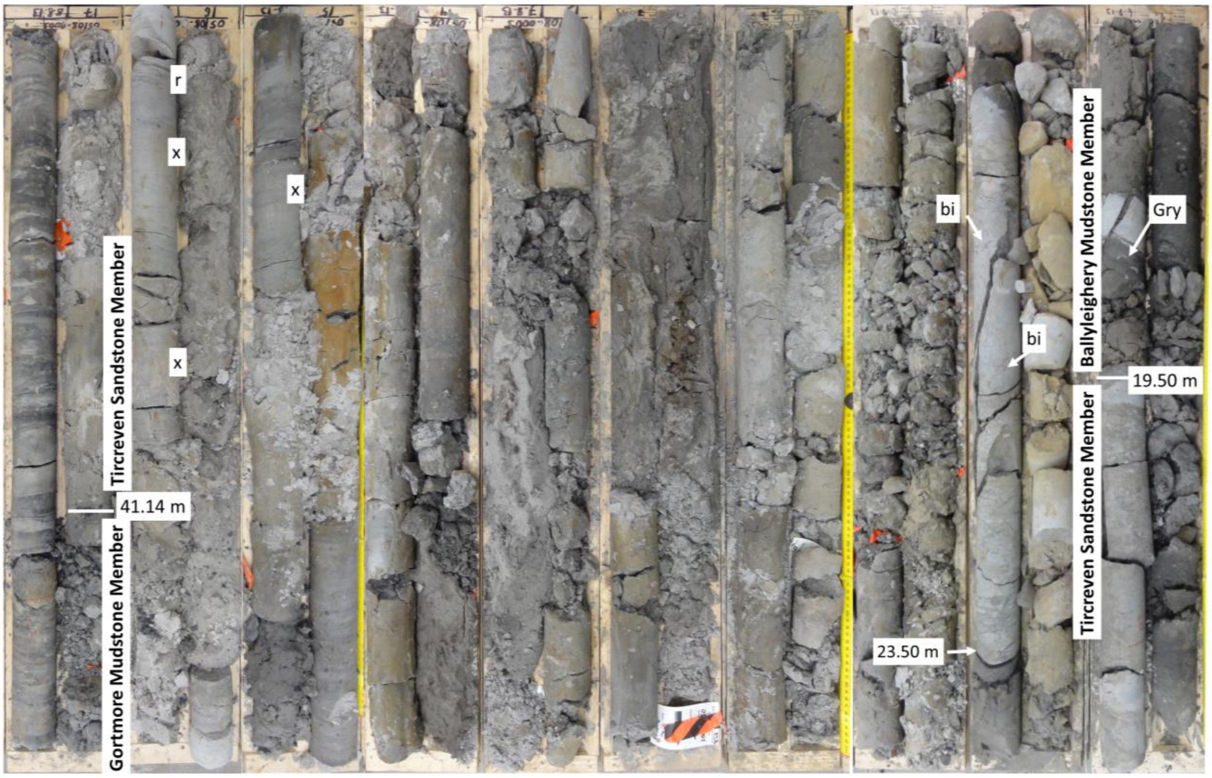


Figure 10. The Tircreven Sandstone Member in core from the NIRE 05/08-0003 Borehole. Intervals of cross-stratified sandstone are marked (x) and ripple cross lamination (r). The upper part comprises calcareous sandstones above 23.50 m and these sandstones are variably bioturbated by bivalve burrows (bi). The claystone overlying the Tircreven Sandstone Member contains *Gryphaea* shells (Gry).

3.2.1.5 Ballyleighery Mudstone Member

Name. Named after the townland of Lower Ballyleighery, west of Tircreven Burn.

Type section. The type section is located in the Tircreven Burn, where 27.33 m of largely obscured section were recorded by Bazley et al. (1997).

Reference section(s). None.

Lithology. Dark grey claystones with fossiliferous, nodular limestones and argillaceous limestones containing abundant *Gryphaea* and crinoids. Fauna recorded by Bazley et al. (1997) from the Tircreven Burn section include *Gryphaea*, *Plagiostoma*, *Oxytoma*, the ammonites *Arnioceras semicostatum* (Young and Bird) and *Euagassiceras* sp., along with crinoid ossicles, and the brachiopod *Calcirhynchia*.

Definition of lower boundary. The base is obscured in the Tircreven Burn but in the NIRE 05/08-0003 Borehole, it is sharp and marked by a change from light grey and brown sandy limestones to dark-grey, laminated claystones and nodular limestones (Fig. 10).

Definition of upper boundary. The upper boundary is unconformable with the overlying Upper Cretaceous Hibernian Greensand Formation.

Age. Microfossils and palynology from this unit have not provided conclusive ages younger than the Hettangian (see discussion below), but the ammonite records from the underlying Tircreven Sandstone Member suggest that the lower part of the Ballyleighery Mudstone Member is at least younger than the Scipioneanum Subchronozone (mid-Semicostatum Chronozone) of the Sinemurian. Ammonites found during this research and those recorded by Bazley et al. (1997) from the upper, exposed part of the Ballyleighery Mudstone Member close to the unconformity with the Cretaceous suggest that it ranges up into the Sauzeanum Subchronozone (Semicostatum Chronozone).

Depositional setting. The top of the Tircreven Sandstone Member is relatively sharp and suggests either the abrupt cessation of sand supply or progressive deepening and retrogradation of facies. The fine grain-size and the fauna suggest a more open marine, offshore shelf setting.

3.3. Discussion of the sedimentological record

The most distinctive sedimentological aspect of the uppermost Triassic to lower Jurassic strata in the Lough Foyle Basin is the recognition that there were periods of increased supply of coarse sediment (Drummans Siltstone and Tircreven Sandstone members) within an otherwise mudstone-dominated succession. This is represented by a cycle of ripple-laminated and bioturbated siltstones due to increased sediment supply and current activity that could be associated with progradation of the distal or interdistributary part of a delta (Drummans Siltstone Member). Higher in the succession there is a repetition of ripple-laminated and bioturbated siltstone that is then sharply overlain by bioturbated silty sandstones, organic clays, and clean cross-stratified sandstones (lower Tircreven Sandstone Member). The root traces and *Diplocraterion* burrows suggest shallow marine episodic sand supply and locally abundant plant material preclude it being a fully offshore environment and instead suggest a nearshore setting with connection to a distributary system. Flooding of the delta or channel switching resulted in deposition of sandstone in a more shelfal setting (upper Tircreven Sandstone Member), which was eventually overlain by offshore muds as the sediment supply was lost.

Sandstone units are a relatively rare phenomena within the lower part of the Lias Group onshore UK, although they do occur in the Hebrides Basin (Simms et al., 2004; Hesselbo and Coe, 2000). In offshore basins around Ireland (North Celtic Sea Basin, Fastnet Basin and Slyne Basin), there are Sinemurian sandstone units indicating that shallowing and/or increased sediment input to the basins during this time occurred on a regional scale (Murphy and Ainsworth, 1991; Kessler and Sachs, 1995; Ewins and Shannon, 1995; Pritchard, 2013; Merlin, 2020; Raine et al., 2020a).

4. Biostratigraphy of the Upper Triassic to Lower Jurassic post-rift sequence

4.1 Ammonite Biostratigraphy

There is limited biostratigraphic detail currently available from ammonites in the Lough Foyle Basin, but a summary is given here, some of these records have already been discussed above. The most complete records were published by Bazley et al. (1997) who documented the ammonite stratigraphy of the Magilligan Borehole. *Psiloceras planorbis* was recorded at 183.69 m depth and shallower. In the NIRE 05/08-0003 Borehole the lowest *Psiloceras* sp. was found at 155.17 m depth. In the Magilligan Borehole *Caloceras* occurred up to 181.18 m depth. The deepest Schlotheimeid, as it was referred to, was recorded at 179.45 m depth (Bazley et al., 1997) and marks the base of the Liasicus Chronozone, with *Waehneroceras portlocki* at 158.44 m. *Waehneroceras* was recorded as shallow as 132.66 m and above this there were no ammonites recovered between this level and the base of the sill. Bazley et al. (1997) also recorded younger assemblages that included both *Schlotheimia* from below the Tircreven Sandstone Member at Tircreven Burn and at Tircorran Burn. *Waehneroceras* was also recorded from Tircorran Burn (Bazley et al., 1997) indicating that the boundary between the Liasicus and the Angulata chronozones is present at outcrop but poorly exposed.

Higher in the succession, ammonites are scarce from the Tircreven Sandstone Member and although palynological evidence from above this unit suggests a Hettangian palynoflora (see below), ammonites in the National Museum of Northern Ireland (NMNI) collections and additional records from the survey mapping by Bazley et al. (1997) include *Euagassiceras sauzeanum* (d'Orbigny) and *Arnioceras,* and in the current study one large section of *Agassiceras* sp. was recorded from the carbonate cemented sandstones in the upper part of the member. The assemblage (if all located from the upper fossiliferous part of the member) indicates that the Sauzeanum Subchronozone of the Semicostatum Chronozone (Early Sinemurian) is represented. No marine body fossils have so far been found in the lower part of the member and the age of this section is taken to be Hettangian from the palynological data.

Ammonites from the highest unit, the Ballyleighery Mudstone Member, close to the boundary with the overlying Cretaceous include late species of *Coroniceras*, and *Arnioceras semicostatum*, along with *Eugassiceras,* which also indicate a level in the Semicostatum Chronozone.

While most of the Hettangian ammonite zones are represented, ammonites are yet to confirm the presence of the Sinemurian Bucklandi Chronozone and the lowest subchronozone of the overlying Semicostatum Chronozone and these may either be condensed in the lower part of the Tircreven Sandstone Member, or more likely, represented by a hiatus in the middle of that unit, where there is a distinct facies change, marking a flooding event and the transition to shelf sandstone deposition.

4.2 Calcareous Micropalaeontology.

A total of 31 micropalaeontology samples were collected from the Lias and Penarth groups of the NIRE 05/08-0003 Borehole at intervals of between 2 and 7 m with an additional 5 samples from the Tircreven Burn section. Micropalaeontological samples were processed at the University of Birmingham using the freeze-thaw method (Kennedy and Coe, 2014), some taking up to 18 cycles due to the level of induration/cementation. The outcrop samples of siltstone and silty sandstone recovered from the Tircreven Burn section were much more easily broken down using a 1–2% solution of hydrogen peroxide for less than an hour. A total of 10,632 specimens were counted from 31 core samples, 12 of the core samples and three from the Tircreven Burn section were barren of calcareous microfossils. The stratigraphic distribution of the key taxa is illustrated in Figure 11.

Samples from the Penarth Group are generally devoid of calcareous microfossils although the lowest sample examined (179.43 m, base of the Westbury Formation) yielded specimens of the calcareous foraminifera *Eoguttulina liassica* (Strickland) and the uppermost sample of the Lilstock Formation (161.70 m) yielded a single species of ostracod (*Ogmoconchella aspinata* Drexler), both taxa are known to occur in the uppermost Penarth Group elsewhere in the UK. Despite these low diversity and low abundance records, they contrast with the Carnduff-1 Borehole, in the Larne Basin (Boomer et al., 2020b), where no calcareous microfossils were recorded from the Penarth Group.

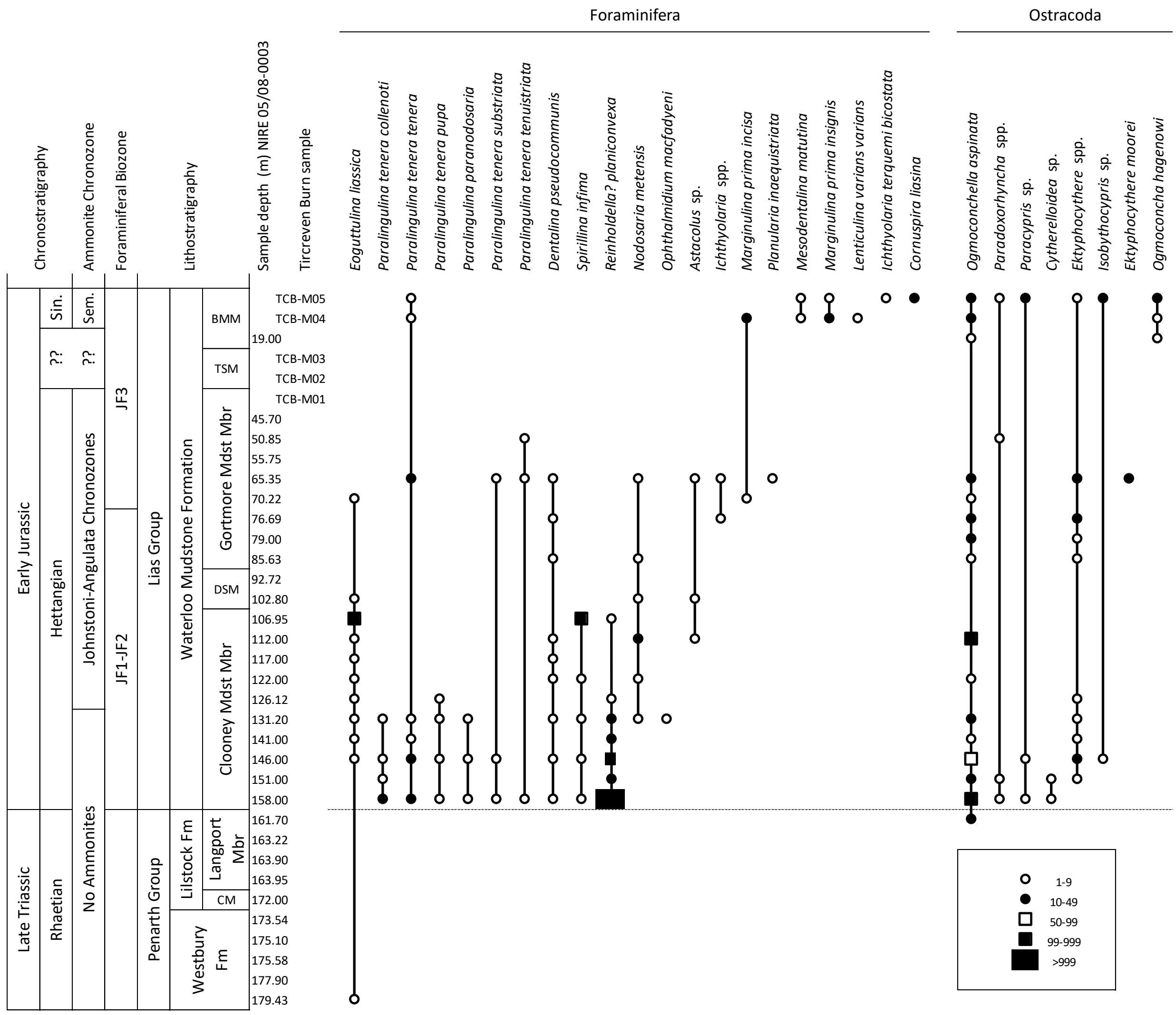


Figure 11. Stratigraphical distribution and relative abundance of the most abundant calcareous microfossil taxa (Foraminifera and Ostracoda) encountered in the NIRE 05/08-0003 Borehole and the Tircreven Burn section. Dotted line indicates the interpreted base of the Jurassic. CM = Cotham Member, DSM = Drummans Siltstone Member, TSM = Tircreven Sandstone Member, BMM = Ballyleighery Mudstone Member.

The relatively low abundance of specimens and low diversity of the foraminiferal assemblages throughout the Penarth Group and the overlying Lias Group, compared with other records of this age in Northern Ireland (Boomer et al., 2020a, b), makes it difficult to assess their biostratigraphical context. However, the consistent presence of *Paralingulina tenera collenoti* (Terquem) between 158.00 and 131.20 m confirms assignment of that interval to foraminiferal biozones JF1-2 (Hettangian) (Copestake and Johnson, 2014) with the first occurrence of *Marginulina prima incisa* (Franke) indicating the base of JF3 (latest Hettangian to early Sinemurian) at 70.72 m. These data confirm a likely age of Hettangian for much of the studied interval. The microfossils do not provide unequivocal evidence for early Sinemurian sediments as none of the taxa recorded have their first appearance after the latest Hettangian but that possibility cannot be discounted.

The foraminiferal zonation is supported by the ostracods which, although also of low diversity and abundance, include *Ogmoconchella aspinata* (Drexler) throughout (latest Rhaetian to early Sinemurian range) with *Ogmoconcha hagenowi* Drexler occurring in the youngest three samples examined (TCB-M05 to 19.00 m), the latter indicating an age of latest Hettangian to earliest Sinemurian. The upper limit of these two ostracod taxa suggest an age no younger than earliest Sinemurian (Bucklandi Chronozone age, Boomer and Ainsworth, 2009) for the youngest sample studied, but again do not absolutely confirm a Sinemurian age for any part.

The diversity of earliest Jurassic ostracod and foraminifera assemblages are lower than recorded in the Rathlin and Larne basins of the region (Boomer et al., 2020a, b) and this probably reflects local environmental control, possibly due to relatively shallower water conditions in the Lough Foyle Basin than at other sites in Northern Ireland.

The peak abundance of the dominant foraminifera species *Reinholdella? planiconvexa* (Fuchs) (158.00 m in NIRE 05/08-0003), represents over 9,000 specimens in the sample at 158.00 m and is clearly associated with a flooding event which is marked in core by a bioturbated and shelly mudstone (158.09–157.88 m depth) overlain by an upward change to darker, more finely laminated claystones (Fig. 4). A similar spike in the abundance of this species is also noted in the very earliest Hettangian of the Lias Group in both the Ballinlea-1 and Carnduff-1 boreholes (see references above) and is probably of regional correlative value, occurring just above the base of the Jurassic across Northern Ireland. However, the same event is recorded across other parts of the UK at a slightly younger level, where it usually marks the base of foraminiferal Zone JF2 in the mid-Planorbis Chronozone.

4.3 Palynology

Seventeen palynological samples were examined from the NIRE 05/08-0003 Borehole and seven from the Tircreven Burn outcrop (Fig. 12). Note that the outcrop samples are not from the same horizons as those for calcareous microfossils, hence the different coding. Samples were processed using standard palynological techniques, involving acid digestion using HCl, HF and HNO_3 (Wood et al., 1996). Each sample was subject to a count of 200 individual palynomorphs, with the remainder of the residue scanned for additional taxa (outside the count), abundances of the main diagnostic taxa are shown on Figure 12.

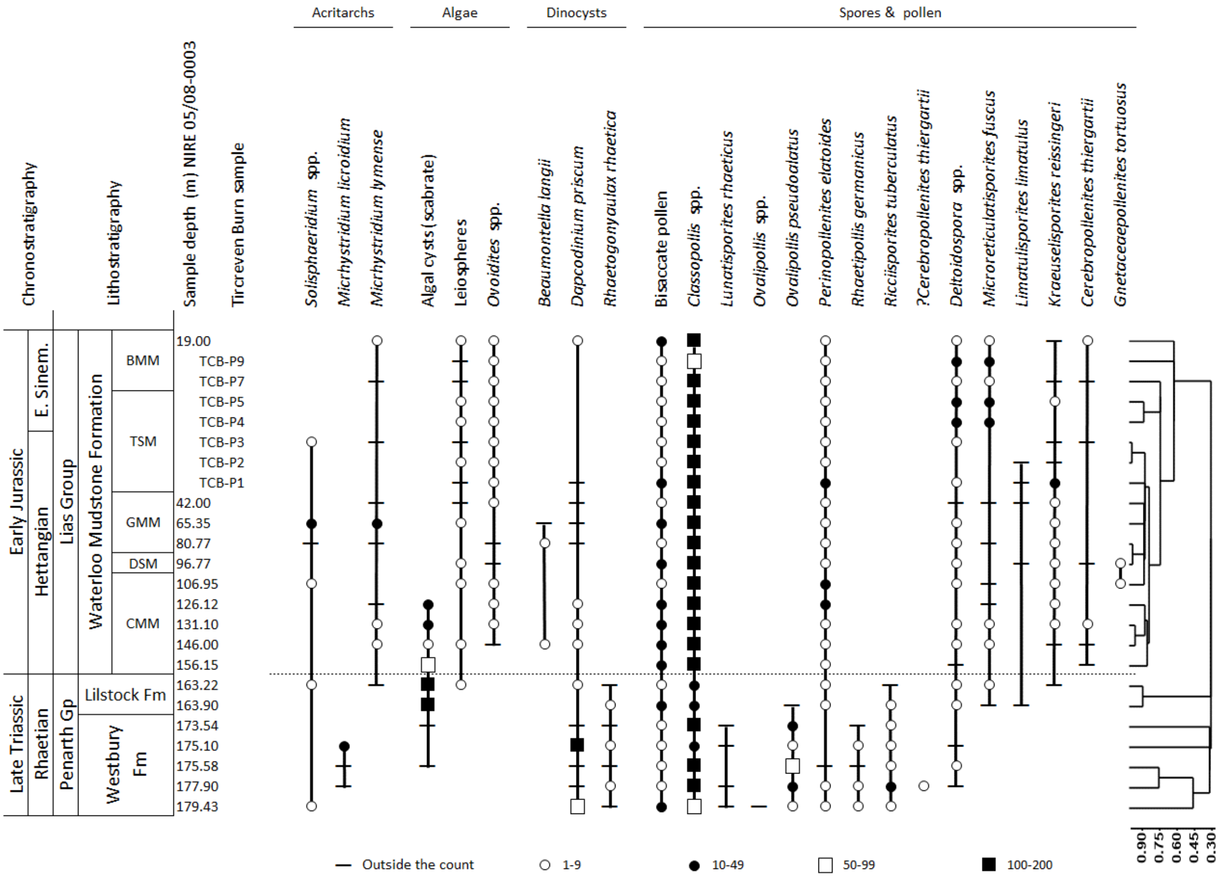


Figure 12. Stratigraphical distribution and relative abundance of the most abundant palynomorphs encountered in core from the NIRE 05/08-0003 Borehole and the Tircreven Burn section. Dotted line indicates the interpreted base of the Jurassic. Cluster diagram (UPGMA, Bray-Curtis similarity index) on right confirms a major palynofloral change at the Triassic-Jurassic boundary, the next most significant change is within the lower part of the Tircreven Sandstone Member. CMM = Clooney Mudstone Member, DSM = Drummans Siltstone Member, GMM = Gortmore Mudstone Member, TSM = Tircreven Sandstone Member, BMM = Ballyleighery Mudstone Member.

Rich, well-preserved palynofloras were recorded from both the NIRE 05/08-0003 Borehole and the Tircreven Burn outcrop, this is in marked contrast to the relatively poorly-preserved palynofloras documented from Waterloo Bay, Larne (Simms and Jeram, 2007) where poor recovery and preservation was attributed to diagenetic degradation of organic material and elevated thermal maturation due to the proximity of Paleogene igneous intrusions.

The dominant palynomorph throughout the Lough Foyle Basin samples is the miospore *Classopollis,* often occurring in large clusters of individuals. The five lowest samples studied (core depth 179.43 to 173.54 m) were taken from the Westbury Formation and include Late Triassic, Rhaetian index miospores such as *Ovalipollis pseudoalatus* (Thiergart)*, Rhaetipollis germanicus* Schultz and *Lunatisporites rhaeticus* (Schulz) (Kürschner & Waldemaar Herngreen, 2010; Cirilli, 2010). These taxa range no younger than Late Triassic, Rhaetian. In addition, the dinocyst *Dapcodinium priscum* Evitt is abundant (40%) at some levels.

The earliest assemblages are comparable to records from the Westbury Formation of Dorset (Howard et al., 2009) and to records of the same unit in the Larne Borehole (at core depth 92.66 m; Warrington and Harland, 1975) as well as an offshore BGS shallow borehole (75/41) from the Loch Indaal Basin, located about 90 km to the north-north east (core depths 24.10–30.30 m; Warrington, 1997) indicating the widespread development of these assemblages during the early Rhaetian.

The co-occurrence of *L. rhaeticus, R. germanicus, O. pseudoalatus* with superabundant *D. priscum* is similar to the assemblage recorded by Bonis et al. (2009) and Hillebrandt et al. (2013) in the Schattwald Beds at the base of the Tiefengraben Member of the Kendelbach Formation GSSP for the base of the Hettangian in Austria.

Low diversity assemblages were recorded from samples at 156.15 m and 163.22 m, the latter sample includes rare specimens of *Ricciisporites tuberculatus* Lundblad and *Rhaetogonyaulax rhaetica* (Sarjeant) and while both taxa are most characteristic of the Rhaetian, they have been documented, albeit in very low numbers, in Hettangian strata (Fenton, unpublished data). The latter species is restricted to the Triassic in both the Lough Foyle and Larne basins (Boomer et al., 2020b), while the former ranges through to the Hettangian in both areas. Another recognisable event across the boundary in both the Lough Foyle and Larne basins is the high abundance of scabrate algal cysts in the Lilstock Formation. Abundance then deceases rapidly into the Waterloo Mudstone Formation.

Cerebropollenites thiergartii Schultz occurs from 156.15 m depth upwards and is a key marker species, generally documented as ranging no older than Hettangian. However, the species was recorded in low abundance immediately below the Triassic–Jurassic boundary in the Carnduff-1 Borehole (Boomer et al., 2020b) with its first abundant record at the base of the Jurassic at that site. The Triassic-Jurassic boundary at Carnduff was interpreted based on a combination of the carbon-isotope profile and palynology. It is considered to have an entirely Jurassic occurrence in the Lough Foyle Basin, occurring as it does above the base of Jurassic foraminiferal assemblages. A questionable, poorly preserved specimen was also noted at 177.90 m in the Westbury Formation in the NIRE 05/08-0003 Borehole.

Limatulisporites limatulus (Playford) (163.90 m to TCB-P2, latest Triassic to Hettangian in this study) and *Gnetaceapollenites tortuosus* (Mädler) (106.95 m to 96.77 m, both Hettangian) are known from Rhaetian strata elsewhere but have occasionally been documented in Hettangian or younger strata (e.g. Fakhr, 1967). However, the former species straddles the Triassic–Jurassic boundary in the Larne Basin (Boomer et al., 2020b) while *G. tortuosus* is restricted to short range in the Hettangian as it does in the Larne Basin, this may be of regional significance. The latter taxon has been documented by Fakhr (1967, pl.42, figs 1-7) as *Gnetaceaepollenites* sp.A. from the Conybeari Subzone of the Bucklandi ammonite chronozone, earliest Sinemurian from Harbury Quarry, Warwickshire. The same species was also recorded from the mid-late Hettangian at Carnduff (Boomer et al., 2020b) and therefore appears to have an exclusively Hettangian range in Northern Ireland.

Based on the records from the Tircreven Burn outcrop (samples TCB-P1 to TCB-P9) that demonstrate a continuous occurrence of *Microreticulatisporites fuscus* (Nilsson) with samples yielding multiple specimens, an age of no younger than Hettangian is suggested for the lower part of the Tircreven Sandstone Member up as far as the base of the calcareous sandstones. The borehole sample at 19.00 m depth contained a single specimen of *M. fuscus* and most likely represents a reworked specimen based on the ammonite records from the Tircreven Burn section.

Dapcodinium priscum, observed as a single specimen at the base of the TSM outcrop (sample TCB-P1) and also at the top of the borehole (19.00 m), further supports a Hettangian age for the youngest samples studied. Although this dinocyst is known to extend into the very earliest Sinemurian, Bucklandi ammonite chronozone, it is more commonly encountered in Hettangian and Rhaetian strata. Although some of the palynomorphs recorded in the youngest samples are known to range into the earliest Sinemurian, there is no unequivocal palynological evidence to indicate a Sinemurian age in these samples.

All palynofloras examined are considered to have been deposited in marine environments, with varying abundances of marine microplankton present throughout. All assemblages are dominated by *Classopollis*, considered to be derived from a cheirolepidiacean parent flora, which had an environmental preference for saltmarsh or mangrove-type settings subject to an arid/semi-arid climatic regime (Riding et al., 2013). Elevated numbers of acanthomorph acritarchs at 65.35 m are potentially a feature of correlative value. However, they do not achieve the abundances documented from the basal Blue Lias Formation at St. Audries Bay (van de Schootbrugge et al., 2007).

Cluster analysis of the palynomorph data (Fig. 12, right hand part) indicates a clearly-defined, major assemblage composition change between samples 136.22 m and 156.15 m depth from the NIRE 05/08-0008 Borehole that coincides, within sampling resolution, to the boundary between the Penarth Group and the Lias Group. The next most significant assemblage change occurs between samples TCB-P3 and TCB-P4 in the Tircreven Sandstone Member from the Tircreven Burn section and this further supports the possible hiatus within that unit as proposed above.

All of the Early Jurassic samples, except at 156.15 m depth, yielded sieved kerogen dominated by structured humic plant debris, the latter primarily of vitrinitic origin in the form of laths. Subordinate proportions of inertinitic laths, cortical tissue and structured sapropels also occur. The relative paucity of cortical tissue is of interest, as this component is considered to be preferentially susceptible to transportation and/or biodegration via infaunal browsing. Alternatively, the paucity may be solely due to the predominance of vitrinitic laths derived from drifted wood debris. In contrast, the kerogen from 156.15 m is overwhelmingly dominated by amorphous organic matter (AOM), suggesting a phase of water-mass oxygen-deficiency/photic zone euxinia and potential dysoxia/anoxia at the sediment-water interface. Comparable features have been documented from the St. Audries Bay succession in Somerset and also in Germany (van de Schootbrugge et al., 2007, 2013).

The oldest sample, from the Penarth Group (179.43 m), is also overwhelmingly dominated by AOM. In contrast to the AOM-dominated kerogen from 156.15 m, where marine microplankton are absent, the palynoflora comprises an almost monotypic dinocyst assemblage dominated by *D. priscum*, often occurring in large aggregates of individuals. These features suggest low energy sedimentation beneath a restricted water column with bottom-water oxygen deficiency. *Dapcodinium priscum* is interpreted to be the cyst of a euryhaline, opportunistic dinoflagellate (Courtinat and Piriou, 2002).

The youngest samples examined, including those from the Tircreven Burn section, are again dominated by *Classopollis*, occurring as singletons, tetrads and clusters of individuals. Wetland or swamp-derived spores (e.g. *Deltoidospora*) occur in high numbers within the Tircreven Sandstone Member, reflecting increased terrigenous derived material. The increase in abundance of swamp spores upwards through the succession reflects an overall progradational trend up to sample TCB-P9. The swamp-derived spores exhibit variable preservation that is considered to result from mixing of components derived directly from the parent fern plant and locally reworked spores from soil profiles where bacterial and fungal decay had occurred.

An increase in abundance of the brackish/freshwater alga *Ovoidites* spp. is associated with the increase in swamp-derived spores, likely sourced from delta-top/coastal plain lacustrine environments. The marked increase in terrigenous material between samples TCB-P3 and TCB-P4 (also reflected in the cluster diagram, Figure 12) may support the possibility of a short-duration intra-Hettangian hiatus associated with the onset of progradation of the Tircreven Sandstone Member.

5. Summary

This paper deals with boreholes and outcrops from the Magilligan Peninsula and the slopes of Binevenagh in the northwest part of Northern Ireland. The study area lies in the centre of the Lough Foyle Basin, an opposing half-graben to the more extensive Rathlin Basin. The basin was partly exhumed following the Early Jurassic and prior to deposition of the Late Cretaceous during the Late Cimmerian phase of uplift. Examination of the post-rift succession spanning the uppermost Triassic to Lower Jurassic has identified a number of progradational cycles, the cause of which is likely to be related to sea-level fluctuation rather than tectonic controls.

The Westbury and Lilstock formations of the Penarth Group are similar in facies and thicknesses to other basins across Northern Ireland (Raine et al., 2020a), although they are finer-grained in the Lough Foyle Basin, possibly representing either a more sheltered setting or a lack of supply of silt- and sand-grade sediment. The Langport Member shows pronounced differences with that of the Larne Basin in that the Lough Foyle Basin is characterised by blue-grey claystones and fine-grained porcellanous limestones, with ooidal grainstones towards the top. This contrasts with the dark grey, bioturbated and fossiliferous siltstones and silty claystones of the same unit in the Larne Basin. In this respect the Langport Member of the Lough Foyle Basin bears more similarity with the Langport Member typical of southwest England.

The Jurassic succession contains a number of siltstone and sandstone units that are newly described in this paper but are not recorded in other basins across Northern Ireland. They represent progradation of nearshore environments associated with a distributary fluvial system that developed on the edge of the Irish Landmass and are interpreted to reflect fluctuations in relative sea-level. Subsequently, flooding of the delta led to deposition of a series of shelf sands on which a marine fauna became established.

The microfossil biostratigraphy provides useful correlations with the Larne and Rathlin basins (Boomer et al., 2020a, b). The present study supports the observation that calcareous benthic microfossils are all but absent from Rhaetian sediments in Northern Ireland in contrast to South Wales and southwest

England (Ainsworth and Boomer, 2009; Copestake, 1989), the one exception in this study being a single species record of low foraminiferal abundance in a single Westbury Formation sample (Fig. 11). Palynomorphs show no conclusive evidence for sediment younger than Hettangian age for the lower part of the Tircreven Sandstone Member, with ammonite evidence from the upper part indicating that several subzones may be missing at the base of the Sinemurian. Calcareous microfossil samples confirm a Hettangian age for much of the succession but have not yielded diagnostically Sinemurian taxa above the Tircreven Sandstone Member. More detailed sampling of the youngest beds may help identify any hiatus in a section where ammonites are sparse and could confirm a Sinemurian age for the Ballyleighery Mudstone Member. At present, the only conclusive evidence for an earliest Sinemurian age at the top of the studied succession comes from a few ammonites.

As might be expected, the microfossils suggest a nearshore, marginal marine setting throughout much of the Rhaetian, with dinocysts present throughout, though often in low abundance. Spore and pollen records support a nearshore environment throughout, with highest concentrations of terrestrial markers associated with the Tircreven Sandstone Member.

Data availability

The micropalaeontological and palynological data used to compile this paper are available at the University of Birmingham eData repository and can be accessed at https://doi.org/10.25500/edata.bham.00000553 (Raine et al., 2020b).

Acknowledgements

The authors acknowledge the support of the Geological Survey of Northern Ireland for providing access to the Foyle Basin core material. Azrin Azmi acknowledges the financial support of Ministry of Higher Education Malaysia and the National University of Malaysia while undertaking a PhD at the University of Birmingham. Philip Copestake thanks Merlin Energy Resources Ltd and Jim Fenton thanks CGG Robertson for their respective support in undertaking this work. Robert Raine carried out work under the SLA between the Department for the Economy and the British Geological Survey and publishes with the permission of the Department and the Executive Director of the British Geological Survey (UKRI). The Department of Agriculture, Environment and Rural Affairs are thanked for permission to conduct palaeontological sampling at the Tircreven ASSI. We are extremely indebted to two anonymous reviewers for their attention to detail and constructive comments.

References

Anderson, T.B., Parnell, J., Ruffell, A.H., 1995. Influence of basement on the geometry of Permo-Triassic basins in the northwest British Isles. In: Boldy, S.A.R. (Ed.), Permian and Triassic Rifting in Northwest Europe. Geological Society, London, Special Publications 91, 103–122.

Ainsworth, N.R., Boomer, I., 2009. Triassic. In: Whittaker, J.E., Hart, M.B. (Eds), Ostracods in British Stratigraphy. The Micropalaeontological Society, Special Publications. The Geological Society, London. 165–174.

Bazley, R.A.B., Brandon, A., Arthurs, J.W., 1997. Geology of the country around Limavady and Londonderry. Geological Survey of Northern Ireland, Technical Report GSNI/97/1. 96pp.

Bonis, N.R., Kürschner, W.M., Krystyn, L., 2009. A detailed palynological study of the Triassic-Jurassic transition in key sections of the Eigberg Basin (Northern Calcareous Alps, Austria). Review of Palaeobotany and Palynology 156, 376-400.

Boomer, I., Azmi, A., Copestake, P., Raine, R., 2020a. Lower Jurassic (Hettangian-Pliensbachian) microfossil biostratigraphy of the Ballinlea-1 well, Rathlin Basin, Northern Ireland, United Kingdom. Proceedings of the Geologists' Association. This volume.

Boomer, I., Ainsworth, N.R., 2009. Lower Jurassic (Hettangian-Toarcian). In: Whittaker, J.E., Hart M.B. (Eds), Ostracods in British Stratigraphy. Micropalaeontology Society, Special Publication. Geological Society of London. 175-197.

Boomer, I., Copestake, P., Raine, R., Azmi, A., Fenton, J., Page, K., O'Callaghan, M., 2020b. Stratigraphy, palaeoenvironments and geochemistry across the Triassic-Jurassic boundary transition at Carnduff, County Antrim, Northern Ireland. Proceedings of the Geologists' Association. This volume

Broughan, F.M., Naylor, D., Anstey, N.A., 1989. Jurassic rocks in the Kish Bank Basin. Irish Journal of Earth Sciences 10, 99–106.

Cirilli, S., 2010. Upper Triassic–lowermost Jurassic palynology and palynostratigraphy: a review. In: Lucas, S.G. (Ed.), The Triassic Timescale. Geological Society Special Publication, 334. 285-314.

Copestake, P., 1989. The Triassic. In: Jenkins, D.G., Murray, J.W. (Eds.), Stratigraphical Atlas of Fossil Foraminifera (2nd ed.). Chichester, Ellis Horwood Limited, pp. 97–124.

Copestake, P., Johnson, B., 2014. Lower Jurassic Foraminifera from the Llanbedr (Mochras Farm) Borehole, North Wales, UK. Monographs of the Palaeontographical Society, 167(641), 1-403.

Courtinat, B., Piriou, S., 2002. Palaeoenvironmental distribution of the Rhaetian dinoflagellate cysts *Dapcodinium priscum* Evitt, 1961 emend Below, 1987 and *Rhaetogonyaulax rhaetica* (Sarjeant) Loeblich and Loeblich 1976 emend Harland *et al*. Emend Below 1987. Geobios 354, 429-439.

Evans, R.B., Evans, D., 1987. Geophysical investigations around Lough Foyle, Ulster. British Geological Survey Report RG 87/4, 43pp.

Ewins, N.P., Shannon, P.M., 1995. Sedimentology and diagenesis of the Jurassic and Cretaceous of the North Celtic Sea and Fastnet basins. In: Croker, P.F., Shannon, P.M. (Eds.), The Petroleum Geology of Ireland's Offshore Basins. Geological Society, London, Special Publications 93, 139–169.

Fakhr, B.Y., 1967. Pollen and spores from the Lower Lias marine sediments of England. Ph.D. Thesis, University of Birmingham, 357pp.

Fitzsimons, S., Parnell, J., 1995. Diagenetic history and reservoir potential of Permo-Triassic sandstones in the Rathlin Basin. In: Croker, P.F., Shannon, P.M. (Eds.), The Petroleum Geology of Ireland's Offshore Basins. Geological Society, London, Special Publications 93, 21–35.

Gallois, R.W., 2008. The stratigraphy of the Penarth Group (Late Triassic) of the East Devon coast. Geoscience in South-West England 11, 287–297.

Gallois, R.W., 2009. The lithostratigraphy of the Penarth Group (Late Triassic) of the Severn Estuary area. Geoscience in South-West England 12, 71–84.

Green, P.F., Duddy, I.R., Hegarty, K.A., Bray, R.J., Sevastopulo, G., Clayton, G., Johnson, D., 2000. The post-Carboniferous evolution of Ireland: evidence from thermal history reconstruction. Proceedings of the Geologists' Association 111, 307–320.

Hall, J., Brewer, J.A., Matthews, D.H., Warner, M.R., 1984. Crustal structure across the Caledonides from the 'WINCH' seismic reflection profile: influences on the evolution of the Midland Valley of Scotland. Transactions of the Royal Society of Edinburgh: Earth Sciences 75, 97 –109.

Hesselbo, S.P., Coe, A.L., 2000. Jurassic sequences of the Hebrides Basin, Isle of Skye, Scotland. In: Graham, J.R., Ryan, A. (Eds), Field Trip Guidebook, International Sedimentologists Association Meeting, Dublin, pp. 41-58. Dublin: University of Dublin.

Hillebrandt, A.V., Krystyn, L., Kürschner, W.M., Bonis, N.R., Ruhl, M., Richoz, S., Schobben, M.A.N., Urlichs, M., Bown, P.R., Kment, K., Mcroberts, C.A., Simms, M., Tomãsových, A., 2013. The Global Stratotype Sections and Point (GSSP) for the base of the Jurassic System at Kuhjoch (Karwendel Mountains, Northern Calcareous Alps, Tyrol, Austria). Episodes 36 (7), 162-198.

Hillis, R.R., Holford, S.P., Green, P.F., Dore, A.G., Gatliff, R., Stoker, M., Thomson, K., Turner, J.P., Underhill, J.R., Williams, G., 2008. Cenozoic exhumation of the southern British Isles. Geology 36, 371-374.

Howard, A., Warrington, G., Carney, J., Ambrose, K., Young, S.R., Pharaoh, T., Cheney, C., 2009. Geology of the Nottingham district: memoir for 1:50 000 geological sheet 126 (England and Wales). Nottingham, UK, British Geological Survey, 212pp.

Ivimey-Cook, H.C., Hodges, P., Swift, A., Radley, J.D., 1999. Bivalves. In: Swift, A., Martill, D.M. (Eds), Fossils of the Rhaetian Penarth Group. Palaeontological Association, Field Guides to Fossils, 9, 83–127.

Jeram, A., Simms, M.J., Hesselbo, S.P., Raine, R., 2021. Carbon isotopes, ammonites and earthquakes: Key Triassic-Jurassic boundary events in coastal sections of south-east County Antrim, Northern Ireland, UK. Proceedings of the Geologists' Association. This volume.

Johnson, H., Leslie, A.B., Wilson, C.K., Andrews, I.J., Cooper, R.M., 2005. Middle Jurassic, Upper Jurassic and Lower Cretaceous of the UK Central and Northern North Sea. British Geological Survey Research Report, RR/03/001. 42pp.

Kennedy, A.E., Coe, A.L., 2014. Development of the freeze-thaw processing technique for disaggregation of indurated mudrocks and enhanced recovery of calcareous microfossils. Journal of Micropalaeontology 33, 193–203.

Kessler, L.G., Sachs, S.D., 1995. Depositional setting and sequence stratigraphic implications of the Upper Sinemurian (Lower Jurassic) sandstone interval, North Celtic Sea/St George's Channel Basins, offshore Ireland. In: Croker, P.F., Shannon, P.M. (Eds.), The Petroleum Geology of Ireland's Offshore Basins. Geological Society, London, Special Publications 93, 171–192.

Kürschner, W.M. & Waldemaar Herngreen, G.F., 2010. Triassic palynology of central and northwestern Europe: a review of palynofloral diversity patterns and biostratigraphic subdivisions. In: Lucas, S.G. (Ed.), The Triassic Timescale. Geological Society Special Publication 334, 263-284.

Laborde-Casadaban, M., Homberg, C., Schnyder, J., Borderie, S., Raine, R., 2021. Does soft sediment deformations in the Late Triassic and Early Jurassic of the UK record seismic activity during the break-up of Pangea? Proceedings of the Geologists' Association. This Volume.

Manning, P.I., Robbie, J.A., Wilson, H.E., 1970. Geology of Belfast and the Lagan Valley, Memoir of the Geological Survey of Northern Ireland, 242pp.

Merlin Energy Resources Consortium, 2020. The Standard Stratigraphic Nomenclature of Offshore Ireland: An Integrated Lithostratigraphic, Biostratigraphic and Sequence Stratigraphic Framework. Project IS16/04 Atlas, for Petroleum Infrastructure Programme (PIP).

Mitchell, W.I., 2004. Chapter 10 Triassic. In: Mitchell, W.I. (Ed.), The Geology of Northern Ireland – Our natural foundation (Second Edition). Geological Survey of Northern Ireland Belfast, pp. 133–144.

Murphy, N.J., Ainsworth, N.R., 1991. Stratigraphy of the Triassic, Lower Jurassic and Middle Jurassic (Aalenian) from the Fastnet Basin, offshore south-west Ireland. Marine and Petroleum Geology 8 (4), 417-429.

Naylor, D., Philcox, M.E., Clayton, G., 2003. Annaghmore-1 and Ballynamullan-1 Wells, Larne–Lough Neagh Basin, Northern Ireland. Irish Journal of Earth Sciences 21, 47-69.

Opazo Mele, L.F., Page, K., 2021. Palaeoecological patterns of change in marine invertebrate faunas across the end-Triassic mass extinction event: evidence from Larne, Northern Ireland. Proceedings of the Geologists' Association. This volume.

Penn, I.E., Holliday, D.W., Kirby, G.A., Kubala, M., Sobey, R.A., Mitchell, W.I., Harrison R.K., Beckinsale, R.D., 1983. The Larne No. 2 Borehole: discovery of a new Permian volcanic centre. Scottish Journal of Geology, 19, 333–346. https://doi.org/10.1144/sjg19030333.

Portlock, J.E., 1843. Report on the Geology of the County of Londonderry, and of Parts of Tyrone and Fermanagh. HMSO, Dublin, 784 pp.

Pritchard, G. 2013. Prospectivity of the Slyne Basin. Presentation, Atlantic Ireland 2013 Conference, Dublin. https://www.pip.ie/page/350.

Raine, R., Copestake, P., Simms, M.J., Boomer, I., 2020a. Uppermost Triassic to Lower Jurassic sediments of the Island of Ireland and its surrounding basins. Proceedings of the Geologists' Association. This volume.

Raine, R., Fenton, J., Azmi, A., Boomer, I., Copestake, P., 2020b. Palaeontological and geochemical data supporting Raine, et al., Uppermost Triassic to Lower Jurassic stratigraphy in the Lough Foyle Basin of Co. Londonderry, Northern Ireland. University of Birmingham eData https://doi.org/10.25500/edata.bham.00000553.

Riding, J.B., Leng, M.J., Kender, S., Hesselbo, S.P., Feist-Burkhardt, S., 2013. Isotopic and palynological evidence for a new Early Jurassic environmental perturbation. Paleogeography, Palaeoclimatology, Palaeoecology 374, 16-27.

Ruffell, A., Shelton, R., 1999. The control of sedimentary facies by climate during phases of crustal extension: examples from the Triassic of onshore and offshore England and Northern Ireland. Journal of the Geological Society 156, 779-789.

Sampson, G.V., 1802. Statistical Survey of the County of Londonderry, with observations on the means of improvement; drawn up for the consideration, and under the direction of the Dublin Society. Graisberry and Campbell, Dublin. p. 102

Simms, M.J., 2003. Uniquely extensive seismite from the latest Triassic of the United Kingdom: evidence for bolide impact? Geology 31, 557–560.

Simms, M.J., 2007. Uniquely extensive soft-sediment deformation in the Rhaetian of the UK: evidence for earthquake or impact? Palaeogeography, Palaeoclimatology, Palaeoecology 244, 407–423.

Simms, M. J., Chidlaw, N., Morton, N., Page, K.N., 2004. British Lower Jurassic Stratigraphy. Geological Conservation Review Series Volume 30. Joint Nature Conservation Committee, Peterborough, 458 pp.

Simms, M.J., Jeram, A.J., 2007. Waterloo Bay, Larne, Northern Ireland: a candidate Global Stratotype Section and Point for the base of the Hettangian Stage and Jurassic System. ISJS Newsletter 31 (1), 50-68.

Swift, A., 1999. 2. Stratigraphy (including biostratigraphy). In: Swift, A., Martill, D.M. (Eds), Fossils of the Rhaetian Penarth Group. Palaeontological Association Field Guides to Fossils: Number 9. The Palaeontological Society, London, 15–30.

Tate, R., 1867. On the Lower Lias of the North-east of Ireland. Quarterly Journal of the Geological Society 23, 297-305.

Underhill, J.R., Partington, M.A., 1993. Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphic evidence. In: Parker, J.R., (Ed.), Petroleum geology of Northwest Europe: Proceedings of the 4th conference: The Geological Society of London, London, 337–345.

Van de Schootbrugge, B., Tremolada, F., Rosenthal, Y., Bailey, T.R., Feist-Burkhardt, S., Brinkhuis, H., Pross, J., Kent, D.D., Falkowski, P.G., 2007. End-Triassic calcification and blooms of organic-walled 'disaster species'. Paleogeography, Palaeoclimatology, Palaeoecology 244, 126-141.

Van de Schootbrugge, B., Bachan, A., Suan, G., Richoz, S., Payne, J., 2013. Microbes, mud and methane: cause and consequence of recurrent Early Jurassic anoxia following the end-Triassic mass extinction. Palaeontology 56 (4), 685–709.

Warrington, G., 1997. The Penarth Group – Lias Group succession (Late Triassic-Early Jurassic) in the East Irish Sea Basin and neighbouring areas: a stratigraphic review. In: Meadows, N.S., Trueblood, S.R., Hardman, M., Cowan, G. (Eds.), Petroleum geology of the Irish Sea and adjacent areas. Geological Society London, Special Publication 124, 33-46.

Warrington, G., Harland, R., 1975. Palynology of the Trias and Lower Lias of the Larne Borehole. Bulletin of the Geological Survey, Great Britain 50, 37–50.

Warrington, G., Audley-Charles, M.G., Elliott, R.E., Evans, W.B., Ivimey-Cook, H.C., Kent, P.E., Robinson, P.L., Shotton, F.W., Taylor, F.M., 1980. Triassic. Geological Society, Special Report 13. 78pp.

Wignall, P.B., Atkinson, J.W., 2020. A two-phase end-Triassic mass extinction. Earth-Science Reviews 208, 103282. https://doi.org/10.1016/j.earscirev.2020.103282.

Wilson, H.E., Manning, P.I., 1978. Geology of the Causeway Coast. Memoir of the Geological Survey of Northern Ireland, Sheet 7. HMSO, Belfast, pp.172.

Wood, G.D., Gabriel, A.M., Lawson, J.C., 1996. Palynological techniques – processing and microscopy. In: Jansonius, J., McGregor D.C. (Eds), Palynology: principles and applications. American Association of Stratigraphic Palynologists Foundation 1, 29-50.

Woodland, A.W., 1971. The Llanbedr (Mochras Farm) borehole. Report of the Institute of Geological Sciences 71/18. 115pp.

Ziegler, P.A., 1981. Evolution of sedimentary basins in North-West Europe. In: Illing, L.V., Hobson, G.D. (Eds), Petroleum Geology of the Continental Shelf of North-West Europe. Heyden and Son, London, 3–42.