# Lower Jurassic (Hettangian–Pliensbachian) microfossil biostratigraphy of the Ballinlea-1 well, Rathlin Basin, Northern Ireland, United Kingdom.

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*Abstract*

The thickest section of Early Jurassic strata known from onshore Ireland (total Jurassic thickness 566 m) is reported from the Ballinlea-1 well (Rathlin Basin) situated on the north coast of Northern Ireland. A biostratigraphical and palaeoenvironmental assessment is presented for this section largely based on calcareous benthic microfossils (foraminifera and ostracods). The Early Jurassic Waterloo Mudstone Formation (Lias Group) of Northern Ireland has previously received little micropalaeontological attention, therefore this work provides an opportunity to enhance palaeogeographic and palaeoenvironmental understanding for the Early Jurassic of the province, and this paper illustrates the key microfossil taxa of this age from Ireland for the first time. The records, based on ditch-cuttings samples, demonstrate a stratigraphical range from Hettangian to Early Pliensbachian, consistent with other wells and boreholes in this basin. The assemblage compositions are comparable to those elsewhere in the European boreal Atlantic realm. Hettangian to earliest Sinemurian microfossil assemblages are generally of low diversity and are numerically dominated by metacopid ostracods with occasional influxes of foraminifera. Gradually, foraminiferal abundance (often dominated by species of the Lagenida) come to exceed those of the ostracods in the Early Sinemurian reaching their greatest diversity in the Late Sinemurian. The sediments are considered to represent an inner to mid-shelf environment throughout while the record thickness for this region indicates ongoing syn-sedimentary fault movement along the basin margins within this period.

*KEYWORDS: Ostracoda, foraminifera, Waterloo Mudstone Formation, Hettangian, Sinemurian, Pliensbachian.*

## 1. Introduction and Geological Setting

Exposures of Early Jurassic sediments in Northern Ireland are relatively rare and are largely restricted to small (a few 10s of metres at most) coastal exposures (Figure 1). They often sit below cliffs of Late Cretaceous chalk (the Ulster White Limestone Group) and Paleogene basalts of the Antrim Lava Group (Mitchell, 2004). The exposures are discontinuous, faulted and their weakly consolidated nature makes them prone to landslip. Subsurface records of latest Triassic and Early Jurassic sediments are known from a number of boreholes and exploration wells but this paper deals with the thickest sequence of Early Jurassic age sediments known from onshore Ireland, recovered from the Ballinlea-1 exploration well in the Rathlin Basin on the north coast of Ireland.

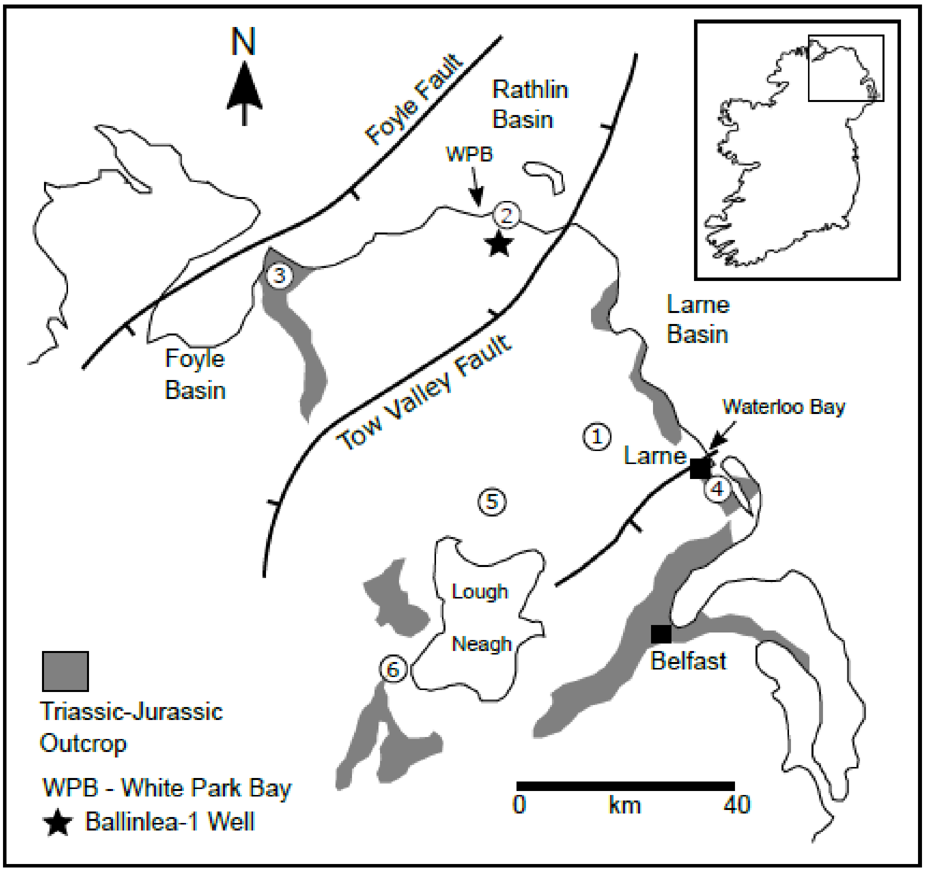


Figure 1. Distribution of Triassic and Jurassic sediments in Northern Ireland, together with location of the main sedimentary basins, bounding faults and locations referred to in this work (1. Ballytober-1 well, 2. Port More Borehole, 3. Magilligan Borehole and borehole NIRE 05/08-0003, 4. Larne-1 and Larne-2 boreholes, 5. Ballymacilroy Borehole, 6. Mire House Borehole). The map is modified from George (1967), Warrington (1997) and Middleton et al. (2001).

Largely continuous records across the latest Triassic to earliest Jurassic interval are known from the region. Simms and Jeram (2007) summarised the occurrence of Late Triassic sediments in the Larne Basin at Waterloo Bay, noting that red-beds of the Mercia Mudstone Group were overlain by siltstones of the Collin Glen Formation, both Norian (Warrington, 1995) and those are, in turn, disconformably overlain by Rhaetian sediments of the Penarth Group, divided into a lower Westbury Formation and an upper Lilstock Formation (Mitchell, 2004). Although there is evidence from across Northern Ireland to suggest that this succession of lithostratigraphic units occurs across many parts of the province (Raine et al., in press, a), outcrops of Late Triassic age sediments have not been recorded within the Rathlin Basin and neither are sediments of this age proven with any certainty from the Ballinlea-1 well.

A broadly conformable boundary between the Penarth Group and the Waterloo Mudstone Formation is recorded in the Magilligan borehole to the west of the Ballinlea-1 well (Bazley et al., 1997) although this has not been proven at the Port More borehole due to the presence of an intrusive sill (Wilson and Manning, 1978; Warrington, 1997) with only the Westbury Formation representing the Penarth Group. While the Triassic-Jurassic boundary interval is exposed at Larne (Simms and Jeram, 2007) and in the nearby Carnduff-1 and 2 boreholes (Boomer et al., in press) by contrast, the Lias Group from the Ballytober-1 borehole (also located in the Larne Basin) unconformably overlies the Mercia Mudstone Group (Fynegold Petroleum, 1991), which is similar to that occurring in the Ballinlea-1 well.

Early Jurassic sediments from Northern Ireland are assigned to the Waterloo Mudstone Formation (Lias Group) which is broadly equivalent to the Blue Lias Formation and part of the Charmouth Mudstone Formation of Great Britain. The most significant outcrops in Northern Ireland occur at Waterloo Bay, Larne (Simms and Jeram, 2007), previously a candidate GSSP (Global Stage Stratotype and Point) for the Triassic/Jurassic boundary, and at White Park Bay (Wilson and Manning, 1978; Mitchell, 2004), all other exposures are only of a few metres in thickness. While the majority of outcrops are of very earliest Jurassic (Hettangian to Early Sinemurian) age, the exposures at White Park Bay are of latest Sinemurian to Early Pliensbachian age.

Prior to the drilling of the Ballinlea-1 exploration well, the thickest Early Jurassic successions onshore Ireland had been recorded in boreholes at Port More (270 m), Mire House (125 m), Magilligan (76.5 m), Ballymacilroy (86 m) and Larne-1 (51 m), whilst the nearby Larne-2 borehole encountered Mercia Mudstone Group at the surface (Figure 1). In the subsurface, the youngest known Early Jurassic sediments in Northern Ireland are of the Ibex Chronozone (Early Pliensbachian) in the Port More Borehole (Warrington, 1997), demonstrating that the Waterloo Mudstone Formation in the Rathlin Basin appears more complete than elsewhere in the province, and this may be a consequence of different structural histories in the different basins between the early Jurassic and mid-Cretaceous, the next youngest lithostratigraphic unit.

## 2. The Ballinlea-1 exploration well

The Ballinlea-1 well is located on the north Antrim coast (55° 11’ 22” N; 6° 22’ 21” W; Figure 1) about 7 km south west of Ballycastle. The Rathlin Basin developed due to the reactivation of pre-existing fault systems during the late Palaeozoic followed by early Mesozoic extensional movement related to rifting along the margins of Pangaea (McCaffrey and McCann, 1992; Johnston, 2004; Holdsworth *et al*., 2012). The Rathlin Basin trends broadly northeast-southwest, deepening south-eastwards into the Tow Valley Fault (McCann, 1988) and extends northwards, offshore, between the Antrim coast and the Isle of Islay (western Scotland). The eastern extent of the basin is concealed under the Paleogene basalts of the Antrim Lava Group (Johnston, 2004).

The Ballinlea-1 well was drilled as a hydrocarbon exploration well, by Rathlin Energy and its partner Mancal Energy in 2008, targeting a Palaeozoic structure. The section encountered represents the thickest gross section of Lower Jurassic sediments known from the onshore area of Ireland (604 m total; net thickness just 566 m due to a large Paleogene intrusion within the sequence). Substantially thicker successions are known, however, from offshore the Republic of Ireland, for instance in the North Celtic Sea Basin, where around 2000 m of Lias Group sediments are proven in well sections (Copestake and Johnson, 2014; Raine et al., in press, a) and in the Slyne Basin, offshore west of Ireland (Trueblood, 1992). The Jurassic sediments in the Ballinlea-1 well occur unconformably beneath a relatively thin cover (15 m) of Cretaceous chalk of the Ulster White Limestone Group, above which lies 92 m of Paleogene Antrim Lava Group (Figure 2). Above the studied section there is a further sequence of mudstones and recrystallized chalk associated with intrusive dolerite, this has been interpreted as a faulted repetition of sediments belonging to the uppermost Waterloo Mudstone Formation and lowermost Ulster White Limestone Group, presumably related to Paleogene volcanism. The Early Jurassic Waterloo Mudstone Formation principally comprises grey, calcareous mudstones with occasional thin grey limestones and silty mudstones. The succession is intruded by a Paleogene dolerite sill between 630-668 m. This study focuses on the largely continuous Early Jurassic succession from 343 m to 947 m measured depth below KB (kelly bushing), all depths are given relative to KB. Samples below this depth are considered to represent the Collin Glen Formation, equivalent to the Blue Anchor Formation, due to the sedimentology of the cuttings (greenish-grey and pinkish-grey claystone).

Riding (2010) undertook a preliminary age assessment of this well based on the occurrence and changing relative abundance of palynomorphs and some of those findings are incorporated into the age assessment below. At the time of drilling, the operator, Rathlin Energy, commissioned a biostratigraphic study of the Carboniferous succession in the Ballinlea-1 well, however, no biostratigraphic analysis was carried out on the Lower Jurassic sections, which lay above the prospective target interval of the well.

In order to provide a more detailed stratigraphic and palaeoenvironmental interpretation of this well using calcareous microfossils, a total of 120 ditch-cuttings samples (from 255m – 980 m), at approximately 5 m intervals, were provided by the Geological Survey of Northern Ireland (GSNI). Seventy of these samples were processed using a combination of hydrogen peroxide method and multiple freeze-thaw cycles. Samples of approximately 70 g were studied at around 10 m intervals, though occasionally a 5 m interval was used. Once processed, half, quarter or smaller residue splits, sufficient to provide 250–300 microfossil specimens where possible, were totally picked above 125 µm size fraction. Additional scans through the 63 µm fraction were undertaken to identify smaller species not encountered in the larger fractions. The residues contained various quantities of foraminifera, ostracods, micro-bivalves, micro-gastropods, echinoderm and ophiuroid fragments, while mica, pyrite, carbonaceous materials, iron nodules and quartz grains were distributed irregularly throughout.

## 3. Previous studies of Early Jurassic microfossils from Northern Ireland

Tate (1870) made the first published reference to Lias microfossils in Northern Ireland when he recorded the presence of *Dentalina obliqua* from the *'Lower Lias, Belemnite Shales'* of *'Island Magee'* (*sic*.). In the same volume, Wright (1870) referred to Tate's record and then listed a further twenty species of foraminifera from sediments at Ballintoy on the North Antrim Coast. A report by the Belfast Naturalists' Field Club (Wright, 1878; p.268-269) briefly noted additional Lias microfossil records from coastal outcrops in County Antrim. All these historical records referred foraminifera to incorrect, modern species names, however. Almost a century later, McGugan (1965) provided a brief checklist and drawings of some foraminifera (and noted the occurrence of at least three species of ostracods) that were recovered from inter-tidal exposures at White Park Bay. However, a number of errors in identification ultimately led him to suggest an erroneously old age of Angulata Chronozone (latest Hettangian) for these sediments, though that would have fitted with the age of most other coastal exposures in the province. Those exposures are now known to be of Late Sinemurian to Early Pliensbachian age (Simms and Edmunds, in press). The occurrence of both ostracods and foraminifera at Waterloo Bay was noted by Simms and Jeram (2007) from a single sample in the lowest part of the Waterloo Mudstone Formation. Copestake and Johnson (1989, 2014) also referenced the occurrence of foraminiferal marker taxa from outcrop samples from Northern Ireland held by industrial service companies.

The geographically closest sections to be studied in any detail come from offshore the west coast of the Republic of Ireland (Ainsworth, 1990; North Porcupine, Slyne and Erris basins), the Hebrides Basin, western Scotland (Ainsworth and Boomer, 2001) and the Llanbedr (Mochras Farm) Borehole of west Wales (Boomer, 1991; Copestake and Johnson, 2014) although these are all located in different depositional basins. Copestake and Johnson (1989, 2014) defined a foraminiferal biozonation scheme (JF biozones) that is applicable across north west Europe and is tied to the standard ammonite chronostratigraphy. This foraminiferal biozonation scheme is applied in the current study to interpret the chronostratigraphic succession represented by the Waterloo Mudstone Formation penetrated in the Ballinlea-1 well while additional data from the ostracods of the Mochras Borehole (Boomer, 1991) are also incorporated into the biostratigraphic interpretation.

## 4. Ballinlea-1 Early Jurassic microfossil biozonation biostratigraphy

More than 100 species of foraminifera (2 species of agglutinating, 98 calcareous benthonic) and more than 40 species of ostracods are recorded from this well, some of these records are of low abundance taxa and poorly preserved material. Most of the samples yielded microfaunal assemblages, but abundance was variable, some levels were barren, and the highest abundance observed was 46 microfossil specimens per gram of dry sediment.

As the material is entirely from ditch cuttings, the scheme is based on first downhole occurrences (FDOs). Downhole caving can obscure the last downhole occurrences and render such bioevents unreliable. Given the common occurrence and the generally well-preserved nature of the microfossil assemblages, the scheme here is considered to be relatively robust. The occurrence of the key marker species (foraminifera and ostracods) is shown against the lithostratigraphic succession in the well (Figure 2). Note that the interpreted age intervals given below, and as shown in Figure 2, are extended downwards to the top of the underlying interpreted age interval. The key microfossil marker taxa and some of the most abundant species are illustrated in figures 3 and 4 (all specimens are deposited in the collections of the Lapworth Museum of Geology, University of Birmingham).

Partington *et al*. (1993) outlined a biozonation scheme (MJ zones) for the North Sea and onshore north west Europe that combined information from foraminifera and ostracods. There is currently a review of North Sea JF sequences in progress (Copestake and Partington, in prep.) and some of the information from that work is incorporated into the age interpretations below. A rangechart for the most abundant ostracod and foraminiferal taxa is provided as an online resource at DOI: 10.25500/edata.bham.00000492.

4.1 Interval 343 m-480 m; Early Pliensbachian.

The FDOs of the foraminiferal species *Vaginulinopsis denticulatacarinata* at 345 m, *Mesodentalina varians haeusleri* at 385 m, abundant *Brizalina liasica* at 400 m and *Paralingulina tenera subprismatica* at 410 m (which increases in numbers below 425 m) are indicative of the JF9 foraminiferal biozone (Copestake and Johnson, 2014), of Early Pliensbachian age. The presence of *V. denticulatacarinata* is particularly age diagnostic and this occurrence matches intervals within the Charmouth Mudstone of an equivalent age in eastern England (Lincolnshire) (see figured forms in Copestake and Johnson, 1989).

This interval includes the FDO of the ostracod species *Ogmoconchella danica* (410 m) which, together with *Ogmoconchella mouhersensis*, defines a Late Sinemurian to Early Pliensbachian ostracod zone in the Danish Embayment (Michelsen, 1975). Partington *et al*. (1993) described an MJ7a microfaunal subzone in the northern North Sea, characterised in part by the FDO of *O. danica*, that was ascribed by them to an intra Early Pliensbachian age (Ibex to Jamesoni ammonite chronozone). However, *O. danica* was not recorded younger than the Sinemurian at Mochras (Boomer, 1991), in the Hebrides (Ainsworth and Boomer, 2001) or on the Dorset Coast (Park, 1987).

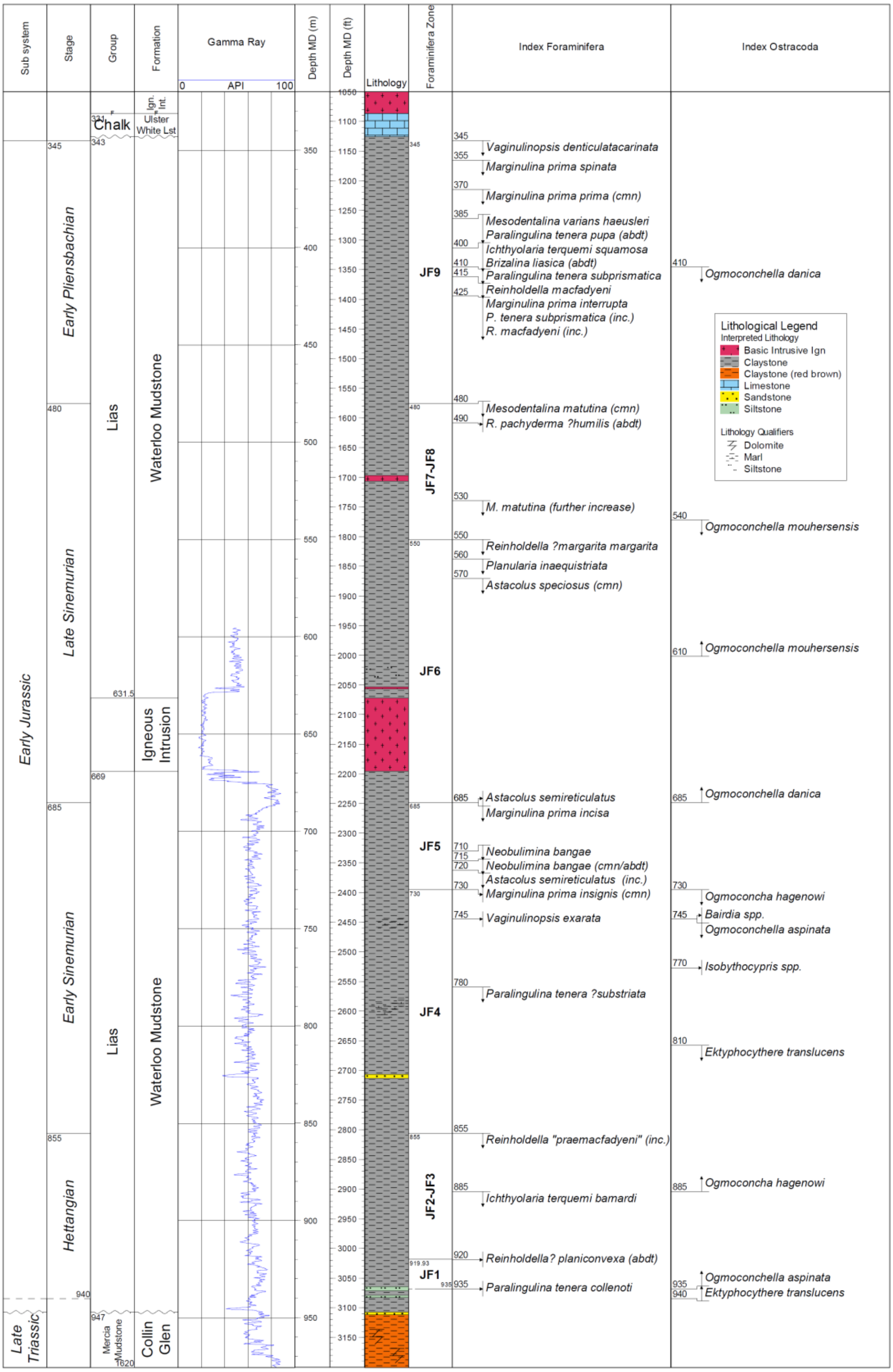


Figure 2. Lias Group lithological units, chronostratigraphy, lithostratigraphy, gamma ray log and key microfossil bioevents for the Ballinlea-1 exploration well.

*O. danica* and *O. mouhersensis* have been found together in a number of samples from exposures of the Waterloo Mudstone Formation in the intertidal zone of White Park Bay, about 6 km north of the Ballinlea-1 well. Although those outcrops range in age from latest Sinemurian to earliest Pliensbachian based on ammonite collections (Simms and Edmunds, in press), it has not been possible to establish with certainty, a precise age of the samples from which those assemblages were recovered. Based on a number of unpublished industrial exploration wells, it is likely that *O. danica* ranges into the earliest Pliensbachian (Nigel Ainsworth, pers. comm.).

In addition to the foraminiferal marker species noted above, the interval is characterised by the consistent and common presence of members of the *Marginulina prima* plexus, including *M. prima prima*, *M. prima spinata* and *M. prima interrupta*. Members of the *Paralingulina tenera* plexus are common to abundant, including *P. tenera pupa* and *P. tenera tenera* and *P. tenera tenuistriata*. Of particular note is the presence of *Reinholdella macfadyeni* at and below 415 m, becoming common at 450 m. This species is more typical of the Toarcian in onshore British and offshore Ireland successions, but is known from pre-Toarcian intervals in some parts of the United Kingdom, including the Yorkshire coast area, where it ranges as old as the Turneri Chronozone (Early Sinemurian) (Copestake et al., 2019).

The interval also contains *Nodosaria issleri*, which appears at 400 m and below. This species has been described as a Late Sinemurian restricted taxon (see discussion in Copestake and Johnson, 2014) and its occurrence in Ballinlea-1 in this interval is at odds with the Early Pliensbachian interpretation outlined here on the basis of the assemblage discussed above. An alternative interpretation, that the section is of Late Sinemurian age from 400 m, is possible but cannot be unequivocally substantiated.

Riding's (2010) study of palynomorphs from Ballinlea-1 determined the interval 355 – 500 m to be Pliensbachian due to the dominance of bisaccate pollen and the miospore *Perinopollenites elatoides* which distinguished it from the lower samples of the well which were dominated by *Classopollis.* Riding's sampling interval was quite coarse, just 11 samples in total through the well with about 100 m resolution around the Late Sinemurian to Early Pliensbachian interval. However, his findings are not inconsistent with the microfossil-determined age. It is notable that Riding's (2010) study did not recover any of the standard dinoflagellate cyst species that are known to occur in Pliensbachian to Sinemurian successions of the UK and the Republic of Ireland.

4.2 Interval 480 m-685 m; Late Sinemurian

The FDO of common *Mesodentalina matutina* at and below 480 m is considered to mark the top of the Late Sinemurian interval, based on the known distribution of this species from onshore and offshore UK successions (see Copestake and Johnson, 1989, 2014). This interval, down to the top of the underlying biozone, represents the JF7 to JF8 biozones of the latter authors. The increase in *Astacolus speciosus* at 570 m is further diagnostic of this interpreted age and biozone.
The presence of abundant specimens of *Reinholdella pachyderma*, possibly attributable to the subspecies *humilis*, in the sample at 490m is notable. If correctly attributed to this subspecies, this correlates with the known occurrence from onshore UK (Mochras Borehole and several other localities in eastern England) of this taxon between the Raricostatum Chronozone and Jamesoni Chronozone. Its abundance below the top of the interpreted Late Sinemurian at Ballinlea-1 suggests that this abundance level represents the uppermost part of the Raricostatum Chronozone (Aplanatum Subchronozone and above) at this depth.

The presence of a probable specimen of *Reinholdella margarita margarita* at 550 m, if correctly attributed, marks the top of the JF6 biozone that equates with the Obtusum Chronozone, of intra Late Sinemurian age. The FDO of *Planularia inaequistriata* at 560 m is notable. While this species is known to range to the top of the Late Sinemurian in Europe, it does not occur commonly above the Late Sinemurian Obtusum Chronozone, JF6 foraminiferal biozone, in the UK. Its occurrence at this depth closely below the interpreted top of the latter biozone, is consistent with the interpretation of this biozone at this depth.

4.3 Interval 685 m-855 m; Early Sinemurian

The FDO of *Astacolus semireticulatus* at 685 m indicates an Early Sinemurian age, and the JF5 foraminiferal biozone at this depth. This species extinction is in the Turneri Zone (Copestake and Johnson, 2014). The FDO of *Marginulina prima incisa* is also recorded at this depth. This species is long ranging (Hettangian-Pliensbachian), however, it only consistently occurs as high as the Semicostatum Chronozone (Copestake and Johnson, 2014).

The FDO of *Neobulimina bangae* at 710 m, which becomes common at 715 m and abundant at 720 m is further confirmation of the Early Sinemurian, and the lower part of the JF5 biozone. This species becomes common in the Semicostatum Chronozone across its area of distribution and this chronozone can therefore be inferred to be present from 715 m. An increase in numbers of

*A. semireticulatus* is observed at 720 m, which is further evidence for the presence of the Semicostatum Chronozone, given that this species occurs commonly in this chronozone (in the Sauzeanum Subchronozone) in the Mochras Borehole, in association with the increase in numbers of *N. bangae* (Copestake and Johnson, 2014).

The FDO of *Marginulina prima insignis* (common) at 730 m is notable. This subspecies ranges as high as the Pliensbachian, however, its peak abundance occurs in the Bucklandi Chronozone, as in the Hebrides Basin and at Mochras (Copestake and Johnson, 2014). This bioevent is interpreted to mark the top of the intra Early Sinemurian JF4 foraminiferal biozone in the Ballinlea-1 well, which is confirmed by the restriction of *N. bangae* to the section above this level (this species ranges no older than the Bucklandi Chronozone.

The FDO of the ostracods *Ogmoconcha hagenowi* and *Ogmoconchella aspinata* (at 730 m and 745 m respectively) indicate the top of the O. hagenowi Ostracod subzone, O. aspinata Ostracod Zone of the Mochras Borehole, equivalent to the top of the Bucklandi Ammonite Chronozone according to Boomer (1991). This was later refined as the Rotiforme Subchronozone following zonal revision in Copestake and Johnson (2014). The events have a similar age on the Yorkshire coast (Copestake et al., 2019) and elsewhere in the onshore area (Boomer and Ainsworth, 2009).

The FDO of the ostracod *Ektyphocythere translucens* occurs at 810 m. This species ranges from latest Triassic to Early Sinemurian in onshore UK sections (Boomer and Ainsworth, 2009) ranging as high as the Bucklandi Chronozone in Yorkshire (Lord in Copestake *et al*., 2019), however, in the Mochras Borehole the species upper range limit is within the upper Hettangian (Boomer, 1991). In the Larne Basin this species has a short range from Angulata Chronozone (latest Hettangian) to the base of the Bucklandi Chronozone (earliest Sinemurian) (Boomer *et al*. in press).

### 4.4 Interval 855 m-935 m; Hettangian

The FDO of *Reinholdella "praemacfadyeni"* at 855 m marks the top of the JF2 foraminiferal biozone, which is interpreted to indicate the upper limit of the Hettangian, the species is common at this depth, its informal name has been chosen to reflect its resemblance to the younger species, *R. macfadyeni*. *R. "praemacfadyeni"* was first noted in an exploration well in the South West Approaches, Melville Sub-basin (Well 73/1-1; Hooker et al., 1982) where it marks the top of the interpreted Hettangian, in association with the ostracod species *Kinkelinella medioreticulata*;

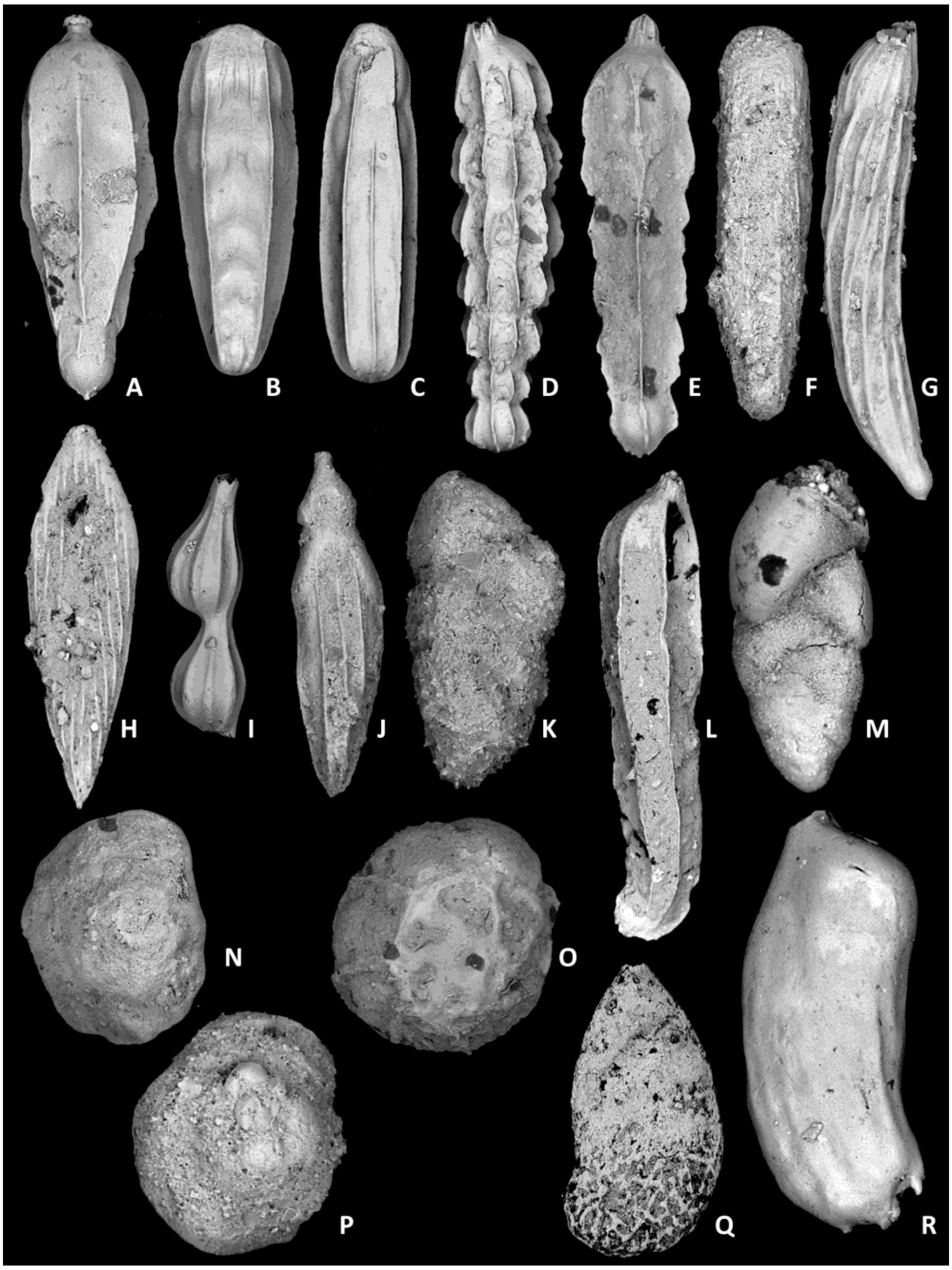


Figure 3. Ballinlea-1 key foraminiferal taxa. A. *Nodosaria issleri*, 400 m, (BU 5440), 330 µm long. B. *Paralingulina tenera tenera*, 845 m, (BU 5441), 530 µm long. C. *Paralingulina tenera subprismatica*, 520 m, (BU 5442), 500 µm long. D. *Marginulina prima interrupta*, 520 m, (BU 5443), 860 µm long. D. *Marginulina prima spinata*, 570 m, (BU 5444), 725 µm long. F. *Paralingulina tenera collenoti*, 935 m, (BU 5445), 640 µm long. G. *Mesodentalina matutina*, 475 m, (BU 5446), 1065 µm long. H. *Ichthyolaria terquemi squamosa*, 490 m, (BU 5447), 535 µm long. I. *Mesodentalina varians haeusleri*, 530 m, (BU 5448), 610 µm long. J. *Ichthyolaria terquemi barnardi*, 885 m, (BU 5449), 370 µm long. K. *Neobulimina bangae*, 885 m, (BU 5450), 265 µm long. L. *Marginulina prima incisa*, 685 m, (BU 5451), 910 µm long. M. *Brizalina liasica*, 410 m, (BU 5452), 270 µm long. N. *Reinholdella "praemacfadyeni"*, 855 m, (BU 5453), 450 µm long. O. *Reinholdella macfadyeni*, 430 m, (BU 5454), 460 µm long. P. *Reinholdella? planiconvexa*, 920 m, (BU 5455), 210 µm long. Q. *Astacolus semireticulatus*, 720 m, (BU 5456), 345 µm long. R. *Vaginulinopsis denticulatacarinata*, 425 m, (BU 5457), 590 µm long.

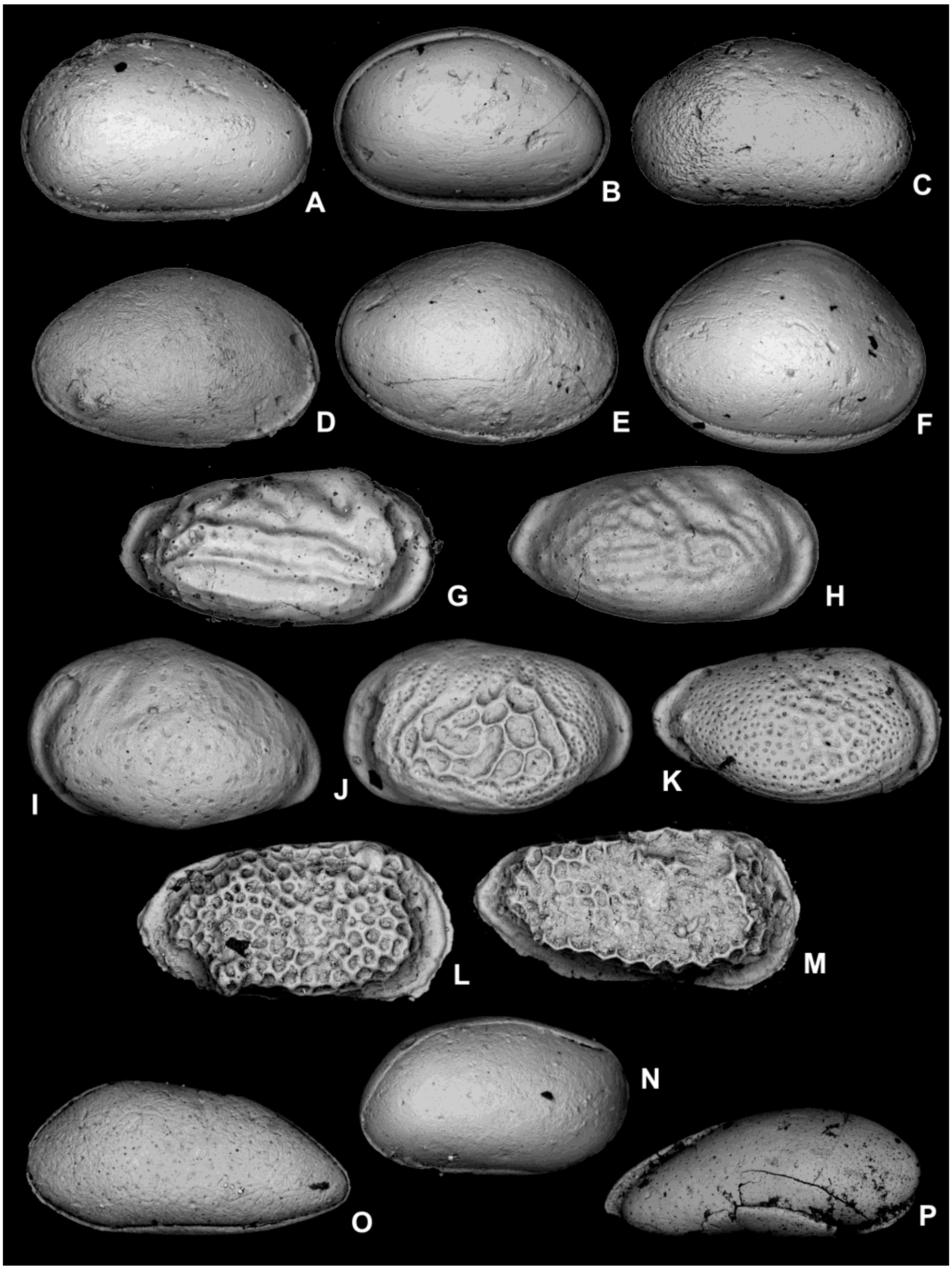


Figure 4. *Ballinlea-1 key ostracod taxa.* A. *Ogmoconchella aspinata* 920 m, (BU 5458), 515 µm long. B. *Ogmoconchella danica* 490 m, (BU 5459), 600 µm long. C. *Ogmoconchella mouhersensis* 540 m, (BU 5460), 640 µm long. D. *Ogmoconchella aequalis* 490 m, (BU 5461), 300 µm long. E. *Ogmoconcha* cf. *O. eocontractula* 510 m, (BU 5462), 530 µm long. F. *Ogmoconcha hagenowi* 800 m, (BU 5463), 750 µm long. G. *Pleurifera harpa* 400 m, (BU 5464), 580 µm long. H. *Pleurifera vermiculata* 490 m, (BU 5465), 510 µm long. I. *Ektyphocythere translucens* 845 m, (BU 5466), 530 µm long. J. *Ektyphocythere* sp. 845 m, (BU 5467), 480 µm long. K. *Gammacythere ubiquita* 410 m, (BU 5468), 560 µm long. L. *Eucytherura gassumensis* 845 m, (BU 5469), 380 µm long. M. *Eucytherura oeresundensis* 425 m, (BU 5470), 350 µm long. N. *Isobythocypris* sp. 845 m, (BU 5471), 590 µm long. O. *Paracypris* sp. 425 m, (BU 5472), 350 µm long. P. *Liasina lanceolata* 410 m, (BU 5473), 660 µm long.

both species are abundant at this level in the 73/1-1 well. *R*. "*praemacfadyeni*" is known from other sections, including the Southern North Sea (e.g. 48/22-1 well) in the interpreted Hettangian. It is restricted to the Hettangian to basal Sinemurian (Bucklandi Chronozone), as in the Yorkshire coast area (Copestake et al., 2019, as *R*. cf. *macfadyeni*). Its common occurrence appears to be restricted to the Hettangian.

The FDO of *Ichthyolaria terquemi barnardi* occurs at 885 m, the species is Hettangian restricted and is a marker for the JF2 biozone (Copestake and Johnson, 2014). The flood abundance of *Reinholdella*? *planiconvexa* occurs at 920 m. This abundance level is known from onshore UK in the mid to lower part of the Hettangian over the Planorbis Chronozone, Johnstoni Subchronozone to Liasicus Chronozone, Portlocki Subchronozone interval, within the JF2 foraminiferal biozone (Copestake and Johnson, 2014).

The occurrence of *Paralingulina tenera collenoti* at 935 m suggests an age within the range of late Rhaetian (Triassic) to Hettangian. In view of the absence of sediments that are unequivocally assigned to the Penarth Group (uppermost Triassic) from the well (in which the LFO of *P. tenera collenoti* occurs in onshore UK sections; Copestake, 1989), the occurrence at 935 m is considered to mark the deepest indication of Hettangian age in the foraminiferal associations. This accords closely with the palynological determination for the base of the Jurassic at 945 m (Riding, 2010) based on the presence of *Riccisporites tuberculatus* and the absence of distinctive Rhaetian markers such as *Rhaetipollis germanicus* and *Rhaetogonyaulax rhaetica*. Other palynological records from Northern Ireland confirm that the latter two taxa are indeed restricted to the Triassic in this region, however, *R. tuberculatus* is not recorded younger than the Triassic in the nearby Foyle Basin (Raine et al., in press, b) although it does continue through into the Early Jurassic in the Larne Basin (Boomer et al., in press). The detailed palynological record around the Triassic-Jurassic boundary in the latter work suggests that the presence of *R. tuberculatus* and the absence of *R. germanicus* and *R. rhaetica* could be anywhere from the base of the Langport Member to the Johnstoni Ammonite Subchronozone. It has also worth noting that no calcareous microfossil assemblages have so far been recovered from the Penarth Group or the very lowest levels of the Lias Group from elsewhere in Northern Ireland (Boomer et al., in press; Raine et al, in press, b).

Although the lowest mudstone samples examined (950-980 m) yielded greenish-grey and pinkish-grey claystone fragments, not unlike those of the latest Triassic Penarth Group in the Larne and Foyle basins, there is no unequivocal biostratigraphical microfossil or palynological evidence from the Ballinlea-1 samples to support such an age. These samples contained just a few microfossils which are considered to have been the result of caving. It is therefore assumed that all of the overlying grey mudstones recorded in Ballinlea-1 (345 to 945 m) can be assigned to the Waterloo Mudstone Formation which is otherwise represented by medium-dark grey siltstones and claystones with subordinate limestones.

## 5. Faunal and Palaeoenvironmental summary

All of the sediments examined are considered to have been deposited in a relatively well-oxygenated, marine, inner shelf environment, (Based on the continued presence of benthic micro- and macrofossils throughout. Riding (2010) also concluded that the moderately-preserved, low diversity assemblages, which include acritarchs, pointed to deposition in an open marine setting throughout the Waterloo Mudstone Formation.

The changing abundances and diversity (as species richness) of both ostracods and foraminifera are shown in Figure 5. Throughout the Waterloo Mudstone Formation, the microfossil specimens are generally very well-preserved. Foraminiferal assemblages are dominated by the Order Lagenida but representatives of important accessory taxa assigned to the Miliolida, Buliminida and families Ceratobuliminidae and Spirillinidae are also recorded. The foraminiferal assemblages are initially dominated by genus *Paralingulina*, followed, in decreasing abundance, by *Lenticulina* and *Marginulina*, these latter genera dominate from the early Sinemurian onwards. The ostracod assemblages are numerically dominated by the Order Metacopina which are present in almost every sample, peaks in specimen abundance match very closely the abundance of Metacopina in a sample. There is an increasing abundance and diversity of the Order Podocopina recorded from the mid-part of the Early Sinemurian onwards.

### 5.1 Hettangian

Low abundances of benthic microfossils are noted during the very earliest Hettangian for both groups but then increase into the mid-late Hettangian, this pattern is also observed elsewhere in Britain for the period. The peak in ostracod abundance in the late Hettangian is typically dominated by low-diversity assemblages of Metacopina, specifically *Ogmoconchella aspinata*.

Broadly concomitant with that peak is a single, short lived influx of *Reinholdella? planiconvexa*. Despite this specific event in a single sample, ostracods are often numerically dominant in Hettangian to early Sinemurian assemblages across Europe (usually represented by two species, *O. aspinata* and *Ogmoconcha hagenowi*). These earliest Jurassic peaks in opportunistic taxa are also known from many other sections of the same age.

## 5.2 Early Sinemurian

Faunal turnover at 740 m sees the foraminifera become more diverse and numerically dominant over the ostracods for the first time, all later microfossil assemblages are numerically dominated by foraminifera.

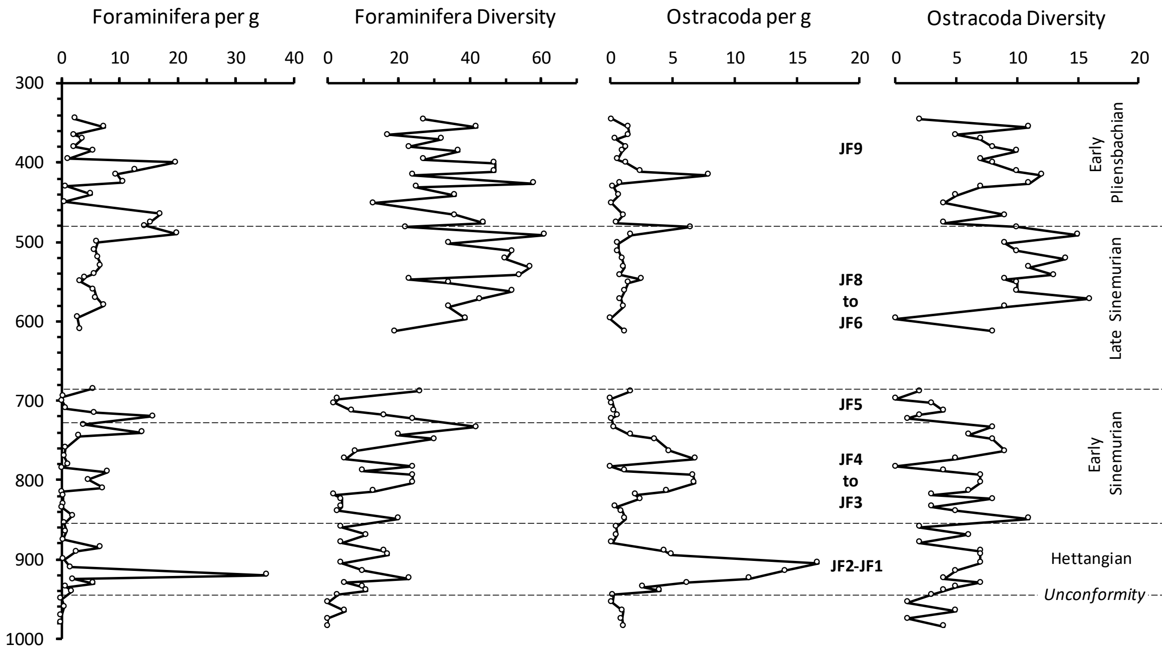


Figure 5. Changing diversity (species richness) and relative abundance (specimens per gram, dry sediment) for foraminifera and ostracods in Ballinlea-1 well, depth scale is in metres. The break in the record indicates the position of a Paleogene intrusion. JF zones after Copestake and Johnson (1989, 2014). Species richness includes taxa not identified to species level.

Sediment residues between 820 m and 845 m yielded relatively abundant quartz grains with micro-ironstone nodules at 820 m. Intervals of early Sinemurian sandstone deposition are recorded 35 km to the west at Tircreven Burn (Mitchell, 2004; Raine et al. in press, b) and it may be that the Ballinlea-1 sediments represent a distal equivalent, possibly gravity flow deposits, that relate to sediment input from the west (Raine et al., in press, b).

Between 615 and 675 m the core is intruded by Paleogene volcanics that resulted in limited contact metamorphism, making fossil extraction impossible on a handful of samples. There is no evidence for any significant stratigraphic break associated with the intrusion.

### 5.3 Late Sinemurian

The broad pattern of diversity (species richness) sees both groups peaking in the late Sinemurian (foraminifera 61 species, ostracods 16) and this could represent the establishment of stable mid-shelf conditions that succeeded shallower water environments in the earliest Jurassic. Hallam (1978) and Copestake and Johnson (2014) noted that the latest Sinemurian witnessed a major transgression in Europe. The assemblages in this period are dominated by *Paralingulina* with increasing abundance of *Lenticulina*, while ostracods continue to be dominated by the Metacopina.

### 5.4 Early Pliensbachian

The microfaunal assemblages remain diverse in the earliest Pliensbachian but record a slight decrease when compared to the late Sinemurian, the decline may be due to a minor fall of sea level during the earliest Pliensbachian.

## 6. Summary

The Ballinlea-1 well from North Antrim, Northern Ireland has yielded the thickest sequence of Jurassic sediments known from onshore Ireland (both North and South). The ditch cuttings samples yielded well-preserved and diverse assemblages of calcareous benthic microfossils (ostracods and foraminifera) that can be used to provide a chronostratigraphic age model and give insights into the depositional setting.

The biostratigraphic evidence indicates broadly continuous sedimentation from the earliest Hettangian through to the earliest Pliensbachian. Based on sedimentary and palaeontological evidence these early Jurassic sediments are considered to have been deposited in fully marine conditions with possible changes in water depth noted by broad changes in abundance and diversity. There is no clear evidence for any periods of dysaerobia in this section and this points to the northernmost part of Northern Ireland being a well-oxygenated, shallow shelf sea during the Early Jurassic.

Species richness in the Ballinlea-1 well is much higher than for the Hettangian to early Sinemurian interval than in both the Carnduff-1 (Boomer et al., in press) and the Foyle Basin boreholes available to us (e.g., NIRE 05/08-0003; Raine et al., in press, b). These differences may reflect a more stable, somewhat deeper-water shelf setting in the Rathlin Basin during this period when compared to the Foyle and Larne basins.

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***Data availability***

The 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.00000492.

***Appendix A: Microfossil taxa author citations***

Foraminifera

*Astacolus semireticulatus* Norling, 1968*; Astacolus speciosus* (Terquem, 1858); *Ichthyolaria terquemi barnardi* Copestake and Johnson, 2014; *Ichthyolaria terquemi squamosa* (Terquem and Berthelin, 1875); *Marginulina prima incisa* Franke, 1936; *Marginulina prima insignis* (Franke, 1936); *Marginulina prima interrupta* Terquem, 1866; *Marginulina prima prima* d'Orbigny, 1849; *Marginulina prima spinata* (Terquem, 1858); *Mesodentalina matutina* (d'Orbigny, 1849); *Mesodentalina varians haeusleri* (Schick, 1903)*; Neobulimina bangae* Copestake and Johnson, 2014 (*Neobulimina* sp. 2 *sensu* Bang, 1968); *Paralingulina tenera subprismatica* (Franke, 1936); *Paralingulina tenera substriata* (Nørvang, 1957); *Paralingulina tenera tenera* (Bornemann, 1854); *Reinholdella* cf. *macfadyeni* Copestake, Johnson, Lord and Miller, 2019 (= *R. "praemacfadyeni"* Hooker et al., 1985); *Reinholdella macfadyeni* (Ten Dam, 1947); *Reinholdella margarita margarita* (Terquem, 1866); *Vaginulinopsis denticulatacarinata* (Franke, 1936).

Ostracoda;

*Ektyphocythere translucens* (Blake, 1876); *Eucytherura oeresundensis* (Michelsen, 1975); *Eucytherura gassumensis* (Michelsen, 1975); *Gammacythere ubiquita* Malz and Lord, 1976; *Liasina lanceolata* (Apostolescu, 1959); *Ogmoconcha danica* Michelsen, 1975;
*Ogmoconcha hagenowi* Drexler, 1958; *Ogmoconcha eocontractula* Park, 1984; *Ogmoconchella mouhersensis* (Apostolescu, 1959); *Ogmoconchella aspinata* Drexler, 1958 (= *O. ellipsoidea* Jones, 1872); *Ogmoconchella aequalis* Herrig, 1969; *Pleurifera vermiculata* (Apostolescu, 1959); *Pleurifera harpa* (Klingler and Neuweiler, 1959).

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