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Stratigraphy, palaeoenvironments and geochemistry across the Triassic-Jurassic boundary transition at Carnduff, County Antrim, Northern Ireland.

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Abstract

The latest Triassic to earliest Jurassic transition has been widely studied due the occurrence of a major global extinction associated with a global hyperthermal event in this interval. Furthermore, a number of distinct geochemical events in the global carbon cycle can be recognised in the stable-isotope record across this boundary interval at many localities. Two fully-cored boreholes from East Antrim in Northern Ireland (Carnduff-1 and Carnduff-2) have penetrated sediments of latest Triassic to Early Jurassic age (Rhaetian to Early Sinemurian). Ammonites, foraminifera, ostracods and palynomorphs provide a robust chronology as well as insights to palaeoenvironmental conditions during this period. The sedimentary and palynological evidence support a largely marginal-marine setting for the sediments of the Triassic Penarth Group while a range of palaeontological evidence shows that the Early Jurassic Waterloo Mudstone Formation represents shallow-marine, shelf conditions that represent generally well-oxygenated bottom waters, with little evidence for dysoxia. Detailed ammonite biostratigraphy (ammonites first occur about 7.5 m up from the base of the Lias Group) indicates that the cores represent largely continuous sedimentation through the Hettangian and earliest Sinemurian (to Turneri Chronozone, Birchi Subchronozone). Stable-isotope analysis of both carbonate and organic carbon show a distinct carbon isotope excursion (CIE) in both fractions through the Cotham and Langport members (Lilstock Formation, Penarth Group, latest Triassic) which are considered to correlate with the distinctive 'Initial' CIE witnessed in SW England and probably the GSSP and other sites across the world.

Keywords: Ammonites, Foraminifera, Ostracods, Palynology, Carbon Isotope Excursion

1. Introduction

The latest Triassic to Early Jurassic interval was marked by global sea-level rise (Hallam, 1997) and is recognised as a distinct period of faunal turnover and extinction world-wide (Dunhill et al., 2018). Across NW Europe this interval is usually represented by a transgressive pattern of sedimentation, Rhaetian marginal-marine sediments overlying non-marine Norian aged sediments, and themselves being replaced by fully marine sedimentation during deposition of the Hettangian Lias Group (Wignall and Bond, 2008). The environmental transition across this boundary interval, associated with eustatic sea-level rise, makes correlation difficult and it is only in the last decade that a GSSP (Global Stage Stratotype and Point) for the Triassic/Jurassic boundary has been established at Kuhjoch, in the Austrian Alps (Hillebrandt et al., 2013). In that area, the newly defined Triassic–Jurassic boundary falls within an entirely marine succession, in which ammonites can be used to define the boundary (see Section 3 for further discussion). In the south west of England and in South Wales the earliest part of the marine Lias Group commonly lacks ammonites and was previously referred to as the ‘Pre-planorbis beds’ or ‘Ostrea beds’ (Wignall, 2001) with the result that the very earliest Jurassic ammonite faunas, seen at the GSSP section, are absent (Hillebrandt et al., 2013). Within this interval, other marine macrofossils (e.g. bivalves, brachiopods) are of limited value for correlation, while the palynological evidence may ultimately prove key to establishing links to other sites (Lindström et al., 2017).

There is the potential to correlate the Triassic–Jurassic boundary across large distances using geochemical proxies, particularly through what was defined as the Initial Carbon Isotope Excursion (CIE) at the St Audries section by Hesselbo et al. (2002). A similar event has been identified in the GSSP section at Kuhjoch and at a number of other sections, including the present study. However, the correlation between the events at St Audries and the GSSP has been recently been brought into question (Lindström et al. (2017).

Sediments of latest Triassic/earliest Jurassic age are known to occur in the subsurface across the northern and eastern parts of Northern Ireland (Raine et al., this issue, a) but such records are rare at outcrop. The recovery of cored borehole material through this interval has therefore permitted a detailed study of this

important interval. Two adjacent cores, Carnduff-1 and Carnduff-2 (referred to subsequently as CRN-1 and CRN-2) are just a few km from a regionally significant Triassic–Jurassic boundary succession at Waterloo Bay, near Larne (a candidate GSSP for the boundary by Simms and Jeram, 2007), have provided two successions covering this interval.

The only borehole previously described from the Larne area that encountered Late Triassic and Early Jurassic strata was the 1962 Larne No.1 Borehole that cored 50 m assigned to the Lias Group and a further 21 m of Penarth Group overlying a thick sequence of Mercia Mudstone Group, terminating in the Sherwood Sandstone Group at 1284 m (McCann, 1990; Wilson and Manning, 1975). Unfortunately there is no longer any material remaining from this borehole in the GSNI core archives.

2. Carnduff boreholes

Borehole CRN-1 (Figure 1) [54.837° N, 5.819° W, 115.42 m OD] was drilled within the Larne Basin, in the eastern part of Co. Antrim, in 2013 by Gaelectric Energy Storage as part of a proposed compressed-air energy storage project. The borehole (10 cm diameter through the studied interval) penetrated the Early Jurassic Waterloo Mudstone Formation (Lias Group) between 163.90 m–320.75 m drill depth (all subsequent depths cited here are also ‘drill depth’) and the Penarth Group 320.75m to 340.70 m reaching a total depth (TD) at 922.70 m. Borehole CRN-2 [54.839° N, 5.821° W, 103.55 m OD], a smaller diameter core for the most part (~6.5 cm), was drilled down dip just 235 m to the north west of CRN-1 and encountered the Waterloo Mudstone Formation between 186.35 and 357.13, overlying the Penarth Group which terminated at 378.43, and TD at 970 m (Figure 2). Andeskie et al. (2018) studied the depositional settings of the underlying Triassic Mercia Mudstone Group of the CRN-2 borehole but the current study is the first multidisciplinary study investigating the Late Triassic and Jurassic interval of these boreholes.

Ammonites provide the principal means of dating the sequence, additionally supported by calcareous microfossils (foraminifera and ostracods) and palynomorphs. The microfossils also permit an interpretation

of the Late Triassic – Early Jurassic palaeoenvironments of the Larne Basin. The Carnduff cores are stored at the GSNI (Geological Survey of Northern Ireland) core-store facility in Belfast. For practical reasons, the larger diameter CRN-1 core was initially sampled for calcareous microfossils and palynology while the

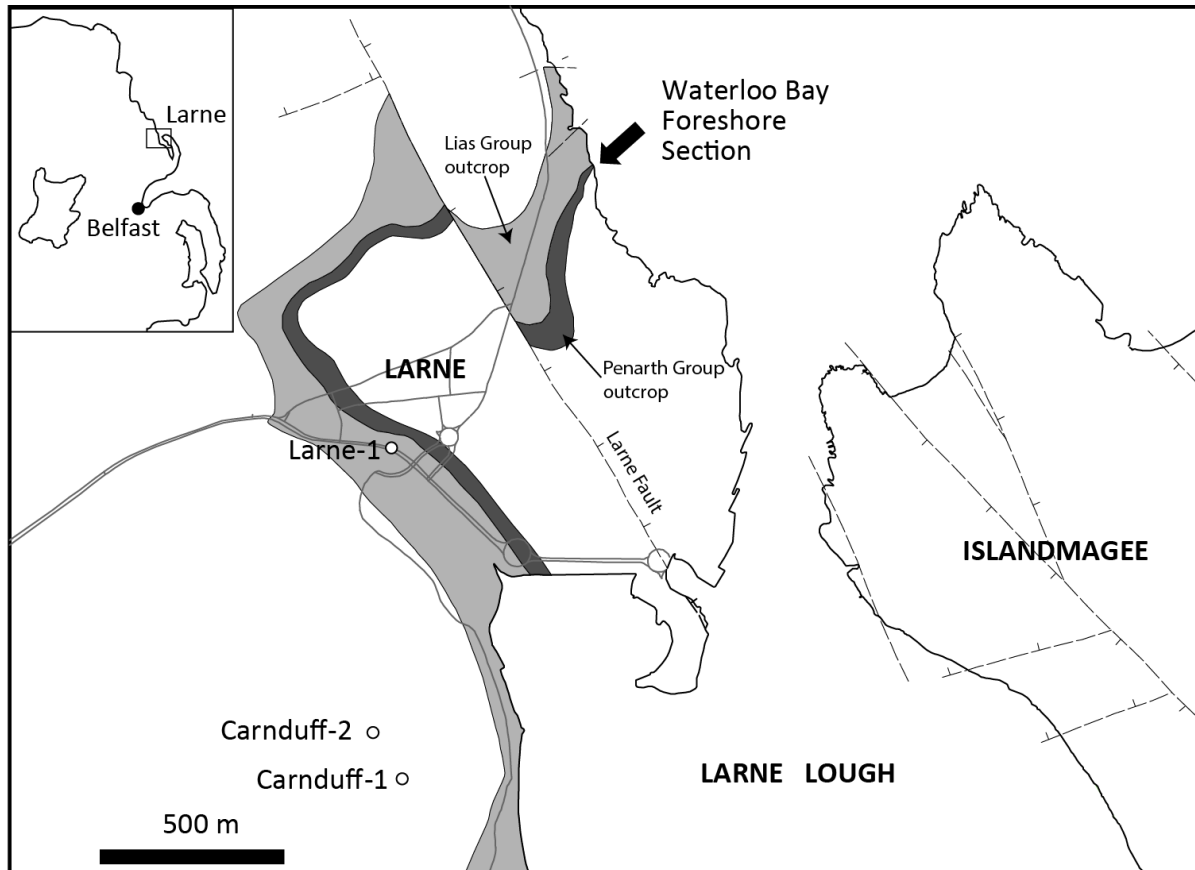


Figure 1. Location map of the Carnduff-1 and Carnduff-2 cores, just south of Larne, County Antrim on the east coast of Northern Ireland.

smaller diameter CRN-2 core was later sampled for Ammonites and geochemistry. Key sedimentary marker beds, lithological boundaries and biostratigraphic events, etc., have been used to establish a correlation model between the two cores, the data is given in Table 1 and the cross-plot for the boundary interval is shown in Figure 2. The boreholes encountered Paleogene basalts of the Antrim Lava Group unconformably overlying chalk of the Cretaceous Ulster White Limestone Group that unconformably overlies the Early Jurassic Lias Group and Triassic Penarth Group deposits. These units overlie considerable thicknesses of Triassic Mercia Mudstone Group sediments (Table 1). In this paper we focus upon the Penarth and Lias groups, the logged intervals are shown in Figures 3 and 4. The Penarth Group was logged in greater detail in CRN-2, along with the corresponding interval on the Waterloo Bay foreshore section (see Figure 1), to

establish robust correlation between the exposed and subsurface records. In the summary log (Figure 3) the distribution of mudstone, calcareous mudstone, strongly calcareous mudstone and limestone

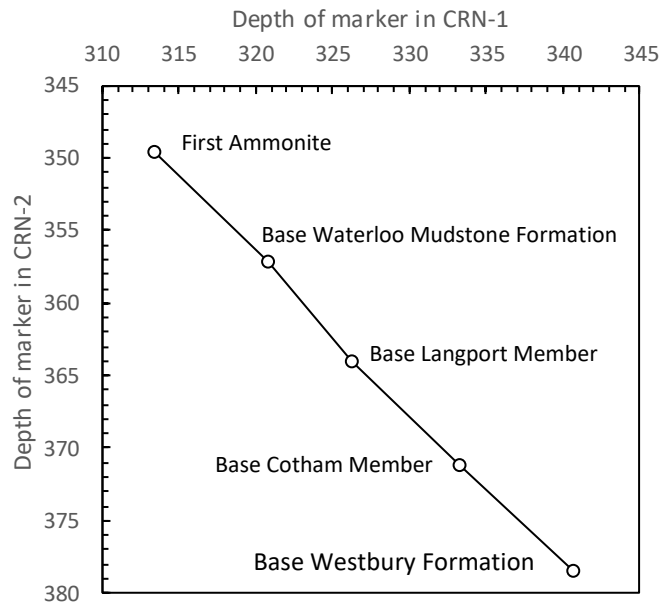


Figure 2. Cross-plot of marker bed depths around the Triassic -Jurassic boundary interval in CRN-1 compared to CRN-2 demonstrating correlation between the two cores.

mudstone are recorded. Correlation of the strata between the two boreholes is relatively straightforward in the Penarth Group, but in the Lias Group this is more difficult due to it being a largely mud-dominated succession with few distinctive horizons and a number of small faults that may well cut out strata. The correlation between the two cores is shown in Figure 3 and is based on a number of features, such as the proportion of carbonate, the thickness and occurrence of individual distinctive limestone beds, the abundance and the occurrence of particular trace fossils and bivalves. Finer-scale variation and additional detail has been recorded in CRN-2 because the core has already been split for ammonite stratigraphy and it allows a more detailed description of the facies. CRN-1 appears to be more affected by faults than CRN-2, with most of the faults inclined to bedding, showing dip-slip slickensides and being locally filled with calcite. Additionally, two intervals of basalt intrusions in CRN-1 may have also exploited pre-existing faults.

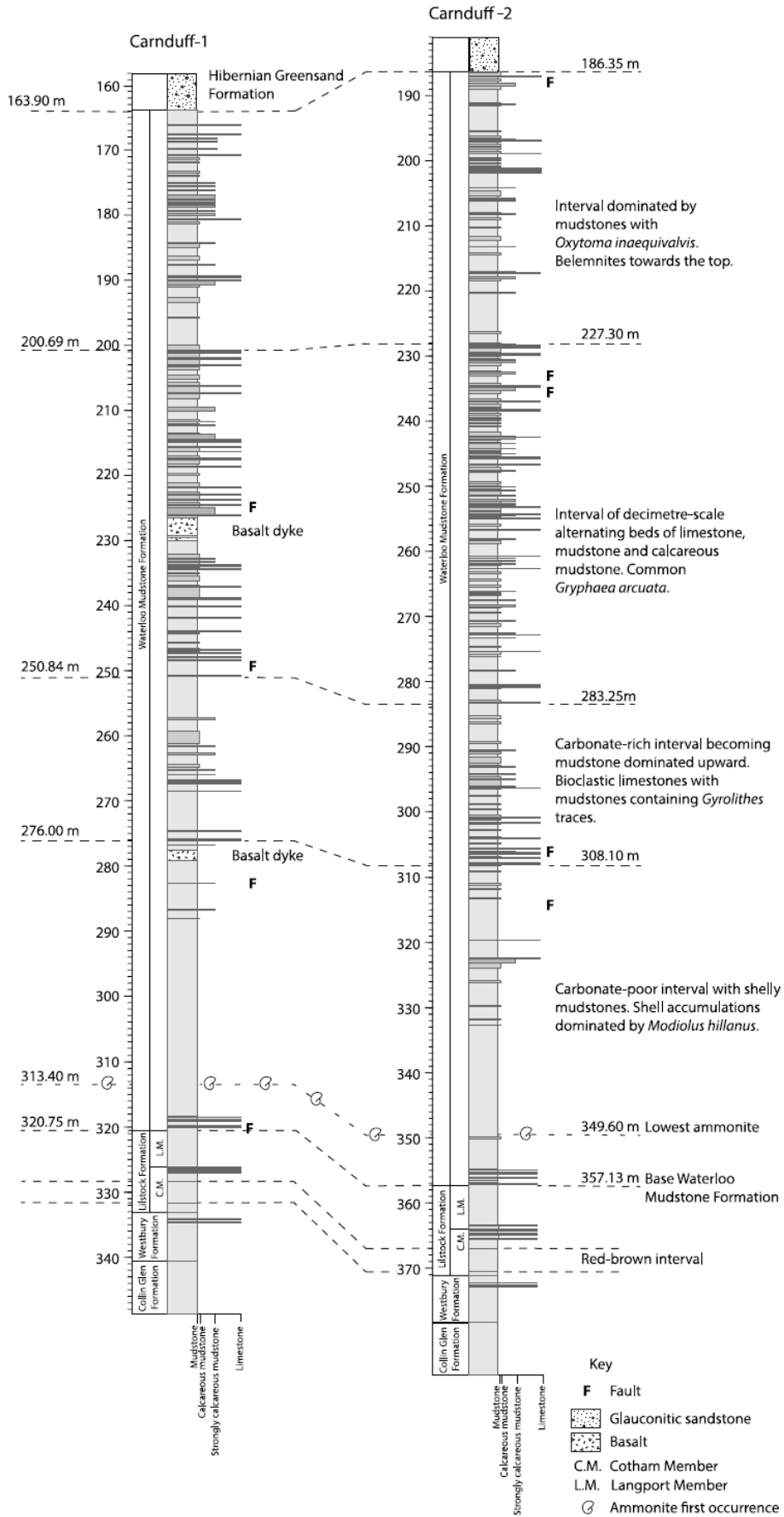


Figure 3. Lithology and indication of key maker horizons between cores CRN-1 and CRN-2.

Carnduff-2

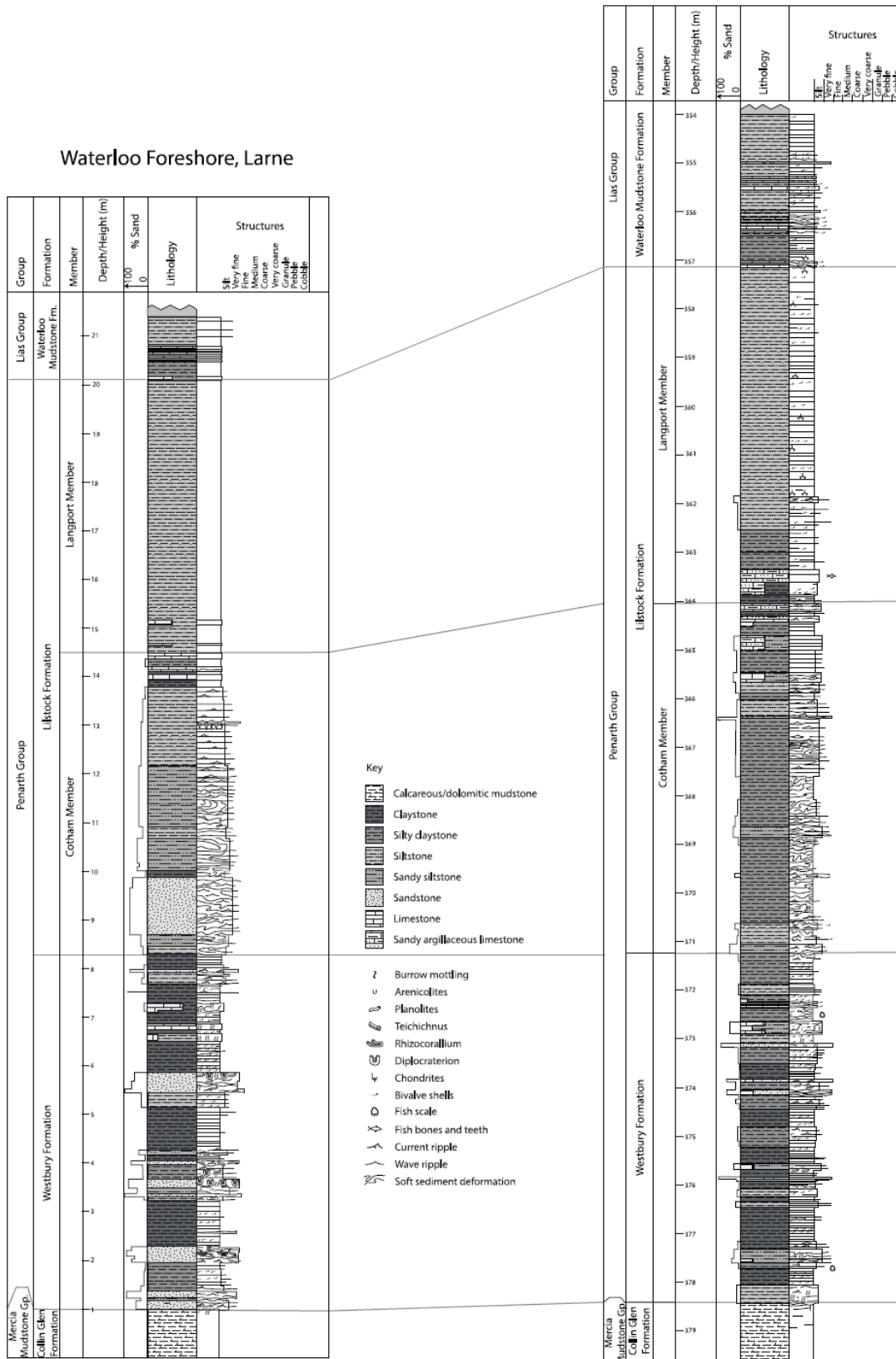


Figure 4. Sedimentary logs of the Waterloo foreshore section and CRN-2 through the Penarth Group. The sedimentary structures, trace fossils and facies are shown and the proposed placement and correlation of lithostratigraphical boundaries.

2.1. Carnduff Cores, Lias Group

The Waterloo Mudstone Formation (Lias Group) in the Carnduff cores is about 156.85 m thick in CRN-1 and 170.78 m in CRN-2 where it is also cut by two Paleogene basalt and dolerite intrusions at 226.60–230.00 m and 277.51–279.15 m, similar to those seen in CRN-1. The sediments comprise medium to dark grey calcareous, bioturbated mudstones, with subordinate grey limestones and siltstones. Beds are commonly fossiliferous, micaceous with some pyrite and phosphate cements. Carbonaceous debris (for example fragments of plant or algae) is noted, together with common records of ammonites, bivalves, micro-gastropods, echinoderm fragments, ophiuroid fragments, foraminifera, ostracods and palynomorphs as well as trace fossils. More rare fossils include fish, lingulid brachiopods, lobster and coral remains.

Bivalve faunas include *Cardinia*, *Pseudolimea*, *Chlamys*, *Plagiostoma*, *Liostrea*, *Modiolus*, *Isocyprina*, *Mactromya*, *Pteromya*, *Gryphaea*, *Entolium*, *Oxytoma*. Bioturbation is variable and is largely dominated by *Chondrites*, with locally common *Teichichnus*, *Thalassinoides*, *?Gyrolithes* isp. and *Rhizocorallium*. The fossil and trace fossil assemblages along with the diverse fauna represent deposition within an open marine shelf setting.

Correlating between the two cores has identified an upper section of mudstone-dominated strata that contains the bivalve *Oxytoma inaequivalvis* and extends down as far as 200.69 m in CRN-1 and 228.06 m in CRN-2 (Figure 3). Below this a succession containing numerous carbonate beds is recognised extending down to 250.84 m in CRN-1 and 283.25 m in CRN-2 (Figure 3). Some of the limestone beds are devoid of shells and have gradational upper and lower boundaries. There are common *Gryphaea arcuata* Lamarck throughout the interval. Underlying this, the succession down to 276.00 m depth in CRN-1 and 308.10 m in CRN-2 is less carbonate-rich and in both boreholes displays characteristic pyrite-preserved helical trace fossils (*?Gyrolithes* isp.) in the mudstone intervals. Carbonate content and the abundance of carbonate beds increase downward through this interval. Many of the limestones are bioclastic and likely to be locally developed. Below this interval, the lower parts of the Waterloo Mudstone Formation are dominated by

mudstone with the lowest 2-3 m having very distinctive silty, highly bioclastic limestones, which contain *Pteromya* sp. and *Liostrea* sp., along with mudstone clasts and display a crinkled and wavy texture. They are discussed more fully by Jeram et al. (this issue). The limestones are separated by dark grey, laminated mudrocks and there is a sharp boundary with the underlying bioturbated, argillaceous siltstones at the top of the Penarth Group at 320.75 m depth in CRN-1. In this core a fault cuts out a few cm of the lowest Waterloo Mudstone Formation and probably a few decimetres of the upper Penarth Group. The base of the Waterloo Mudstone Formation lies at 357.13 m in CRN-2 (Figure 3) and the boundary is better seen. This surface marks an upward reduction in bioturbation, an increase in relative sea-level, accompanied by a reduction in bioturbation, an increase in carbonate and a change from *Protocardia*-dominated siltstones to *Liostrea*-dominated mudstones and limestones. The lowest parts of the Waterloo Mudstone Formation in both cores contains a basal, carbonate-rich interval overlain by dark grey pyritiferous burrowed siltstones and then dark grey laminated claystones with the shelly and silty limestones more common above this.

2.2. Carnduff cores, Penarth Group

The underlying Lilstock Formation (Penarth Group) (top at 320.75 m in CRN-1 and 357.13 m in CRN-2) can be recognised in the cores and correlates well with other sections across Northern Ireland but is markedly different to sections elsewhere in Great Britain (Raine et al. this issue, a). There is a two-fold division of the formation into an upper Langport Member and a lower Cotham Member. The Langport Member is characterised by dark grey and greenish grey heterolithic siltstones and silty claystones. Trace fossils include *Chondrites* and bivalve burrows. There are few limestones except at the base, but this is not typical of the member elsewhere in Northern Ireland (Raine et al. this issue, a). Bivalves are locally common and include *Protocardia*, *Liostrea*, *Pteromya*, *Eotrapezium* and *Modiolus*.

The underlying Cotham Member (top at 326.24 m in CRN-1 and 364.05 m in CRN-2) is dominated by heteroliths of mid greenish-grey and mid red-brown claystones, current and wave-ripple laminated siltstones and minor sandstones, with limestones present in the upper part of the member. The

claystone/siltstone heteroliths display an interval with soft sediment deformation that is seen in both cores. This loosely coincides with a colour change to red-brown mudrocks. Fossils in the Cotham Member are sparse. The basal beds have some *Chlamys valoniensis* (Defrance) and *Rhaetavicula contorta* (Portlock), but above this there is little fauna recovered other than sparse *Eotrapezium* and the trace fossils *Lockeia* and surface trails. The upper beds have some layers of plant debris resembling *Naiadites*. It is not absolutely clear-cut where to place the boundary between the Cotham Member and the overlying Langport Member and for ease it has been placed at an upward change to generally darker grey claystones, overlying the lighter grey, dominantly ripple cross-laminated siltstones of the upper Cotham Member. The complicating factor is that there are a number of limestones that occur below and above this mudstone contact. These superficially resemble the 'White Lias' facies present in SW Great Britain, they are a prominent marker and could be included in either the Cotham Member or the overlying Langport Member. The ones that contain ripple or planar lamination are included in the Cotham Member, whilst the limestones that are more argillaceous, and presumably diagenetic in origin are included in the Langport. It is these limestones that are more typical of the member in the Lough Foyle Basin (Raine et al. this issue, b).

The underlying Westbury Formation (top at 333.32 m in CRN-1 and 371.23 m in CRN-2) comprises very dark grey to black, laminated claystones, subordinate brown sandstones and grey sandy limestones. Bivalve accumulations are abundant in the mudstones and are mostly mono- or bi-specific accumulations of convex upward *Rhaetavicula contorta* and *Protocardia rhaetica* (Merian). *Isocyprina* and *Chlamys valoniensis* are also observed in the cores. Fossils other than bivalves are rare, but some horizons are rich in fish scales and fish teeth. The facies and the fauna are comparable with the Westbury Formation across much of Great Britain, but it lacks the coarse-grained bone beds of the Bristol Channel area. Within the Westbury Formation, beds locally show soft sediment deformation, especially two distinctive sandy limestone units.

Beneath the Penarth Group in the cores (below 340.70 m in CRN-1 and 378.43 m in CRN-2), the Collin Glen Formation of the Mercia Mudstone Group is represented by green mudstones that are largely structureless

and sharply underlie the black claystones of the Westbury Formation. The Collin Glen Formation is an equivalent of the Blue Anchor Formation in Great Britain. The lower part of the formation grades downwards into red mudstones, so the green colour may not be a primary depositional feature.

2.3. Carnduff cores, comparison with Waterloo Bay foreshore

There is a close similarity between the sections in the Carnduff boreholes and the Waterloo Bay foreshore 2.7 km to the NE (Figure 4). The Waterloo Bay foreshore has been described in detail by Ivimey-Cook (1975), Simms (2003), Simms and Jeram (2007), Jeram et al. (this issue). The Carnduff boreholes and the Waterloo Bay foreshore lie on different limbs of an asymmetrical plunging anticline. Beds at Carnduff dip locally towards the west at 10°, whereas the Waterloo Bay foreshore exposes sediments on the opposing limb of the anticline and strata dip 20–25° NW. This limb shows some smaller folds and is dissected by the N–S oriented Larne Fault (Figure 1). Despite the distance, many of the thicknesses of the units are similar (Raine et al., this issue, a). Some of the marker beds can be correlated between the cores and the foreshore, for example two distinctive limestone beds in the Westbury Formation are visible in the Waterloo foreshore section (Figure 4) and the trace fossils in these beds are more visible than they are in core and include *Thalassinoides*, *Teichichnus* and *Diplocraterion*. In the Cotham Member, exposed on the Waterloo foreshore, the slumped horizon documented by Simms (2003), Simms and Jeram (2007), Laborde et al. (this issue), Jeram et al. (this issue) is also seen in the two cores (Figure 4) and is present across Northern Ireland and much of Great Britain (Simms, 2003). The slumped interval loosely coincides with an interval that is marked by being red-brown in an otherwise green-grey coloured succession. This colour change can be correlated between cores and is seen in other sections in Northern Ireland (Raine et al., this issue, a), but on the Waterloo foreshore, where the beds are thermally altered the colour change is not pronounced. A distinctive mud-cracked horizon was also identified at outcrop by Simms and Jeram (2007), but is not present in the cores (Figure 4), although there is a sand-filled fracture that extends down through core CRN-1 from 327.90 m to 328.40 m. The boundaries used here coincide with those of Simms and Jeram (2007) with the exception of that between the Cotham Member and the Langport Member, which was

placed approximately 2 metres higher by them. In core CRN-2 the equivalent level of their Cotham–Langport Member boundary would rest at 361.86 m depth, at the top of an interval of pinstriped siltstones, culminating in a ripple cross-stratified siltstone bed and overlain by *Chondrites* burrowed siltstones.

Group	Formation	CRN-1		CRN-2	
		Depth to Base (m)	Thickness (m)	Depth to Base (m)	Thickness (m)
Antrim Lava	Lower Basalt	153.30		159.57	
	Clay with Flints	156.80	3.50	161.28	1.71
Chalk	Ulster White Limestone	158.05	1.25	181.10	19.82
	Hibernian Greensand	163.90	5.85	186.35	5.25
Lias	Waterloo Mudstone	320.75	156.85	357.13	170.78
Penarth	Lilstock	333.32	12.57	371.23	14.10
	Westbury	340.70	7.38	378.43	7.20
Mercia Mudstone	Collin Glen	348.64	7.94	387.25	8.82
	Port More	373.15	24.51	408.10	20.85
	Knocksoghey	518.40	145.25	536.30	128.20
	Glenstaghey	922.70	404.30	970.00	433.70

Table 1. Depth to base of major post-Palaeozoic lithostratigraphic units in Carnduff boreholes CRN-1 and CRN-2 (Depths modified after SLR Consulting Ireland 2014a, 2014b).

3. Ammonite biostratigraphy (KNP)

Ammonites are the primary correlative tools for marine Jurassic sequences, providing a high-resolution chronostratigraphical framework system using schemes of infra-subchronozonal units known as Biohorizons, which have a potential average resolution of less than 50,000 years (Page, 2017; Weedon et al. 2018). Using biohorizons to correlate borehole sequences is particularly effective, as they allow the recognition of discrete correlatable faunas within chronozones and subchronozones, rather than forcing the drawing of chronozonal boundaries at the first occurrence of any indicator taxon which becomes increasingly problematic and subject to error where the faunal record in the core is scattered. In particular, as it is possible to correlate both biohorizons and the intervals between, uncertainties in correlations can be explicitly demonstrated as an uncertainty interval within which chronozonal boundaries will lie, rather than drawing a potentially misleading or incorrect zonal boundary (see Tables 1 and 2).

Although ammonites are present throughout most of the Jurassic sediments of the Carnduff cores, they are by no means evenly distributed. However, they do record a sequence from the earliest Hettangian through to almost the top of the Early Sinemurian. The observations that follow are primarily the result of studies on core CRN-2 with interpreted equivalent depths given for CRN-1 based on the established core offset. Faunas of the Early Hettangian, upper Tilmanni to Planorbis chronozones are well-represented, although through higher parts of the Stage (Liasicus to Angulata chronozones) there is a much more dispersed fossil record, a pattern consistent with known surface outcrops and records across the region. Similarly, the Early Sinemurian record is scattered, but sufficient specimens have been recovered to indicate the general age of the sequence. There is no clear palaeontological evidence for younger levels. Preservation is generally as crushed shells, occasionally with calcitised shell-material but more commonly as composite internal moulds (*sensu* Kennedy, 1971) with external and internal shell moulds compressed together with no more than a trace of pale degraded original aragonite shell or a brown organic seam between. Rare pyritic casts of nuclei are also present and at one level in the Semicostatum Chronozone, body chambers have an infill of pale-brownish coloured phosphatic material. There is little evidence of any nodular preservation. Many specimens are fragmentary and juveniles and nuclei seem to be frequent.

The fauna is typical of the North West European Province, *sensu* Page (2008) and the appropriate chronozoneal and biohorizonal scheme applicable to the Province are reviewed by Page (2003), based on Page (1992), Dommergues et al. (1994) and Bloos and Page (2000b) for the Sinemurian, and Bloos and Page (2000a, b) and Page (2002, 2005, 2010a, b) for the Hettangian, as further refined by Page in Weedon et al. (2018, 2019). Correlations against this standard are discussed further below. Illustrations of the key taxa are shown in Figure 5.

3.1. Hettangian

Tilmanni Chronozone and the base of the Hettangian Stage: In the absence of the basal Hettangian indicator species, *Psiloceras spelae* (Guex) in North West Europe, the base of the system can be correlated with the Austrian Global Stratotype Section and Point (GSSP – as described by Hillebrandt et al. 2007, 2013; Hillebrandt and Krystn 2009, Ruhl et al., 2009) using the higher of two Carbon isotope excursions, as demonstrated in West Somerset (Clémence et al., 2010; Ruhl and Kurschner, 2011). In addition, where a Milankovitch orbital cyclicity record is well preserved, the base of the system can be placed by counting the appropriate number of cycles down from a recorded ammonite biohorizon, as demonstrated by Weedon et al. (2018) for the well-known sections of the Devon–Dorset coast west of Lyme Regis.

The lowest ammonites in CRN-2, from around 349.14 to 348.93 m (Table 1) are small, smooth psiloceratids with traces of tubercles on their nuclei (although the plications characteristic of the outer whorls of some variants are not obvious in the Carnduff material). This fauna corresponds to *Psiloceras* ex gr. *erugatum* (Phillips), indicating the *erugatum* Biohorizon (Hn2), considered by Page (2010a,b) to be best incorporated in the upper part of the Tilmanni Chronozone, the lowest zone of the Jurassic System at its GSSP. The *erugatum* fauna is currently the lowest Jurassic ammonite confirmed across Britain and Ireland, as the stratigraphical record of a psiloceratid nucleus from the Penarth Group (presumed to be of Rhaetian age) by Donovan et al. (1989) near Bristol is problematic and has not been reproduced.

Planorbis Chronozone, Planorbis Subchronozone: The Planorbis Chronozone is well represented in the Carnduff boreholes and shows a similar succession of faunas to those described by Simms and Jeram (2007) on the coast at Waterloo Bay. Many of these faunas can be grouped within the biohorizons listed for the Hettangian by Page in Weedon et al. (2018).

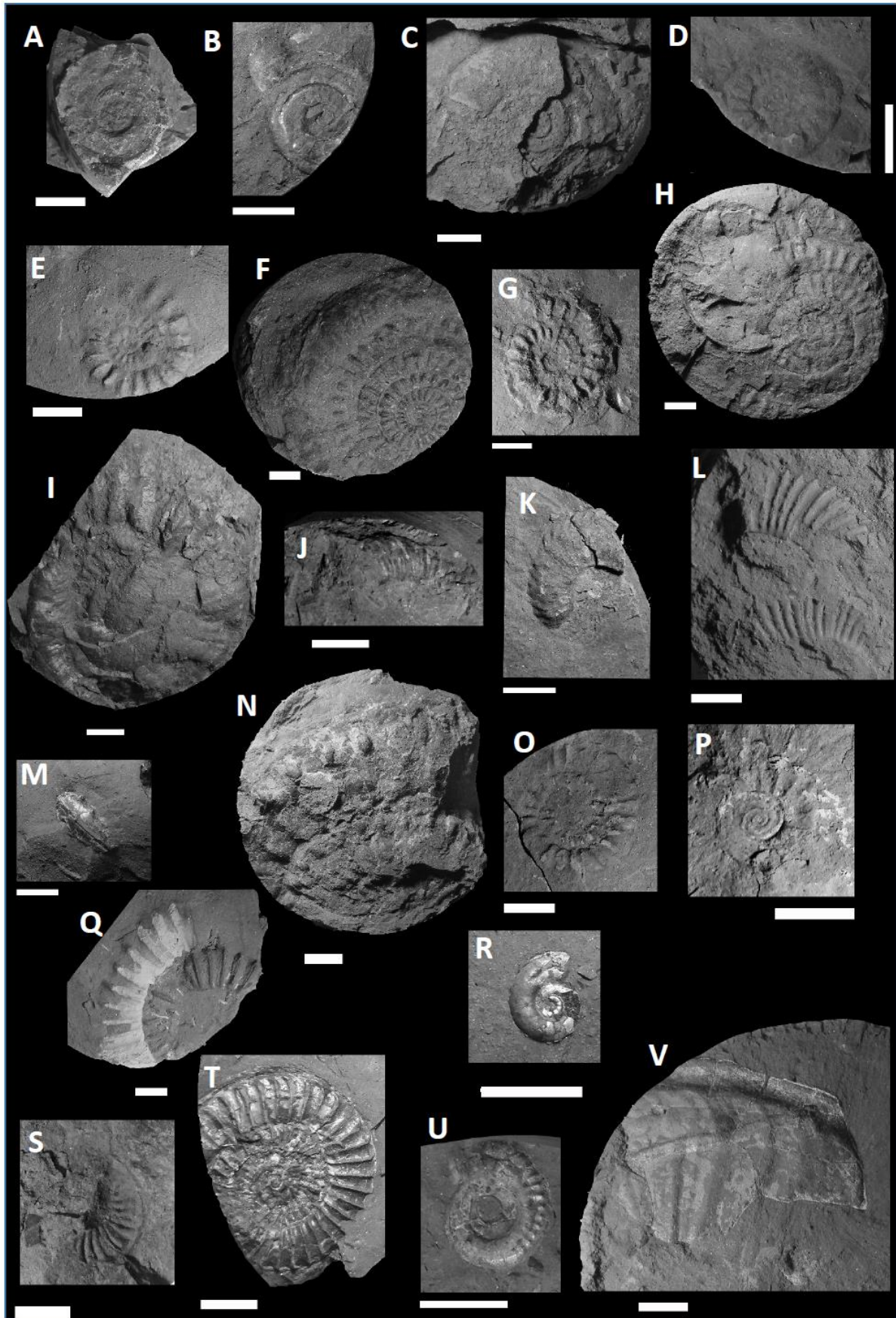


Figure 5. Hettangian and Lower Sinemurian ammonites from the Carnduff-2 Borehole.

- A. *Psiloceras* cf. *erugatum* (Phillips); Hn2-*erugatum* Biohorizon, Tilmanni Chronozone (349.14 m depth). BELUM K 2019.1.1.
- B. *Neophyllites* cf. *imitans* Lange; Hn3-*imitans* Biohorizon, Planorbis Subchronozone, Planorbis Chronozone (348.27 m depth). BELUM K 2019.1.2.
- C. *Psiloceras* ex gr. *Planorbis* (J. de C. Sowerby); Hn5-*planorbis* α - Hn6-*planorbis* β biohorizons, Planorbis Subchronozone, Planorbis Chronozone (347.14 m depth). BELUM K 2019.1.3.
- D. *Psiloceras plicatum* (Quenstedt) ; Hn7-*plicatum* Biohorizon, Planorbis Subchronozone, Planorbis Chronozone (345.36 m depth). BELUM K 2019.1.4.
- E. *Caloceras* cf. *aries* Lange; Hn10-aff. *aries* Biohorizon, Johnstoni Subchronozone, Planorbis Chronozone (340.79 m depth). BELUM K 2019.1.5.
- F. *Caloceras* cf. *johnstoni* (J. de C. Sowerby); Hn12 -*johnstoni* Biohorizon, Johnstoni Subchronozone, Planorbis Chronozone (325.50 m depth). BELUM K 2019.1.6.
- G. *Caloceras* cf. *torus* (d,Orbigny); Hn13a- aff. *torus* Biohorizon, Johnstoni Subchronozone, Planorbis Chronozone (337.40 m depth). BELUM K 2019.1.7.
- H. *Caloceras* cf. *intermedium* (Portlock); Hn13b- grp. *intermedium* Biohorizon, Johnstoni Subchronozone, Planorbis Chronozone (330.46 m depth). BELUM K 2019.1.8.
- I. *Waehneroceras* (*Macrogrammites*) sp. [M]; Hn16b- grp. *portlocki* - Hn17c -cf. *latimontanum* biohorizons, Portlocki Subchronozone, Liassic Chronozone (311.04 m depth). BELUM K 2019.1.9.
- J. *Waehneroceras* (*Saxoceras*) sp.; Hn18a- *laqueus* - Hn19d-aff. *bloomfieldense* biohorizons, Laqueus Subchronozone, Liassic Chronozone (305.40 m depth). BELUM K 2019.1.10.
- K. *Schlotheimia* ex gr. 'sp 1a' and 'sp. 1b' of Page in Weedon et al. (2018); Hn20a- *Schlotheimia* sp. 1 - Hn20c-*hadrotychus* biohorizons, Extranodosa Subchronozone, Angulata Chronozone (294.65 m depth). BELUM K 2019.1.11.
- L. *Schlotheimia* cf. *similis* Spath/ *stenorhyncha* Lange; Hn23a-grp. *stenorhyncha* - Hn23b-*similis* biohorizons, Complanata Subchronozone, Angulata Chronozone (274.63 m depth). BELUM K 2019.1.12.
- M. *Vermiceras* sp.; ?Sn1-*quantoxense* Biohorizon, Conybeari Subchronozone, Bucklandi Chronozone (259.11 m depth). BELUM K 2019.1.13.
- N. *Coroniceras* cf. *defneri* (Oppel); Sn5c-*silvestri* - Sn6-cf. *defneri* biohorizons, Conybeari Subchronozone, Bucklandi Chronozone (249.24 m depth). BELUM K 2019.1.14.
- O. *Coroniceras* cf. *kridion* (Hehn); ?Sn9-*kridion* Biohorizon, Rotiforme Subchronozone, Bucklandi Chronozone (235.00 m depth). BELUM K 2019.1.15.
- P. *Arnioceras* sp.; Sn11-aff. *isis* - Sn14-*multicostatum* biohorizons, Bucklandi Subchronozone, Bucklandi Chronozone (232.34 m depth). BELUM K 2019.1.16.
- Q. *Arnioceras* cf. *bodleyi* (J. Buckman); Sn16-*bodleyi* - Sn17b-*alcinoe* biohorizons, Lyra Subchronozone, Semicostatum Chronozone (210.44 m depth). Note partial infill of body-chamber by pale phosphate. BELUM K 2019.1.17.
- R. *Euaggasiceras* sp.; Sauzeanum Subchronozone, Semicostatum Chronozone (200.55m depth) BELUM K 2019.1.18.
- S. *Caenisites* cf. *brooki* (J. Sowerby); Sn25: *brooki* Biohorizon, Brooki Subchronozone, Turneri Chronozone (196.44 m depth). BELUM K 2019.1.19.
- T. *Arnioceras* cf. *hartmanni* (Oppel); Sn26: *hartmanni* Biohorizon, Brooki Subchronozone, Turneri Chronozone (190.75 m depth). BELUM K 2019.1.20.
- U. *Microderoceras inexpectans* Spath; Sn30-*subturneri* Biohorizon, Birchi Subchronozone, Turneri Chronozone (188.93 m depth). BELUM K 2019.1.21.
- V. *Caenisites* cf. *subturneri* Spath; Sn30-*subturneri* Biohorizon, Birchi Subchronozone, Turneri Chronozone (190.06 m depth). BELUM K 2019.1.22.

Scale bars = 1cm; Photographs by Robert Raine; all specimens held in the Ulster Museum Collections, Belfast.

		All depths approximate*	
		Ammonite Chronozone	Ammonite Subchronozone
		BASE CRN-2 (metres, observed)	
LOWER SINEMURIAN	Turneri	Birchi	190.27-190.18
		Brooki	200.55-196.44
	Semicostatum	Sauzeanum	208.82-207.41
		Scipionianum	210.44-208.82
		Lyra	232.34-210.94
	Bucklandi	Bucklandi	234.62-232.34
		Rotiforme	247.66-244.99
		Conybeari	259.29
	HETTANGIAN	Angulata	Depressa
Complanata			294.65-293.96
Extranodosa			305.40-299.14
Liasicus		Laqueus	311.04-308.36
		Portlocki	313.06-311.74
Planorbis		Johnstoni	340.79
		Planorbis	348.93
Tillmanni		349.10	

Table 2. Summary Ammonite chronozone for the Waterloo Mudstone Formation in the CRN-2 core. (* some depths are associated with uncertainties, for example, the absence of ammonites, or the absence of marker taxa).

The base of the Planorbis Chronozone and Subchronozone is recognisable in Carnduff 2 at 348.27 m depth though the presence of *Neophyllites* cf. *imitans* Lange, a more involute species than *N. antecedens* Lange above. Although the distinctive simplified ‘pseudoceratitic’ sutures of the genus are not visible in any of the available specimens, additional features such as relatively steep umbilical edge can also be used to distinguish the genus from *Psiloceras* ex gr. *planorbis* (J. de C. Sowerby) above (Bloos and Page, 2000b). Available material indicates that the *imitans* Biohorizon (Hn3) is present from 348.35 to 348.27 m and the *antecedens* from 348.27 to 347.45 m in CRN-2 (see Table 2).

Younger faunas of the Subchronozone include *P.* ex gr. *planorbis* from 347.37 to 346.59 m depth (*planorbis* α to *planorbis* β biohorizons (Hn5 – Hn6)), bluntly ribbed *Psiloceras plicatum* (Quenstedt) from 345.79 to 344.66 m (*plicatum* Biohorizon (Hn7)), evolute smooth *Psiloceras* ex gr. *sampsoni* (Portlock) from 344.26

to 343.80 m (*sampsoni* Biohorizon (Hn8)) and plicate and relatively evolute *Psiloceras bristoviense* Donovan from 343.74 to 342.74 m (*bristoviense* Biohorizon (Hn9)).

Planorbis Chronozone, Johnstoni Subchronozone: Typical coarsely ribbed *Caloceras* cf. *aries* Lange correlates the base of the Johnstoni Subchronozone at 340.79 m (= *aries* Biohorizon (Hn10)), and is followed by a sequence of *Caloceras* faunas which, although less abundant in terms of specimens than the subchronozone below, enable the recognition of most of the biohorizons of the subchronozone. Faunas include *Caloceras* cf. 'sp.2' of Page (2005 - a form with straight, blunt ribbing), from 340.63 to 340.61 m (*Ca.* cf. sp.2 Biohorizon (Hn11a)), *Ca.* sp. cf. 'sp.3' (of Page in Weedon et al., 2018) at 339.39 m (*Caloceras* sp. 3 Biohorizon (Hn11c)), *Caloceras* ex gr. *johnstoni* (J. de C. Sowerby) (with relatively strong blunt ribbing, including on nuclei), from 339.10 to 338.06 m (*johnstoni* Biohorizon (Hn12)), *Caloceras* cf. *torus* (d,Orbigny) from 337.91 to 337.40 m (ribs less blunt than *johnstoni* and not as close as *intermedium* Portlock from above; *C.* aff. *torus* Biohorizon (Hn13a)), *Caloceras* cf. *intermedium* from 335.00 to 326.91 m (with close, straight ribbing; ex gr. *intermedium* Biohorizon (Hn13b)) and *Caloceras* cf. 'post' *intermedium* (of Page in Weedon et al., 2018) from a possible record at 324.45 to 313.60 m (with relatively widely spaced ribs on its outer whorl; post-*intermedium* Biohorizon (Hn13c)).

There is an interval in the core between 326.91 and 324.45 m in which the faunal sequence appears to be repeated, however, with *johnstoni*-like *Caloceras* at 325.50 m and *intermedium*-like forms at 324.53 m. the significance of these records is not clear, but could suggest some repetition of the sequence by faulting or that a 'new' fauna are present, one not recorded in West Somerset or Lavernock, Glamorgan, where the subchronozone is best documented.

Liasicus Chronozone: The record of Liasicus Chronozone faunas in the Carnduff boreholes is very poor and only a few ammonites are recorded. These include *Waehneroceras* at 311.72 m and 311.4 m – the latter strongly ribbed – suggesting the Portlocki Subchronozone, with evolute *Saxoceras*-style *Waehneroceras* at

308.2 m and 305.4 m and a fragment of a probable alsatitid at 308.2 m indicating the Laqueus Subchronozone.

Angulata Chronozone: Similarly, *Angulata Chronozone* faunas are very sparse with relatively involute and close ribbed *Schlotheimia* at 294.65 m and blunt-ribbed ?*Sunrisistes* at 299.14 m suggesting the lower part of the *Extranodosa* Subchronozone and specifically the *Hadrotychus* Horizon. That the subchronozone ranges higher is suggested by strongly ribbed *Schlotheimia* at 293.96 m, 291.79 m and an additional fragment of the genus at 293.96 m – however, similar morphs are also known in the *Complanata* Subchronozone. Finely ribbed *Schlotheimia* at 274.65 m, however, is consistent with the *Complanata* Subchronozone. The highest recorded *Schlotheimia* fragment, at 266.5 m, is not, however, subzonally diagnostic.

3.2. *Sinemurian*

Bucklandi Chronozone, Conybeari Subchronozone: The base of subchronozone, and hence the *Sinemurian* Stage can be placed with reasonable certainty in Carnduff-2 by the presence of fragmentary *Vermiceras* cf. *quantoxense* Bloos and Page, indicating the *quantoxense* Biohorizon (Sn1) and hence the base of the *Sinemurian* Stage (Bloos and Page 2002). Although fragmentary *Metophioceras* is also present at higher levels (249.63 m and probably at around 247.66 m and 248.03 m - although these records are difficult to distinguish from *Vermiceras*), two further biohorizons can be recognised, the *rotarius* Biohorizon (Sn3a) at 257.55 m with cf. *Epammonites rotarius* (Buckman) and the *rotator* Biohorizon (Sn4) at 294.24 m with *Coroniceras* cf. *rotator* (Reynés) (a noded form within the late *Conybeari* Subchronozone, hence predating the replacement of unnoded *Metophioceras* by noded *Corniceras* which characterises the base of the overlying *Rotiforme* Subchronozone

Bucklandi Chronozone, Rotiforme to Bucklandi subchronozones: The presence of straight-ribbed, noded *Coroniceras* cf. *defneri* (Oppel) from 244.99 m indicates the lowest part of the subchronozone, probably

biohorizons Sn5c (*silvestri* Biohorizon) to Sn6 (cf. *defneri* Biohorizon). Although no typical, distinctively curve-ribbed *Coroniceras* ex gr. *rotiforme* (J. de C. Sowerby) have been observed immediately above (i.e. indicating biohorizons Sn7a -7b), the presence of more gently curved-ribbed *Coroniceras* from 239.40 m suggests a post Sn7b Biohorizon level, close to Sn8 (*caprotinum* Biohorizon). Small *Coroniceras* cf. *kridion* (Hehl) from 235.27-234.62 m suggests the *kridion* Biohorizon (Sn9). The only other record from the Subchronozone is *Charmasseiceras* at 240.79 m.

In the absence of *Vermiceras scylla* (Reynés) of the Sn10 Biohorizon, the base of the overlying Bucklandi Subchronozone is difficult to place, the next stratigraphical useful faunas being the occurrence of the lowest *Arnioceras* at 232.34 m, indicating a level no lower than Sn11 (aff. *isis*) Biohorizon (*sensu* Page, 1992 as faunas from this interval on the West Somerset coast are currently under revision). The specimen from CRN-2 has a relatively long initial smooth stage (c.10 mm) followed by straight, relatively spaced-out ribbing to the preserved diameter of just over 15 mm. This morphology is consistent with a microconch from the Bucklandi Subchronozone. A small (c.10 mm) noded ammonite at 229.6 m, may represent *Arietites*, as this style of ribbing irregularity is typical of nuclei of the *Arietites*–*Asteroceras* lineage.

Semicostatum Chronozone: In the absence of large, late coronoceratids of the genus *Paracorniceras* and later *Agassiceras* and *Euagassiceras*, correlation of the subchronozones of the Semicostatum Chronozone can be problematic, despite the frequent abundance of the small arietitid genus *Arnioceras*. The latter genus currently suffers from an almost impenetrable taxonomic quagmire, which often makes accurate identification of successive faunas difficult or impossible. Nevertheless, when systematically sampled, successive assemblages can often be distinguished, and work is currently underway to resolve these taxonomic problems and enable the genus to be much more reliably used as a stratigraphical indicator, perhaps of sub-global value. The correlations presented here, therefore, must be considered to be provisional.

Arnioceras is common as expected, including records at 199.78, 199.71, 199.07, 199.06, ?203.74, ?204.64, 207.65, 209.11, 209.13, 208.69 and 210.94 to 210.44 m (“?” indicates uncertain records). The last fauna has body chambers characteristically filled with pale buff-coloured phosphate. Although none of the recorded specimens are particularly diagnostic, the latter is more consistent with Lyra Subchronozone forms than anything from a higher or lower subchronozone, as it appears to have affinities with *Arnioceras* ex gr. *bodleyi* (J. Buckman). A possible *Agassiceras*, with relatively high whorls, close straight ribbing and a high keel at 208.82 m suggests the succeeding Scipionanum Subchronozone, and possible *Euagassiceras* at 200.55, 202.39, 207.35 and 207.41 m (including both smooth and coarse ribbed forms). A partially pyritised nucleus of *Pararnioceras* is present at 207.39 m although fragments of large arietitids at 203.45 and 208.30 m are essentially indeterminate, but not inconsistent with large agassiceratids or *Pararnioceras*.

Turneri Chronozone: The second biohorizon of the Brooki Subchronozone (*brooki* Biohorizon (Sn25)) is confirmed by the presence of *Caensites* cf. *brooki* (J. Sowerby) from 197.43-196.44m, and hence the base of the Subchronozone must lie in the interval from 196.44 to 190.07 m. Although undiagnostic *Arnioceras* is present at 193.48 m, *Arnioceras* cf. *hartmanni* (Oppel) is abundant from 190.79 to 190.27 m indicating the *hartmanni* Biohorizon (Sn26 - in association with ?*Sulciferites* sp. juvenile at 190.79 m) but no more diagnostic faunas are present in CRN-2 until 190.18-188.82 m where weak-ribbed, high-keeled *Caensites* cf. *subturneri* Spath at 190.06 m, (with a probable nucleus at 190.23 m), *Microderoceras inexpectans* Spath, including at 190.18 m and 188.83 m and *Promicroceras* cf. *capricornoides* (Quenstedt) at 189.44 m, *Cymbites* at 188.84 m and a possible early *Epophioceras* at 188.82 m would indicate the *subturneri* Biohorizon (Sn30), already within the Birchi Subchronozone. The micromorph ammonite *Cymbites* is also recorded at several other levels through the *Turneri* Chronozone (e.g. 192.39 and around 190 m).

Although the affinities of the ammonites recovered from the uppermost part of CRN-2 are ambiguous, and probably represent fragmentary and juvenile arietitids (e.g. at 187.00 and 187.87 m), there is nothing to suggest that they are not still of Birchi Subchronozone age.

4. Calcareous Microfossil (AA, IB, PC)

4.1. Calcareous Microfossil Assemblages

A total of twenty-eight samples were examined for microfossils between 170.70 m to 326.00 m in CRN-1, using the techniques described by Boomer et al. (this issue). The abundance of both foraminifera and ostracods is highly variable, while diversity is low (most samples falling between 5–20 species of foraminifera and 2–10 species of ostracods). Throughout much of the core the Order Lagenida dominates the foraminiferal assemblages both in terms of abundance and diversity, whilst the ostracod assemblages are dominated by the Metacopina until the early Bucklandi Subchronozone, after which, podocopid taxa generally become more abundant. The stratigraphic distribution of the most abundant and age-diagnostic taxa is shown on figure 6, some of these are illustrated in figure 7.

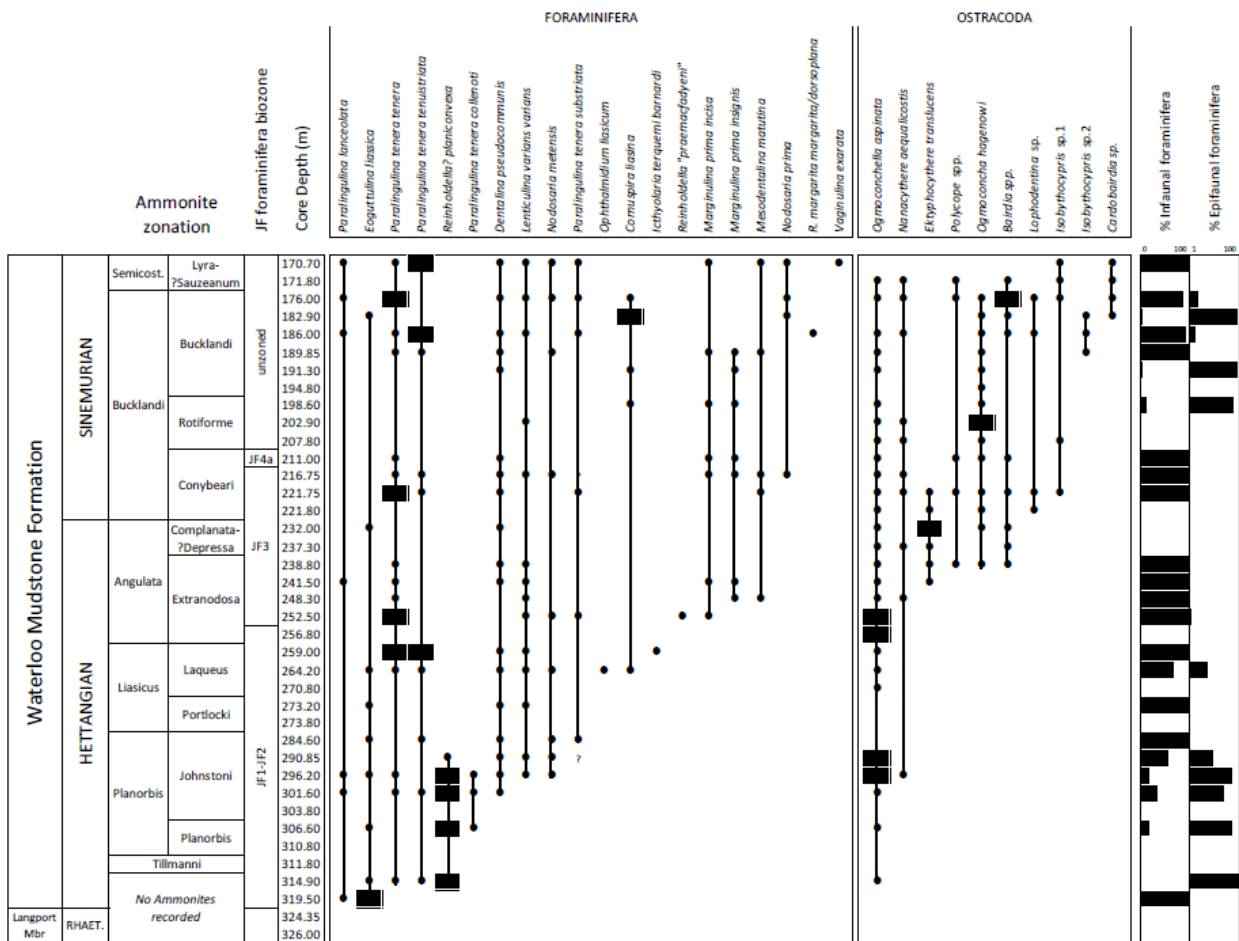


Figure 6. Stratigraphic distribution of the most abundant and most age-diagnostic taxa of foraminifera and ostracods encountered in the CRN-1 borehole. Black dots are occurrences of <100 specimens, rectangles indicate >100 specimens. Ammonite Zonation based on correlation to CRN-2. Columns on the right hand represent the changing proportions of infaunal and epifaunal foraminifera.

Two Late Triassic samples from the Lilstock Formation (at 324.35 m and 326.00 m) were examined, but both proved barren of microfossils, it is likely that more extensive sampling of the Penarth Group may encounter distinct layers with foraminifera and/or ostracod assemblages as these have been described from elsewhere in Britain (Ainsworth and Boomer, 2009; Copestake and Johnson, 1989; Lord and Boomer, 1990). Some acetic-acid preparations kindly made available by Andrew Jeram and examined by IB yielded poorly-preserved remains of the brackish to freshwater ostracod genus *Darwinula* from the Langport Member of the Lilstock Formation, but no other microfossils. The presence of *Darwinula* indicates reduced salinity conditions in some parts of that unit, the same genus has also been record in latest Triassic to earliest Jurassic sediments from offshore west and southwest Ireland (Ainsworth, 1989; 1990).

The oldest observed microfossils (319.50 m) occur close to the base of the Waterloo Mudstone Formation (Lias Group) representing a low diversity assemblage (4 species) dominated by *Eoguttulina liassica*, previously described as an opportunistic species (Nocchi & Bartolini, 1994). The next youngest sample (314.90 m) contained a marked influx of the robertininid species *Reinholdella? planiconvexa*. This 'flood' continues up to 296.20 m and is characteristic of the Hettangian Stage (Planorbis Ammonite Chronozone; Copestake and Johnson, 2014), similar events are noted in the Rathlin (Boomer et al., this issue) and Foyle (Raine et al., this issue, b) basins.

Following the *Reinholdella* flood, the foraminiferal assemblages are generally dominated by representatives of the Lagenida, particularly those of the *Paralingulina tenera* plexus, through much of the remaining Waterloo Mudstone Formation, although there are localised peaks of the miliolid *Cornuspira liasina* in the Bucklandi Ammonite Subchronozone (at 182.90 m, 191.30 m and 198.60 m). These flood occurrences coincide with periods when *Paralingulina* is absent or rare and may represent a change from infaunal (*Paralingulina*-dominated) to epifaunal (*Cornuspira*-dominated) assemblages suggesting a change in the bottom-water environmental conditions.

Ostracod assemblages are initially dominated (in the Planorbis Chronozone, earliest Hettangian) by the metacopid *Ogmoconchella aspinata* and, together with another metacopid, *Ogmoconcha hagenowi*, these species comprise more than 90% of the total ostracods in many of the samples from which they were recorded. However, they are very rare to absent in the three youngest samples studied, from the latest Bucklandi Ammonite chronozone onwards. This marked change in the ostracod assemblage, from dominance to complete absence of metacopid taxa, can also be recognised in a number of other UK sections as an early Sinemurian event (Boomer, 1991; Boomer et al., this issue). During this event, representatives of the cytheroidean genera *Bairdia* and *Isobythocypris* often become abundant.

Figure 7. All specimens from CRN-1, housed in the Lapworth Museum of Geology, University of Birmingham, catalogue numbers pre-fixed BIRUG.

- A. *Paralingulina tenera collenoti*, 296.2 m. BU5417, 825 µm.
- B. *Paralingulina tenera substriata*, 284 m. BU5418, 355 µm.
- C. *Marginulina prima incisa*, 211 m. BU5419, 740 µm.
- D. *Marginulina prima insignis*, 211 m. BU5420, 515 µm.
- E. *Nodosaria metensis*, 216.75 m. BU5421, 390 µm.
- F. *Vaginulinopsis exarata*, 170.7 m. BU5422, 840 µm.
- G. *Planularia inaequistriata*, 211 m. BU5423, 560 µm.
- H. *Cornuspira liasica*, 182.9 m. BU5424, 310 µm.
- I-J. *Reinholdella "praemacfadanyi"*, I. dorsal view, 252.5 m. BU5425, 405 µm. J. umbilical view, 252.5 m. BU5426, 475 µm.
- K-L. *Reinholdella? planiconvexa*, 306.60 m. K. dorsal view, L. side view, BU5427, 180 µm.
- M-N. *Reinholdella margarita*, M. dorsal view, 186 m. BU5428, 305 µm. N. umbilical view, 186 m. BU5429, 320 µm.
- O. *Polycope cerasia*, 182.9 m. BU5430, 375 µm.
- P. *Polycope cinncinata*, 182.9 m. BU5431, 415 µm.
- Q. *Ophthalmidium liasicum*, 264.2 m. BU5432, 220 µm.
- R. *Eoguttulina liassica*, 319.5 m. BU5433, 335 µm.
- S. *Isobythocypris* sp.A., 176 m. BU5434, 725 µm.
- T. *Cardobairdia* sp., 176 m. BU5435, 420 µm.
- U. *Lophodentina* sp.A., 189.85 m. BU5436, 390 µm.
- V. *Ektyphocythere translucens*, 273.2 m. BU5437, 555 µm.
- W. *Bairdia* sp.A., 176 m. BU5438, 700 µm.
- X. *Nanacythere aequalicostata*, 221.75 m. BU5439, 310 µm.

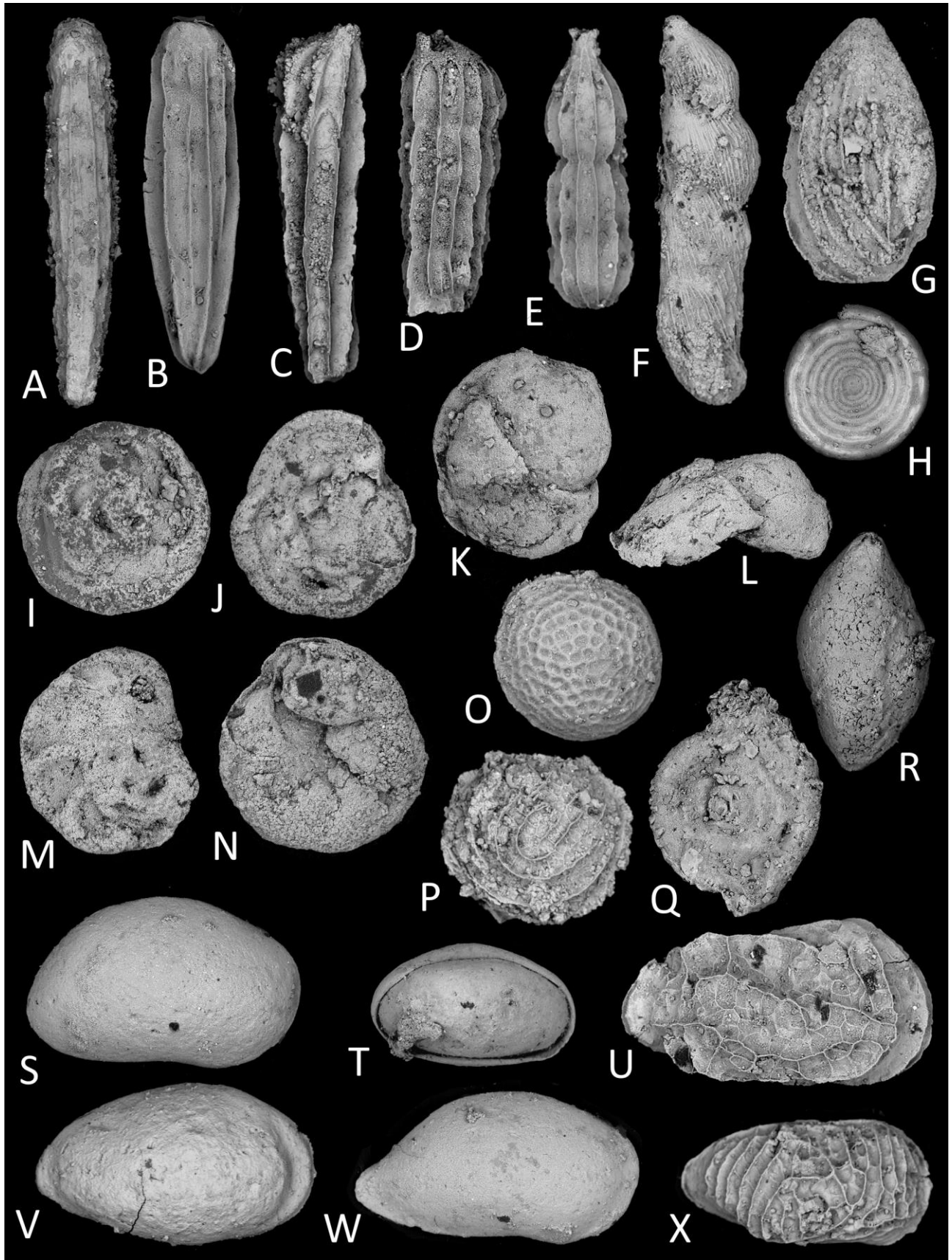


Figure 7. Key species of calcareous microfossils recorded from CRN-1.

4.2. *Calcareous Microfossil Biostratigraphy*

The Late Triassic and Early Jurassic intervals in the borehole contain several age diagnostic assemblages and marker species of foraminifera and ostracods. It is possible to recognise some elements of the foraminiferal assemblages and biozones (JF biozones) for this interval, defined by Copestake (1989) for the Rhaetian and Copestake and Johnson (1989, 2014) for the Hettangian – Early Sinemurian. In addition, there are some similarities with the foraminiferal associations recorded by Clémence and Hart (2013) and Copestake (1989) around the Triassic/Jurassic boundary interval in south west England (Somerset coast). Since the study is based upon core samples, both first appearances (LDOs, last downhole occurrences) and last appearances (FDOs, first downhole occurrences) of marker taxa may be utilised for biostratigraphic subdivision.

The deepest sample studied for microfauna from the borehole, at 319.50 m, contains an abundance of the foraminiferal species *Eoguttulina liassica*, together with *Paralingulina lanceolata* and various smooth *Prodentalina* spp. This sample is from the lowest beds of the Waterloo Mudstone Formation (Lias Group),

The lowest occurrences of *Paralingulina tenera collenoti*, together with *P. tenera tenuistriata* are recorded at 314.90 m suggesting the base of the JF1 foraminiferal biozone. This biozone is known to include the uppermost part of the Langport Member in south-west Britain (Copestake, 1989; Copestake and Johnson, 2014) and represents the first incoming of typical “Jurassic” foraminiferal associations even though the age of the lower part of this biozone is latest Rhaetian as now defined. In the CRN-1 borehole the base of this biozone occurs in the lower part of the Waterloo Mudstone Formation. That no calcareous microfossils were observed in this borehole from the two samples examined in Penarth Group echoes a similar observation in exploration wells offshore Ireland (N. Ainsworth and P. Copestake, unpublished data).

The JF1 biozone normally extends upwards into the lower part of the Hettangian, with the upper limit based on the incoming (appearance) of common to abundant *Reinholdella? planiconvexa* in the upper part of the

Planorbis Chronozone (Copestake and Johnson, 1989; 2014). However, in CRN-1 the abundance of the latter species with the incoming of *P. tenera collenoti* at 319.50 m, therefore the JF1 and JF2 biozones cannot be separated in this borehole. Furthermore, the abundant *R.? planiconvexa* event at Carnduff occurs significantly older than the usual level of the base of JF2, in fact in the Tilmanni Chronozone. This level may correlate with an abundance peak of unspiciated "*Reinholdella*" (which, from the figured specimens, appear to be *R.? planiconvexa*) recorded by Clémence and Hart (2013) from the Somerset coast at Doniford, south west England, also in the Tilmanni biozone. The FDO of abundant *R.? planiconvexa* is recorded in the upper Planorbis Chronozone to lowermost Liasicus ammonite Chronozone of the Hettangian in onshore Britain (Copestake and Johnson, 2014); the top of the abundant occurrence of this species in CRN-1 is at 296.20 m, still within the Planorbis Chronozone as determined above. The ostracod assemblages in the range 296.20 to 290.85 m (Johnstoni Subchronozone) are dominated by *Ogmoconchella aspinata* which is also abundant at the base of the Angulata Chronozone and is recorded in most other samples.

Abundant *P. tenera collenoti* at 306.60 m suggests a level within the Planorbis Chronozone at this depth, in agreement with the ammonite zonal interpretation (see Section 3). The defined marker species for the base of the JF3 foraminiferal biozone, *Dentalina langi*, associated with the incoming of common *Paralingulina tenera substriata*, were not recorded from the borehole, though low numbers of the latter taxon are recorded from 284.6m and above. A proxy for this biozone, however, is the incoming of *Marginulina prima insignis*, which occurs at 252.50 m. At this depth, the presence of an, as yet informal species of *Reinholdella*, referred herein as *R. "praemacfadyeni"*, is of note. This species has been figured and recorded from the Hettangian to earliest Sinemurian of the Yorkshire coast, eastern England by Copestake *et al.* (2019, as *R. cf. macfadyeni*) and also from a hydrocarbon exploration well in the South West Approaches, Melville Sub-basin, offshore south-west Britain (Hooker *et al.*, 1983, as *R. "praemacfadyeni"*). This taxon is a marker for the Angulata to earliest Bucklandi chronozones, and its occurrence at Carnduff in the Angulata Chronozone is consistent with this. An additional marker for the lower limit of the JF3 biozone is the incoming of

Mesodentalina matutina, which occurs at 248.30 m. This species was also used in the Mochras Borehole to define the base of this biozone, in the absence of *D. langi* (Copestake and Johnson, 2014).

A further feature of the JF3 biozone is the base of the common occurrence of *M. prima insignis* also at 248.30 m, becoming abundant together with *M. prima incisa* at 211.00 m. The latter depth is interpreted as representing the upper part of the Bucklandi Chronozone (Rotiforme–Bucklandi subchronozones, supported by the ammonite records in CRN-2), based on the known occurrence of the taxon in onshore Britain (Copestake and Johnson, 2014) and the deepest sample in which the JF4 foraminiferal biozone can be identified. *M. prima incisa* is also common at 211.00 m, however, this subspecies' peak abundance is normally in the Angulata Chronozone (Copestake and Johnson, 2014). The FDOs of common to abundant ostracod species *O. hagenowi* and *O. aspinata* at 189.50 m generally indicate a level within the Bucklandi Chronozone, this is consistent with the age assessment based on the ammonite occurrences in CRN-2 and the foraminiferal ranges noted above.

Forms of *Reinholdella margarita* (intermediates between subspecies *margarita* and *dorsoplana*) are recorded from 186.00 m, at a level placed in the Bucklandi Subchronozone on ammonite evidence. This is slightly younger than the level at which subspecies *R. margarita dorsoplana* first occurs in onshore Britain, in the Rotiforme Subchronozone (Copestake and Johnson, 2014).

The occurrence of *Vaginulinopsis exarata* at 170.70 m is of note as this species becomes common in the Semicostatum Chronozone elsewhere in Britain (Copestake and Johnson, 2014). This is the youngest level sampled for microfauna in the CRN-1 borehole and supports the interpretation of an age no younger than Early Sinemurian (Semicostatum Chronozone equivalent) at the top of the Waterloo Mudstone Formation recorded in this borehole. The notable absence of taxa such as *Astacolus semireticulatus* and *Neobulimina bangae*, which appear at higher levels within the Semicostatum Chronozone in Britain (see Copestake and

Johnson, 2014), and which are present in nearby Ballinlea-1 well, indicate that the youngest sample studied from CRN-1 represents a level no younger than the early part of the Semicostatum Chronozone.

The ostracod assemblages in the youngest part of the core examined are dominated by unornamented species of Metacopina such as *Ogmoconchella aspinata*, later joined by *Ogmoconcha hagenowi* which then becomes the more abundant species. *Ektyphocythere translucens* appears at the top of the Extranodosa Subchronozone, together, these three species are characteristic of the late Hettangian to earliest Sinemurian stages (Boomer and Ainsworth, 2009).

Importantly, the combination of ammonites together with the calcareous microfossils confirms that the two biostratigraphic schemes support each other in the Larne Basin, notwithstanding minor differences noted. There do not appear to be any significant, systematic disparities when compared to other sites in the UK where those groups have been investigated in tandem.

5. Palynology (JF & IB)

In the absence of ammonites from the Penarth Group sediments, palynomorphs have served to help constrain both the age of the latest Triassic units, as well as indicate their changing environment of deposition. The palynological remains also assist correlation with other Triassic–Jurassic boundary sites (see summaries in Korte et al., 2019; Lindström et al., 2017).

5.1. Palynology Methodology

Forty-two samples from borehole CRN-1 were processed using standard palynological procedures, involving acid digestion using HCl, HF and HNO₃ (Wood et al., 1996). Each sample was subject to a count of 200 individual palynomorphs, with the remainder of the slide scanned for additional taxa. A set of slides is lodged at the British Geological Survey in Keyworth, UK. A suite of samples was taken to represent all of the main lithological units from the uppermost Collin Glen Formation up to the top of Waterloo Mudstone

Formation with the greatest concentration of sampling around the boundary between the Penarth Group and the Lias Group. The palynological evidence is discussed below by lithological unit, with the sample interval recording the core depths of the basal and uppermost samples investigated in each unit, a semiquantitative representation of the most abundant and stratigraphically significant taxa is shown in Figure 8.

5.2. *Uppermost Collin Glen Formation (3 samples, 345.10–341.80 m)*

Only the uppermost few metres of this formation were sampled, which extends to a depth of 348.64 m in CRN-1. An impoverished palynoflora recovered from within the Collin Glen Formation (formerly “Tea Green Marls”) at 345.10 m yielded *Dapcodinium priscus*, *Suessia swabiana*, *Rhaetogonyaulax rhaetica* and *Rhaetipollis germanicus* supporting a stratigraphic position no older than the upper part of the Blue Anchor Formation in Nottinghamshire (Morbey, 1975). Elevated numbers of *R. germanicus* are recorded at 341.80 m and 342.40 m, where the species attains 5-6% of the palynoflora, a quantitative event that may be correlative with an 8% spike in the Larne No. 1 Borehole at 102.11 m (Warrington and Harland, 1975). However, sample spacing within Larne No. 1 is broad, hence the low confidence in such correlation.

5.3. *Westbury Formation (3 samples, 338.90–333.32 m)*

A significant improvement in recovery of Rhaetian palynofloras occurs between 332.50 m and 342.40 m with rich and diverse assemblages encountered, facilitating confident correlation with comparable Westbury Formation and Lilstock Formation successions elsewhere in the U.K. (e.g. Morbey, 1975; Warrington, 1997a, 1997b, 2005). *Ricciisporites tuberculatus* increases in abundance through the uppermost part of the Collin Glen Formation and this continues into the Westbury Formation, reaching a peak of 34% near the top of the latter formation (333.40 m). This peak may be correlative with a maximum (52.5%) in the Larne No. 1 Borehole at 92.66 m (Warrington and Harland, 1975) and has been highlighted as a widespread event by Lindström et al. (2017).

Structured humic plant debris occurs in high abundance between 332.50 m and 342.40 m, with varying proportions of AOM. The latter component increases notably at and below 333.40 m becoming dominant at 338.90 m. High abundance of this kerogen component is interpreted to reflect periods of water mass restriction and dysoxic/anoxic bottom conditions.

5.4. Cotham Member, Lilstock Formation (2 samples, 332.50–327.10 m)

A marked microfloral turnover occurs at the base of this unit with the virtual disappearance of previously dominant taxa such as *R. tuberculatus* and *Classopollis meyeriana* and the first influxes *Botryococcus* spp. and algal cysts. An impoverished palynoflora at 327.10 m sees the co-occurrence of *O. pseudoalatus* and *Rhaetogonyaulax rhaetica* confirming a late Rhaetian age.

The high abundance of *Botryococcus* spp., at 332.50 m, suggests significant input of freshwater into a restricted marine/estuarine type setting. The occurrence of many large, well-preserved colonies of the colonial alga suggests close proximity to a perennial lacustrine environment at this time. It is also worthy of note that swamp-derived spores (e.g. *Deltoidospora* spp., *Acanthotriletes varians*) achieve maximum numbers and diversity within the Penarth Group, confirming increased terrigenous influences relative to both the under- and overlying units.

The palynomorphs recovered from 327.10 m are impoverished in terms of abundance and diversity and occur with degraded kerogen suggesting oxidative processes either at the sea floor or subaerially. In contrast, the rich palynoflora from 332.50 m is characterised by superabundant *Botryococcus* spp. in association with marine dinocysts (e.g. *Dapcodinium priscus*). The relatively high numbers of *D. priscus* is of interest, as this taxon is considered to have been euryhaline and may reflect restricted conditions.

5.5. Langport Member, Lilstock Formation (6 samples, 326.00 – 321.20 m)

This interval is characterised by a rise in the abundance of bisaccate pollen and also an abundance of scabrate algal cysts (often in large clusters of individuals), which is interpreted to reflect a brief phase of potentially low salinity surface water conditions. Between 326.00 m and 322.10 m a superabundance of these algal cysts may provide a further potential correlative datum within the Lilstock Formation in Northern Ireland and may be correlative with a potentially similar datum documented by Warrington and Harland (1975) in the nearby Larne No. 1 Borehole, where a “profusion of small, thin walled crumpled bodies” is documented at 89.92 m from a unit they designated as ‘Upper Rhaetic’.

At 322.50 m and 326.00 m specimens of *Callialasporites turbatus* are observed. This distinctive species is normally present in late Toarcian – late Albian strata. However, rare occurrences have been noted in the Penarth Group at Lavernock Point, South Wales (JF pers. obs.). The occurrence of this taxon may also possess local correlative value in Northern Ireland. At 324.35 m there is a notable increase in the proportion of swamp-derived spores, in the form of increased numbers of *Deltoidospora* spp., *Acanthotriletes varians* and *Todisporites minor*, accompanied by an increase in plant cuticle. This feature is interpreted to reflect a brief phase of enhanced terrigenous input into a shallow marine environment. However, the spores do not reach the high, relative abundances seen in the Langport Mbr in SW England (Bonis et al. 2010), this is often referred to as a ‘fern spike’ and also characterises the latest Triassic Triletes Beds of the Germanic Basin (van Schootbrugge et al., 2009).

A confident uppermost Triassic level is suggested at 322.10 m, with the first downhole appearance of *Limbosporites lundbladii* and an increase in numbers of *R. tuberculatus* (albeit outside the count), this is 1.35 m below the base of the Lias Group, pointing to a possible base Jurassic level within the uppermost Langport Member of the Lilstock Formation or lowermost Waterloo Mudstone Formation (base at 321.20 m). An additional palynologically-defined indicator for the Late Triassic could be taken at 320.20 m, just below the base of the Waterloo Mudstone Formation, based on the first appearance in CRN-1 of

Cerebropollenites thiergartii, a palynology datum that has been used by many authors (e.g. Bonis et al., 2009) as a marker for the base of the Jurassic.

5.6. Waterloo Mudstone Formation (32 samples, 320.30 m to 170.70 m)

Specimens of *C. thiergartii* occur consistently at and above 319.50 m in CRN-1 and although they have a base occurrence at 321.20 m in the underlying Langport Member, they likely reflect an age no older than very latest Triassic. It is important to note that the first/oldest Hettangian ammonites are recovered from 349.60 m in borehole CRN-2, and 313.40 m in CRN-1. However, it is known that these do not represent the oldest Hettangian ammonite species and it is likely that there is an earliest Hettangian interval at Carnduff below the first recorded ammonites. Specimens of *C. thiergartii* have been documented below the inception of *Psiloceras spelae tirolicum* and just above the Initial CIE at Kuhjoch and within the “Pre-Planorbis Beds” at St Audries Bay (Lindström et al., 2017). In summary, palynological evidence suggests that a Triassic–Jurassic boundary could be drawn somewhere between 321.20 m and 322.10 m in the Langport Member of the Lilstock Formation in CRN-1.

All palynofloras recovered from the Lias Group are of relatively shallow marine origin, with varying abundances of marine microplankton. Almost all palynofloras are dominated by pollen assigned to *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). The occurrence of tetrads and large clusters of individuals suggests their relative proximity to source. Elevated numbers of acanthomorph acritarchs are encountered at 248.30 m and 259.00 m, a feature of potential correlative value. However, they do not achieve the abundances documented from the basal Blue Lias at St Audries Bay (van de Schootbrugge et al., 2007).

The core samples from the Lias Group generally yield sieved kerogen dominated by structured humic plant debris. The latter is 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 suggests an offshore setting, some distance from the shoreline, during the deposition of this unit. However, the kerogens from 238.80 m, 241.50 m, 259.00 m, 284.60 m and 306.60 m to 319.50 m are overwhelmingly dominated by amorphous organic matter (AOM). This reflects phases of water mass oxygen-deficiency/photoc zone euxinia and potential dysoxia/anoxia at the sediment/water interface, although the continued presence of benthic microfossils throughout these intervals suggests that conditions never became significantly dysoxic. Comparable features have been documented from the St Audries Bay succession in Somerset and Germany (van de Schootbrugge et al., 2007, 2013).

At 314.90 m the occasional to common occurrence of *Leiofusa jurassica* is noted (outside the count), with individuals present in clusters. Elevated numbers of this netromorph acritarch are known to be of potential intra-Hettangian correlative value in northwest Europe. Increased numbers of this species have been documented in the basal part of the Lias α (alpha) 1-2 in the Rødby-1 borehole at 1839 ft and in correlative subsurface strata offshore Netherlands (Lund, 1977; pers. obs., respectively). A small peak (5%) in occurrence of *L. jurassica* has also been documented from within the lower part of the Blue Lias Formation at St Audries Bay (Bonis et al., 2010).

The youngest occurrence of *Gnetaceaepollenites tortuosus* at 238.80 m is of stratigraphic interest, it was documented by Fakhr (1967) as *Gnetaceaepollenites* sp. A (*Ibid.* pl.42, figs 1-7) from the Conybeari Subchronozone (Bucklandi Chronozone, earliest Sinemurian) from Harbury Quarry, Warwickshire. This species has, however, been recorded from Hettangian and Rhaetian strata in Northern Ireland and Austria (JF, pers. obs.). A specimen of *Aratrisporites minimus* is present in the same assemblage, a species reported to be stratigraphically restricted to the Hettangian stage in Germany. In southwest Germany it has been observed only in the Portlocki Subchronozone (Liasicus Chronozone) at Hagenack Quarry, Pfrondorf near

Tübingen, SW Germany, in a unit c.2 m above the 'Ppsilonotenbank' (JF pers. obs.). The species has also been documented from the Hettangian of the Hochalpengraben section in the Eiberg Basin, Austria (Bonis *et al.*, 2009). The Hettangian index species *Microreticulatisporites fuscus* is recorded at and below 252.50 m. Specimens of *Ricciisporites tuberculatus* are observed up to 296.20 m, a taxon known to possess an intra-Hettangian extinction datum. In CRN-1 this level appears to fall within the Planorbis Chronozone, as inferred by correlation with the ammonite zonation from CRN-2 (see Section 3).

The interval 221.75–198.60 m represents a late Hettangian–early Sinemurian age, based on its stratigraphic position below a positively dated early Sinemurian, Bucklandi Chronozone at 191.30 m and the lowest occurrence of *Cerebropollenites mesozoicus* at 221.75 m. The latter species usually becomes a consistent component of assemblages at the base of the early Sinemurian, compatible with its occurrence in this borehole. However, rare occurrences of the species have been observed in the Angulata Chronozone within the Redcar Mudstone Formation in the Yorkshire Basin (JF pers. obs.). The Hettangian–Sinemurian restricted species *Echinitosporites* sp. A *sensu* Bujak and Williams, 1977 is observed at 202.90 m and 216.75 m. Few published records of this distinctive taxon occur, although it has been documented from Sinemurian–Hettangian sediments on the Mazagan Plateau, offshore Morocco (Fenton, 1984). The upper limit of the Hettangian is, therefore, determined palynologically at 232.00 m, based on the absence of *C. mesozoicus*, this is consistent with the interpreted depth for the base of the Bucklandi Chronozone based on ammonite records (Table 2).

The youngest occurrence of *Beaumontella langii* at 191.30 m, and the co-occurrence of *Cymatiosphaera* sp. D. *sensu* Wall, 1965, confirms an age no younger than the Bucklandi Chronozone of the Early Sinemurian, the latter species being restricted to that chronozone. The marine palynofloras between 170.70 m and 189.85 m contain no specific age-diagnostic indices, although an Early Sinemurian age can be confidently assigned, based on the absence of the, usually widespread, Late Sinemurian–restricted dinocyst *Liasidium variabile* and the 'earliest' Sinemurian age assigned to the core sample at 191.30 m.

6. Stable-isotope records from CRN-2

The Late Triassic mass extinction event is accompanied by a distinct perturbation in the global carbon cycle that is manifested in the carbon stable-isotope record from many sites worldwide (Ruhl et al., 2011; Korte et al., 2019). Volcanism associated with the Central Atlantic magmatic province (CAMP) is thought to have played a significant role in both global climate change and the associated changes in carbon cycling.

Hesselbo et al. (2002) described two negative Carbon Isotope Excursions (CIEs) from the St Audries section, an “Initial” latest Rhaetian excursion followed by an earliest Hettangian “Main” negative excursion. A third “Precursor” event has also been described in some sections, occurring prior to the initial event. The initial excursion is of relatively short duration, making it very distinct on many geochemical profiles, however, the Main CIE is of longer duration and is not always clearly distinguished. The geochemical signals associated with the Triassic–Jurassic boundary interval are recorded at a number of localities around the world, these were reviewed by Korte et al. (2019).

Variations in lithologies, the degree of completeness in the sedimentary record and problematic biostratigraphic data can make it difficult to correlate clearly between Triassic–Jurassic boundary records. However, given the presumably short-lived nature of the Initial CIE in particular, being associated with volcanic outgassing of isotopically-light CO₂ and related processes, it should be possible to use this isotope event to correlate across large distances.

6.1. Stable-isotope methodology

More than 300 samples were taken over a 200 m interval in core CRN-2 for the study of bulk stable-isotopes ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) for both the inorganic and organic fractions. Sampling interval varied depending on the stratigraphic level, with the Triassic–Jurassic boundary interval being most heavily sampled (every 20–25 cm). Samples of about 0.5 cm³ were extracted from the cores using a power drill and steel bits, the

sediment was stored in HDPE flip-top vials. Stable-isotopes of inorganic $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ were determined using a continuous-flow Isoprime/Elementar IRMS with Multiflow preparation line at the University of Birmingham GEMS facility. Sample size varied from $\sim 250\ \mu\text{g}$ to about 3 mg in order to obtain sufficient carbonate material for analysis. Results are reported relative to Vienna PDB using IAEA standards NBS-18 and NBS-19. Internal reproducibility on these analyses was always better than 0.08 $\delta^{13}\text{C}$ and 0.15 $\delta^{18}\text{O}$.

A subset of the samples used for inorganic carbon analysis were then selected for decarbonation and subsequent analysis of the $\delta^{13}\text{C}$ composition of the bulk organic component of the sediment. Samples of between 0.5 and 6 mg were decarbonated in 10 ml 5% HCl for at least 24 hrs and repeated if still reacting. The acid was then decanted and 3 cycles of deionised water rinsing took place, each followed by settling period of at least 6 hrs. Samples or dried residue were then weighed into tin cups and analysed on an Elementar Pyrocube, with combustion at 850° C, internal precision was usually better than 0.05 ‰.

6.2. Results

The St Audries Bay coastal outcrop in Somerset, SW England (Hesselbo et al., 2002), is generally taken as the standard isotope reference section for the Triassic-Jurassic boundary interval. The latest Triassic to Early Jurassic CIEs are primarily identified from their organic carbon records ($\delta^{13}\text{C}_{\text{org}}$), the carbonate fraction is much more susceptible to diagenesis and rarely demonstrates close agreement. Stable-isotope records of the carbonate fraction ($\delta^{13}\text{C}_{\text{carb}}$) at Carnduff (Figures 9A and 9B) show a marked CIE throughout the Lilstock Formation with a recovery phase continuing into the Waterloo Mudstone Formation. By contrast, the Initial CIE in the organic fraction at Carnduff is confined to a shorter interval through the Lilstock Formation. At St Audries the Initial CIE ($\delta^{13}\text{C}_{\text{org}}$) is restricted to a few data points in the uppermost Cotham Member and lowermost Lilstock Member. Notwithstanding any differences in the completeness of the sedimentary record of the two sections, or differing sedimentation rates, the Initial CIE is a more discrete event at St Audries compared to Carnduff although their minima do coincide.

Higher up in the sequence, within the Waterloo Mudstone Formation, the carbonate $\delta^{18}\text{O}$ record (Figure 9B) also displays weak cyclicity on a scale of about 6–10 m with a range of 2–3‰. While this is also likely to have been affected by diagenesis, the cyclicity may well reflect variability in the primary sedimentation, similar to the contemporaneous “Blue Lias” facies of southern Britain, and warrants further geochemical, especially elemental, investigation. Similar cyclicity is also noted in the % carbonate record (Figure 9C).

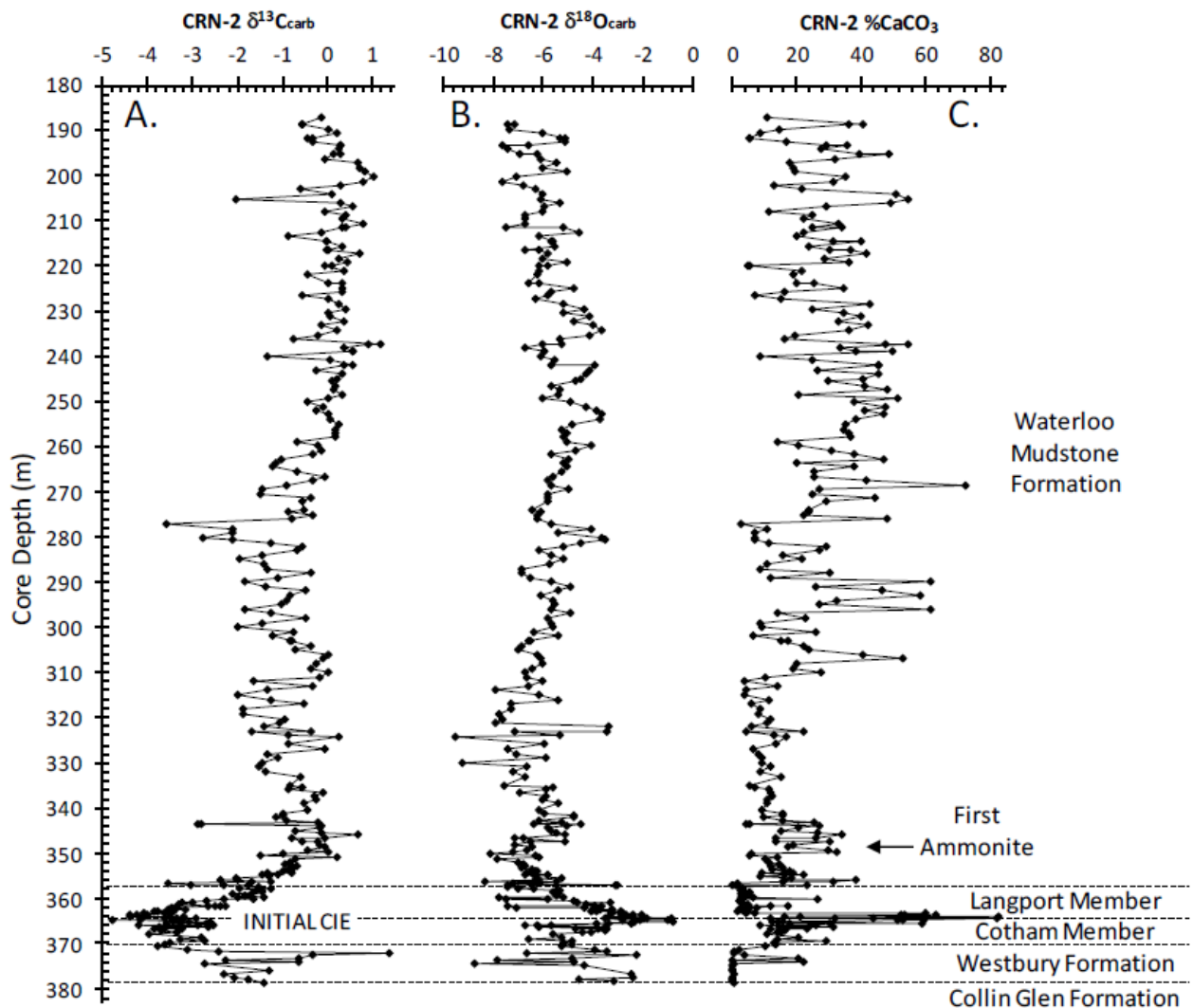


Figure 9. Stable-isotope ratios, A. $\delta^{13}\text{C}$ and B $\delta^{18}\text{O}$ of the inorganic fraction and C. % carbonate record through CRN-2. For details of the Triassic-Jurassic boundary interval see figure 10. Dashed lines indicate boundaries between lithostratigraphic units.

Figure 10B clearly illustrates the Initial CIE in the $\delta^{13}\text{C}_{\text{org}}$ and demonstrates a strong coincidence with the minimum in the $\delta^{13}\text{C}_{\text{carb}}$. The $\delta^{13}\text{C}_{\text{org}}$ also indicates a Hettangian Main CIE onset at the very base of the Waterloo Mudstone Formation which is not clear in the $\delta^{13}\text{C}_{\text{carb}}$. A single data point in the $\delta^{13}\text{C}_{\text{org}}$ points to possible evidence of a Precursor CIE present in the Carnduff record, further work is clearly needed.

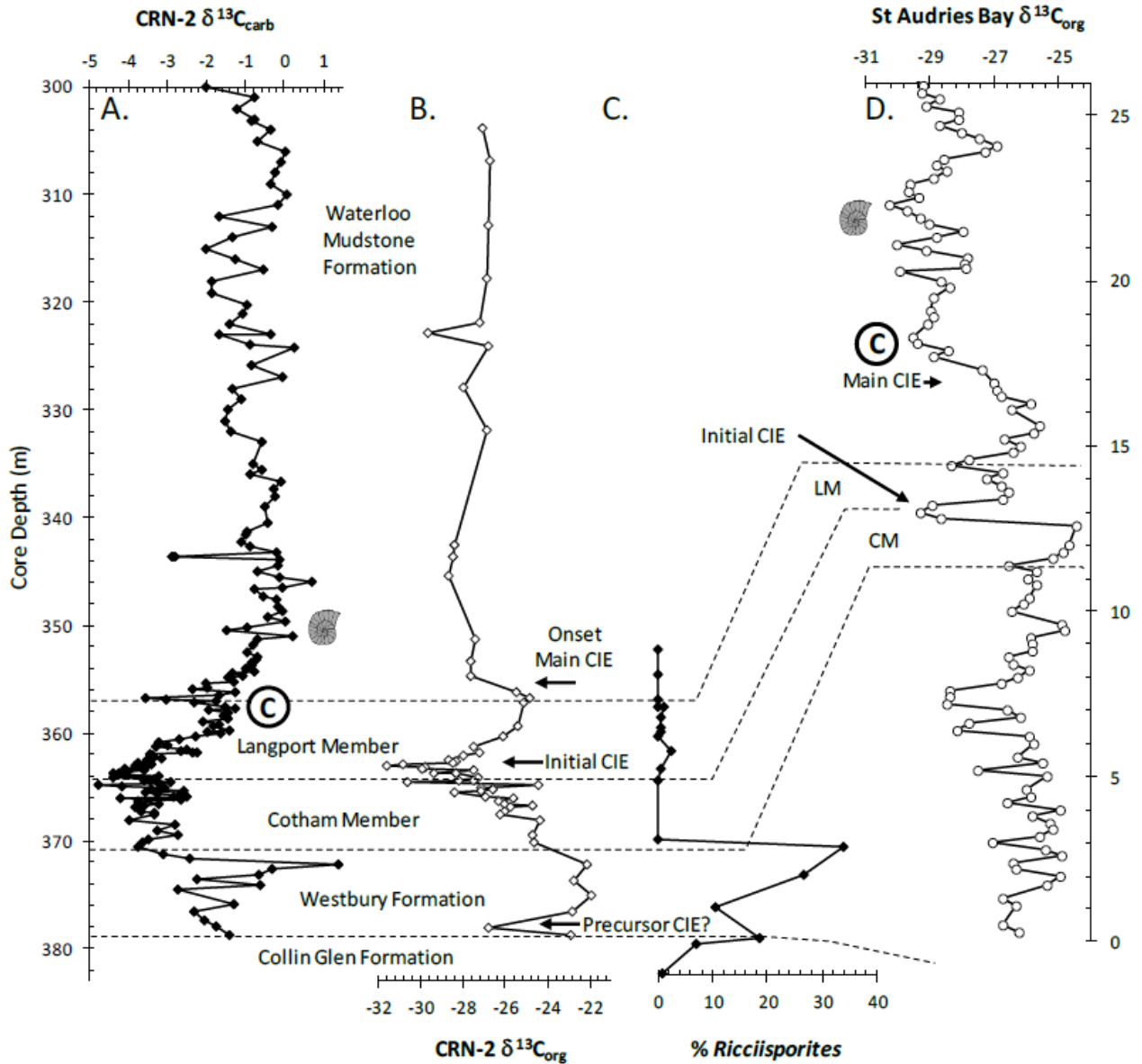


Figure 10. Detailed stable-isotope record through the Triassic–Jurassic boundary interval at Carnduff compared to St Audries Bay with additional biostratigraphic markers. Ammonite symbol marks their first occurrence at each site, the letter C marks the first occurrence of *Cerebropollenites thiergartii* in each section. A. $\delta^{13}\text{C}_{\text{carb}}$ CRN-2, B. $\delta^{13}\text{C}_{\text{org}}$ CRN-2, C. % *Ricciisporites* for comparison with Lindstrom et al. (2014), D. $\delta^{13}\text{C}_{\text{org}}$ from St Audries Bay.

The relatively high sedimentation rate through this key interval at Carnduff (base Westbury Member to base Lias Group is 21.30 m at Carnduff compared with c. 12.5 m at St Audries Bay) suggests that the more complete, and also relatively unweathered Carnduff record could provide a more detailed insight into volcanism, carbon-cycling and related processes during this interval. It is not our intention to undertake a detailed discussion of the stable-isotope record of the Carnduff cores at this time, further stable-isotope and geochemical analyses are planned as part of a subsequent study.

7. Correlation with the GSSP, Kuhjoch, Austria and discussion of the Triassic-Jurassic Boundary

Hillebrandt et al. (2013) established the base of the Jurassic boundary at Kuhjoch at the first occurrence of the ammonite *Psiloceras spelae tirolicum*. Placement of the Triassic–Jurassic boundary at sites away from the GSSP continues to prove problematic. Biostratigraphic correlation is hampered by the extinction crisis in the latest Triassic as well as the often unfavourable facies for marker fossils such as ammonites.

Lindström et al. (2017) established a revised correlation of north-west European Triassic–Jurassic boundary sections based on a combination of radiometric dates, $\delta^{13}\text{C}$ isotope events and palynological signatures, especially the relative abundance of spores *Ricciisporites* and *Polypodiisporites* in the latest Triassic, though it is uncertain how local climate conditions might contribute to the record of sporiferous plants. Korte et al. (2019) discussed to key role that geochemical signatures play in correlating Triassic-Jurassic boundary sequences across long distances.

7.1 Palynology

Palynological comparisons between the current study and those of Bonis et al. (2009) and Hillebrandt et al. (2013) at the GSSP locality at Kuhjoch, Austria demonstrates quantitative differences in palynofloral composition that are interpreted to reflect local differences in the composition of the contemporaneous vegetation related to local palaeoenvironmental conditions rather than stratigraphic differences. However, selected miospore events may be of potential correlative value between Austria and Northern Ireland. Figure 10 illustrates a correlation of the latest Triassic to very earliest Jurassic interval between the St

Audries Bay and Carnduff sections, based on lithostratigraphy, carbon stable-isotopes and some palynological evidence.

Increased numbers of *K. reissingeri* (reported as *Heliosporites reissingeri* in the Austrian material) are encountered at and below 320.30 m in CRN-1 (= c.357.80 m CRN-2; equivalent depths in CRN-2 are c.37.5 m deeper than in CRN-1) and the species is continuously present throughout the Waterloo Mudstone Formation. At Kuhjoch, elevated numbers of this taxon characterise the *Trachysporites – Heliosporites* (TH) Zone in an interval that overlies the Schattwald Beds which immediately succeed the Initial CIE.

Based on a short abundance-interval of *Polypodiisporites polymicroforatus* noted across many of the European localities, Lindström et al. (2017) concluded that the Schattwald Beds are chronostratigraphically equivalent to the Cotham Member (*sensu* St Audries Bay section, UK). However, this species is not recorded in the Carnduff cores. Lindstrom et al. (*Ibid.*) also used the changing relative abundance of *Riccisporites* for correlation but the pattern is not always consistent between localities. The relative abundance of *Riccisporites* at Carnduff is noted on Figure 10C where there is marked decline in abundance coinciding with the onset of the Initial CIE.

At the GSSP, the first occurrence of the spore *Cerebropollenites thiergartii* was taken as an additional indicator for the base of the Jurassic where it occurred 3 m below the first occurrence of the ammonite marker *Psiloceras spelae tirolicum*. The first occurrence of *C. thiergartii* at Carnduff occurs at a depth of 321.20 m in CRN-1 (equivalent to a depth of approximately 358.07 m in CRN-2), this is within the Langport Member of the Lilstock Formation, just 0.45 m below the base of the Waterloo Mudstone Formation, close to the top of the Initial CIE and about 8 m below the first ammonite at Carnduff. However, its first consistent occurrence begins at 319.50 m in CRN-1.

The same event occurs about 4 m above the base of the Blue Lias Formation (Lias Group) at St Audries Bay at the onset of the Main CIE indicating a significant offset between these two bioevents over just a few 100 km (Figure 10). This serves to reinforce the difficulties of using some of the palynological datums as precise markers. Other markers agree more closely, for example the top of high numbers of *R. tuberculatus* in CRN-1 (top Westbury Fm.) correlates well with St Audries Bay and the same is true for the last occurrence of the same species in both records, just into the Main CIE.

7.2 Stable-isotopes

It is not our intention to undertake a detailed discussion of the stable-isotope record of the Carnduff cores at this time, further stable-isotope and geochemical analyses are planned as part of a subsequent study.

Korte et al. (2019) point to the geologically rapid injection of isotopically light CO₂ into the atmosphere during CAMP volcanism and the utility of such events as stratigraphical markers over great distances, emphasising their importance in overcoming problems in palaeontological archives where there may be ecological constraints and controls.

The Initial CIE in the $\delta^{13}\text{C}_{\text{TOC}}$ at Carnduff covers much of the Lilstock Formation with the most negative stable-isotope values at the top of the Cotham Member to lowermost Langport Member. This suggests that the Lilstock Formation must correlate with an interval below the base of the Schattwald Beds at Kuhjoch where the CIE occurs at the GSSP, some 5.8 m below the Triassic-Jurassic boundary level (Hillebrandt et al., 2013). The Schattwald Beds cannot therefore be correlated to the Cotham Member as suggested by Lindstrom et al. (2017).

It follows that, if the Initial CIE at Carnduff and Kuhjoch represent the same event, then the Triassic-Jurassic boundary at Carnduff must be within the very highest part of the Langport Member or above (i.e. in the Waterloo Mudstone Formation). It must therefore be between the top of the Initial CIE (359.42 m CRN-2;

321.5 m CRN-1) and the first occurrence of ammonites (349.6 m CRN-2; 313.3 m CRN-1) a 10-11 m interval in each core based on the CIE data. Palynology would suggest between 321.20 and 322.10 m (CRN-1, 358.66 to 359.56 for CRN-2) based on the first occurrence of *Cerebropollenites thiergartii*.

8. *Palaeoenvironmental interpretation*

The palaeontological evidence indicates a marine depositional environment throughout with marine dinocysts present throughout most of the Penarth Group and marine ostracods, foraminifera and ammonites throughout the Lias Group. There is no sedimentary or faunal evidence to suggest complete anoxia in the bottom waters. Benthic foraminiferal morphogroups have been used to interpret the oxygenation status of bottom waters and the interstitial environments (Jorrißen et al., 1995; Jones & Charnock, 1985) and this approach has been applied to Early Jurassic assemblages (e.g. Reolid et al., 2014; Rita et al., 2016; Józsa et al. 2018). However, there must be some uncertainty as to how applicable the ecological models, established in modern deep-sea environments, are applicable to deep-time ecosystems. Furthermore, the composition of most Early Jurassic benthic foraminiferal assemblages is often dominated by elongate uniserial taxa such as *Paralingulina*, *Marginulina* and *Mesodentalina*, and these taxa are often dominate earliest Jurassic assemblages even where conditions are interpreted to be well-oxygenated.

Some of the morphological schemes employed can be complex (e.g. Reolid et al., 2019) and given the reservations above, these may not be appropriate for this study. Notwithstanding these comments, a much reduced, bi-modal scheme is demonstrated on the right-hand side of figure 6 where the relative proportions of infaunal and epifaunal benthic foraminiferal taxa are shown. Note that some samples did not yield any benthic foraminifera while records with less than 5 specimens were omitted from the calculations. These data broadly show the dominance of epifauna in the very earliest Hettangian, largely driven by the abundant occurrence of the opportunist *Reinholdella? planiconvexa* with the remainder of the core dominated by infauna, other than for three samples in the mid- to late Bucklandi Chronozone. These changes may reflect strong environmental changes, interestingly, most samples are dominated by one of these two modes of life, few are equally distributed.

It is not possible to say what role oxygenation plays in these assemblage changes, though some insight might be gained from the preservation of amorphous organic matter (AOM) in the palynological residues (well-preserved AOM usually reflects minimal oxidation). The relationship between foraminiferal morphogroups and preservation of AOM in CRN-1 is inconclusive, some samples with well-preserved AOM (e.g. 314.90 and 306.06 m) are dominated by epifaunal taxa while other samples (e.g. 238.80, 241.50 and 259.00 m) are dominated by infauna. It should be noted that ostracods are complex metazoans with presumably higher biological oxygen requirements than the foraminifera, they are present in most samples and often highly abundant.

9. Conclusions.

The Carnduff-1 and Carnduff-2 boreholes have revealed relatively continuous records of sedimentation across the Penarth and Lias groups that encompass the Triassic-Jurassic boundary interval. Palaeontological evidence, predominantly from the Lias Group, provides a robust chronology for that unit while a combination of palynology and carbon-isotope profiles permits a correlation between Northern Ireland and similar intervals across Europe, including the Triassic-Jurassic GSSP at Kuhjoch, Austria. The palaeontological and sedimentary evidence supports restricted and marginal marine facies throughout the Penarth Group and normal marine conditions throughout most of the Lias Group, though the basal few metres are devoid of both ammonites and calcareous microfossils.

The relatively high sedimentation rate through this interval at Carnduff (base Westbury Member to base Lias Group 23.6 m at CRN-2, compared with c.12.5 m at St Audries Bay, North Somerset) suggests that the relatively unweathered, and possibly more complete, Northern Ireland record could provide a more detailed insight into volcanism, carbon-cycling and related processes during this interval than is otherwise available for NW Europe. Figure 10 provides a lithostratigraphic correlation of the latest Triassic to earliest Jurassic interval between St Audries Bay and Carnduff with carbon stable-isotopes and palynological markers highlighted.

The integrity of the stable-isotope record suggest that these cores could prove to be important geochemical archives for further studies investigating the processes of Late Triassic volcanism in the Central Atlantic Magmatic Province and its impact upon global climates, especially relating to the latest Triassic extinction event.

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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.00000487> (Boomer et al., 2020).

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Figure 10. Detailed stable-isotope record through the Triassic–Jurassic boundary interval at Carnduff compared to St Audries Bay with additional biostratigraphic markers. Ammonite symbol marks their first occurrence at each site, the letter C marks the first occurrence of *Cerebropollenites thiergartii* in each section. A. $\delta^{13}\text{C}$ inorganic CRN-2, B. $\delta^{13}\text{C}$ organic CRN-2, C. % *Riccisporites* for comparison with Lindstrom et al. (2014), D. $\delta^{13}\text{C}$ organic from St Audries Bay.

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