LATE TRIASSIC TO EARLY JURASSIC MICROFOSSILS AND PALAEOENVIRONMENTS OF THE

WATERLOO MUDSTONE FORMATION, NORTHERN IRELAND

By

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ABSTRACT

Northern Ireland Waterloo Mudstone Formation has received relatively little attention due to the scarcity of exposures and poor availability of subsurface records. The recent recovery of latest Triassic to Early Jurassic strata from boreholes permits further study of biostratigraphical and palaeoenvironmental using foraminifera and ostracods. The samples are from boreholes (Ballinlea-1, Magilligan and Carnduff-1) and exposures (White Park Bay, Tircrevan Burn, Larne, Ballygalley, Ballintoy and Kinbane Head). The age of the sections, established using foraminiferal biozonation ranges from latest Triassic (Rhaetian) to earliest Pliensbachian (JF9a).

The assemblages recovered broadly similar to those elsewhere in NW Europe; European Boreal Atlantic Realm. The latest Rhaetian to earliest Sinemurian low diverse microfossil assemblages dominant by metacopid ostracods with occasional influx of opportunist foraminifera but gradually, foraminiferal abundances exceed the ostracods in the Early Sinemurian onwards with their highest diversity in the Late Sinemurian. The foraminiferal assemblages are dominated by foraminifera of the Lagenida, other groups include the Miliolida, Buliminida and Robertinida. Based on the microfossils, the sediments are considered to represent confined inner shelf environment in latest Rhaetian to Hettangian then gradually recovered to well-oxgenated, open marine deposits of outermost inner shelf to middle shelf in Early Sinemurian to Early Pliensbachian.

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Chapter 1

Introduction

1.1 Introduction

During the Permian and Triassic, supercontinent Pangea rotated anticlockwise and moved northward (Hesselbo, 2012; Holdsworth *et al.*, 2012) as part of its ongoing break-up. By the Jurassic (Brenchley & Rawson, 2006; Cope, 2006; Hesselbo, 2012; Holdsworth *et al*., 2012), Britain and Ireland moved further north from 30°N to 40°N latitude (Simms, 2004; Hesselbo, 2012; Holdsworth *et al*., 2012). During this time, the climate was dry summers but cooler wet winters towards the north UK (Hudson & Trewin, 2002; Cope, 2006; Hesselbo, 2012).

The Late Triassic-Early Jurassic progressive transgression (Figure 1.2) which was triggered by continual rifting of Pangea and consequent global sea-rise (Hudson & Trewin, 2002; Brenchley & Rawson, 2006; Holdsworth *et al.,* 2012) resulted in a transition of the Permian-Triassic semi-arid (non-marine setting across much of north west Europe) to a Jurassic marine setting (Cope, 2006; Hesselbo, 2012). The sea-level rise (Figure 1.3) also led on to the widespread deposition of mudrocks across much of Britain and Ireland (Hesselbo, 2012). Although during earliest Jurassic much of the UK generally lay beneath shallow shelf sea (Figure 1.1), the London Platform, south-west of England, Mendip Hills, south-west Wales and much of Scotland and Ireland are presumed to have been land areas (Bradshaw *et al*., 1992; Cope, 2006) (Figure 1.1). These land areas

contributed sediments to the formation of Jurassic rocks in adjacent basins but the main source

was probably from the Scandinavian landmass (Cope, 2006).
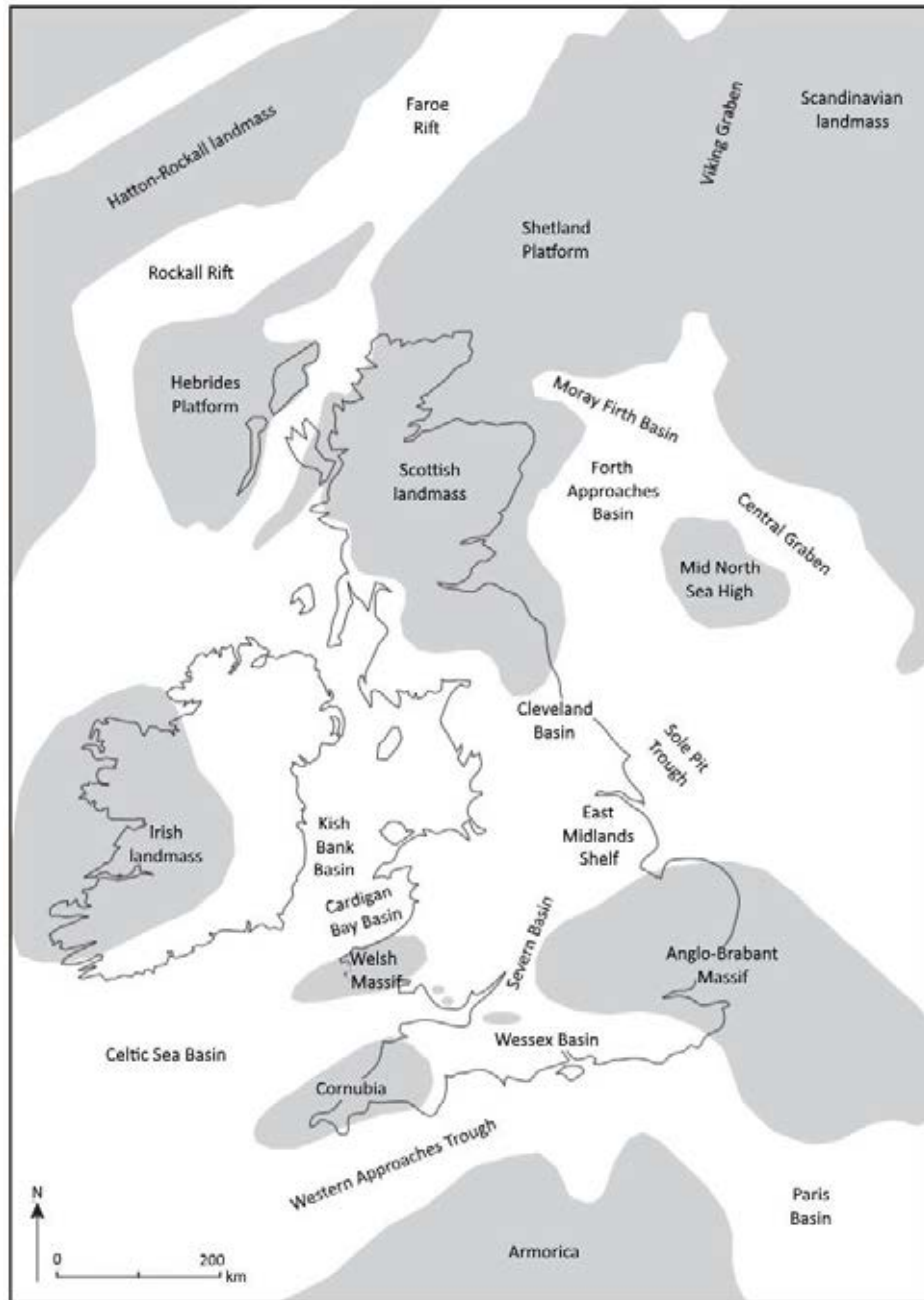
Figure 1.1: UK and adjacent areas during the Hettangian, Early Jurassic (light shading: sea, dark shading: land). After Bradshaw *et al*. (1992), modified by Simms (2004).
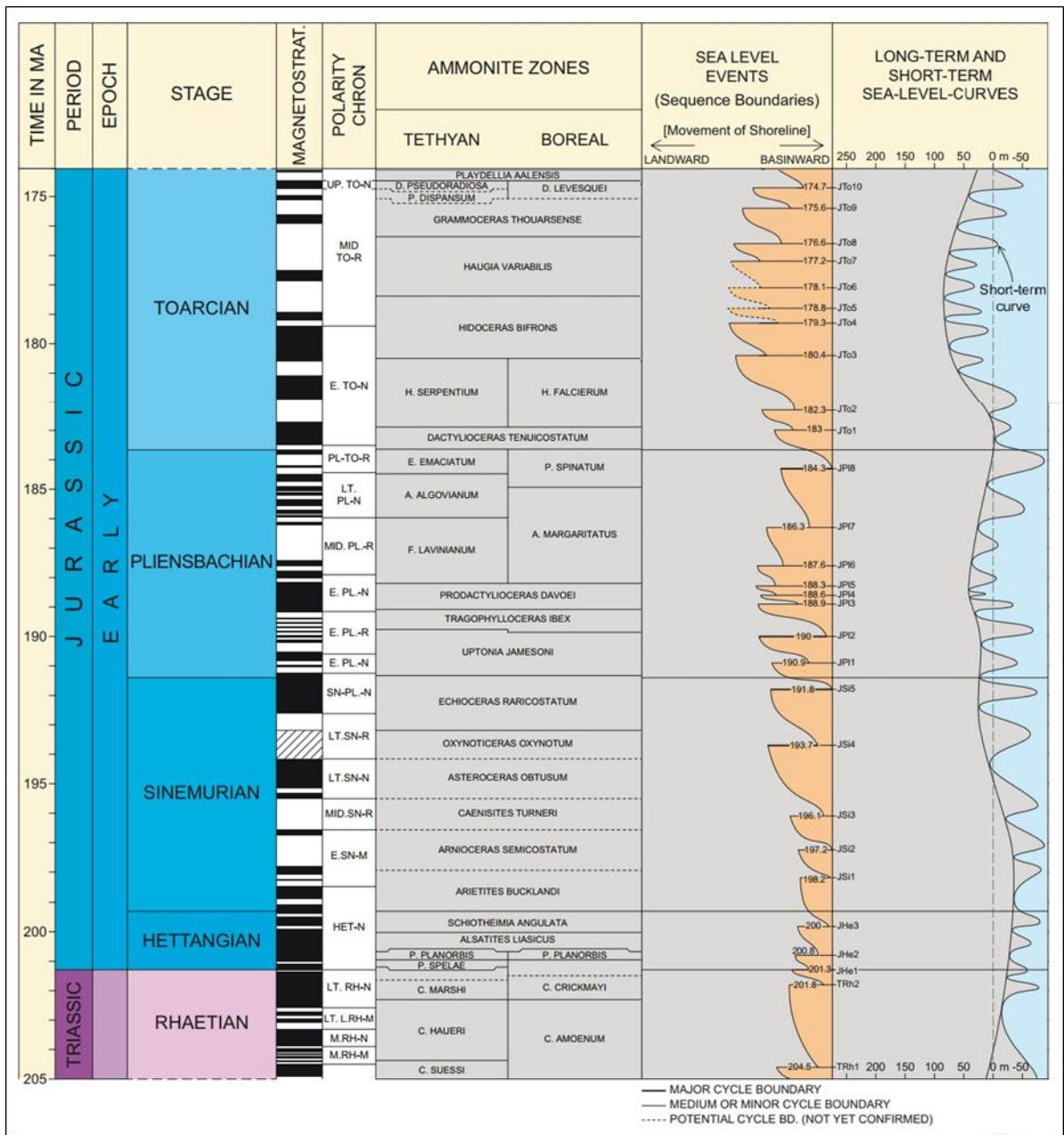
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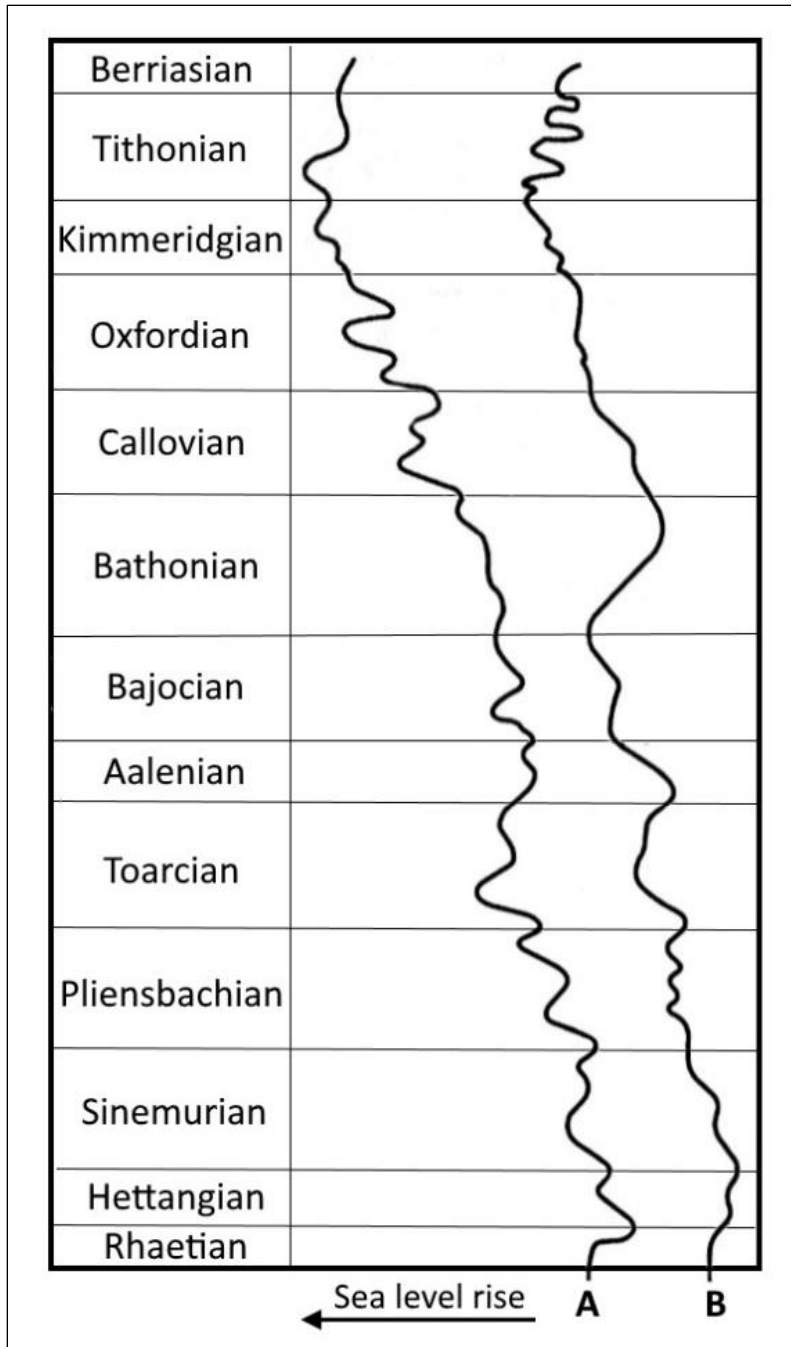
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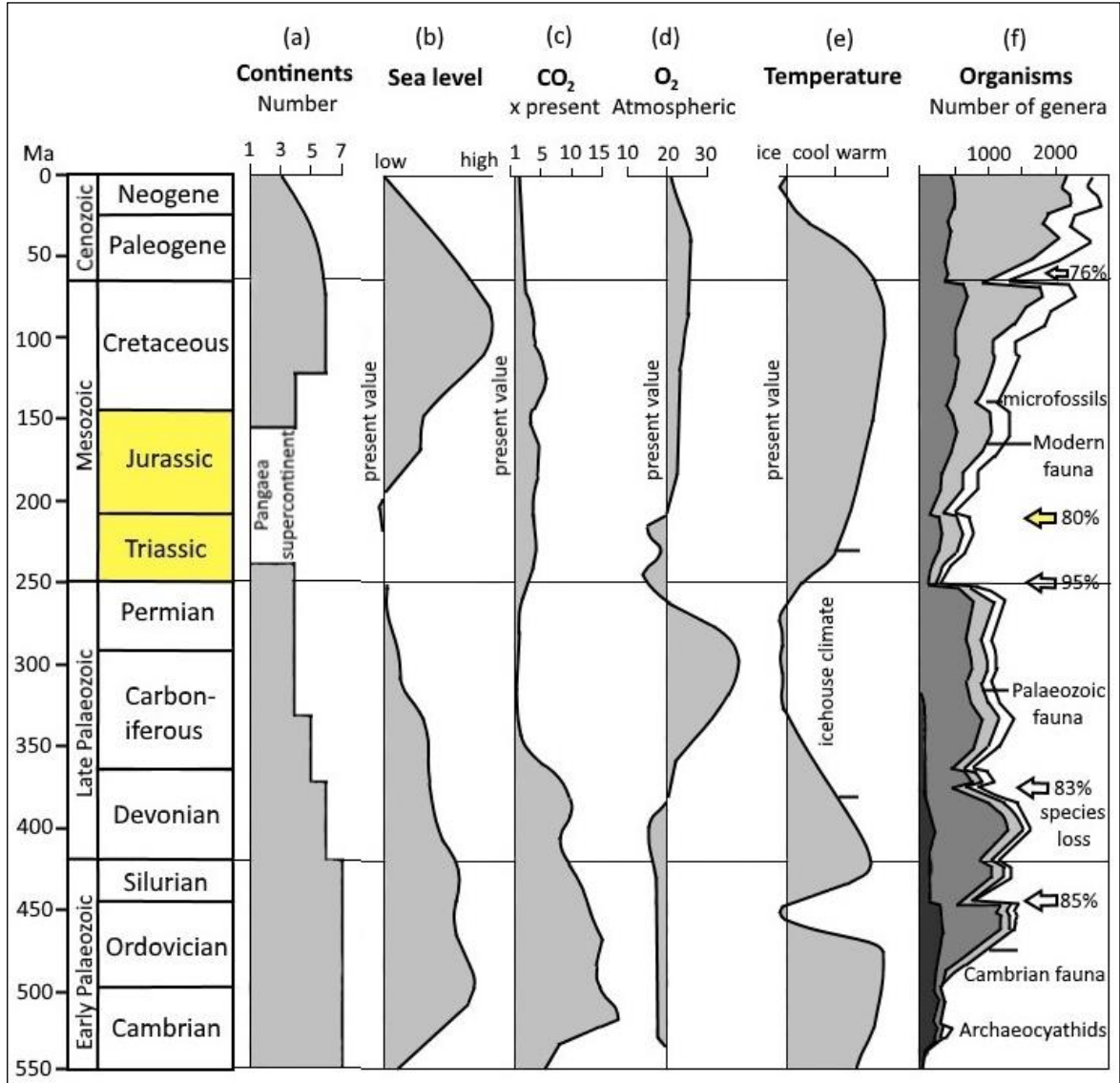
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The transgression and warm climate also supported a rich marine fauna, particularly ammonites and densely vegetated land areas (Reeves *et al.*, 2006; Howells, 2007). These marked the recovery from Triassic-Jurassic extinction; one of the ''big five'' Phanerozoic mass extinctions(Figure 1.4) (Newell, 1963; Hallam, 1990; Hallam & Wignall, 1997; Hallam & Wignall, 1999; Hesselbo, 2012) that resulted in the extinction up to 80% of marine species (Wignall & Bond, 2008; Holdsworth *et al.,* 2012; Barash, 2015). This mass extinction is thought to have been triggered by the Central Atlantic Magmatic Province basaltic eruption (Hallam & Wignall, 1997; Wignall & Bond, 2008; Deenen *et al.*, 2010; Hesselbo, 2012; Barash, 2015), sea-level fall (Hallam 1981; Hallam & Wignall, 1997; Hallam & Wignall, 1999; Wignall & Bond, 2008, ; Holdsworth *et al.,* 2012) and extraterrestrial impact (Hallam & Wignall, 1997; Hesselbo, 2012; Barash, 2015).

1.2 Rathlin, Lough Foyle and Larne basins tectonic setting

The three boreholes examined for this research are from three different basins (Figure 1.5 and Table 1.1); Rathlin Basin, Lough Foyle Basin and Larne Basin. The Ballinlea-1 borehole is situated at the middle of the Rathlin Basin (north Co. Antrim), whereas the Magilligan Borehole (Londonderry) is located in the Lough Foyle Basin, southwest of the Rathlin Basin. The Carnduff-1 borehole is located in the east of Co. Antrim; Larne Basin. The development of these basins was contributed by pre-existing fault reactivation, newly formed Mesozoic extensional faults and Pangea rifting (McCaffrey & McCann, 1992; Johnston, 2004; Holdsworth *et al.*, 2012).

The Rathlin and Lough Foyle basins are situated next to each other and both are post-Variscan transtensional half-graben basins comprising mostly Permian and Triassic fill (Johnston, 2004). The Rathlin Basin is an elongate, almost trapezoid-shaped basin (Anderson *et al.,* 1995) and trends northeast-southwest (McCann, 1988) to NNW-SSE (Johnston, 2004), deepening towards the southeast into the Tow Valley Fault (McCann, 1988). This basin is situated onshore under north Antrim and Londonderry and continues offshore between the Irish coast and Islay (McCann, 1988; McCaffrey & McCann, 1992; Fitzsimons & Parnell, 1995). According to Fitzsimons & Parnell (1995), the Foyle and Tow Valley faults (Figure 1.5) control the extent of the Rathlin Basin. This basin is separated from the Lough Neagh-Larne Basin to the south by the Highland Border Ridge (McCaffrey & McCann, 1992).

Whilst Lough Foyle Basin is bounded by Foyle Fault of northeast-southwest orientation and the basin elongated and deepens to the southeast underneath the Lough (Johnston, 2004). The east of this basin is concealed under the Antrim Plateau (Johnston, 2004).

The Larne Basin is NE-SW orientated and is the southwest extension of the Midland Valley in Scotland which partially lies onshore Northern Ireland, continue offshore through the North Channel seaway (Shelton 1997; Dunnahoe, 2016). The sediments in Larne basin thicken to the west and range from Carboniferous to Cenozoic but the thickest and predominant are Permo-Triassic sequences (Shelton, 1997; Dunnahoe, 2016). Triassic-Cretaceous sediments from this

basin crop out in the Larne area yet the remainder are concealed beneath the Antrim Plateau (Johnston, 2004).
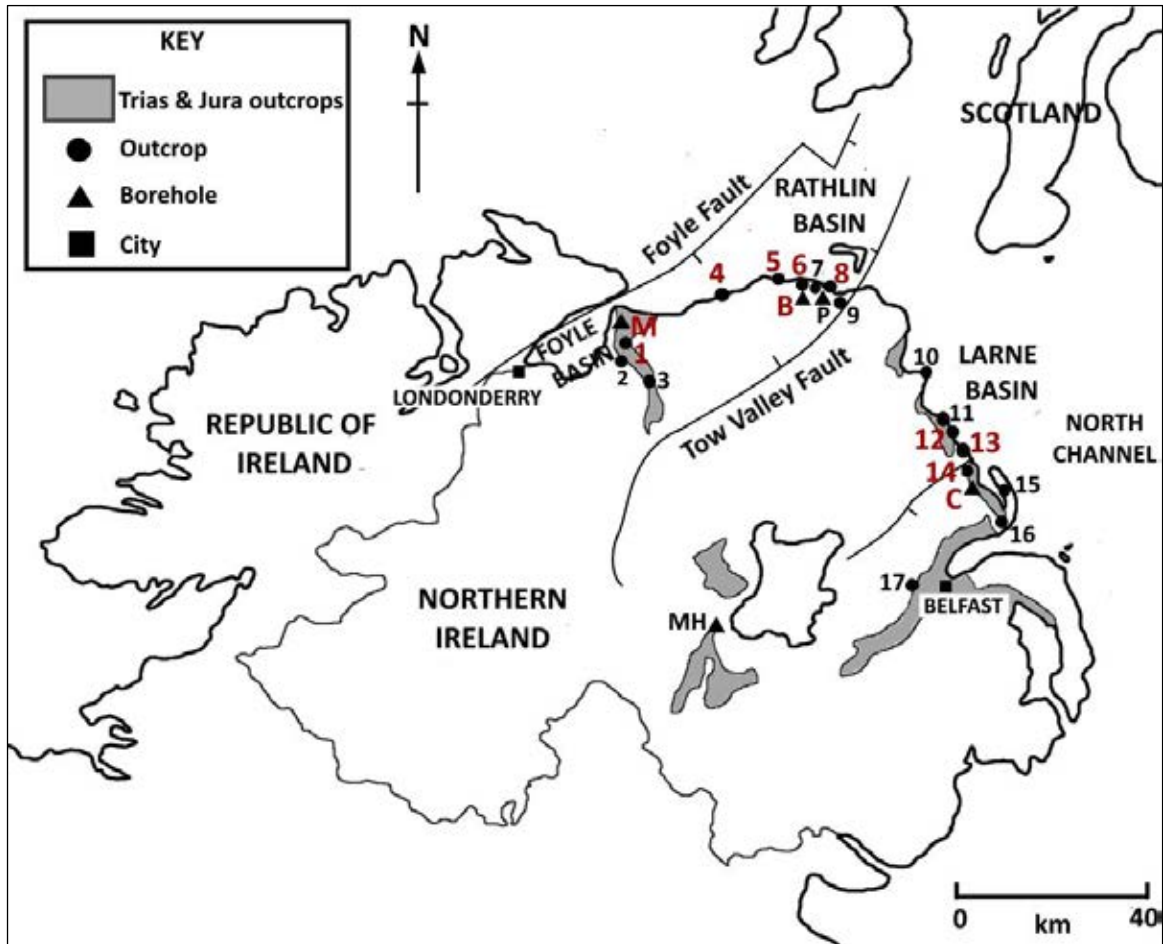
Figure 1.5: Distribution of Triassic and Jurassic sediments in Northern Ireland, together with location of Rathlin Basin, Foyle Basin, Larne Basin, boreholes (B: Ballinlea-1; M: Magilligan; C: Carnduff-1; P: Port More; MH: Mire House) and localities containing Triassic and Jurassic exposures (1: Tircrevan Burn; 2: Ballymaglin; 3: Tircorran; 4: Portrush; 5: Whitepark Bay; 6: Ballintoy; 7: Portnakillew; 8: Kinbane Head 9: Ballycastle; 10: Garron Point; 11: Glenarm; 12: Minnis; 13: Ballygalley; 14: Waterloo Bay; 15: Whitehouse; 16: White Head; 17: Collin Glen). The map is modified from George (1967), Warrington (1997) and Middleton *et al*. (2001).

Locality	Grid reference
Ballinlea-1 Borehole	D 03765 39317
Magilligan Borehole	C 70039 33251
Carnduff-1 Borehole	D 40150 00983
Ticrevan Burn	C 70126 32552
Portrush	C 85725 41021
White Park Bay	D 02271 44184
Ballintoy	D 03625 45177
Kinbane Head	D 08951 43354
Minnis	D 33835 13695
Ballygalley	D 37901 07956
Waterloo Bay, Larne	D 40786 03768

Table 1.1: The grid references of examined or visited localities.

1.3 Late Triassic and Early Jurassic sequences in Northern Ireland

The upper part of the Mercia Mudstone Group is the Collin Glen Formation formerly termed the 'Tea Green Marls'; it consists mainly of calcareous greenish grey to dull green mudstone and is devoid of red beds (Bazley & Thompson, 2001). However, Mitchell (2004) stated that the basal Collin Glen Formation has around 1 m thick of alternating red and green mudstone subsequently

by 10 m pale greenish green silty mudstone with thin beds of auto-brecciated micrite. Similarly to the Blue Anchor Formation in the southern Britain (equivalent of Northern Ireland Collin Glen Formation; Warrington, 1997); it is characterised by predominantly grey-green with few thin beds of red-brown mudstone in the lower part, while upper part mainly composed of greenish grey silty mudstone (Barton *et al.,* 2011).

The Mercia Mudstone Group lies disconformably below the Penarth Group (Mitchell, 2004). The group is divided into the Westbury Formation and Lilstock Formation. The Westbury Formation based on Larne No. 1 borehole (Mitchell, 2004) and Waterloo section (Simms & Jeram, 2007) comprises black and dark grey shale with silty laminae and thin sandstones. The formation has bivalve dominated levels with low diversity marine faunas (Simms & Jeram, 2007). The Lilstock Formation possesses brown-grey mudstone and dark grey micaceous mudstones both with siltstone laminae (Bazley & Thompson, 2001; Mitchell, 2004).

The best Penarth Group-Lias Group boundary is exposed at Waterloo Bay, Larne (Simms & Jeram, 2007) (Figure 1.6) marked the conformable base of the Lias Group (Waterloo Mudstone Formation) at the dark-grey, shelly-mudstone facies. The boundary also crops out at White House, Islandmagee and Collin Glen (Wilson, 1972). Meanwhile, in the northern part of Co. Antrim, this boundary has not been observed in any exposures. This conformable boundary is recorded in boreholes such as at Port More (Wilson & Manning, 1978) and Magilligan (Bazley *et al.*, 1997) by
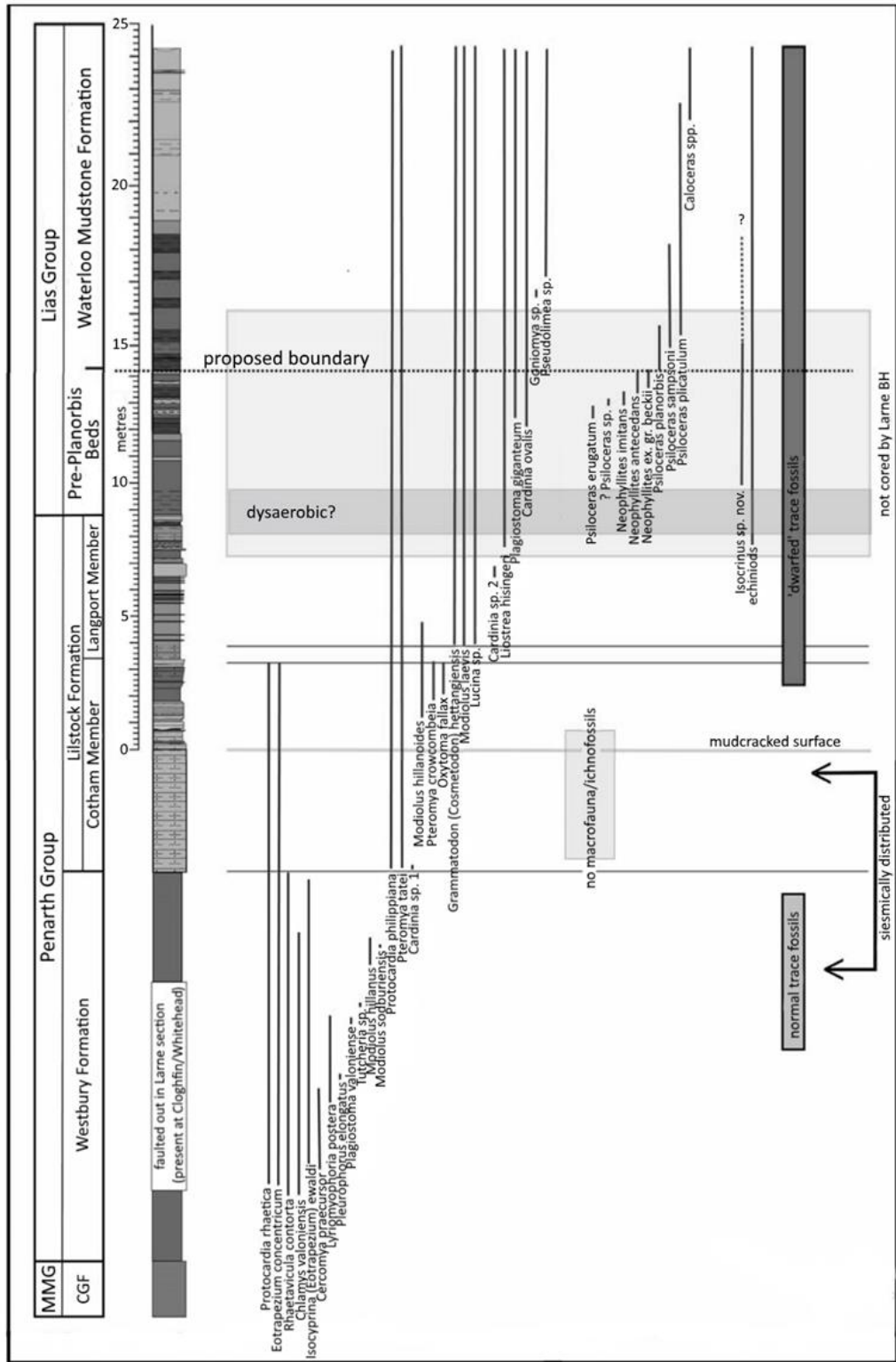
Figure 1.6: Penarth-Lias boundary and Triassic-Jurassic boundary exposed at Waterloo, Larne, east Co. Antrim with range of macrofaunas and microfaunas (Simms & Jeram, 2007).

contrast, the Lias Group from Ballytober-1 Borehole unconformably overlies the Mercia Mudstone Group (Fynegold Petroleum, 1991).

The Waterloo Mudstone Formation named after the Waterloo Bay, Larne (Mitchell, 2004; Simms & Jeram, 2007); is dominated by grey calcareous mudstones with subordinate laminae of silty mudstone and fossiliferous limestone (Broughan *et al*. 1989; Bazley & Thompson, 2001; Mitchell, 2004). Besides the argillaceous dominance, arenaceous facies do occur but only in early Sinemurian strata. A thin (13 m) sandstone bed within which there are a few organic rich 'coals' (Tircrevan Sandstone Member) are well-preserved at Tircrevan Burn; Co. Londonderry (Mitchell, 2004).

Exposures of the Late Rhaetian to Early Pliensbachian Waterloo Mudstone Formation in Northern Ireland are relatively rare, mostly small (Figure 1.5), discontinuous, faulted and prone to landslip as they are rest unconformably below cliffs of Late Cretaceous chalk and Paleogene basalt (Wilson, 1972; Ivimey-Cook, 1975; Broughan *et al*., 1989; Warrington, 1997; Cripps *et al.,* 2002; Mitchell, 2004). The Waterloo Mudstone Formation exposures confined to the Late Triassic-Early Jurassic period and can be observed at numbers of localities (Figure 1.5), for example Ballintoy Harbour (Wilson & Manning, 1978), Collin Glen (Anderson, 1954 in Charlesworth, 1960; Reid & Bancroft, 1986), Barney's Point (Island Magee; Ivimey-Cook, 1975; Griffith & Wilson, 1982; Charlesworth, 1960), Waterloo Bay, Larne (Charlesworth, 1960; Reid & Bancroft, 1986; Broughan *et al.*, 1989; Mitchell, 2004; Simms & Jeram, 2007), Ballymaglin (Reid & Bancroft, 1986), Tircorran

(Reid & Bancroft, 1986), Garron Point (Ivimey-Cook, 1975; Griffith & Wilson, 1982; Reid & Bancroft, 1986), Glenarm (Reid & Bancroft, 1986), Portnakillew (Wilson, 1972; Reid & Bancroft, 1986; McCann, 1988) , Portrush (Charlesworth, 1960; Wilson & Robbie, 1966; Wilson, 1972; Wilson & Manning, 1978; Reid & Bancroft, 1986; McCann, 1988; Warrington, 1997; Mitchell, 2004); Tircrevan Burn (Reid & Bancroft, 1986; Mitchell, 2004), Kinbane (Wilson & Robbie, 1966; Wilson & Manning, 1978) Whitehead (Charlesworth, 1960; Ivimey-Cook, 1975; Griffith & Wilson, 1982) and White Park Bay (Charlesworth, 1935, 1960; Wilson & Robbie, 1966; Wilson, 1972; Wilson & Manning, 1978; Reid & Bancroft, 1986; McCann, 1988). The outcrops are thin, rarely exceeding 30 m in thickness and often occur around the coastal margins of the Paleogene Antrim Basalt Plateau (Antrim Lava Group; Wilson, 1972).

However, thicker Early Jurassic successions have been penetrated in boreholes (Figure 1.7); Port More borehole (270 m; Wilson & Manning, 1978; Shelton, 1997; 250 m; McCann, 1988; Broughan *et al.*, 1989; Parnell *et al.*; 1992; 248 m; Mitchell, 2004), Mire House borehole (125 m; Charlesworth, 1960; Warrington, 1997; Mitchell, 2004), Magilligan borehole (90 m; McCann, 1988; 68 m, Broughan *et al.*, 1989), Larne-1 borehole (51.5 m; Manning & Wilson, 1975; Broughan *et al.*, 1989; Shelton, 1997) and Ballymacilroy (86 m; Broughan *et al.*, 1989).

Most of Northern Ireland's Early Jurassic outcrops possess Planorbis and Angulata chronozone (Hettangian) strata (Charlesworth, 1960). Yet, some younger sections are observed from the Waterloo section, Larne (up to Bucklandi Chronozone, earliest Sinemurian) and Collin Glen (up to

Obtusum Chronozone, earliest Late Sinemurian; Charlesworth, 1960). Generally, the younger sections are more commonly exposed along the northern coast of Co. Antrim such as at Portrush (Raricostatum Chronozone, latest Sinemurian; Wilson & Manning, 1978) and Kinbane Head (Ibex Chronozone, Early Pliensbachian; Wilson & Robbie, 1966). Based on Charlesworth (1935, 1963) the Waterloo Mudstone Formation at White Park Bay reaches as high as the Davoei Chronozone (Early Pliensbachian). However, Wilson & Manning (1978) affirmed that the White Park Bay Waterloo Mudstone Formation exposures only belongs to the Raricostatum (Late Sinemurian) and Ibex Chronozones (Early Pliensbachian) which is unconformably overlain by the Cretaceous Ulster White Limestone Formation at the eastern end of the bay (Oweynamuck; Wilson & Manning, 1978). Some sections of the Waterloo Mudstone Formation at White Park Bay had been intruded by numbers of minor dolerite sill, this has caused induration of the adjacent mudstone (Symes *et al.,* 1888) but only to less than 1 m. Similarly, the Late Sinemurian, ammonite-rich exposures at Portrush have been metamorphosed to hornfels due to the contact with the Paleogene dolerite of the Portrush Sill (Wilson, 1972; Mitchell, 2004). Such intrusions are also observed in the Ballinlea-1 borehole (630 m-668 m and 238 m-330 m).

For subsurface, the youngest Northern Ireland Early Jurassic sediments; Ibex Chronozone (Early Pliensbachian) are recovered from Port More Borehole (Warrington, 1997). This demonstrates that the Waterloo Mudstone Formation in the Rathlin Basin appear more complete than in the Larne-Lough Neagh Basin (Ivimey-Cook, 1975). The differences in this completeness are a consequence of structural events that occurred between the Pliensbachian and Cenomanian

Figure 1.7: Correlation of lithostratigraphic logs of Triassic and Jurassic successions from Northern Ireland boreholes; Port More (Wilson & Manning, 1978); Mire House (Fowler & Robbie, 1961), Magilligan (Bazley *et al*., 1997) and Ballinlea-1 (this study).

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(Warrington, 1997); faulting (George, 1967; Fletcher, 1997 in Warrington, 1997) and pre-Cretaceous erosion (Broughan *et al.*, 1989).

There is no in-situ evidence for Jurassic sediments younger than early Pliensbachian although fragments of younger sediments have been discovered along north coast such as Ballintoy and Portrush (Wilson & Manning, 1978). Numerous authors proposed that these blocks are glacial erratics, possibly from the Inner Hebrides, western Scotland (Versey, 1958; Warrington, 1997 & Wilson & Robbie, 1966). More local sources are suggested as Rathlin Island (Wilson & Robbie; 1966) or offshore exposures in the Rathlin and Kish Bank basins (Warrington, 1997). Furthermore, the basal Cretaceous conglomerate that crops out at Oweynamuck (Wilson & Robbie, 1966; Wilson & Manning, 1978) and Murlough Bay (Hartley 1933; Versey 1958; Savage 1963; Wilson & Robbie 1966; Wilson 1972, 1981; Wilson & Manning 1978) contain remanie of late Early Jurassic fossils which were described by Hartley (1933 in Wilson & Robbie, 1966) as Toarcian ammonites, most probably *Dactylioceras* from the *crassum* group.

Based on the presence of Mid and Late Jurassic beds on Skye and Mull, it is possible that more recent Jurassic beds were once present in Northern Ireland but have been eroded during pre-Cretaceous erosion (Wilson, 1972), possibly following uplift during the Kimmerian (George, 1967; Bradshaw *et al.*, 1992; Hancock & Rawson, 1992; Shelton, 1997) to Early Cretaceous (George, 1967; Shelton, 1997; Warrington, 1997) or Cenomanian periods (Bradshaw *et al.*, 1992; Hancock & Rawson, 1992).

1.4 The Lias Group in the Great Britain

The Lias Group had been deposited in Wessex Basin (include parts of Somerset and South Wales), Severn Basin (=Worcester Basin; with adjoining Bristol-Radstock Shelf), Cleveland Basin and East Midlands Shelf (Cox *et al*., 1999; Hobbs *et al*., 2012), Cardigan Bay Basin (Woodland, 1971; Boomer, 1991; Copestake & Johnson, 2014), Cheshire Basin (Evans *et al*., 1993; Warrington, 1997); Carlisle Basin (Ivimey-Cook *et al*., 1995; Warrington, 1997) and Portland-Wight Basin (Ainsworth & Riley, 2010).

The Early Jurassic exposures in England (Figure 1.8) extend in continuous northeast-southwest trending exposures from Yorkshire (Hesselbo & Jenkyns, 1998; Hesselbo *et al*., 2000; Simms, 2004; Cope, 2006; Price & Ford, 2009) in the north through Lincolnshire (Kemp & McKervey, 2001), the Midlands (Ambrose, 2001; Cope, 2006), Gloucestershire (Simms, 2003); the Cotswolds (Donovan *et al*., 2005), Somerset (Hylton, 1998, 1999) to the Dorset coast in the south (House, 1989; Hesselbo & Jenkyns, 1998; Kemp & McKervey, 2001; Wignall, 2001; Cope, 2006; Gallois, 2009; Barton *et al*. 2011; Hobbs *et al*., 2012). The most significant exposures of Lias Group are exposed at coastal cliff sections in between Lyme Regis and Bridport (Dorset; House, 1989; Hobbs *et al.*, 2012), between Robin Hood's Bay and Redcar (Yorkshire; Hesselbo *et al.,* 2000; Hobbs *et al*., 2012), St. Audrie Bay (Somerset; Warrington *et al*., 1994) and East Quantoxhead, (West Somerset; Hylto, 1998, 1999).

Even though continuous cliffs between Pinhay Bay and Lyme Regis possess a full thickness of Blue

Lias sections (Gallois, 2009; Barton *et al*., 2011), the type section for this formation are from

Saltford railway cutting near Bath (Donovan, 1956; Torrens & Getty, 1980; Ambrose, 2001). About

203 m thick of Early Jurassic strata crop out in the cliff north of the village of East Quantoxhead,

approximately 6 km east of Watchet (Page, 1995; Hylton, 1998, 1999; Bloos & Page, 2002). The

Hettangian-Sinemurian transition is approximately 5 times thicker than other equivalent

sequences (Hylton, 1998) plus well-developed Early Sinemurian ammonite faunas helped support

this section for selection as the Global Stratotype Section and Point (GSSP) for the base of the

Sinemurian and hence the Hettangian-Sinemurian boundary (Page, 1995; Bloos & Page, 2002).

Whilst, the outcrops from Robin Hood's Bay (Wine Haven, Yorkshire) provide another GSSP

section, but for the base of the Plienbachian (Hesselbo *et al.*, 2000; Meister *et al.*, 2006). In 1994,

Warrington *et al*. proposed the cliff at the west side of St. Audrie's Bay, Somerset as a GSSP for

the base of the Hettangian. However, this section (Warrington *et al*., 1994) was not selected as

the GSSP of the base Hettangian in favour of the Kuhjoch section, Karwendel Mountain in Austria

(Von Hillebrandt *et al*., 2007).

The Lias Group had traditionally been subdivided into the Lower, Middle and Upper, but to

replace these imprecise divisions and provide a stable guideline, British Geological Survey with

support of the Geological Society of London developed a formational framework for the Lias

Figure 1.8: Surface and subsurface map of England and Wales Lias Group and sedimentary basin. After Cox *et al.* (1999) and Simms (2004).

Group onshore area of England and Wales and divided the Lias Group into 12 formations (Cox *et al.*, 1999). The formations are listed in Table 1.2 according to their basins, whereas the age and lithologies descriptions are summarized in Table 1.3. Copestake & Johnson (2014) also discussed and illustrated about these different successions (Figure 1.9).

In Wales, Lias Group exposures are limited to the Vale of Glamorgan, South Wales (Wobber, 1968; Hesselbo & Jenkyns, 1998; Cope, 2006; Sheppard *et al.*, 2006; Howells, 2007) but thick Jurassic strata are recorded around Wales; Cheshire, the Celtic Sea, Bristol Channel and Cardigan Bay basins (Howells, 2007). In the Vale of Glamorgan, about 150 m thick of late Rhaetian (pre-planorbis)-Early Sinemurian (Semicostatum Ammonite Chronozone) Blue Lias formation (Waters & Lawrence, 1987; Wilson *et al.*, 1990) lies conformably on top of the Penarth Group, and is divided into three members in ascending order St. Mary's Well Bay Member, Paper Shales and Bull Cliff Member (Howells, 2007). The Early Jurassic succession (Hettangian-Toarcian) in Wales discovered in Mochras Borehole, Cardigan Bay Basin (at 1304.95 m) is the thickest known Early Jurassic succession in Britain (Woodland, 1971; Boomer, 1991; Hesselbo, 2012; Hesselbo *et al.*, 2013; Copestake & Johnson, 2014). Due to this thickness, the Pliensbachian basal ammonite biozone is twice the thickness of Robin Hood's Bay Pliensbachian sequence, this emphasizes the global importance of Mochras Borehole in stratigraphy (Hesselbo *et al.*, 2013).

Basin		Formation (in ascending stratigraphical order)
Cleveland		Redcar Mudstone, Staithes Sandstone, Cleveland Ironstone, Whitby Mudstone, Blea Wyke Sandstone
Wessex		Blue Lias, Charmouth Mudstone, Dyrham, Beacon Limestone, Bridport Sand
Worcester		Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone, Bridport Sand
East Midlands Shelf	South	Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone.
	North	Scunthorpe Mudstone, Charmouth Mudstone, Marlstone Rock, Whitby Mudstone

Table 1.2: Formations of Lias Group based on basins (Cox *et al.*, 1999).

Formation	Age	Lithologies
Blue Lias	latest Rhaetian-Sinemurian (Bucklandi, Semicostatum, Turneri, Obtusum or Oxynotum Ammonite Chronozone)	Thin bed argillaceous limestone alternating with calcareous mudstone or siltstone
Scunthorpe Mudstone	latest Rhaetian-Late Sinemurian (Obtusum or Oxynotum Ammonite Chronozone)	Grey calcareous or silty mudstone with thin beds of argillaceous limestone either bioclastic or micritic and calcareous siltstone
Redcar Mudstone	Hettangian (Planorbis Ammonite Chronozone)-Pliensbachian (Davoei Ammonite Chronozone)	Grey fossiliferous mudstones and siltstones with subsidiary thin beds of shelly limestone at the base and fine-grained carbonate-cemented sandstone at the top

Charmouth Mudstone	Sinemurian (base within Bucklandi, Semicostatum, Turneri or Obtusum Ammonite Chronozone)	Dark grey, light grey and blueish grey mudstones and dark grey laminated shales, some areas have profuse argillaceous limestone or sideritic nodules; some levels comprise 'paper shale' or silt and fine sandstone beds.
Staithes Sandstone	Early Pliensbachian (Davoei Ammonite Chronozone)-Late Pliensbachian (Margaritatus Ammonite Chronozone)	Silty sandstone with 2 to 4 m thick of fine-grained laminated sandstone
Dyrham	Early Pliensbachian (Davoei Ammonite Chronozone)-Late Pliensbachian (Margaritatus Ammonite Chronozone)	Light, dark or greenish grey silty and sandy mudstone with interbedded silt or very fine sandstone
Cleveland Ironstone	Late Pliensbachian (Margaritus-Spinatum Ammonite Chronozone)	Mudstone, siltstone and silty sandstone with rhythmic thin seams of sideritic and berthierine-ooidal ironstone at the top of formation
Marlstone	Late Pliensbachian (Spinatum Ammonite Chronozone)-Early Toarcian (Tenuicostatum Ammonite Chronozone)	Sandy, shell-fragmental, ferruginous berthierine-ooidal limestone with ferruginous and calcareous sandstone
Beacon Limestone	Late Pliensbachian (Spinatum Ammonite Chronozone)-Late Toarcian (Thouarsense Ammonite Chronozone)	Variable colour of limestone with ferruginous-ooidal in the lower section and nodular in the upper section
Whitby	Late Pliensbachian (topmost Spinatum Ammonite Chronozone)-Toarcian	Medium and dark grey fossiliferous mudstone and siltstone with thin siltstone or silty mudstone and occasional calcareous sandstone

Blea Wyke Sandstone	Late Toarcian (Levesquei Ammonite Chronozone)	Fine-grained sandstone with grey-weathering argillaceous below while yellow-weathering and silty above
Bridport Sand	Toarcian-Aalenian	Grey micaceous siltstone and fine-grained sandstone which some weathered to yellow or brown; locally with calcite-cemented beds, doggers or lenticular masses (sand-burrs) and infrequent argillaceous strata

Table 1.3: Age and lithologies descriptions of Lias Group's formations (Cox *et al.,* 1999).

The Early Jurassic exposures in Scotland are small and relatively few small; for example, the Dunrobin Coast section (north-east Scotland) and remnants along the Solway Firth Basin (south Scotland; Simms, 2004). The only extensive and well-preserved Scottish Jurassic sediments crop out in the Inner Hebrides and nearby areas; with important sections at Skye, Raasay, Eigg, Muck and Mull, with smaller exposures at Rum, Shiant Isles, Applecross, Ardnamurchan and Morvern (Hesselbo & Jenkyns, 1998; Hudson & Trewin, 2002; Morton, 2004; Simms, 2004). The Jurassic strata of 1494 m thick are discovered within the deepest part of the Hebrides-Little Minch Basin, while for onshore regions, the extensive Early Jurassic beds are documented in Skye; 40% (500 m out of total thickness; 1300m) of the Jurassic sequences belong to Early Jurassic sediments of Hettangian to middle Pliensbachian age (Hesselbo *et al*., 1998; Ainsworth & Boomer, 2001). In
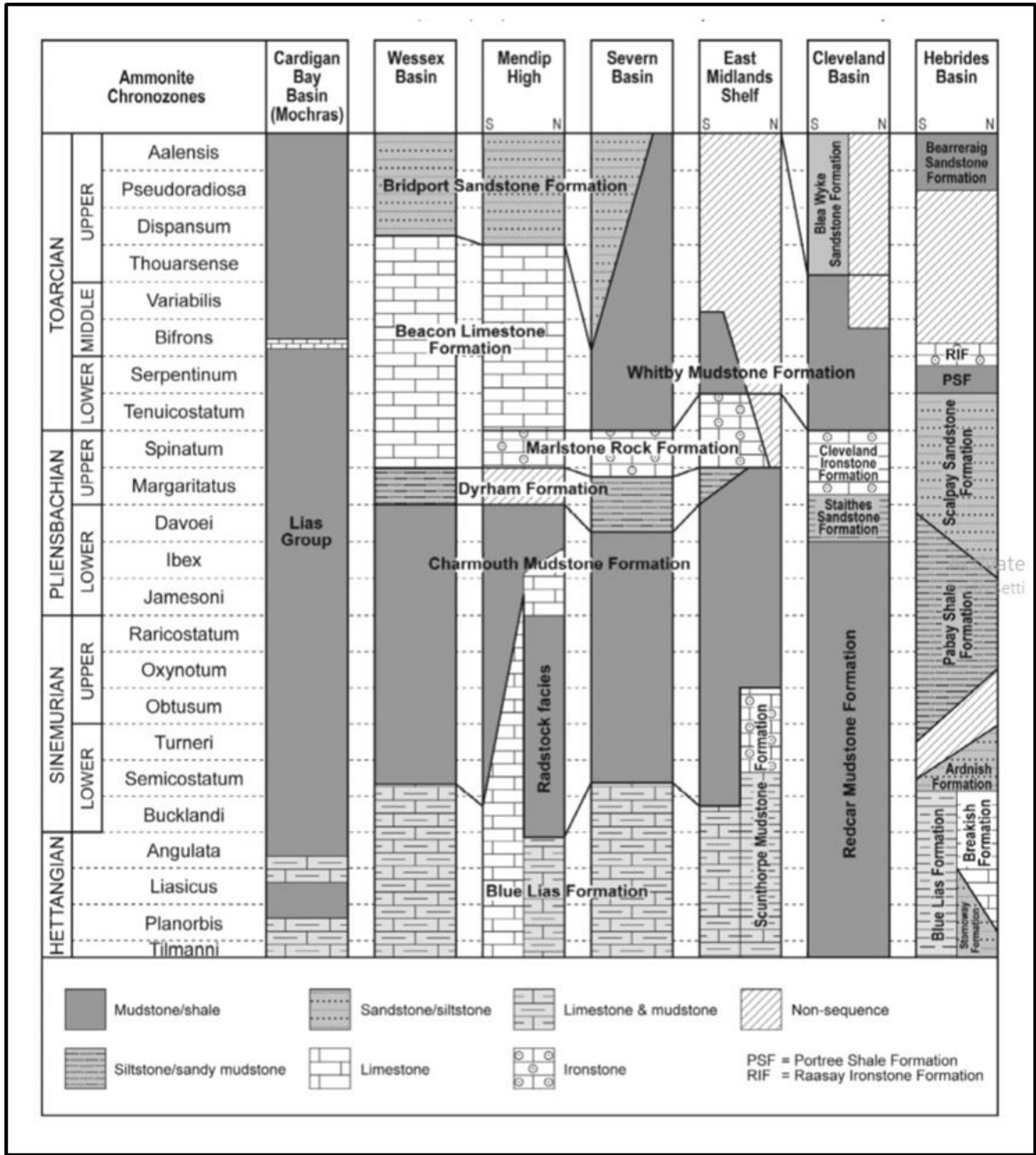
Figure 1.9: Comparison of Early Jurassic successions in the UK (Copestake & Johnson, 2014).

general, Scottish Early Jurassic sequences have a greater proportion of coarse clastic sediments than their English equivalents, for example, in the Moray Firth region (Hudson & Trewin, 2002).

The earliest Jurassic lithologies which deposited in the northern part of Inner Hebrides (Skye-Pabay-Raasay) consist of shallow marine facies; alternating of limestones, sandstone, mudstone and siltstones. (Hesselbo *et al*., 1998; Hesselbo & Coe, 2000). These facies known as the Breakish Formation, ranges from Hettangian to earliest Sinemurian age (Morton, 1999; Hesselbo *et. al*, 1998; Hesselbo & Coe, 2000). This formation overlies by the Pabay Shale Formation of Early Sinemurian to middle Pliensbachian age (Hesselbo *et al*., 1998; Hesselbo & Coe, 2000) which has well-developed sandstone unit (Torosay Sandstone Member) at it Early Sinemurian-Late Sinemurian boundary. Torosay Sandstone Member incompletely crop out at few localities on the southeastern coast of Mull (Hesselbo *et al*., 1998).

1.5 Microfossils biozonation schemes

Even though high-resolution ammonite zones have been achieved in outcrops studies, the shortage of macrofossils in the core material has prohibited their use for borehole materials (Partington *et al.* 1993). According to Copestake (1993), the microfossils are more valuable to determine biostratigraphy of borehole because of their small size (allow them to survive destruction by the drilling bit), abundance and rapid evolution. Thus, the application of

microfossils as stratigraphic markers has developed in response to the requirements of the oil industry.

The first Early Jurassic foraminifera zonal scheme was produced by Bartenstein & Brand (1937) due to the need of correlating subsurface sequences during oil exploration in the onshore western Germany (Haynes 1981, Simms *et a*l. 2004, Copestake & Johnson, 2014). Their works are well illustrated and important (Barnard 1949) although most of the species proposed are long-range species (Copestake & Johnson, 2014). The similar attempt then followed by Barnard (1949) based on the study of the Dorset Early Jurassic foraminifera specimens. He correlated the foraminifera with the ammonite chronozone; from Planorbis to Daveoi Ammonite Chronozone. In another Europe regions, Bang from Denmark (1968) and Norling from Sweden (1972) are one of the earliest author applied this kind of biozonation. Michelsen (1975) also initiated the microfossils zonation scheme but he only focused on Hettangian-Pliensbachian ostracods from the offshore Danish embayment. Later in 1987, Park presented Early Jurassic (only up to Early Pliensbachian) ostracods biozonation based on the southern North Sea Basin records. A comprehensive examination of exploration wells by Ainsworth (1989, 1990) provided detail studies of ostracods faunas from offshore southwest Ireland. Another ostracods zonation scheme also established by Boomer (1991) but from the Mochras Borehole samples. In 1981 and 1989, Copestake & Johnson outlined the Jurassic foraminifera biozones based on the several boreholes in the Great Britain. Later, Partington *et al.* (1993) established a scheme (MJ zones) specific to the Jurassic of the North Sea Basin. They calibrated the microfossils (dinoflagellate cyst, radiolaria, ostracods and

foraminifera) with each event of maximum flooding surface. In 1998, Ainsworth *et al.*, also constructed biostratigraphic zonation of the latest Triassic to the earliest Cretaceous but only from three different groups; ostracods (Zone OJ), foraminifera (Zone FJ) and dinocyst (Zone DJ). These biozonations were established for English Channel boreholes and its adjacent onshore areas. Meanwhile, at the offshore Inner Hebrides Scotland, Ainsworth and Boomer (2001) determined the age of the well L134/5-1 sections based on the abundant and the first appearance of the foraminifera and ostracods stratigraphic markers. Few years later, the same authors published an ostracods range chart that produced from several sections of the Great Britain and Ireland (Boomer & Ainsworth, 2009). They only included Early Jurassic short-range ostracods and correlated them with standard ammonite zonation.

The latest and most up to date foraminifera biozonation scheme was established by Copestake & Johnson (2014). Both of them are 30 years' experienced stratigraphers (foraminifera-based) in the oil industry. This scheme almost similar to Copestake & Johnson (1989), but the zonations are details published in Copestake & Johnson (2014), especially in terms of biozones and subzones. The biozones are erected on the basis of short range species (either their inception or extinction), common, abundant or their period of acme zone (Copestake & Johnson, 2014).

The biostratigraphic microfossils markers not just useful for hydrocarbon exploration but also for other purpose such as determination of macrofossils age. For instance, Lomax *et al*. (2017) used foraminifera and ostracods bioevents to assign the specific age of *Ichthyosaurus communis.* This

Stages/Substages	Ammonite Chronozones	Ammonite Subchrono-zones	Foraminifera Zones	First Appearances ('Bases')	Last Occurrences ('Tops')	Markers
Upper Toarcian	Aalensis	Fluitans - Mactra	JF16			R. macfadyeni ●
	Pseudoradiosa	Pseudoradiosa - Levesquei				
	Dispansum	Gruneri - Insigne		N. pseudoregularis		
	Thouarsense	Fallaciosum - Bingmanni		S. mochrasensis, L. dorbignyi ●		Consistent P. tenuistriata
Middle Toarcian	Variabilis		JF15			V. subvitreus ● (North Sea)
	Bifrons	Crassum		T. jurensis, consistent L. dorbignyi	L. payardi	
		Fibulatum				
		Commune	JF14		P. obonensis, M. prima spinata, M. prima prima, P. tenera occidentalis, consistent P. tenera tenera, consistent P. terquemi	L. quenstedti
Lower Toarcian	Serpentinum	Falciferum		C. longuemari gr. consistent, C. collezi ●		
		Exaratum	JF13	L. payardi, A. chicheryi ●		
	Tenuicostatum	Semicelatum	b		M. prima interrupta, S. sublaevis sublaevis, S. aragonensis, consistent I. terquemi terquemi, I. terquemi squamosa, E. aspera	
		Tenuicostatum				
		Clevelandicum	JF12	S. aragonensis		R. macfadyeni ●
		Paltum		P. obonensis		H. lincolnensis
Upper Pliensbachian	Spinatum	Hawskerense	a			
		Apyrenum		S. sublaevis sublaevis ●	H. lincolnensis ●, M. matutina ●	
	Margaritatus	Gibbosus	JF11			L. muensteri acutiangulata ●
		Subnodosus		I. terquemi mediumcostata		Consistent M. varians haeusleri
		Stokesi	JF10		Consistent V. denticulata-carinata	Consistent P. tenera subprismatica
Lower Pliensbachian	Davoei	Figulinum	b			
		Capricornus				
		Maculatum				
	Ibex	Luridum	JF9	H. lincolnensis		
		Valdani				
		Masseanum				
	Jamesoni	Jamesoni	a			
		Brevispina				
		Polymorphus				
		Taylori		Consistent/common V. denticulatacarinata	N. issleri	Common M. matutina, V. listi, A. speciosus
Upper Sinemurian	Raricostatum	Aplantum	JF8			
		Macdonnelli		P. tenera occidentalis		
		Raricostatoides				
		Densinodulum		I. terquemi squamosa		M. varians haeusleri ●
	Oxynotum	Oxynotum		M. prima spinata, M. prima interrupta,		
		Simpsoni	JF7			
	Obtusum	Denotatus				
		Stellare			R. margarita	N. bangae
		Obtusum	JF6	N. issleri	A. semireticulatus	
Lower Sinemurian	Turneri	Birchi				Consistent / L. tenera subprismatica
		Brooki	JF5	R. margarita		
	Semicostatum	Sauzeanum		M. matutina ●		V. listi
		Scipionianum		A. semireticulatus		N. bangae
		Lyra	b		I. liassica ●	N. bangae
	Bucklandi	Bucklandi	JF4			
		Rotforme	a		D. langi, L. tenera substriata,	
		Conybeari	JF3	D. langi, P. tenera substriata ●	I. terquemi barnardi	M. prima incisa, M. prima insignis, I. liassica (●)
Hettangian	Angulata	Complanata-Depressa		Consistent P. inaequistriata		
		Extranodosa	JF2		Consistent P. tenera collenoti	
	Liasicus	Laqueus		P. inaequistriata		
		Portlocki			Common P. tenera collenoti	
	Planorbis	Johnstoni		I. terquemi barnardi		R? planiconvexa ●
		Planorbis	JF1			
	Tilmanni					
Rhaetian				P. tenera collenoti		P. tenera plexus ●

Figure 1.10: Early Jurassic foraminifera biozonation for British and northern European area (filled circles represent abundance increases). After Copestake & Johnson, 2014.

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fossil is stored in the Lapworth Museum of Geology, University of Birmingham and has no provenance data. Thus, the best way to identify it age is by using microfossils analysis.

In this study, author decided to refer the most recent foraminifera biozonation schemes (after Copestake & Johnson, 2014) (Figure 1.10) with the aid of ostracods range chart published by Boomer & Ainsworth (2009). Although the microfossils bioevents can also influence by the local environment, remarkable uniformity of Early Jurassic species across north-west Europe make the correlation of Northern Ireland microfossils with these schemes possible.

As mentioned before, both of these schemes are correlated with the ammonite chronozone. Unfortunately, it is difficult for author to correlate ammonite chronozone with microfossils markers herein due to the limitation of provided samples. The main analysed borehole; Ballinlea-1 is ditch cuttings, thus no ammonite records can be found (usually absence due to the destruction by drilling bit). Whereas, Magilligan and Carnduff-1 are core sample yet only Carnduff-1 has recorded few good preservation ammonites. However, the detail classifications of these ammonites are still carrying out by Kevin Page. In view of the lack information on ammonite data, the author decided to just focus on foraminifera and ostracods to determine the specific age of the examined sequences.

1.6 Aims and objectives

Although there are a few previous studies on Early Jurassic foraminifera from Northern Ireland (e.g. McGugan, 1965) and data has been included in wider reviews (Copestake & Johnson, 1981, 1989), no comprehensive studies have been attempted for benthic microfaunas through these Early Jurassic successions. Thus, the primary aim of this research is to carry out a biostratigraphical study of Early Jurassic sediments from northern Irish boreholes and exposures to establish the full chronostratigraphic range of sediments preserved. The age of the youngest sediment at any one locality help define the upper erosional surface of the Early Jurassic sediments in this region. Detailed examination of foraminiferal and ostracods occurrences also will assist in the comparison of local microfossil biozonations with established schemes.

The objectives of this research are as follows:

1) To identify foraminifera and ostracods species from latest Triassic to Early Jurassic boreholes in Northern Ireland (samples provided by GSNI, the Geological Survey of Northern Ireland) and collections of Early Jurassic outcrop material from the accessible coastal localities.

2) To observe and record recovery patterns in benthic microfaunas after the late Triassic mass extinction, their recovery being associated with the latest Triassic-Early Jurassic transgression.

3) To propose specific Early Jurassic stages and lithostratigraphy of the studied strata based on the stratigraphic foraminifera and ostracods, with the aid of few macrofaunas (in some cores, an ammonite and bivalves are presence) and lithologies.

4) To assess the palaeoecology of the microfossils and thereby establish the depositional palaeoenvironments of the studied sections based on the presence of indicator species (foraminfera and ostracods).

5) To compare the results between the studied sequences. The localities are compared and correlated in terms of their microfaunas distribution, biozonation, age-range and palaeoenvironment.

6) To compare the Northern Ireland Jurassic microfaunas with records from adjacent regions; England, Wales, Scotland and the Irish Sea Basin.

7) To summarise the latest Triassic to Early Jurassic palaeogeographical settings of counties Antrim and Londonderry.

1.7 Thesis overview

The thesis is organised into ten chapters with 28 plates.

Chapter 1 provides review of the previous works on the Early Jurassic sediments of Great Britain and Northern Ireland. This chapter also explains about tectonic setting of studied basins and the history of Early Jurassic biostratigraphic biozonation schemes. At the end of introductory chapter, the objectives and aims of this research are listed.

The second chapter exclusively discusses about the disaggregation techniques applied to the samples. The methods are explained according to their localities for better understanding. There are two breakdown techniques used herein, hence the results of these different processing techniques also included in this chapter. Besides laboratory procedures, the relative abundance and Fisher's alpha diversity are also mentioned herein.

Chapter 3 presents detail stratigraphically and environmentally important benthic foraminifera and ostracods recovered from the analysed Northern Ireland sections. These selected species are discussed in terms of their morphology, variation, dimension, material and range.

Chapter 4 is specific for Ballinlea-1 Boreholes. The outcome of the microfossils study of this borehole enables detail explanation in it microfaunas assemblages, age and biozonation. The

interpretation of Early Jurassic palaeoenvironment and oxygenation level are established based on the microfossils environmental markers.

Chapter 5 also presents the similar contents like chapter 4, but the microfossils data are from Carnduff-1 Borehole. The chapter describes biostratigraphy, foraminifera biozonation, age and palaeoenvironment of the Waterloo Mudstone Formation (latest Triassic-Early Jurassic).

Chapter 6 includes two examined localities; Magiliigan Borehole and Tircrevan Burn. Both sites are closed to each other in which the Waterloo Mudstone Formation exposed at the Tircrevan Burn is the continuation sequences of the subsurface beds from the Magilligan Borehole. The results of the studies are discussed in terms of their microfossils assemblages, biozonation, chronostratigraphic age and palaeoenvironment.

Chapter 7 demonstrates the microfossils records of all exposures visited during the fieldwork together with their proposed biozonation and palaeoenvironmental interpretation. The collected samples are from the Antrim coast; White Park Bay, Ballintoy, KI nbane Head, Ballygalley and Waterloo.

The microfaunas analysis from three examined boreholes are compared in Chapter 8. The comparisons not only limited to these boreholes, but the existence of foraminifera and ostracods index markers are differentiated with adjacent regions too.

Chapter 9 will provide palaeogeography and palaeobiogeography summaries of Northern Ireland Waterloo Mudstone Formation. The summaries are initiated based on the type assemblages of foraminifera and ostracods recovered.

The final chapter; chapter 10 is the conclusion of the main findings of this research. In addition with few suggestions for future works.

The photographs images (Figure A-C) and SEM images (Plates 1-29) of microfossils and few macrofossils frgaments are present right after the reference section.

Chapter 2

Methodology

2.1 Samples and disaggregation methods

The material studied in this research comes from a number of localities located at Co. Antrim and Co. Londonderry, Northern Ireland. Access to three boreholes (Ballinlea-1, Carnduff-1 and Magilligan) was permitted by the Geological Society of Northern Ireland while complimentary surface samples were collected from the exposures of Tircrevan Burn, White Park Bay, Ballintoy, Kinbane Head, Ballygalley and Waterloo Bay.

2.1.1 Ballinlea-1 Borehole

The Ballinlea-1 hydrocarbon exploration well situated in the Rathlin Basin, north coast of Co. Antrim has proven the thickest sequence of Early Jurassic sediments in Northern Ireland; 605m with 120 cutting samples available for study. Stratigraphically, the borehole ranges from the Paleogene Antrim Lava Group (youngest) to the Late Triassic Mercia Mudstone Group (oldest). Our research interest focuses mainly on Early Jurassic samples and few Late Triassic sections which were recorded from 345 m to 980 m depth. The sequences are interrupted by a dolerite sill from 630 m to 668 m. A total of 120 samples (BAL255 to BAL980) at 5 metres intervals were

provided by GSNI (Geological Survey of Northern Ireland), of which 54 were chosen to undergo

two different disaggregation methods and another 17 samples had previously been picked by an

MSci student; Mark Jeffs (but sorted and identified by author). Two different methods of

disaggregation were applied; hydrogen peroxide and freeze-thaw method. The reason for

applying two different methods are explained in section 2.2. The first 30 cutting samples from

BAL345 to BAL610 were processed by using hydrogen peroxide method. About 70 g of cuttings

sample each was soaked in approximately 3% hydrogen peroxide for one hour. The soaking

duration was increased if the sample is indurated and not break down initially.

Another 34 cuttings samples (BAL685 to BAL980) underwent a freeze-thaw method. Again,

approximately 70 g of each sample was selected, placed in a small plastic tray, then tap water was

added until it covered the sediment. The tray was placed in a freezer until the water completely

freeze before it was taken out for thawing. The cycle can be repeated once or twice a day. The

softer rocks only required 3 freeze-thaw cycles to break down fully, but more cemented can took

up about 18 cycles to disaggregate well.

All the processed samples were washed through a 63 µm sieve and the retained sediment placed

inside an oven at 50°C overnight. Once dried, a half or quarter split of each sample was separated,

sufficient to provide 250-300 specimens and this was then dry-sieved to provide fractions at 63

µm, 125 µm, 250 µm and 500 µm. Sediment greater than 125 µm was usually totally picked with

additional scans through the 63 µm fraction to identify species not encountered in the larger

fractions. The presence of microfossils, macrofossils fragments and minerals were taken note (refer to Appendix E, G, I, J and L). However, the author only picked microfossils for further study. The microfossils were then classified according to their species and mounted on the 32 cells slide using water-soluble Gum Tragacanth glue.

2.1.2 Carnduff-1 Borehole

The Carnduff-1 borehole is from Larne Basin and was a salt exploration borehole. A total of 28 Late Triassic (Lilstock Formation) to Early Jurassic (Waterloo Mudstone Formation) Carnduff-1 core samples were selected from Geological Survey of Northern Ireland core store in Belfast. All these samples were processed by using freeze-thaw method. About 20 g-40 g of each sample was crushed by mortar and pestle then placed in small containers and weighed. The container was then filled with tap water and stored inside the freezer for approximately 12-24 hours. Later, it was placed in oven until it completely thawed. These freeze-thaw cycles were repeated 3 to 4 times depending on the sediments cementation. Subsequently, the disaggregated samples were washed through the 63 µm sieve under flowing tap water and dried in the oven at about 50°C for a day. After the final weight recorded, full to quarter or 1/8 fractions of the dry residues were sieved into 4 different fractions and all microfossils observed were picked, counted and identified for analysis. The extracted microfossils were lightly glued by Gum Tragacanth on 32 cell slides.

2.1.3 Magilligan Borehole

The Magilligan Borehole is a mineral exploration borehole situated in the Lough Foyle Basin. About 1 cm thick of each core sample (35 samples in total) were given by Geological Survey of Northern Ireland for this study. The provided samples belong to the Westbury Formation (Late Triassic) up to the Waterloo Mudstone Formation (Early Jurassic). From these 35 samples, only 28 samples were chosen to undergo freeze-thaw method. Approximately 10-20 g of each core sample was crushed by mortar and pestle to get pea-sized mudrock lumps. Later, the sediment was soaked in tap water before storing in the freezer. The frozen sample then thawed in the oven for few hours. The repetition of freeze-thaw only took 4 cycles to obtain a soft sample, but the more indurated ones took up to 18 cycles. If some samples were still unsuccessfully disaggregated, the hydrogen peroxide technique was applied but for just 5-15 minutes. Further steps are similar as in Ballinlea-1 (section 2.1.1) and Carnduff-1 (section 2.1.2) sections.

2.1.4 Tircrevan Burn exposure

One of the best early Jurassic outcrops are exposed along the Tircrevan Stream which was accessed easily when in low flow. We worked upstream to collect approximately 200 g of well-preserved outcrop. Only 5 bags of different samples were taken for further study. The exposures were cleaned first to avoid contamination.

The collected samples were cleaned and dried before undergoing processing. Later, about 30 g – 50 g sample each was soaked in 3% hydrogen peroxide for an hour before washed through 63 μm sieve. The subsequent processes are similar to those described in Ballinlea-1 section above (section 2.1.1).

2.1.5 Other outcrop localities

We visited seven localities (White Park Bay, Portrush, Ballintoy Harbour, Kinbane Head, Ballygalley, Minnis and Waterloo Bay) situated at Co. Antrim to observe the Waterloo Mudstone Formation outcrops. Out of these seven localities, the hand samples only taken from five localities (Table 2.1) using a cold chisel and hammer. The collected samples later processed by hydrogen peroxide methods for an hour.

The broken samples then washed through 63 μm sieve and fully dried inside the oven. The subsequent steps are as in Ballinlea-1 section (section 2.1.1).

Locality	Grid reference	Type of sample	Number of processed samples	Processing technique	Average number of microfossils picked per sample (the barren samples are not included in the calculation)
Ballinlea-1 Borehole	D 03765 39317	Cutting	71	Hydrogen peroxide and freeze-thaw	167
Carnduff-1 Borehole	D 40150 00983	Core	28	Freeze-thaw	285
Magilligan Borehole	C 70039 33251	Core	28	Freeze-thaw, only few soaked in hydrogen peroxide	81
Tircrevan Burn	C 70126 32552	Outcrops	5	Hydrogen peroxide	180
White Park Bay	D 02271 44184	Outcrops	7	Hydrogen peroxide	125
Waterloo Bay, Larne	D 40786 03768	Outcrops	1	Hydrogen peroxide	71
Ballygalley	D 37901 07956	Outcrops	1	Hydrogen peroxide	104
Ballintoy Harbour	D 03625 45177	Outcrops	1	Hydrogen peroxide	80
Kinbane Head	D 08951 43354	Outcrops	1	Hydrogen peroxide	117

Table 2.1: Summaries of processed samples from all studied localities.

2.2 Result of the different processing techniques

Throughout the disaggregation process of Ballinlea-1 samples, only two techniques had been applied herein; hydrogen peroxide method and freeze-thaw method. At the beginning, the Ballinlea-1 samples (BAL345-BAL610) were broken down by soaking them for one hour in dilute hydrogen peroxide (H_2O_2). This method broke down the sample successfully, unfortunately, the present of low to common pyrite in these samples made the usage of hydrogen peroxide is inappropriate. Kennedy & Coe (2014) concluded that the use of hydrogen peroxide can cause damage and dissolution of fragile calcium carbonate and pyritised microfossils. Kennedy & Coe (2014) also observed pitting morphology on the surface of pyritised microfossil processed using hydrogen peroxide, however, the same pyritised microfossil extracted by using freeze-thaw method preserved well with no evidence of damage to the tests. Thus, I decided to continue the remaining Ballinlea-1 samples (BAL685-BAL980) by using freeze-thaw technique. There is no direct comparison can be made in the term of preservation because no same sample has been tested for two different technique. However, if compared from the SEM images of different samples processed by different methods (for example BAL845 with BAL530), no obvious difference can be observed.

For Magilligan, a few samples were initially tested by using hydrogen peroxide to see the rate of disaggregation. Alas, the sample cannot break down well as most of the Magilligan samples are well cemented than Ballinlea's. So, different approach had been used for the whole Magilligan

samples. Kennedy & Coe (2014) describe freeze-thaw as effective method to breakdown the indurated rocks compared to the hydrogen peroxide technique. Therefore, I decided to apply freeze-thaw method to all Magilligan samples, even though some of them took about 18 freeze-thaw cycles. Furthermore, the use of this method proved to be a good decision as few depths such as MAG106.95 comprises abundant of pyritised microfossils. The usage of freeze-thaw technique on MAG106.95 resulted on well-preserved pyritised microfossils without any damage or pitting on their tests. This supported the observations of Kennedy & Coe (2014) regarding the advantage of freeze-thaw method on pyritised specimens.

The freeze-thaw technique was also applied to the Carnduff-1 samples. Most of the extracted microfossils are poorly preserved but these are due to the calcite overgrowth on the test walls not because of the technique used.

For outcrop samples, none of them were disaggregated by freeze-thaw method due to time constraints. Therefore, all of them were broken down using diluted hydrogen peroxide for short period of time (less than an hour) and the preservation of extracted microfossils are great despite delicate calcium carbonate test.

2.3 Microfossil relative abundance

The number of microfossils (abundance) is variable, it not only depends on the weight of picked residues but also the richness of the microfossil contents in each sample. Due to these variations, the raw abundance data should not be used directly as this will cause some bias. Therefore, the author normalised the assemblage abundance by calculate the amount of microfossils predicted per 10 g (initial weight). Below was the formula used to calculate this abundance:

$$\text{Relative abundance (per 10 grams)} = \frac{\text{Total of microfossils picked (raw abundance)}}{\text{Initial weight of analysed sample (g)}} \times 10 \text{ grams}$$

The data were plotted by using StrataBugs software. These results are shown in Figure 4.2, Figure 5.6, Figure 6.3, Figure 7.21, Figure 7.23, Figure 7.25, Figure 7.27, and Figure 7.29.

2.4 Species richness and Fisher's alpha index diversity

The diversity is the number of different species (richness) in a certain community or a sample. Some of the main aims of this study are to compare species diversity throughout each core and to compare with patterns of Early Jurassic foraminifera and ostracod diversity on much larger scales. The numbers of species found are partly related to the weight of the residue studied. Thus, the only concern when comparing the diversity is how to prevent bias by sample size. This

problem can be overcome by using an appropriate measurement. According to Magurran (1988) and Hayek & Buzas (1997), Fisher's alpha index is one of the frequent used formula to calculate the foraminiferal diversity. Even though the species dominance cannot be detected by using Fisher's alpha, it can avoid sample size bias (Shochat *et al*. 2004). For this study, author preferred to express the species diversities in Fisher alpha index.

Fisher alpha index is a measure of species diversity based on logarithmic parameter (Murray 2006, 2014; Barjau-González *et al*., 2012), in which the number of species represented by one individual, two individual and so on can be predicted (Murray, 2006). Below is the formula of Fisher's alpha index diversity (Fisher *et al*., 1943):

$$S = n_1 \left(1 + \frac{x}{2} + \frac{x2}{3} + \ldots\right)$$

Where S is the total number of species in the sample, n_1 the number of species represented by single specimens, and *x* is a constant having a value <1 but approaching this value as the size of sample is increased.

Meanwhile, n_1 can be calculated from *N*(1-*x*), *N* being the total number of individual specimens. As the size of the sample is increased, n_1 approaches α.

Different type of indices can be obtained from StrataBugs software. As per discussed above, the author only used Fisher's alpha index to calculate the diversity. The Fisher's alpha diversity data

for this research are plotted in Figure 4.2, Figure 5.6, Figure 6.3, Figure 7.2, Figure 7.24, Figure

7.26, Figure 7.28, and Figure 7.30.

Chapter 3

Northern Ireland benthic microfaunas

3.1 Foraminifera taxonomy

3.1.1 Introduction

Foraminifera are the most diverse and abundant microfossil group discovered from this research; 7 orders, 16 families, 29 genera and 167 species of benthic foraminifera, the most common being Lagenida in associate with order Robertinida, Miliolida and Buliminida.

The generic and suprageneric classifications applied in this study essentially from Loeblich and Tappan (1998), whilst the species classification is mainly referred to Copestake & Johnson (2014) as it is the most up to date Early Jurassic foraminifera scheme available. In this research, few foraminifera specimens are not able to identify in species level, thus named as Genus sp. A. Only the stratigraphical significance unidentifiable forms are included herein. The synonym will not be listed fully, only limited to the original designation and major generic shift. However, additional synonymies are included if there are description or illustration provided and closely similar to this study diagnosis taxa.

The preservation relatively good to moderate in all localities albeit domination of fragile tests such as aragonitic *Reinholdella* and thin calcitic *Paralingulina tenera* plexus. The only exceptional is Carnduff-1 as most of it samples consist poor preservation of foraminifera; frequent visible calcite overgrowth on the test walls.

This section only mentioned about important stratigraphic, environmental and abundant taxa. The remaining taxa are listed in Appendix B. The morphology of the species below discussed fully under description. Any distinctive variation within the species will also be explained but under variation section. Whilst, the remarks described about how to distinguish the species with other almost similar appeareance taxa or any other comments which author feels relevant or important to discuss. The full range of each species will be first written followed by each localities range of that particular species.

The range mentioned below are total range of the species from Copestake & Johnson (2014) together with the range of the species in each examined locality. Dimensions for the species are given in microns and all measurements are for the maximum distance excluded spines. Foraminifera SEM digital photomicrographs captured mainly using Phenom Pro and few by Joel 6060 and presented in Plate 1-19. The normal images of some specimens also taken using Canon DSLR and included under Figure A-Figure C (right before Plate 1).

3.1.2 Systematic descriptions

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CLASS FORAMINIFERIDA d'Orbigny, 1826

Order LAGENIDA Lankester, 1885

Superfamily NODOSARIOIDEA Ehrenberg, 1838

Family NODOSARIIDAE Ehrenberg, 1838

Genus PARALINGULINA Gerke, 1969 emend.

Paralingulina tenera (Bornemann, 1854) plexus

Paralingulina tenera collenoti (Terquem, 1866)

(Plate 1, figs 14, 15, 16 & 17)

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1866 *Marginulina collenoti* Terquem, p. 424, pl. 17, figs 1a-1b.

1876 *Lingulina striata* Blake, p. 455, pl. 18, figs 16, 16a.

1956 *Lingulina tenera* Bornemann form A ''*striata*'' Barnard, p. 275-279, pl. 2, 3, fig. 1.

1957 *Geinitzina tenera* (Bornemann) subsp. *striata* (Blake); Nørvang, p. 54-55, figs. 1a-1c, 2.

1981 *Lingulina tenera collenoti* (Terquem); Copestake & Johnson, p. 94-95, pl. 6.1.3, fig. 7.

1989 *Lingulina tenera collenoti* (Terquem); Copestake & Johnson, p. 178, pl. 6.2.4, fig. 7.

2014 *Paralingulina tenera collenoti* (Terquem); Copestake & Johnson, p. 189-191, pl. 8, fig. 16.

Description: Test elongate, uniserial, flattened, non-sulcate and almost parallel-sided with rpunded margin. Spherical proloculus followed by 8-10 gently arched chamber increasing in width only in first two chambers, later chambers remain same size until the final one. The surface has 8-10 longitudinal, irregular, similar strength, few discontinuous ribs and disappear before the oval aperture. Sutures are gently arched, flush except for the latter sutures; often depressed.

Remark: *Paralingulina tenera* plexus from Hettangian age appear almost similar to *P. t. collenoti* (Figure 3.1)*.* Most of them especially *P. t. pupa* are long like *P. t. collenoti*. However, they are differentiate based on their outline; *P. t. collenoti* almost parallel-sided while *P. t. pupa* is divergent-sided. *P. t. collenoti* ribs are irregular and discontinuous, whereas *P. t. pupa* has longitudinal, equal strength, and regular ribbing. *P. t. substriata* exist right after the extinction of *P. t. collenoti* and the features almost similar too but it is shorter, has median sulcus, carinated margin and comprises two irregular dominant ribs with interstital ribs in between them.

Dimension: Magilligan (pl. 1, fig. 14) length 534 µm, width 139 µm; (pl. 1, fig. 17) length 724 µm, width 168 µm. Ballinlea-1 (pl. 1, fig. 15) length 641 µm, width 153 µm. Carnduff-1 (pl. 1, fig. 16) length 679 µm, width 185 µm.

Material: Ballinlea-1 Borehole 32 specimens; Magilligan Borehole 30 specimens; Carnduff-1 Borehole 39 specimens.

Range: Total range: Late Rhaetian-Hettangian (Angulata Ammonite Chronozone, Copestake & Johnson 1981, 1989, 2014). Range of studied samples: Early-Mid Hettangian (Ballinlea-1 Borehole and Carnduff-1 Borehole), Mid Hettangian (Magilligan Borehole).

Paralingulina tenera pupa (Terquem, 1858)

(Plate 1, figs 9, 10, 11, 12, 13, 18 & 19)

1866 *Marginulina pupa* Terquem, p. 429, pl. 17, figs 7a-f.

1941 *Lingulina tenera* var. *pupa* (Terquem), Macfadyen, p. 52-53, pl. 3, figs. 53a, b.

1949 *Lingulina tenera* var. *pupa* (Terquem), Barnard, p. 367, figs. 6b, d.

1956 *Lingulina tenera* Bornemann forms I, H Barnard, p. 274, pl. 2; pl. 3, figs. 8-12.

1957 *Geinitzina tenera* (Bornemann) subsp. *pupa* (Terquem); Nørvang, p. 61-62, figs. 32-43.

1957 *Geinitzina tenera* (Bornemann) subsp. *praepupa* Nørvang, p. 60, figs. 30, 31.

1989 *Lingulina tenera pupa* (Terquem); Copestake & Johnson, p. 178, pl. 6.2.4, fig. 13.

2014 *Paralingulina tenera pupa*; Copestake & Johnson, p. 192-193, pl. 8, figs. 5, 12, 13, 18-20, 22, 26.

Description: Test multilocular, uniserial, pupiform, inflated and divergent-sided with round marginal. Spherical proloculus succeeding by 5-6 arched chambers gradually increase in width in latter chambers. Some forms yield slightly smaller final chamber compared to it previous chamber, but most of specimens seen have almost similar size of both latter chambers. The

surface is ornamented by two main ribs each side. These main ribs comprise finer interstitial ribs and continuous through the depressed sutures. Suture sometimes flush. Aperture terminal, central, slit-like and slight produced.

Variation: *P. t. pupa* exhibits varieties of forms. In latest Rhaetian to Hettangian stage reflected intermediate form of *P.t pupa* and *P. t collenoti* (Figure 3.1); *P. t. pupa* is long but has divergent-sided and equal strength of regular longitudinal ribs. The subspecies gradually revolute to the younger stage, where this species become more resemble to *P. t. tenuistriata* in Early Sinemurian stage. However, in Late Sinemurian, few flattened forms with equal strength of fine ribs which occasionally appeared discontinuously.

Remark: Intermediate form of *P.t. pupa* can be distinguished from *P.t. tenuistriata* by it rounded margin, absence of keeled and the interstitial striations are nearly strong like the main ribs and appear almost continuous. This intermediate form is difficult to differentiate just by using the microscope still the features details especially ribbing can be observed clearly by using SEM.

Dimension: Magilligan (pl. 1, fig. 9) length 450 µm, width 147 µm; (pl. 1, fig. 19) length 801 µm, width 183 µm. Ballinlea-1 (pl. 1, fig. 10) length 435 µm, 148 µm; (pl. 1, fig. 11) length 535 µm, width 135 µm, diameter of aperture 60 µm; (pl. 1, fig. 12) length 574 µm, width 140 µm, diameter of aperture 43 µm. Carnduff-1 (pl. 1, fig. 13) length 585 µm, width 137 µm; (pl. 1, fig. 18) length 746 µm, width 128 µm.

Material: Ballinlea-1 Borehole 1027 specimens; Magilligan Borehole 16 specimens; Carnduff-1 Borehole 45 specimens; White Park Bay 33 specimens; Ballintoy 2 specimens; Kinbane Head 13 specimens.

Range: Total range: Hettangian-Late Jurassic (Copestake & Johnson, 2014). Range of studied samples: Hettangian-Early Pliensbachian (Ballinlea-1 Borehole, Mid Hettangian-Early Sinemurian (Magilligan Borehole), Hettangian-Early Sinemurian (Carnduff-1 Borehole), Late Sinemurian (White Park Bay, Ballintoy and Kinbane Head).

Paralingulina tenera subprismatica (Franke, 1936)

(Plate 2, figs 10-15)

1936 *Nodosaria subprismatica* Franke, p. 48, pl. 4, fig. 17

1941 *Lingulina tenera* Bornemann; Macfadyen, p. 51-52, pl. 3, figs. 52a, b.

1956 *Lingulina tenera* Bornemann form B ''*prismatica*''; Barnard, p. 275-277, pl. 2.

1957 *Geinitzina tenera* (Bornemann) subsp. *subprismatica* (Franke); Nørvang, p. 57-58, figs. 11, 12, 14, 15.

1981 *Lingulina tenera subprismatica*(Franke); Copestake & Johnson, p. 95-96, pl. 6.1.3, figs 5, 6.

1984 *Lingulina acuformis* (Terquem); Riegraf *et al.*, p. 687, 699, pl. 7, fig. 179.

1989 *Lingulina tenera subprismatica* (Franke); Copestake & Johnson, p. 179, pl. 6.2.4, fig. 11.

2014 *Paralingulina tenera subprismatica* (Franke); p. 193-194, pl. 8, fig. 8.

Description: Test is uniserial, elongate, narrow, parallel-sided and non-compressed. Hexagonal in cross-section and keeled margin. Perforate wall. It proloculus; spherical in shaped commonly has basal spine but the recovered specimens mostly absence of spine. The test is made up of 5-7 chambers of almost same sizes but few specimens yield slightly smaller final chamber. The sutures are nearly horizontal, clearly depressed and thick. Each side of *P. t. subprismatica* has two primary longitudinal, parallel to sides, narrow ribs which stop before reaching the aperture. Few specimens exhibit 1 or 2 narrow interstital ribs each side. These interstitial ribs have equal strength as the main ribs. The aperture is similar like other *Paralingulina tenera* subspecies; terminal and oval.

Variation: Main *P. t. subprismatica* specimens found are typical form but intermediate form of *P. t. subprismatica* and *P. t. tenera* do occurred (Figure 3.1).

Remark: These two subspecies share same feature; has few ribs usually just two main ribs each side. The confusion usually happens in intermediate form of *P. t. subprismatica*. This is because, this form normally has slightly divergent-sided. However, it can be distinguished from *P. t. tenera* by it test outline; *P. t. subprismatica* is more elongate, narrower, only slightly diverge and hexagonal cross-section.

Dimension: Ballinlea-1 (pl. 2, fig. 10) length 459 μm, width 141 μm, diameter of aperture 34 μm; (pl. 2, fig. 11) length 527 μm, width 136 μm, diameter of aperture 64 μm; (pl. 2, fig. 12) length

506 µm, width 135 µm; (pl. 2, fig. 13) length 443 µm, width 145 µm; (pl. 2, fig. 14) length 276 µm, width 88 µm, diameter of aperture 29 µm; (pl. 2, fig. 15) length 255 µm, width 95 µm, diameter of aperture 25 µm.

Material: Ballinlea-1 Borehole 484 specimens; White Park Bay 9 specimens.

Range: Total range: end Early Sinemurian (Turneri Ammonite Chronozone)-Late Pliensbachian Margaritatus Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Early-Late Sinemurian (Ballinlea-1 Borehole), Late Sinemurian (White Park Bay).

P*aralingulina tenera substriata* (Nørvang 1957)

(Plate 1, figs. 1-3)

1957 *Geinitzina tenera* (Bornemann) subsp. *substriata* Nørvang, p. 55, figs. 3-10.

1981 *Lingulina tenera substriat*a (Nørvang); Copestake & Johnson, p. 95-96, pl. 6.1.3, fig. 8.

1989 *Lingulina tenera substriata* (Nørvang); Copestake & Johnson, p. 179, pl. 6.2.4, fig. 12.

1998 *Lingulina tenera* plex. *substriata* (Nørvang); Hylton, p. 205-206, pl. 1, fig. 5.

2014 *Paralingulina tenera substriata* (Nørvang); Copestake & Johnson, p. 194-195, pl. 8, fig. 6.

Description: Test uniserial, divergent, keeled and has indistinct sulcus. Subconical to spherical proloculus followed by 5-6 chambers which their width gradually increases until the final

chamber, still slightly smaller final chamber does occur infrequently. The sutures are generally flush except for few specimens; the latter sutures are depressed. This subspecies has two irregular, discontinuous, interrupted or wavy primary ribs with the presence of shorter, incomplete, discontinuous, sometimes slightly oblique secondary ribs. The aperture is terminal, central and oval in shaped.

Remark: *P. t. substriata* is differs from *P. t. collenoti* as *P. t. substriata* is less compressed test, has slightly median sulcate, keeled marginal and comprises two stronger, irregular main ribs. *P. t. substriata* almost similar to the *P. t. tenuistriata* except for *P. t. substriata* has irregular ribs; whereas *P. t. tenuistriata* possesses regular, continuous main ribs.

Dimension: Carnduff-1 (pl. 1, fig. 1) length 923 μm, width 238 μm; (pl. 1, fig. 2) length 699 μm, width 311 μm; (pl. 1, figs. 3) length 709 μm, width 198 μm.

Material: Ballinlea-1 Borehole 12 specimens; Carnduff-1 Borehole 270 specimens.

Range: Total range: Hettangian (Planorbis Ammonite Chronozone, Planorbis Ammonite Subchronozone)-Early Sinemurian (Bucklandi Ammonite Chronozone, Conybeari Ammonite Subchronozone, Copestake & Johnson 1981, 2014). Range of studied samples: Hettangian-Early Sinemurian (Ballinlea-1 Borehole), Hettangian-Early Sinemurian (Magilligan Borehole), Hettangian-Early Sinemurian (Carnduff-1 Borehole).

Paralingulina tenera tenera (Bornemann, 1854)

(Plate 2, figs. 1-9)

1854 *Lingulina tenera* Bornemann, p. 38, pl. 3, figs 24a-c.

1949 *Lingulina tenera* Bornemann; Barnard, p. 365, fig. 6a.

1956 *Lingulina tenera* Bornemann forms B ''*tenera*'', D, E, G, J Barnard, p.275-280, pl.1 , figs. 1 ,2 ,9a , b; 10a, b; pl.2; pl.3, figs 4, 5, 13.

1957 *Geinitizina tenera* (Bornemann) subsp. *tenera* (Bornemann); Nørvang, p. 58-60, figs. 18-23.

1957 *Geinitizina tenera* (Bornemann) subsp. *carinata* Nørvang, p. 62-63, figs. 46-48, 51, 54.

1984 *Lingulina tenera tenera* Bornemann; Riegraf *et al.,* p. 688, 699, pl. 7, fig. 174-175.

1989 *Lingulina tenera tenera* Bornemann; Copestake & Johnson, p. 179, pl. 6.2.4, fig. 12.

1998 *Lingulina tenera* plex. *tenera* Bornemann; Hylton, p. 205-206, pl. 1, fig. 6.

2014 *Paralingulina tenera tenera* (Bornemann); Copestake & Johnson, p. 195-196, pl. 8, figs. 7, 10, 21, 25.

2017 *Paralingulina tenera tenera* (Bornemann); Lomax *et al.,* p. 3, fig. 2; 1-3.

Description: Uniserial. Keeled subspecies with variety of forms; pupiform, flaring or subtriangular. *P. t. tenera* contains well-defined median sulcus. This species has 5-10 arched chambers with flush sutures within. The surface is smoother than other *Paralingulina tenera* subspecies; each side has two longitudinal, narrow to sharp predominant ribs. These primary ribs are parallel to the side and disappear at the mid final chamber without reaching the oval aperture.

Variation: Most of the microspheric forms are flaring or subtriangular test; normally made up of 5-6 chambers only and flush sutures throughout the test. For megalospheric, the test generally in pupiform which the chamber size slowly wider and higher except for the constricted last chamber. The megalospheric sutures are flush in the beginning chamber but later become depressed especially final sutire. Secondary, continuous or discontinuous, fine ribs literally occur in the middle of primary ribs; noticed from end Hettangian to basal Early Sinemurian specimens.

Remark: *P. t. tenera* sometimes can be confused by *P. t. subprismatica*. However, *P. t. tenera* is more compressed, broader and diverge-sided.

Dimension: Ballinlea-1 (pl. 2, fig. 1) length 843 μm, width 225 μm; (pl. 2, fig 2) length 731 μm, width 236 μm; (pl. 2, fig. 3) length 635 μm, width 174 μm; (pl. 2, fig. 5) length 539 μm, width 191 μm; (pl. 2, fig. 6) width 126 μm, thickness 93 μm, diameter of aperture 27 μm; (pl. 2, fig. 7) length 351 μm, width 143 μm; (pl. 2, fig. 8) length 405 μm, width 178 μm, diameter of aperture 48 μm; (pl. 2, fig. 9) length 376 μm, width 229 μm. Carnduff-1 (pl. 2, fig. 4) length 603 μm, width 271 μm.

Material: Ballinlea-1 Borehole 779 specimens; Magilligan Borehole 100 specimens; Carnduff-1 Borehole 869 specimens; White Park Bay 158 specimens; Tircrevan Burn 3 specimens; Larne 1 specimen.

Range: Total range: Norian (Late Triassic)-Late Toarcian (Pseudoradiosa Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Rhaetian-Early Pliensbachian (Ballinlea-1 Borehole), Mid hettangian-Early Sinemurian (Magilligan Borehole), Rhaetian-Early Sinemurian (Carnduff-1 Borehole), White Park Bay (Late Sinemurian-Early Pliensbachian), Tircrevan Burn (Early Sinemurian), Larne (latest Hettangian).

Paralingulina tenera tenuistriata (Nørvang 1957)

(Plate 1, figs. 4-8)

1957 *Geinitzina tenera* (Bornemann) subsp. *tenuistriata* Nørvang, p. 56-57, figs 13, 16, 17, 24.

1957 *Geinitzina tenera* (Bornemann) subsp. *pupoides* Nørvang, p. 60, figs 27, 29.

1984 *Lingulina tenera praepupa* (Nørvang); Riegraf *et al*., p. 688, 699, pl. 7, fig. 173.

1984 *Lingulina tenera tenuistriata* (Nørvang); Riegraf *et al*., p. 688, 699, pl. 7, fig. 176.

1998 *Lingulina tenera* plex. *tenuistriata* (Nørvang); Hylton, p. 205-205, pl. 1, fig. 7.

2014 *Paralingulina tenera tenuistriata* (Nørvang); Copestake & Johnson, p. 197, pl. 8, figs. 4, 11, 17.

Description: Uniserial, broad or elongate test with keeled periphery. Median sulcus occurs in between two main, strong, continous ribs on both sides of test. Secondary fine, discontinuous striations (interrupted across sutures) are often occurred. Pupiform test has spherical proloculus;

whereas subtriangular test comprises subconical proloculus. This subspecies contains up to 8 arched chambers and flush to depressed sutures. The aperture is terminal, central and open oval.

Variation: The megalospheric usually in pupiform shape, while microspheric either flaring or subtriangular form.

Remark: *P. t. tenuistriata* is differentiate by *P. t. pupa* by its finer, discontinuous secondary striations, contrary to *P. t. pupa* which has almost equal strength and continuous primary and secondary striations. *P. t. tenuistriata* also slightly resemble to *P. t. substriata* but it differs by its well-defined predominant ribs, whereas *P. t. substriata* has irregular primary ribs.

Dimension: Ballinlea-1 (pl. 1, fig. 4) width 80 μm, thickness 60 μm, diameter of aperture 21 μm; (pl. 1, fig. 5) width 161 μm, thickness 68 μm, diameter of aperture 54 μm; (pl. 1, fig. 6) length 330 μm, width 168 μm; (pl. 1, fig. 7) length 500 μm, width 156 μm, diameter of aperture 59 μm; (pl. 1, fig. 8) length 430 μm, width 155 μm, diameter of aperture 77 μm.

Material: Ballinlea-1 Borehole 796 specimens; Carnduff-1 Borehole 377 specimens; Maglligan Borehole 21 specimens; White Park Bay 23 specimens; Kinbane Head 14 specimens; Ballintoy 6 specimens.
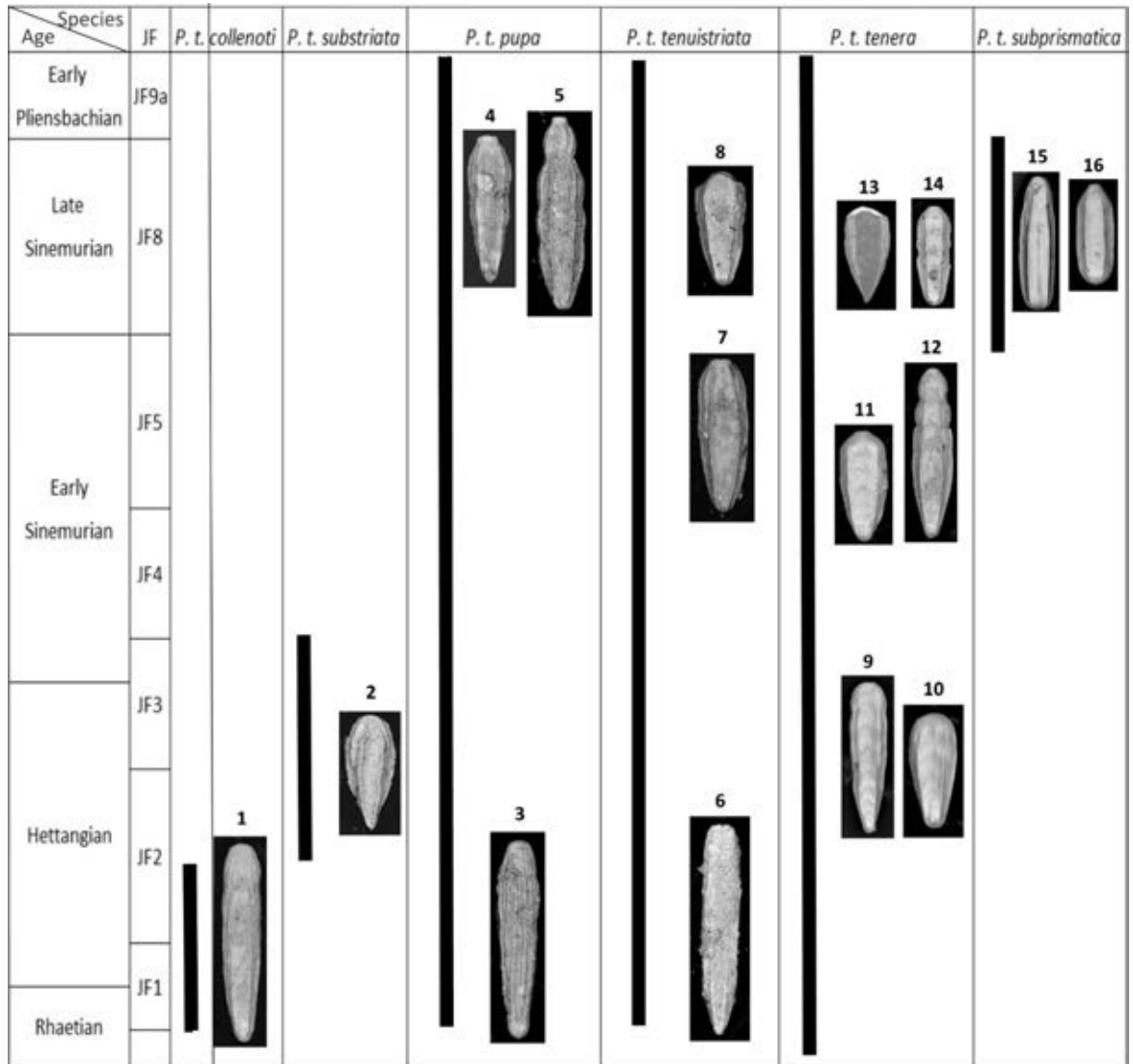
Figure 3.1: Summary of *Paralingulina tenera* plexus range chart from all analysed localities (Northern Ireland). 1: Typical form of *P. t. collenoti*, 2: typical form of *P. t. substriata*, 3: intermediate form of *P. t. pupa* and *P. t. collenoti*, 4: typical form of *P. t. pupa*, 5: intermediate form of *P. t. pupa* and *P. t. tenuistriata*, 6: longer form of *P. t. tenuistriata*; 7: typical form of *P. t. tenuistriata*, 8: intermediate form of *P. t. tenuistriata* and *P. t. occidentalis*, 9: longer form of *P. t. tenera*, 10,11 & 12: typical form of *P. t. tenera*, 13: intermediate form of *P. t. tenera* and *P. t. occidentalis*, 14: intermediate form of *P. t.tenera* and *P. t. subprismatica*, 15 & 16: typical form of *P. t. subprismatica*.

Range: Total range: Rhaetian-Late Toarcian (Copestake & Johnson, 2014). Range of studied samples: Mid Hettangian-Early Pliensbachian (Ballinlea-1 Borehole), Rhaetian-Early Sinemurian (Carnduff-1 Borehole), Mid Hettangian-Early Sinemurian (Magilligan Borehole), Late Sinemurian (White Park Bay, Ballintoy and Kinbane Head).

Genus ICHTHYOLARIA Wedekind, 1937

Ichthyolaria terquemi barnardi (Copestake & Johnson, 2014)

(Plate 3, fig. 4)

2014 *Ichthyolaria terquemi barnardi* ssp. nov. (Copestake & Johnson, 2014), p. 150-152, pl. 11, figs. 10, 17-19.

Description: Small, uniserial, flattened test, divergent-sided, lanceolate, rounded margin, 5- 7 chevron-shaped chambers, increase gradually except for the last chamber which smaller than it previous chamber. It has flush sutures, but final suture compressed. The surface comprises of 3- 4 longitudinal ribs which end before the last two final chambers. Generally, the margin is keeled except for the latest chamber; rounded. The aperture is terminal, radiate and produced in short neck.

Dimension: Ballinlea-1 (pl. 3, fig. 4) length 363 µm, width 98 µm.

Material: Ballinlea-1 Borehole 4 specimens.

Range: Total range: mid Hettangian (latest Planorbis Ammonite Chronozone-latest Angulata Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: mid Hettangian (Ballinlea-1 Borehole).

Ichthyolaria terquemi squamosa (Terquem & Berthelin, 1875)

(Plate 3, figs 11 & 12)

1875 *Frondicularia squamosa* Terquem & Berthelin, p. 37, pl. III, figs 3 a, b.

1941 *Frondicularia sulcata* var. *squamosa* Terquem & Berthelin; Macfadyen, p. 61, pl. 4, fig. 61.

1981 *Frondicularia terquemi muelensis* Ruget and Sigal; Copestake & Johnson, p. 93-94, pl. 6.1.2, fig. 12.

1984 *Frondicularia squamosa* Terquem & Berthelin; Riegraf *et al.*, p. 684, 697-698, pl. 6, fig. 154.

1989 *Frondicularia terquemi muelensis* Ruget & Sigal; Copestake & Johnson, p. 174, pl. 6.1.2, figs 12, 13.

1994 *Ichthyolaria squamosa* (Terquem & Berthelin); Herrero, p. 290-291, pl. 1, fig. 8.

2006 *Ichthyolaria squamosa* (Terquem & Berthelin); Herrero, p. 344-345, pl. 1, fig. 9.

2014 *Ichthyolaria terquemi squamosa* (Terquem & Berthelin); Copestake & Johnson, p. 155-156, pl. 11, figs. 1, 7-9.

Description: Uniserial, divergent, fragile, thin, flattened test from earliest chamber to the final one, with no swollen in final chamber and no sulcus. Each side contains up to 9 equal spaced ribs, fine and parallel ribs. It yields margin keeled but some rounded. The chevron-shaped chambers contain flush sutures in between. The aperture is centre, radiate and terminal.

Dimension: Ballinlea-1 (pl. 3, fig. 11) length 531 µm; width 152 µm; White Park Bay (pl. 3, fig. 12) length 762 µm; width, 173 µm.

Material: Ballinlea-1 Borehole, 12 specimens; White Park Bay, 7 specimens; Ballintoy, 2 specimens.

Range: Total range: Late Sinemurian (Oxynotum Ammonite Chronozone)-Early Toarcian (serpentinum Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Late Sinemurian (Ballinlea-1 Borehole, White Park Bay and Ballintoy).

Genus NODOSARIA Lamarck, 1812

Nodosaria issleri Franke, 1936

(Plate 4, figs. 2, 3, 5, 6, 7 & 8)

1908 *Nodosaria aequalis*; Issler, p. 54, pl. 2, fig. 94

1936 *Nodosaria issleri* Franke, p. 53, pl. 5, fig. 6

1957 *Nodosaria issleri* Franke; Nørvang, p. 79, fig. 82

1981 *Nodosaria issleri* Franke; Copestake & Johnson, p. 97, 99, pl. 6.1.4, figs 1, 2.

1989 *Nodosaria issleri* Franke; Copestake & Johnson, p. 182, pl. 6.2.5, fig. 11.

2014 *Nodosaria issleri* Franke; Copestake & Johnson, p. 168-169, pl. 7, figs. 15, 16, 22.

Description: Multilocular and the chambers added in linear series (uniserial). This circular cross-section test exhibits ovate proloculus followed by drum-shaped chambers those increasing in height and width towards the final chamber. The test literally rectilinear but some slightly curvate at the early chambers. The surface is ribbed by 6-8 sharp ribs; continuous through the depressed, straight sutures. The ribs fusing as basal spine and disappear near the mid of the final chamber. The aperture is single; either radiate or round aperture produce on short neck.

Remark: *N. issleri* is differentiate from *N. mitis* by their ribs; *N. issleri* ribs do not reach aperture, contrary to *N. mitis* which the ribs continuous until the aperture.

Dimension: Ballinlea-1 (pl. 4, fig 2) width 108 µm, diameter of aperture 26 µm; (pl. 4, fig. 3) length 262 µm, width 92 µm, diameter of aperture 17 µm; (pl. 4, fig. 5) length 337 µm, width 103 µm, diameter of aperture 13 µm; (pl. 4, fig. 6) length 343 µm, width 133 µm, diameter of aperture 32 µm; (pl. 4, fig. 7) length 411 µm, width 151 µm, diameter 34 µm; (pl. 4, fig. 8) length 483 µm, width 172 µm, diameter of aperture 38 µm.

Material: Ballinlea-1 Borehole, 28 specimens; White Park Bay, 7 specimens.

Range: Total range: Late Sinemurian (Obtusum Ammonite Chronozone-Raricostatum Ammonite Chronozone, Copestake & Johnson 1981, 2014). Range of studied samples: Early-Late Sinemurian (Ballinlea-1 Borehole), Late Sinemurian (White Park Bay).

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Genus PSEUDONODOSARIA Boomgaart, 1949

Pseudonodosaria vulgata (Bornemann, 1854) group

(Plate 7, figs. 1-8, 13)

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1854 Glandulina vulgata Bornemann, p. 31, pl. 2, figs la, b; 2a, b.

1941 *Pseudoglandulina tenuis* (Bornemann); Macfadyen, p. 48-49, pl. 3, fig. 49.

1941 *Pseudoglandulina tenuis* (Bornemann); Macfadyen, p. 49-50, pl. 3, fig. 50.

1949 *Pseudoglandulina vulgata* (Bornemann); Barnard, p. 358-359. 365, fig. 4e.

1957 *Pseudoglandulina vulgata* (Bornemann) var. pupoides (Bornemann); Nørvang, p. 81, figs. 83-84.

1957 *Pseudoglandulina vulgata* (Bornemann); Nørvang, p. 80-81, fig. 85.

1957 *Pseudoglandulina vulgata* (Bornemann) var. irregularis (Franke); Nørvang, p. 82, fig. 86.

1989 Pseudonodosaria vulgata (Bornemann); Copestake & Johnson, p. 183, pl. 6.2.5, figs 12, 13.

2014 *Pseudonodosaria vulgata* (Bornemann); Copestake & Johnson, p. 200-201, pl. 10, figs. 1-7, 9-14.

1984 *Pseudonodosaria vulgata* (Bornemann); Riegraf *et al.*, p. 687, 692-693, pl. 1, fig. 35.

2006 *Pseudonodosaria vulgata* (Bornemann); Herrero, p. 344-345, p. 1, fig. 19.

Description: Uniserial, circular cross-section species with variable test either parallel, divergent or convergent sided. Semi-spherical proloculus and rounded margin. The test is made up of 4-7 drum-shaped chamber; literally the wide length is greater than height. The chambers' diameter increasing rapidly in early chambers but almost same diameter or decreasing in latter chambers. The surface normally smooth but some exhibits faint striations. The sutures are straight, horizontal, flush or depressed. The aperture is centre, terminal, rounded or radiate with slightly produced. Few specimens have ring like feature on their final chamber, right before aperture.

Dimension: Magilligan (pl. 7, fig. 2) length 265 µm, width 111 µm. Ballinlea-1 (pl. 7, Fig. 1) length 419 µm, 118 µm, diameter of aperture 28 µm; (pl.7, fig. 3) length 312 µm, width 110 µm, diameter of aperture 29 µm; (pl. 7, fig. 4) length 326 µm, width 133 µm, diameter of aperture 33 µm; (pl. 7, fig. 5) length 360 µm, width 136 µm, diameter of aperture 31 µm; (pl. 7, fig. 6) length 347 µm, width 122 µm, diameter of aperture 30 µm; (pl. 7, fig. 7) length 419

µm, width 115 µm, diameter of aperture 28 µm; (pl. 7, fig. 8) length 434 µm, width 100 µm, diameter of aperture 26 µm; (pl. 7, fig. 13) length 587 µm, width 254 µm.

Material: Ballinlea-1 Borehole 83 specimens; Carnduff-1 Borehole 5 specimens; White Park Bay 7 specimens; Ballintoy 3 specimens; Kinbane Head 2 specimens.

Range: Total range: Rhaetian-Late Cretaceous (Copestake & Johnson, 2014). Range of studied samples: Mid Hettangian-Early Pliensbachian (Ballinlea-1 Borehole), Mid Hettangian-Early Sinemurian (Carnduff-1 Borehole), Late Sinemurian-Early Pliensbachian (White Park Bay), Late Sinemurian (Ballintoy and Kinbane Head).

Genus MARGINULINA d'Orbigny, 1826 emend

Marginulina prima d'Orbigny, 1849 plexus

Marginulina prima incisa Franke, 1936

(Plate 8, figs. 16-18)

1936 *Marginulina incisa* Franke, p. 78, pl. 8, fig. 11.

1989 *Marginulina prima incisa* Franke; Copestake & Johnson, p. 180, pl. 6.2.5, fig. 2.

2014 *Marginulina prima incisa* Franke; Copestake & Johnson, p. 274-275, pl. 13, figs. 9, 12.

2017 *Marginulina prima incisa* Franke; Lomax *et al.*, p. 3, fig. 2, no. 7

Description: Test uniserial, elongate, long, narrow and rectilinear; some specimens has curve or incomplete coiled in early stage. This elongate test is made up of 6-8 oblate chambers with straight to slightly oblique, horizontal, flush sutures. The test has 8 well-developed, parallel, coarse ribs those reached aperture. The terminal margin has eccentric, radiate and protruding aperture.

Remark: *M. p. incisa* and *M. p. insignis* are longest subspecies among their subspecies. These two subspecies are distinguished by the presence of aperture face and oblique ribs. *M. p. incisa* is devoid of thickening on aperture face as their ribs reach aperture. These ribs are entirely parallel without any oblique ribs in between.

Dimension: Carnduff-1 (pl. 8, fig. 16) length 542 μm, width 155 μm, diameter of aperture 45 μm. Ballintoy (pl. 8, fig 17) length 923 μm, width 188 μm. Ballinlea (pl. 8, fig. 18) length 913 μm, width 200 μm, diameter of aperture 63 μm.

Material: Ballinlea-1 Borehole 100 specimens; Magilligan Borehole 1 specimen; Carnduff-1 Borehole 45 specimens; Tircrevan Burn 11 specimens.

Range: Total range: Hettangian (Angulata Ammonite Chronozone)- Late Pliensbachian (Spinatum Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Early Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole), Early Sinemurian (Magilligan Borehole and Tircrevan Burn), latest Hettangian-Early Sinemurian (Carnduff-1 Borehole).

Marginulina prima insignis (Franke, 1936)

(Plate 8, figs. 19-21)

1936 *Dentalina insignis* Franke, p. 36, pl. 3, figs 11a, b.

1957 *Marginulina prima prima* d'Orbigny var. *insignis* (Franke); Nørvang, fig. 103.

1989 *Marginulina prima insignis* Franke; Copestake & Johnson, p. 180, pl. 6.2.5, fig. 1.

2014 *Marginulina prima insignis* (Franke); Copestake & Johnson, p. 275-276, pl. 13, fig. 8.

2017 *Marginulina prima insignis* (Franke); Lomax *et al.*, p. 3, fig. 2, no. 6.

Description: Uniserial, for early stage, the test slightly curved but not completely enrolled. Test is elongated and broad with circular to ovate in cross-section. The proloculus is big and spherical followed by oblate chambers wider as added. The surface comprises coarse, parallel, longitudinal ribs which fused as thickening on aperture surface. However, short oblique ribs occasionally happened in between the predominant ribs.

Remark: This species is differentiated by its presence of umbrella-like fussion ribs on aperture face and existence of oblique ribs.

Dimension: Ballinlea-1 (pl. 8, fig. 19) length 1071 µm, width 239 µm, diameter of aperture 65 µm; (pl. 8, fig. 20) length 932 µm, width 247 µm, diameter of aperture 64 µm. Carnduff-1 (pl. 8, fig. 21) width 189 µm, diameter of aperture 57 µm.

Material: Ballinlea-1 Borehole 83 specimens; Carnduff-1 Borehole 59 specimens; Tircrevan Burn 20 specimens; White Park Bay 1 specimen.

Range: Total range: Hettangian (Angulata Ammonite Chronozone)-Late Pliensbachian (Spinatum Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Early Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole), latest Hettangian-Early Sinemurian (Carnduff-1 Borehole), Early Sinemurian (Tircrevan Burn).

Marginulina prima interrupta Terquem, 1866

(Plate 8, figs. 10-12)

1866 *Marginulina interrupta* Terquem, p. 426, pl. 17, figs 4a-c.

1981 *Marginulina prima interrupta* (Terquem); Copestake & Johnson, p. 95, 97, pl. 6.1.3, fig. 11.

1989 *Marginulina prima interrupta* Terquem; Copestake & Johnson, p. 180, pl. 6.2.5, fig. 3.

2014 *Marginulina prima interrupta* Terquem; Copestake & Johnson, p. 276-277, pl. 13, figs. 1, 2, 7.

Description: 4-6 oblate chambers arranged in uninserial and elongate manner. The chambers are slowly wider toward the final chamber. The ribs are sharp, parallel and longitudinal; appear from proloculus continue upwards but fused in thickened aperture face. The ribs are distinctly interrupted at straight, horizontal, depressed sutures. The terminal, eccentric aperture is radiate or has bifurcating elements.

Variation: Infrequent intermediate form of *M. p interrupta* and *M. p. spinata* are recovered from end Late Sinemurian sediments. This form almost developed projected ribs near its sutures.

Dimension: Ballinlea-1 (pl. 8, fig. 10) length 331 µm, width 113 µm, diameter of aperture 32 µm; (pl. 8, fig. 11) length 386 µm, width 118 µm, diameter of aperture 32 µm; (pl. 8, fig. 12) length 574 µm, width 206 µm, diameter of aperture 52 µm.

Material: Ballinlea-1 Borehole 30 specimens; Kinbane Head 1 specimen.

Range: Total range: Late Sinemurian (Raricostatum Ammonite Chronozone)-Early Toarcian (Tenuicostatum Ammonite Chronozone, Copestake & Johnson 1981, 2014). Range of studied samples: Late Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole), Late Sinemurian (Kinbane Head).

Marginulina prima rugosa Bornemann, 1854

(Plate 8, figs. 1, 6, 14 & 15)

1854 Marginulina rugosa Bornemann, p. 39, pl. 3, figs 26a, b.

1957 *Marginulina prima* d'Orbigny subsp. rugosa Bornemann; Nørvang, p. 90-91, fig. 97.

1984 *Marginulina prima* d'Orbigny; Riegraf *et al.*, p. 685, 697-698, pl. 6, fig. 162.

1989 *Marginulina prima rugosa* Nørvang; Copestake & Johnson, p. 182, pl. 6.2.5, figs 4, 6.

2006 *Marginulina prima* D'Orbigny; Herrero, p. 348-349, pl. 2, fig. 6.

2014 *Marginulina prima rugosa* Bornemann; Copestake & Johnson, p. 280, pl. 13, figs. 4, 5, 14.

Description: Uniserial and divergent test; comprises 4-7 oblate chambers which initially curve (microspheric) or rectilinear (megalospheric form). The sutures are generally flush, straight and horizontal. Sharp, parallel ribs are fused in aperture face but only slightly developed. The aperture is eccentric, terminal, vaguely produced either radiate or contains 6 bifurcating elements.

Variation: The microspheric forms literally have parallel-sided with almost same size of chamber but slightly curve in early chambers. For megalospheric forms, the test is rectilinear and diverge. The chambers increase rapidly towards the latest chamber.

Remark: *Marginulina prima rugosa*, *Marginulina prima praerugosa* and *Marginulina prima prima* need a detailed identification. These three subspecies are distinguished by the existence and thickness of aperture face. *M. p. praerugosa* is the smallest among these three subspecies and the ribs reach aperture cause absence of aperture face. For *M. p. prima*, the aperture face is thicker and well-established compare to *M. p. rugosa* aperture face.

Dimension: Balinlea-1 (pl. 8, fig. 1) thickness 90 μm, diameter of aperture 20 μm; (pl. 8, fig. 6) width 222 μm, diameter of aperture 49 μm; (pl. 8, fig. 14) length 505 μm, width 177 μm, diameter of aperture 44 μm; (pl. 8, fig. 15) length 640 μm, width 228 μm, diameter of aperture 50 μm.

Material: Ballinlea-1 Borehole 183 specimens; Carnduff-1 11 specimens; White Park Bay 2 specimens; Ballintoy 1 specimen; Kinbane Head 3 specimens.

Range: Total range: Early Sinemurian (Bucklandi Ammonite Chronozone)-Early Toarcian (Tenuicostatum Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Early Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole), latest Hettangian-Early Sinemurian (Carnduff-1 Borehole), Late Sinemurian (White Park Bay, Ballintoy and Kinbane Head).

Marginulina prima spinata (Terquem, 1858)

(Plate 8, figs. 7-9, 13)

1941 *Marginulina spinata* Terquem; Macfadyen, p. 39-40, pl. 2, figs. 33a, b.

1957 *Marginulina prima* d'Orbigny subsp. *spinata* Terquem; Nørvang, p. 92.

1981 *Marginulina prima spinata* (Terquem); Copestake & Johnson, p. 95, 97, pl. 6.1.3, fig. 9, 10.

1984 *Marginulina spinata* Terquem; Riegraf *et al.*, p. 685, 697-698, pl. 6, fig. 160.

1989 *Marginulina prima spinata* Terquem; Copestake & Johnson, p. 182, pl. 6.2.5, figs 9, 10.

2006 *Marginulina spinata* Terquem; Herrero, p. 348-349, pl. 2, fig. 18.

2008 *Marginulina spinata* Terquem; Herrero, p. 240, fig. 3.

2014 *Marginulina prima spinata* (Terquem); Copestake & Johnson, p. 280-281.

Description: Uniserial and the test is literally rectilinear but slightly curvate in early phase occasionally occured. The sharp ribs are notched and protruded as spines near the flush sutures. The ribs fused at faintly thickened aperture face and uninterrupted at flush sutures. The spine is frequently observed at the basal of spherical proloculus too. The chambers are gradually increase in size as added until final chamber which contains marginal, radiate and almost eccentric aperture.

Dimension: Ballinlea-1 (pl. 8, fig. 7) width 184 µm, diameter of aperture 54 µm; (pl. 8, fig. 8) length 400 µm, width 103 µm, diameter of aperture 32 µm; (pl. 8, fig. 9) length 297 µm, width 107 µm, diameter of aperture 30 µm. White Park Bay (pl. 8, fig. 13) length 575 µm, width 196 µm, diameter of aperture 50 µm.

Material: Ballinlea-1 55 specimens; White Park Bay 18 specimens; Ballintoy 1 specimen; Kinbane Head 2 specimens.

Range: Total range: Late Sinemurian (Raricostatum Ammonite Chronozone)-Early Toarcian (Serpentinum Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Late Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole and White Park Bay), Late Sinemurian (Ballintoy and Kinbane Head).

Marginulina aff. *turneri* Copestake & Johnson, 2014

(Plate 9, fig. 8)

1981 *Marginulina* sp. A Copestake & Johnson, p. 95, 97, pl. 6.1.3, fig. 13.

2014 *Marginulina turneri* sp. nov. Copestake & Johnson, p. 282-283, pl. 13, figs. 20-22, 27, 28.

Description: Small spherical, spinose proloculus and six ovate chambers are arranged in uniserial series. The chambers sizes are widening rapidly with growth. The aperture is located at dorsal margin, in which rectilinear. However, ventral margin is sharply diverged. This smooth species yields depressed, oblique sutures.

Dimension: Ballinlea-1 (pl. 9, fig. 8) length 566 µm, width 193 µm.

Material: Ballinlea-1 7 specimens.

Range: Total range: Early Sinemurian (Turneri Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: latest Early Sinemurian (Ballinlea-1 Borehole).

Genus DENTALINA Risso, 1826

Dentalina langi Barnard, 1949

(Fig. A1)

1949 *Dentalina langi* sp. nov. Barnard, p. 360-361, fig. 5e.

Description: *D. langi* is a very distinctive species as it test is big and elongate. This arcuate test has 8 ovoid chambers (uniserial) increasing slowly with growth. The surface is ornamented by fine longitudinal oblique ribs those continuous through depressed sutures. The aperture situated at terminal and eccentric but almost centre.

Dimension: Ballinlea-1 (fig. A1) length 1540 μm, width 310 μm, diameter of aperture 90 μm.

Material: Ballinlea-1 Borehole 1 specimens.

Range: Total range: latest Hettangian (Angulata Ammonite Chronozone, Complanata Ammonite Subchronozone, Copestake & Johnson, 2014). Range of studied samples: earliest SInemurian (Ballinlea-1 Borehole).

Genus MESODENTALINA Norling, 1968

Mesodentalina matutina (d'Orbigny, 1849)

(Plate 11, figs. 13-17)

1849 *Dentalina matutina* d'Orbigny, p. 243, no. 259.

1949 *Dentalina matutina* d'Orbigny; Barnard, p. 359-361, fig. 5d.

1957 *Dentalina matutina* d'Orbigny subsp. matutina d'Orbigny; Nørvang, p. 83-85, figs. 88, 90-93.

1957 *Dentalina matutina* d'Orbigny subsp. claviformis Terquem; Nørvang, p. 85, figs. 89.

1981 *Dentalina matutina* (d'Orbigny); Copestake & Johnson, p. 92-93, pl. 6.1.2, fig. 9.

1989 *Dentalina matutina* d'Orbigny; Copestake & Johnson, p. 171, pl. 6.2.2, figs 10, 11.

2014 *Mesodentalina matutina* (d'Orbigny); Copestake & Johnson, p. 250-252, pl. 14, figs. 3, 9-12.

2017 *Mesodentalina matutina* (d'Orbigny); Lomax *et al.*, p. 3, fig. 2, no. 8.

Description: Test is uniserial, elongated and arcuate with ovoid proloculus normally comprises basal spine. This uniserial test has 5-7 chambers with oblique, constricted sutures. Most of the chambers width is greater than it height. This species easily to identified because of their coarse, oblique ribs which either reach aperture or disappear before final chambers. The aperture is terminal, eccentric and radiate.

Variation: The sutures vary depend on the test outline. The microspheric form mostly has flush sutures except for the depressed final suture. But megalospheric exhibits entirely depressed sutures. The intermediate form between *M. matutina* and *M. varians haeusleri* is observed too. These species can be distinguished by their degree of suture constriction; *M. matutina* suture not highly depressed as in *M. varians* hauesleri.

Dimension: Ballinlea-1 (pl. 11, fig. 13) length 734 μm, width 169 μm, diameter of proloculus 106 μm, diameter of aperture 53 μm; (pl. 11, fig. 14) length 720 μm, width 176 μm, diameter of proloculus 64 μm, diameter of aperture 60 μm; (pl. 11, fig. 16) length 1055 μm, width 188 μm, diameter of proloculus 65 μm; (pl. 11, fig. 17) length 967 μm, width 155 μm. White Park Bay (pl. 11, fig. 15) length 562 μm, width 133 μm, diameter of proloculus 42 μm.

Material: Ballinlea-1 Borehole 218 specimens; Magilligan Borehole 5 specimens; Carnduff-1 Borehole 21 specimens; White Park Bay 41 specimens; Tircrevan Burn 2 specimens; Ballintoy 2 specimens; Kinbane Head 4 specimens.

Range: Total range: latest Hettangian (Angulata Ammonite Chronozone)-Late Pliensbachian (Spinatum Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: latest Hettangian-Early Pliensbachian (Ballinlea-1 Borehole), Early Sinemurian (Magilligan Borehole and Tircrevan Burn), latest Hettangian-Early Sinemurian (Carnduff-1 Borehole), Late Sinemurian-Early Pliensbachian (White Park Bay), Late Sinemurian (Ballintoy and Kinbane Head).

Mesodentalina varians haeusleri (Schick, 1903)

(Plate 11, figs. 11 & 12)

1949 *Dentalina häusleri* Schick; Barnard, p. 360-362, fig. 5j.

1957 *Dentalina haeusleri* Franke; Nørvang, p. 86.

1981 *Dentalina varians haeusleri* (Schick); Copestake & Johnson, p. 92-93, pl. 6.1.2, fig. 5.

2014 *Mesodentalina varians haeusleri* (Schick); Copestake & Johnson, p. 254-256, pl. 14, fig. 16.

Description: This elongate, arcuate, uniserial species yields swollen chambers and commonly found in broken form due to it very constricted sutures (cause the test to become fragile). The slightly broad, coarse ribs are sub-parallel to periphery and continuous through the sutures. The aperture is marginal, terminal and radiate.

Dimension: Ballinlea-1 (pl. 11, fig. 11) length 425 µm, width 175 µm; (pl. 11, fig. 12) length 581 µm, width 171 µm, diameter of aperture 60 µm.

Material: Ballinlea-1 Borehole 21 specimens; White Park Bay 3 specimens.

Range: Total range: Early Sinemurian (Semicostatum Ammonite Chronozone)-Middle Toarcian (Bifrons Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Late Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole and White Park Bay).

Family LENTICULINIDAE Chapman, Parr & Collins 1934 emend.

Genus LENTICULINA Lamarck, 1804

*Lenticulina muensteri (*Roemer, 1839) plexus

Lenticulina muensteri muensteri (Roemer, 1839)

(Plate 12, figs 4-10)

1839 Robulina muensteri Roemer, p. 48, pl. 20, figs 29a, b.

1941 *Cristellaria matutina* d'Orbigny; Macfadyen, p. 30-31, pl. 2, fig. 22.

1941 *Cristellaria münsteri* (Roemer); Macfadyen, p. 31-32, pl. 2, fig. 23a, b.

1957 *Lenticulina gottingensis* (Bornemann); Nørvang, p. 104, figs 153-170.

1957 *Marginulina matutina* (d'Orbigny); Nørvang, p. 96-97, figs. 115, 117.

1957 *Marginulina prima* d'Orbigny; Nørvang, p. 98, figs. 116, 121, 122.

1957 *Marginulina lituoides* (Bornemann); Nørvang, p. 97, figs. 118, 120.

1989 *Lenticulina muensteri muensteri* (Roemer); Copestake & Johnson, p. 178, pl. 6.2.4, fig. 2.

2014 *Lenticulina muensteri muensteri* (Roemer); Copestake & Johnson, p. 215-217, pl. 16, figs. 3, 11, 15, 16.

Description: Lenticular and involute planispiral test (may be in tight coiled form or trochospiral form) which convex in cross-section. The keeled usually well-developed at basal area. The final

whorl has 7-9 chambers. The flush suture situated in between the triangular (coiled form) to subtriangular (uncoiled form) shaped of chambers. In trochoid form, the final suture normally slightly depressed. This subspecies has no striation. The aperture is marginal, protruding and radiate.

Remark: *L. muensteri muensteri* differs from other *L. muensteri* subspecies by its smooth umbilical area.

Dimension: Ballinlea-1 (pl. 12, fig. 4) diameter of coil 315 μm , diameter of aperture 66 μm, number of chmabers in final whorl 8; (pl. 12, fig. 6) length 725 μm, diameter of coil 300 μm, diameter of aperture 59 μm, number of chambers in final whorl 9, number of uncoiled chambers 3; (pl. 12, fig. 7) length 673 μm, diameter of coil 432 μm, diameter of aperture 68 μm, number of chambers in final whorl 8, number of uncoiled chambers 2; (pl. 12, fig. 8) length 753 μm, diameter of coil 341 μm, diameter of aperture 76 μm, number of chambers in final whorl 8, number of uncoiled chambers 3. Kinbane Head (pl. 12, fig. 5) diameter of aperture 84 μm. (pl. 12, fig. 9) White Park Bay diameter of coil 373 μm, number of chambers 8. Ballintoy (pl. 12, fig. 10) diameter of coil 481 μm, number of chambers 12.

Material: Ballinlea-1 Borehole 284 specimens; Magilligan Borehole 6 specimens; Carnduff-1 Borehole 2 specimens; White Park Bay 28 specimens; Ballintoy 5 specimens.

Range: Total range: Late Triassic-Early Cretaceous (Copestake & Johnson, 2014). Range of studied samples: Hettangian-Early Pliensbachian (Ballinlea-1 Borehole), Hettangian-Early

Sinemurian (Magilligan Borehole), Hettangian (Carnduff-1 Borehole), Late Sinemurian-Early Pliensbachian (White Park Bay), Late Sinemurian (Ballintoy).

Lenticulina varians (Bornemann, 1854) plexus

Lenticulina varians varians (Bornemann, 1854)

(Plate 13, figs. 2-7)

1854 *Cristellaria varians* Bornemann, p. 41, pl. 4, figs 32-34.

1941 *Cristellaria varians* Bornemann; Macfadyen, p. 35-36, pl. 2, figs 28a, b

1957 *Astacolus varians* (Bornemann); Nørvang, p. 99-101, figs. 123-134.

1984 *Astacolus varians* (Bornemann); Riegraf *et al.*, p. 683, 697-698, pl. 6, fig. 149.

1989 *Lenticulina varians* (Bornemann); Morris & Coleman, p. 214, pl. 6.3.4, fig. 6.

2014 *Lenticulina varians varians* (Bornemann); Copestake & Johnson, p. 222-223, pl. 16, figs. 17, 19-21, 25.

Description: Lenticular and compressed test with rounded or keeled margin. The early chambers are tightly enrolled (involute planispiral) but later stage is high and has tendency to uncoiled. Some specimens exist in trochospiral form. The coiled form has 7-9 subtriangular chambers whereas the uncoiled form usually comprises 4-5 sub-rectangular chambers. The early curve sutures are raised at dorsal margin and merging into the umbilical; without reaching ventral margin. The latter sutures are literally flush. This subspecies yields marginal, radiate and protruding aperture.

Variation: The subspecies recovered in varities of form, but generally in coiled, 1.5 whorl. However, the uncoiled (astocoline) form do occur. Few specimens are vaguely flattened; intermediate of *Lenticulina* and *Planularia*.   In Late Sinemurian, the final stage of chambers has tendency to become polygonal outline.

Dimension: White Park Bay (pl. 13, fig. 2) length 615 µm, diameter of coil 406 µm, diameter of aperture 74 µm, number of chambers in final whorl 10; (pl. 13, fig. 4) thickness 39 µm, diameter of aperture 36 µm. Ballinlea-1 (pl. 13, fig. 3) length 509 µm, diameter of coil 340 µm, diameter of aperture 63 µm, number of chambers in final whorl 9; (pl. 13, fig. 5) length 442 µm, diameter of coil 274 µm, number of chambers in final whorl 8; (pl. 13, fig. 6) length 467 µm, diameter of coil 246 µm, number of chambers in final whorls 8, number of uncoiled chambers 3; (pl. 13, fig. 7) length 761 µm, diameter of coil 362 µm, diameter of aperture 62 µm, number of chambers in final whorl 11, number of uncoiled chambers 4.

Material: Ballinlea-1 Borehole 515 specimens; Magilligan Borehole 8 specimens; Carnduff-1 Borehole 99 specimens; White Park Bay 33 specimens; Tircrevan Burn 1 specimen; Larne 4 specimens; Ballintoy 10 specimens.

Range: Total range: Rhaetian-Bathonian (Copestake & Johnson, 2014). Range of studied samples: Rhaetian-Early Pliensbachian (Ballinlea-1 Borehole), Hettangian (Magilligan Borehole and Larne), Hettangian-Early Sinemurian (Carnduff-1 Borehole), White Park Bay (Late Sinemurian-Early pliensbachian), Tircrevan Burn (Early Sinemurian), Ballintoy (Late Sinemurian).

Lenticulina muensteri ssp. A

(Plate 12, figs. 11-13)

Description: Involute planispiral test, biconvex cross-section. The specimens usually found in tight coiled form but trochospiral form does occurred. Well- developed keeled especially at the basal area of the test and some specimens have sharp narrow keeled. The final whorl normally made up of 9-11 triangular-subtriangular chambers with marginal, protruding and radiate aperture located at the final chamber. The raised sutures merged the protruding umbilical boss. These features differentiate *Lenticulina muensteri* spp. A with *Lenticulina muensteri muensteri* as *L. m. muensteri* contains flush sutures and smooth umbilical boss.

Remark: Few *Lenticulina muensteri* ssp. A specimens look like intermediate form of *Lenticulina muensteri muensteri* and *Lenticulina muensteri subalata* because their tests exhibit partly raised suture and umbilical boss. Yet, most of *Lenticulina muensteri* ssp. A specimens have distinctive protruding umbilical boss and raised suture which closely resemble to *Lenticulina muensteri subalata.* However, *Lenticulina muensteri* spp. A range does not fit *Lenticulina muensteri sublata* range as the latter range is from Late Pliensbachian to Early Cretaceous, whilst former one appeared earlier; Late Sinemurian-Early Pliensbachian. Thus, these specimens are called as *Lenticulina muensteri* ssp. A.

Dimension: Ballinlea-1 (pl. 12, fig. 11) length 678 μm, diameter of coil 575 μm, diameter of aperture 85 μm, number of chambers in final whorl 9; (pl. 12, fig 12.) length cannot be measured because of the broken final chamber, diameter of coil 646 μm, number of chambers

in final whorl 11. Ballintoy (pl. 12, fig. 13) length 975 μm, diameter of coil 803 μm, diameter of aperture 98 μm, number of chambers in final whorl 10.

Material: Ballinlea-1 Borehole 107 specimens; Ballintoy 2 specimens.

Range: Range of studied samples: Late Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole), Late Sinemurian (Ballintoy).

Genus ASTACOLUS de Montfort, 1808 emend.

Astacolus speciosus (Terquem, 1858) group

(Plate 13, figs. 8-12)

1858 *Cristellaria speciosa* Terquem, p. 624, pl. 4, figs 2a, b.

1957 *Marginulinopsis radiata* (Franke); Nørvang, p. 93-94, figs 105, 107.

1989 *Astacolus speciosus* (Terquem); Copestake & Johnson, p. 170, pl. 6.2.2, fig. 5.

2006 *Astacolus speciosus* (Terquem); Herrero, p. 348-349, pl. 2, fig. 19.

2014 *Astacolus speciosus* (Terquem) group Copestake & Johnson, p. 209-211, pl. 16, figs. 26, 31-33.

Description: Test is compressed, broad and auriculate; coiled (loose planispiral) in early phase and uncoiled in later stage with keeled periphery. Typical form has 4 coarse, oblique ribs each side; which the outer ribs are parallel to outline and has 2 shorter ribs within. The sutures are

flush and curve in coiling part, whereas flush and oblique in uncoiling stage. The aperture is marginal and radiate.

Variation: Although the typical form (astacoline form) exhibits 4 ribs each side, some longer. curvilinear form has up to 9 oblique ribs. This rare form comprises slightly enrolled early stage which succeeding by wider chambers which then decrease in width in final chambers. The ribs are coarse, long, oblique, curve, continuous but few short and discontinuous ribs occurred in between them. The sutures entirely flush except for the final one; depressed.

Remark: the longer form of *A. speciosus* sometimes is misclassified with *V. curva*. *A. speciosus* differs by more compressed test and larger coiled. This form is megalospheric form as the length up to 0.80 mm and has well-developed initial coil; which clearly not a feature of megalospheric *V. curva*. This is because only microspheric *V. curva* contains loose early coiled, while megalospheric form is entirely uncoiled.

Dimension: Ballinlea-1 (pl. 13, fig. 8) length 412 μm, width 206 μm, diameter of aperture 36 μm; (pl. 13, fig. 9) length 441 μm, width 220 μm, diameter of aperture 41 μm; (pl. 13, fig. 10) length 535 μm, width 267 μm; (pl. 13, fig. 11) length 804 μm, width 241 μm, diameter of aperture 45 μm; (pl.13, fig. 12) length 538 μm, width 156 μm.

Material: Ballinlea-1 Borehole 184 specimens; Carnduff-1 Borehole 11 specimens; White Park Bay 8 specimens; Kinbane Head 6 specimens.

Range: Total range: Hettangian (Planorbis Ammonite Chronozone)-Late Jurassic (Copestake & Johnson, 2014). Range of studied samples: Mid Hettangian-Early Pliensbachian (Ballinlea-1 Borehole), Mid Hettangian-Early Sinemurian (Carnduff-1 Borehole), Late Sinemurian-Early Pliensbachian (White Park Bay), Late Sinemurian (Kinbane Head).

Genus PLANULARIA Defrance, in de Blainville, 1826

Planularia inaequistriata (Terquem, 1863)

(Plate 14, figs. 1-4)

1863 *Marginulina inaequistriata* Terquem, p. 191, pl. 8, figs 15a-f.

1949 *Planularia inaequistriata* (Terquem); Barnard, p. 374-375, figs. 8, d, g.

1957 *Planularia inaequistriata* (Terquem); Nørvang, p. 102, figs. 148-149.

1981 *Planularia inaequistriata* (Terquem); Copestake & Johnson, p. 98-99, pl. 6.1.4, fig. 5.

1989 *Planularia inaequistriata* (Terquem); Copestake & Johnson, p. 183, pl. 6.2.5, fig. 16.

2008 *Planularia inaequistriata* (Terquem); Herrero, p. 240, fig. 3.

2014 *Planularia inaequistriata* (Terquem); Copestake & Johnson, p. 229-230, pl. 17, figs. 16, 22.

2017 *Planularia inaequistriata* (Terquem); Lomax *et al.,* p. 3, fig. 2, no. 9.

Description: The test is broad, flattened and robust with basal keeled. The initial chambers coiled in loose planispiral which later become uncoiled in the final stage. The width increases rapidly and greater than height. The highest height recorded at dorsal, while the chambers at

ventral part approaching toward the early chambers. The sutures are curve and flush. The surface has fine, oblique ribs end before final chamber. The microspheric form has coarser ribs than the megalospheric form. The aperture is radiate and at the dorsal angle.

Dimension: Ballinlea-1 (pl. 14, fig. 1) length 906 µm, width 435 µm, diameter of aperture 71 µm; (pl. 14, fig. 4) length 695 µm, width 322 µm, diameter of aperture 66 µm. Ballintoy (pl. 14, fig. 2) length 813 µm, width 427 µm; (pl. 14, fig. 3) length 687 µm, width 393 µm.

Material: Ballinlea-1 Borehole 15 specimens; Magilligan Borehole 2 specimens; Carnduff-1 Borehole 1 specimen; Ballintoy 1 specimen.

Range: Total range: Hettangian (Planorbis Ammonite Chronozone)-Late Sinemurian (Raricostatum Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Hettangian-Late Sinemurian (Ballinlea-1 Borehole), Early Sinemurian (Magilligan and Carnduff-1 Boreholes), Ballintoy (Late Sinemurian).

Genus VAGINULINOPSIS Silvestri, 1904

Vaginulinopsis denticulatacarinata (Franke, 1936)

(Plate 14, figs 12 & 13)

1936 *Cristellaria (Astacolus) denticulata-carinata* Franke, p. 102, pl. 9, fig. 38.

1989 Vaginulinopsis denticulatacarinata (Franke); Copestake & Johnson, p. 186, pl. 6.2.6, figs 6, 7.

2014 *Vaginulinopsis denticulatacarinata* (Franke); Copestake & Johnson, p. 237-238, pl. 17, figs. 37, 38.

Description: This uniserial species is planispirally, involute coiled in their early stage yet later become uncoiled, high, elongate and rectilinear. It is ovate in cross-section, slightly compressed with rounded margin. The uncoiled part comprises 8-9 sub-rectangular chambers with flush to slightly depressed, horizontal sutures in between. The microspheric form literally smooth but encompasses denticulate base, while megalospheric has oblique ribs begin at mid-stage chambers continue to basal margin which appear as denticulate. The radiate aperture situated at terminal dorsal angle.

Dimension: Ballinlea-1 (pl. 14, fig. 12) length 265 μm, width 169 μm, diameter of aperture 41 μm; (pl.14, fig. 13) length 587 μm, width 221 μm, diameter of aperture 68 μm.

Material: Ballinlea-1 8 specimens.

Range: Total range: Late Sinemurian (Obtusum Ammonite Chronozone)-earliest Late Pliensbachian (Margaritus Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Late Sinemurian (Ballinlea-1 Borehole).

Superfamily POLYMORPHINOIDEA d'Orbigny, 1839

Family POLYMORPHINIDAE d'Orbigny, 1839

Subfamily POLYMORPHININAE d'Orbigny, 1839

Genus EOGUTTULINA Cushman & Ozawa, 1930

Eoguttulina liassica (Strickland, 1846)

(Plate 15, figs. 9-13)

1846 *Polymorphina liassica* Strickland, p. 31, fig. 6.

1949 *Eoguttulina liassica* (Strickland); Barnard, p. 374-376, figs. 8b, f.

1957 *Eoguttulina liassica* (Strickland); Nørvang, p. 107-108, figs. 180-181.

1984 *Eoguttulina liassica* (Strickland); Riegraf *et al.,* p. 688, 692-693, pl. 1, fig. 51.

1989 *Eoguttulina liassica* (Strickland); Copestake, p. 118, pl. 5.2, figs 10, 12-14.

2006 *Eoguttulina liassica* (Strickland); Herrero, p. 348-349, pl. 2, fig. 1.

2014 *Eoguttulina liassica* (Strickland); Copestake & Johnson, p. 302-303, pl. 18, figs. 10, 14, 15.

Description: This smooth species is ovate in shape and in cross-section. The chambers are added in planes less than 90˚ in spiral arrangement. The sutures are oblique and depressed; cause formation of lobulate periphery. The radiate, centre aperture situated at terminal of the test.

Variation: Shapes may be varying; depending on the sutures either depressed or flush. Depressed sutures resulted on lobulated margin, whereas flush sutures generally formed convex margin.

Dimension: Magilligan (pl. 15, fig. 9) diameter of aperture 26 µm; (pl. 15, fig. 10) thickness 127 µm, diameter of aperture 29 µm, (pl. 15, fig. 13) length 492 µm, width 184 µm, diameter of aperture 54 µm. Carnduff-1 (pl. 15, fig. 11) length 307 µm, width 143 µm. Ballinlea-1 (pl. 15, fig. 12) length 543 µm, width 194 µm, diameter of aperture 49 µm.

Material: Ballinlea-1 Borehole 44 specimens; Magilligan Borehole 139 specimens; Carnduff-1 Borehole 226 specimens.

Range: Total range: Rhaetian-Oxfordian (Copestake & Johnson, 2014). Range of studied samples: Hettangian-Early Pliensbachian (Ballinlea-1 Borehole), Hettangian (Magilligan Borehole), latest Rhaetian-Early Sinemurian (Carnduff-1 Borehole).

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Order ROBERTINIDA Mikhalevich, 1980

Superfamily CERATOBULIMINOIDEA Cushman, 1927

Family CERATOBULIMINIDAE Cushman, 1927

Genus REINHOLDELLA Brotzen, 1948

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Reinholdella pachyderma humilis Copestake & Johnson, 2014

(Plate 17, figs. 4-6)

1981 *Reinholdella pachyderma* subsp. A Copestake & Johnson, p. 101-102, pl. 6.1.5, figs 10, 11.

2014 *Reinholdella pachyderma humilis* Copestake & Johnson, p. 328-329, pl. 21, figs. 15, 18, 19, 21-24.

Description: This white or light grey, opaque, aragonitic species comprises low trochospiral test and rounded periphery. Most of the observed specimens has planar or slightly convex ventral side exhibits filling indistinct umbilicus. The test only has three whorls with 7 chambers in final whorl. The suture is thickened in umbilical and become flush in dorsal.

Dimension: Ballinlea-1 (pl. 17, fig. 4) diameter 443 µm; (pl. 17, fig. 5) diameter 345 µm, number of chambers in final whorl 7; (pl. 17, fig. 6) diameter 317 µm, number of chambers in final whorl 7.

Material: Ballinlea-1 Borehole 67 specimens.

Range: Total range: Late Sinemurian (Raricostatum Ammonite Chronozone)-Early Pliensbachian (Jamesoni Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Late Sinemurian (Ballinlea-1 Borehole).

Reinholdella planiconvexa (Fuchs, 1970)

(Plate 16, figs 1-12)

1970 *Oberhauserella planiconvexa* Fuchs, p. 113, pl. 9.

1981 *Reinholdella*? *planiconvexa* (Fuchs); Copestake & Johnson, p. 101-102, pl. 6.1.5, fig. 12, 16.

1989 *Reinholdella? planiconvexa* (Fuchs); Copestake & Johnson, p. 187, pl. 6.2.6, figs 11, 16.

2013 *Reinholdella* sp. Clémence & Hart, p. 1012-1013, fig. 6, no. 4-7.

2014 *Reinholdella*? *planiconvexa* (Fuchs); Copestake & Johnson, p. 330-331, pl. 20, figs. 16, 19-21, 23-24.

Description: Trochospiral, small, opaque, smooth, circular or ovate and orange in colour test. The dorsal surface is convex, while ventral surface is either planar or concave with umbilical hollow. The whorls are only 2-2.5 with 5 to 6 chambers in final whorl. The sutures are oblique either slightly depressed or flush; resulted on lobulated or smooth margin respectively. The raised circular suture at the centre of dorsal surface is commonly observed too.

Dimension: Ballinlea-1 (pl. 16, fig. 1) diameter 208 μm; (pl. 16, fig. 2) diameter 168 μm. Magilligan (pl. 16, fig. 3) diameter 175 μm; (pl. 16, fig. 4) thickness 66 μm; (pl. 16, fig. 5) diameter 163 μm, number of whorls 2, number of chambers 11, number of chambers in final whorl 5; (pl. 16, fig. 6) diameter 161 μm, number of whorls 2, number of chambers 10, number of chambers in final whorl 5; (pl. 16, fig. 7) diameter 160 μm, number of whorls 1.5, number

of chambers 8, number of chambers in final whorl 5; (pl. 16, fig. 8) thickness 113 µm; (pl. 16, fig. 9) diameter 159 µm; (pl. 16, fig. 10) diameter 146 µm.

Material: Ballinlea-1 Borehole 162 specimens; Magilligan Borehole 9396 specimens; Carnduff-1 Borehole 2160 specimens.

Range: Total Range: Rhaetian-Early Pliensbachian (Jamesoni Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Hettangian-Late Sinemurian (Ballinlea-1 Borehole), Mid Hettangian (Magilligan Borehole), latest Rhaetian-Hettangian (Carnduff-1 Borehole).

Reinholdella robusta Copestake & Johnson, 2014

(Plate 17, figs. 7-11)

2014 *Reinholdella robusta* sp. nov. Copestake & Johnson, p. 331, pl. 20, figs 12, 17, 18, 22.

Description: *R. robusta* is low trochospiral, robust, smooth, large, opaque, circular and orange-brown in colour species. The dorsal surface is highly convex, whereas ventral surface normally planar but slightly concave and convex ventral are observed too. The margin is slightly lobulated or smooth. Most of the specimens found yield close umbilicus. The sutures are thickly raise; cause the chambers to appear depressed.

Variation: Even though literally the sutures are raised throughout all whorls, some specimens reflected depressed sutures in between all chambers in final whorl. The occurrence of depressed sutures causes the formation of lobulated periphery. Deeply sharp and narrow sutures also found resulted from the dissolvation of those raise sutures.

Dimension: Ballinlea-1 (pl. 17, fig. 7) diameter 451 μm, number of chambers in final whorl 7; (pl. 17, fig. 8) diameter 425 μm, number of chambers in final whorl 7; (pl. 17, fig. 9) diameter 429 μm, number of chambers in final whorl 7; (pl. 17, fig. 10) diameter 515 μm; (pl. 17, fig. 11) diameter 400 μm.

Material: Ballinlea-1 Borehole 75 specimens; White Park Bay 3 specimens.

Range: Total range: Late Sinemurian (Obtusum Ammonite Chronozone)-Early Pliensbachian (Ibex Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Late Sinemurian (Ballinlea-1 Borehole and White Park Bay).

Reinhodella sp. A

(Plate 17, figs. 1,2)

Description: Medium size brownish-orange aragonitic test with convex dorsal surface and planar or partly convex smooth ventral side. The test exhibits 2.5-3 whorls with 7 to 8 chambers in the final whorl. The thin raised sutures at dorsal surface merged to become raised

circular suture at the centre. The umbilicus commonly observed as closed but few specimens filled with calcite boss. No keeled observed from this species.

Remark: This species almost identical to *Reinholdella macfadyeni* as both have narrow-sharp raised sutures on dorsal side, closed or small umbilicus with planar or slightly convex ventral surface. Normally these thin raised sutures are not being preserved because they are easily dissolved; cause the species looks like having depressed sutures. The only difference of both species is their range; *Reinholdella macfadyeni* distributed from Late Pliensbachian-Early Aalenian but *Reinholdella* sp. A older in age. Based on these features, Philip Copestake porposed this form as *Reinholdella ''praemacfadyeni''* (personal communication). Unfortunately, due to the proposed name is unpublished yet, so the species will be called as *Reinholdella* sp. A in this thesis.

Dimension: Ballinlea-1 (pl. 17, fig. 1) diameter 378 μm; (pl. 17, fig. 2) diameter 239 μm.

Material: Ballinlea-1 Borehole 14 specimens; Carnduff-1 Borehole 18 specimens.

Range: Range of studied samples: latest Hettangian-Early Sinemurian (Ballinlea-1 Borehole), Early Sinemurian (Carnduff-1 Borehole).

Order MILIOLIDA Lankester, 1885

Suborder MILIOLINA Delage & Hérouard, 1896

Superfamily CORNUSPIROIDEA Schultze, 1854

Family CORNUSPIRIDAE Schultze, 1854

Subfamily CORNUSPIRINAE Schultze, 1854

Genus CORNUSPIRA Schultze, 1854

Cornuspira liasina Terquem, 1866

(Plate 18, figs. 1 & 2)

1866 *Cornuspira liasina* Terquem, p. 474-475, pl. 19, figs 4a, b.

2014 *Cornuspira liasina* Terquem; Copestake & Johnson, p. 107, pl. 4, figs 1,2,5.

Description: Test flattened, smooth, milky white, biconcave, evolute planispirally coiled with globular proloculus. The proloculus are enrolled by a tubular and undivided second chamber. Most observed specimens are microspheric forms as the proloculus are small and has greater whorls (7-9 whorls) than megalospheric (6 whorls). The tubes are narrow except for the last whorl; wider tube with rounded edge and open-end aperture.

Remark: *Cornuspira* easily to be confused with *Sprillina* and *Ammodiscus*. However, *Cornuspira* is calcareous and porcellaneous, while *Spirillina* is calcareous and hyaline, whereas *Ammodiscus* is agglutinated test. When they are preserved as pyrite cast, the differentiation of *Cornuspira* and *Spirillina* can be very difficult, yet the best ways to distinguish them are by

their side shape and edge. Other distinct features between these two genera are their wall appearances; *Cornuspira* has milky white test wall, meanwhile *Spirillina* has a glassy test wall. In addition, *Spirillina* has irregular shape, numerous coarsely pores (or pseudospores), more likely to concavo-convexity and width of whorl is gradually increase.

Dimension: Carnduff-1 (pl. 18, fig. 1) diameter 289 μm, number of whorls 8; (pl. 18, fig 2) diameter 252 μm, number of whorls 9.

Material: Carnduff-1 Borehole 464 specimens; Tircrevan Burn 54 specimens.

Range: Total range: Hettangian-Callovian (Copestake & Johnson, 2014). Range of studied samples: Mid Hettangian-earliest Early Sinemurian (Carnduff-1 Borehole), Early Sinemurian (Tircrevan Burn).

Superfamily NUBECULARIOIDEA Jones, 1875

Family OPHTHALMIDIIDAE Wiesner, 1920 emend

Genus OPHTHALMIDIUM Kübler & Zwingli, 1870 emend

Ophthalmidium macfadyeni macfadyeni Wood & Barnard, 1946

(Plate 18, figs. 8, 14 & 15)

1941 *Ophthalmidium carinatum* (Kübler and Zwingli); Macfadyen, p. 23-25, 74-75, pl. 1, fig. 12.

1946 *Ophthalmidium macfadyeni* sp. nov Wood & Barnard, p. 92, 93, pl. IX.

1989 *Ophthalmidium macfadyeni* Wood & Barnard; Copestake & Johnson, p. 167, pl. 6.2.1, figs. 18, 19.

2014 *Ophthalmidium macfadyeni macfadyeni* Wood & Barnard; Copestake & Johnson, p. 116-118, pl. 5, figs. 1-3, 7, 9, 21a, b, 22.

Description: Test flattened, bilaterally symmetrical and almost like eye-shaped in outline. The proloculus is enrolled planispiral, evolute by 8-10 chambers of 4-5 whorls; a chamber mainly just half of a whorl which wider at proximal ends. It has apertural neck with phialine lip.

Dimension: Ballinlea-1 (pl. 18, fig. 8) length 321 μm, width 157 μm, number of whorls 5; (pl. 18, fig. 14) length 203 μm, width 116 μm, number of whorls 4; (pl. 18, fig. 15) length 197 μm, width 118 μm, number of whorls 4.

Material: Ballinlea-1 Borehole 149 specimens; Carnduff-1 Borehole 3 specimens; White Park Bay 1 specimen.

Range: Total range: Hettangian-Aalenian (Copestake & Johnson, 2014). Range of studied samples: Late Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole), Hettangian (Carnduff-1 Borehole), Late Sinemurian (White Park Bay).

Order SPIRILLINIDA Gorbachik & Mantsurova, 1980

Suborder SPIRILLININA Hohenegger & Piller, 1975

Family SPIRILLINIDAE Reuss & Fritsch, 1861

Genus SPIRILLINA Ehrenberg, 1843

Spirillina infima (Strickland, 1846)

(Plate 18, figs. 5 & 6)

1846 *Orbis infimus* Strickland, p. 30, text-fig. a.

1949 *Spirillina infima* (Strickland); Barnard, p. 352-353, 376, fig. 1g.

2006 *Spirillina infima* (Strickland); Herrero, p. 344-345, p. 1, fig. 6.

2014 *Spirillina infima* (Strickland); Copestake & Johnson, p. 311-312, pl. 19, figs. 8, 9, 14.

Description: The test is discoidal in cross-section and circular in outline. The proloculus is enrolled planispirally by a tubular chamber. The whorls up to 6 which gradually wider as whorl added. The aperture is at open end of the tube.

Remark*:* This species differs from *S. tenuissima* by it lesser number of whorls and wider final whorl. Contary from *S. infima*, *S. tenuissima* has maximum of 10 narrow whorls those only slightly increasing width with growth.

Dimension: Magilligan (pl. 18, fig. 5) thickness 47 μm. Ballinlea-1 (pl. 18, fig. 6) diameter 237 μm, number of whorls 4.5.

Material: Ballinlea-1 Borehole 49 specimens; Magilligan Borehole 110 specimens; Carnduff-1 Borehole 36 specimens; White Park Bay 2 specimens; Larne 1 specimen; Ballygalley 1 specimen.

Range: Total range**:** Hettangian-Portlandian (Copestake & Johnson, 2014). Range of studied samples: Hettangian-Late Sinemurian (Ballinlea-1 Borehole), Hettangian (Magilligan Borehole, Larne and Ballygalley), Hettangian-Early Sinemurian (Carnduff-1 Borehole).

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Order BULIMINIDA Fursenko, 1958

Superfamily BOLIVINOIDEA Glaessner, 1937

Family BOLIVINITIDAE Cushman, 1927

Genus BRIZALINA Costa, 1856

Brizalina liasica (Terquem, 1858)

(Plate 19, figs. 1-4)

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1858 *Textilaria liasica* Terquem, p. 634, pl. 4, figs 12a, b.

1941 *Bolivina liasica* (Terquem); Macfadyen, p. 68, pl. 4, figs. 69a, b.

1957 *''Bolivina'' liasica* (Terquem); Nørvang, p. 109-110, fig. 182.

1981 *Brizalina liasica* (Terquem); Copestake & Johnson, p. 101-102. Pl. 6.1.5, fig. 17.

1984 *Brizalina liasica* (Terquem); Riegraf *et al.*, p. 689, 692-693, pl. 1, figs. 19-20.

1989 *Brizalina liasica* (Terquem); Copestake & Johnson, p. 187, pl. 6.2.6, figs 20, 21.

2014 *Brizalina liasica* (Terquem); Copestake & Johnson, p. 333-334, pl. 18, figs. 17-20, 24-26.

Description*: Brizalina* is a smooth species, which in lanceolate, compressed and elongated shape with rounded margin. The spherical proloculus is followed by 8 chambers; arranged in biserial manner with straight, oblique sutures in between. The early phase has flush sutures but later become depressed. The aperture is elongate and slit.

Variation: Despite of flush or depressed sutures, few specimens encompass thick raised sutures.

Dimension: Ballinlea-1 (pl. 19, fig. 1) width 81 μm; (pl. 19, fig. 2) length 213 μm, width 105 μm; (pl. 19, fig. 3) length 253 μm, width 93 μm; (pl. 19, fig. 4) length 296 μm, width 142 μm.

Material: Ballinlea-1 Borehole 142 specimens; White Park Bay 1 specimen.

Range: Total range: Late Sinemurian (Obtusum Ammonite Chronozone)-Early Toarcian (Tenuicostatum Ammonite Chronozone, Copestake & Johnson 1981, 1989, 2014). Range of studied samples: Late Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole), Late Sinemurian (White Park Bay).

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Superfamily TURRILINOIDEA Cushman, 1927

Family TURRILINIDAE Cushman, 1927

Genus NEOBULIMINA Cushman & Wickenden, 1928

Neobulimina bangae (Copestake & Johnson, 2014)

(Plate 19, figs. 5-8)

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1968 'Neobulimina' sp. 2 Bang, p. 67, tab. 24.

1981 Neobulimina sp. 2 Bang; Copestake & Johnson, p. 101-102, pl. 6.1.5, fig. 14.

1989 Neobulimina sp. 2 Bang; Copestake & Johnson, p. 187, pl. 6.2.6, figs 18, 19.

2014 Neobulimina bangae sp. nov. Copstake & Johnson, p. 335-337, pl. 18, figs. 16, 21-23, 27, 28.

Description: *N. bangae i*s elongated, lanceolate species with divergent side and rounded marginal. The globular chambers are triserial arranged in early stage yet become biserial in latter phase. The sutures are depressed, oblique and straight. The surface usually has hispid ornament throughout all chambers except for last two chambers exhibit smooth surface. The aperture is a U-shaped situated between two final chambers.

Remark: *N. bangae* is differentiated from *B. liassica* by its hispid ornaments and less compresed test.

Dimension: Ballinlea-1 (pl. 19, fig. 5) length 264 µm, width 127 µm; (pl. 19, fig. 6) length 215 µm, width 140 µm; (pl. 19, fig. 7) length 218 µm, width 102 µm; (pl. 19, fig. 8) length 187 µm, width 112 µm.

Material: Ballinlea-1 Borehole 92 specimens.

Range: Total range: Hettangian (Angulata Ammonite Chronozone)-Late Sinemurian (Obtusum Ammonite Chronozone, Copestake & Johnson, 2014). Range of studied samples: Hettangian-Late Sinemurian (Ballinlea-1 Borehole).

Subclass TEXTULARIIA Mikhalevich, 1980

Agglutinated tests. The tests are made up of organic and minerals from sea floor cemented by organic, calcareous or ferric oxide cement.

Superfamily HORMOSINOIDEA Haeckel, 1894

Family REOPHACIDAE Cushman, 1910

Genus *Reophax* de Montfort, 1808

Reophax sp. A

(Plate 19, fig. 10)

Description: The test is agglutinated and uniserial. The early portion has 2-3 oblate chambers arranged in arcuate manner which later become rectilinear (5 chambers) with compressed sutures in between. The aperture is not clearly seen in picked specimens. All the diagnosed specimens had been replaced by pyrite.

Dimension: Magilligan (pl. 19, fig. 10) length 273 µm, width 89 µm.

Material: Magilligan Borehole 40 specimens.

Range: Range of studied samples: Mid Hettangian (Magilligan BHorehole).

Order TEXTULARIIDA Delage & Hérouard, 1896 emend. Kaminski, 2004

Superfamily TROCHAMMINOIDEA Schwager, 1877

Family TROCHAMMINIDAE Schwager, 1877

Subfamily TROCHAMMININAE Schwager, 1877

Genus TROCHAMMINA Parker & Jones, 1859

Trochammina canningensis Tappan, 1955

(Plate 19, fig 11)

1955 *Trochammina canningensis* Tappan, p. 49, pl. 14, figs 15-19.

1984 *Trochammina canningensis* Tappan; Riegraf *et al.*, p. 680, 700, pl. 8, figs. 189, 192.

1989 *Trochammina canningensis* Tappan; Copestake & Johnson, p. 166, pl. 6.2.1, figs 10-12.

2014 *Trochammina canningensis* Tappan; Copestake & Johnson, p. 100, pl. 2, figs 17, 21-23.

Description: This agglutinated species has 6-12 globular chambers which arrange in moderate to high trochospirally; 1.5-2.5 whorls. Test is multiserial; more than three chamber per whorl. The early whorl contains big and distinctive globular chamber, but chambers in final whorl are poorly shaped of globular and smaller than chambers in early whorl. The sutures are moderate

to higly depressed. The aperture is not clearly observed from any recovered specimens. The tests of all observed specimens are replaced by pyrites.

Dimension: Magilligan (pl. 19, fig. 11) diameter 273 µm.

Material: Magilligan Borehole 82 specimens.

Range: Total range: Hettangian-Kimmeridgian (Copestake & Johnson, 2014). Range of studied sample: Mid Hettangian (Magilligan Borehole).

3.2 Ostracods Taxonomy

3.2.1 Introduction

The studied samples recover 69 ostracods species from 19 genera and 5 unknown affinity. The ostracods are from 14 families; Healdiidae, Protocytheridae, Progonocytheridae, Cytheruridae, Trachyleberididae, Cytheridae, Pontocyprididae, Limnocytheridae, Paradoxostomatidae, Bairdiidae, Macrocyprididae, Candonidae, Polycopidae and Cytherellidae. These families belong to suborder Metacopina, Podocopina, Cladocopina and Platycopina. No new species found in this study.

The genus and species naming are referred from Drexler (1958); Malz (1971); Michelsen (1975); Donze (1985); Park (1987, 1988); Ainsworth (1989) and Boomer & Ainsworth (2009).

The synonymies listed herein are not exhaustive, only limited to the original designation and major generic change. However, additional references may be included if illustrations or detailed descriptions are present.

The ostracods preservations are good to moderate, either preserved in carapace form or valves. Despite of this great preservation, few of them are broken into half or smaller fragments, most probably due to the laboratory processes.

This section only deals with abundant, stratigraphically and environmentally significance ostracods documented from studied sections. For Metacopina, all the stratigraphic important species are described in detail but for other suborder; only *Ektyphocythere translucens* and *Acrocythere gassumensis* are selected. The selections are based on their highest numbers among their genus. Other species not described herein are completely listed in the Appendix C.

The measurements given below are the maximum distance and presented in micrometers. The ostracods' SEM images are illustrated in Plates 20-26; captured by Phenom Pro. These SEM images presented most species except for some poorly preserved taxa.

3.2.2 Systematic descriptions

Order PODOCOPIDA Sars, 1866

Suborder METACOPINA Sylvester-Bradley, 1961

Superfamily HEALDIOIDEA Harlton, 1933

Family HEALDIIDAE Harlton, 1933

Genus OGMOCONCHELLA Gründel, 1964

Ogmoconchella aspinata (Drexler, 1958)

(Plate 20, figs 7-13)

1958 *Healdia aspinata* Drexler, p. 505, pl. 21, figs 5a-e; pl. 25, figs. 1-4.

1964 *Ogmoconchella aspinata* (Drexler); Gründel, p. 470, figs. 5-7.

1971 *Ogmoconchella aspinata* (Drexler); Malz, p. 454-455, pl. 5, figs. 21-22.

1971 *Ogmoconcha ellipsoidea* (Jones); Lord, p. 658, pl. 123, figs. 9-13.

1975 *Ogmoconchella aspinata* (Drexler); Michelsen, p. 238-242, pl. 31, fig. 450; pl. 33, figs.

470-471.

1985 *Ogmoconchella aspinata* (Drexler); Donze, p. 106-107, pl. 21, fig. 10.

1987 *Ogmoconchella aspinata* (Drexler); Park, p. 64-65, pl. 4, figs. 10-12.

1989 *Ogmoconchella ellipsoidea* (Jones); Ainsworth, p. 141, 142, 149, 154, pl. 4, fig. 25.

1990 *Ogmoconchella ellipsoidea* (Jones); Ainsworth, p. 192, 199, 205, pl. 5, fig. 16.

2009 *Ogmoconchella aspinata* (Drexler); Franz *et al.*, p. 150, pl. 5, fig. 18.

2009 *Ogmoconchella aspinata* (Drexler); Boomer & Ainsworth, p. 188-189, pl. 1, fig. 12.

Description: Smooth, unornamented, medium-sized species. The carapace is sub-ovate or sub-triangular in lateral view, whereas ovoid in dorsal view. The greatest height marked at posterior of mid-length but few are almost median. The greatest width also situated at posteriorly and greatest length at the mid-height. The larger left valve strongly overlaps right valve with the thickest overlap on dorsal margin. Specifically, the right valve and left valve are differed in shape. The posterior and anterior margins of right valve are evenly rounded and meet at concave ventral margin. In contrast, the left valve exhibits straight to slightly concave ventral margin, whilst it posterior margin evenly rounded compare to anterior margin which is almost acute. Lip sometimes occurred but only appear at anterior margin of right valve. Few right valve of instar specimens possess postereo-ventral spine.

Variation: The overlap area of juvenile form is narrow and even around the margin.

Remark: *Ogmoconchella aspinata* is the most abundant ostracods recorded in Hettangian-Early Sinemurian studied samples. The dominance usually happened from early Hettangian to mid Hettangian age but then their abundance decreases from end Hettangian to early Sinemurian due to the appearance of *Ogmoconcha hagenowi*.

Dimension: Ballinlea-1 Borehole (pl. 20, fig. 7) carapace: length 525 µm, height 341 µm. Magilligan Borehole (pl. 20, fig. 10) left valve: length 579 µm, height 411 µm; (pl. 20, fig. 9) carapace: length 526 µm, height 371 µm. Magilligan Borehole (pl. 20, fig. 13) carapace: length 584 µm, width 316 µm. Carnduff-1 Borehole (pl. 20, fig. 8) carapace: 540 µm, height 383 µm; (pl. 20, fig. 11) right valve: length 518 µm, height 341 µm.

Material: Ballinlea-1 Borehole 951 carapaces, 218 right valves and 247 left valves; Carnduff-1 Borehole 474 carapaces, 574 right valves and 548 left valves; Magilligan Borehole 335 carapaces, 125 right valves and 145 left valves; Tircrevan Burn 13 carapaces, 37 right valves and 29 left valves; Larne 10 right valves and 8 left valves; Ballygalley 10 right valves and 26 left valves.

Ranges: Total range: latest Triassic-Early Sinemurian (Semicostatum Ammonite Chronozone, Boomer & Ainsworth, 2009). Range of studied samples (Figure 3.2): Hettangian- Early Sinemurian (Ballinlea-1 Borehole), Hettangian (Magilligan Borehole), Hettangian-earliest Early Sinemurian (Carnduff-1 Borehole), Early Sinemurian (Tircrevan Burn), end Hettangian (Larne), Hettangian (Ballygalley).

Ogmoconchella danica Michelsen, 1975

(Plate 21, figs 1 & 2)

1975 *Ogmoconchella danica* Michelsen, p. 243-247, pl. 31, figs. 451-454; pl. 32, figs. 456-462; pl. 33, figs. 476-484; pl. 34, figs. 485-489; pl. 41, figs. 574-577.

1987 *Ogmoconchella danica* Michelsen; Park, p. 64-65, pl. 4, figs. 13-16.

2009 *Ogmoconchella danica* Michelsen; Boomer & Ainsworth, p. 189-190, pl. 1, figs. 14.

Description: Smooth, ovate and almost symmetry carapaces with equally rounded outline. The highest point situated just behind the mid-point of arched dorsal margin. The longest length is at the mid-height. The vaguely narrow rounded anterior and broad rounded posterior

pass uniformly through the straight ventral margin and arched dorsal margin. The left valve is overlap the right valve entirely and evenly.

Remark: This species is normally observed in the latest early Sinemurian to early Pliensbachian. They appear right after the extinction of *O. aspinata* and *O. hagenowi*.

Dimensions: Ballinlea-1 Borehole (pl. 21, fig. 1) carapace: length 582 µm, height 397 µm; (pl. 21, fig. 2) left valve: length 617 µm, height 440 µm.

Materials: Ballinlea-1 Borehole 65 carapaces, 43 right valves and 62 left valves; White Park Bay 13 right valves and 2 left valves; Kenbane Head 2 carapaces, 4 right valves and 2 left valves; Ballintoy 3 right valves and 4 left valves.

Ranges: Total range: Late Sinemurian (Obtusum-Raricostatum Ammonite Chronozone, Boomer & Ainsworth, 2009). Range of studied samples (Figure 3.2): end early Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole), Late Sinemurian (White Park Bay), Early Pliensbachian (Kenbane Head and Ballintoy).

Ogmoconchella mouhersensis (Apostolescu, 1959)

(Plate 21, figs 4-7)

1959 *''Ogmoconcha'' mouhersensis* Apostolescu, p. 805, pl. II, figs. 18-19.

1975 *"Ogmoconcehlla mouhersensis''* (Apostolescu); Michelsen, p. 248-249, pl. 32, figs. 465-466; pl. 34, figs. 494-496; pl. 35, figs. 497-502.

1987 *Ogmoconchella mouhersensis* (Apostolescu); Park, p. 64-65, pl. 4, figs. 17-22.

2009 *Ogmoconchella mouhersensis* (Apostolescu), p. 188-189, pl. 1, fig. 13.

Description: The carapace is slightly elongate and sub-ovate in lateral view with the greatest height posteriorly. The dorsal margin arched or greatest height located behind the mid-point which later the margin gently slopes into well-rounded and broad posterior end. The antero-dorsal margin has greater gradient than in postero-dorsal margin. This rectilinear margin merge at rounded, narrow anterior end. Like other *Ogmoconchella*, the ventral margin of *O. mouhersensis* is distinctly concave especially in right valve. Left valve is overlap right valve entirely except for postero-ventral margin. Posterior half of both valves encompass fingerprint ornament. Right valve normally has lip on its anterior end, whereas few specimens yield spine at postero-ventral end.

Remark: *O. mouhersensis* larvae usually do not developed distinct fingerprint structure, make them difficult to differentiate with *O. danica* juveniles as both appear in the same range.

Dimension: White Park Bay (pl. 21, fig. 4) right valve: length 667 µm, height 427 µm; (pl. 21, fig. 5) right valve: length 684 µm, height 433 µm; (pl. 21, fig. 6) left valve: length 684 µm, height 464 µm; (pl. 21, fig 7) left valve: length 611 µm, height 390 µm.

Material: Ballinlea-1 Borehole 19 carapaces, 16 right valves and 13 left valves; White Park Bay

2 carapaces, 19 right valves and 14 left valves.

Range: Total range Late Sinemurian (Obtusum-Raricostatum Ammonite Chronozone, Boomer

& Ainsworth, 2009). Range of studied samples (Figure 3.2): end Early Sinemurian-Late

Sinemurian (Ballinlea-1 Borehole), Late Sinemurian (White Park Bay).

<div align="center">

Genus OGMOCONCHA Triebel, 1941

Ogmoconcha hagenowi Drexler, 1958

(Plate 20, figs 1-4)

</div>

1958 *Ogmoconcha hagenowi* Drexler, p. 508, pl. 21, figs 8a-f; pl. 26, figs. 1-2.

1971 *Ogmoconcha hagenowi* Drexler; Malz, p. 452-453, pl. 4, fig. 17.

1975 *Ogmoconcha hagenowi* Drexler; Michelsen, p. 230-231, pl. 28, figs 419-425; pl. 29, figs.

428-430.

1985 *Ogmoconcha hagenowi* Drexler; Donze, p. 106-107, pl. 21, figs. 14-15.

1987 *Ogmoconcha hagenowi* Drexler; Park, p. 64-65, pl. 4, figs. 7-9.

1989 *Ogmoconcha hagenowi* Drexler; Ainsworth, p. 140, 149, 154 pl. 4, fig. 21.

1990 *Ogmoconcha hagenowi* Drexler; Ainsworth, p. 190, 199, 205, pl. 5, fig. 14.

2009 *Ogmoconchella hagenowi* Drexler; Franz *et al.*, p. 149-150, pl. 5, fig. 16.

2009 *Ogmoconcha hagenowi* Drexler; Boomer & Ainsworth, p. 188-189, pl. 1, fig. 11.

Description: *O. hagenowi* is a smooth species possesses a large carapace with triangular outline (lateral view). The anterior and posterior margin are well-rounded or acute which merge into convex ventral margin and acute dorsal margin. The greatest point is in-front of mid length (antero-medianly), whilst the longest length situated slightly below the mid height. The sides of the carapace in dorsal view are rounded, not flattened. The larger left valve is overlap right valve equally.

Variation: The distinctive triangular appearance normally recorded from adult specimens, whereas the instars show different shape in lateral view. The instar carapaces are slightly longer than adult forms with more anteriorly highest point. Furthermore, their posterior and anterior ends are rounded (not acute like adult form).

Remark: This species is commonly observed from end Hettangian to basal Early Sinemurian sediments.

Dimension: Ballinlea-1 Borehole (pl. 20, fig. 4) carapace: length 454 µm, height 317 µm; (pl. 20, fig. 3) carapace: length 506 µm, width 300 µm. Magilligan Borehole (pl. 20, fig. 2) carapace: length 669 µm, height 504 µm. Carnduff-1 Borehole (pl. 20, fig. 1) right valve: length 641 µm, height 473 µm.

Material: Balinlea-1 Borehole 274 carapaces 68 right valves and 74 left valves; Magilligan Borehole 1 carapace and 1 right valve; Carnduff-1 Borehole 185 carapaces, 169 right valves

and 200 left valves. Tircrevan Burn 9 carapaces, 14 right valves and 9 left valves; Larne 2 right valves and 7 left valves; Ballygalley 10 right valves and 26 left valves.

Range: Total range: late Hettangian (Angulata Ammonite Chronozone)-Early Sinemurian (Semicostatum Ammonite Chronozone, Boomer & Ainsworth, 2009). Range of studied samples (Figure 3.2): end Hettangian-Early Sinemurian (Ballinlea-1 Borehole & Carnduff-1 Borehole), late Hettangian (Magilligan Borehole), Early Sinemurian (Tircrevan Burn), end Hettangian (Larne).

Ogmoconcha eocontractula Park, 1984

(Plate 20, figs 5 & 6)

1984 *Ogmoconcha eocontractula* Park, p. 67-70, pl. 11, figs 1-2.
1987 *Ogmoconcha eocontractula* Park; Park, p. 64-65, pl. 4, fig. 1-6.

Description: The test is smooth, medium-large with sub-triangular to sub-ovate outline. The anterior margin very broad, symmetry and smoothly rounded which continue until the convex ventral margin. Poster-dorsal margin is steeply slope to a narrower rounded, asymmetry posterior end. The greatest height in front of mid-point; anteriorly. The longest length located near the mid-height of the test. Left valve slightly larger than right valve and overlap in narrow but equally manner. A distinct convex margin is observed from ventral margin.

Remark: The adult forms of *O. eocontractula* are closely identical to *O. contractula* but they are differed in range; Early Sinemurian-Early Pliensbachian and Late Pliensbachian respectively. Meanwhile, the juvenile carapaces are almost similar to *Ogmoconcha amalthei amalthei* but *O. eocontractula* is devoid of median concavity (lateral surface), which present on median of *O. amelthei amelthei*. This flattened or concave feature is also observed in *O. contractula*; resulted on concave margin from dorsal view. Furthermore, all features explained in description best suit *O. eocontractula* rather than *O. amelthei*, especially it range. The *O. eocontractula* usually occurred together with *O. danica* in Late Sinemurian to Early Pliensbachian beds.

Dimension: Ballinlea-1 Borehole (pl. 20, fig. 5) carapace: length 496 µm, height 354 µm; (pl. 20, fig. 6) left valve: length 676 µm, height 481 µm.

Material: Ballinlea-1 Borehole 72 carapaces, 37 right valves and 48 left valves; White Park Bay 12 carapaces, 41 right valves and 19 left valves; Ballintoy 2 carapaces, 1 right valve and 1 left valve.

Range: Total range: Early Sinemurian-Late Sinemurian (Park, 1987, 1988). Range of studied samples (Figure 3.2): end Early Sinemurian-Early Pliensbachian (Ballinlea-1 Borehole), Late Sinemurian (White Park Bay), Early Pliensbachian (Ballintoy).

Age / Species	latest Rhaetian	Hettangian	Early Sinemurian	Late Sinemurian	Early Pliens.
Ogmoconchella aspinata	▬▬▬▬▬▬▬▬▬▬▬▬	▬▬▬▬			
Ogmoconcha hagenowi		▬▬▬			
Ogmoconchella danica				▬▬▬▬▬▬▬▬	
Ogmoconchella mouhersensis				▬▬▬▬▬▬▬▬	
Ogmoconcha eocontractula				▬▬▬▬▬▬▬▬	
Ogmoconchella gruendeli				▬▬▬▬	
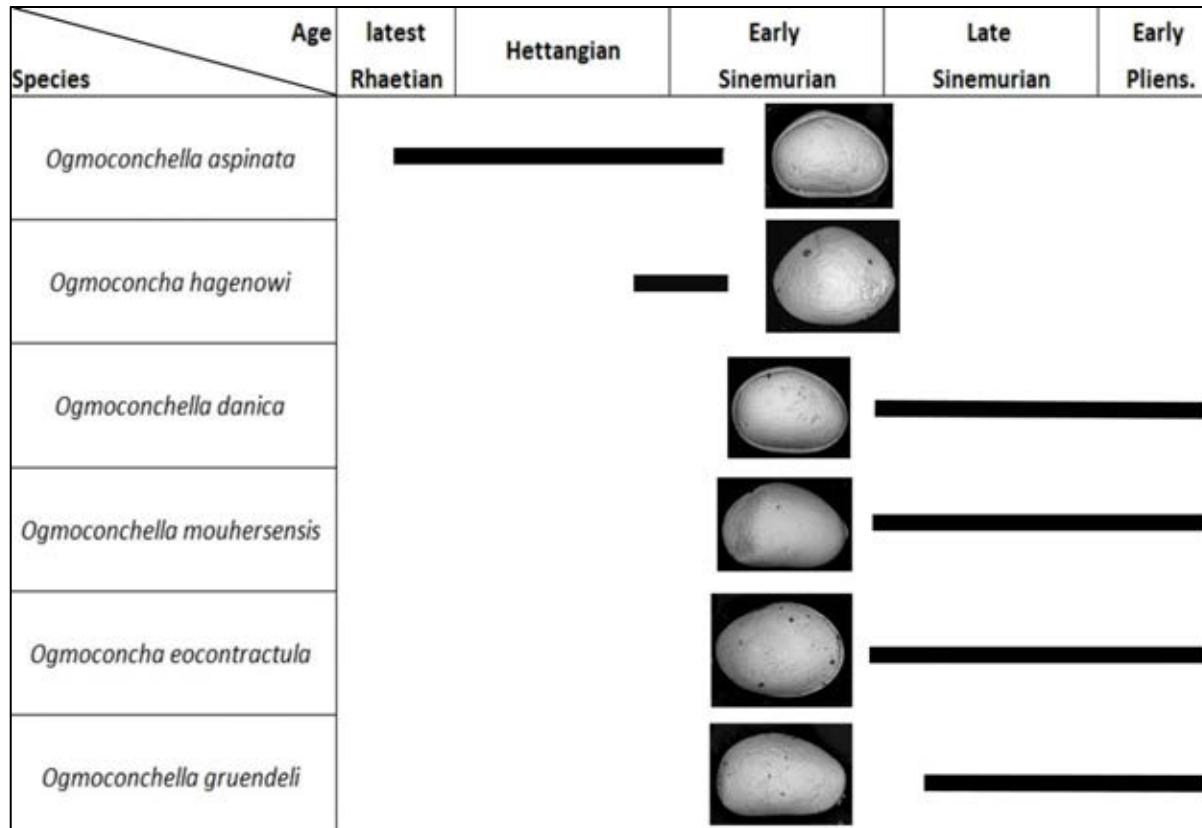
Figure 3.2: Range chart of biostratigraphical Metacopina from studied localities (Northern Ireland).

Suborder PODOCOPINA Sars, 1866

Superfamily CYTHERACOIDEA Baird, 1850

Family PROTOCYTHERIDAE, Ljubimova, 1955

Subfamily KIRTONELLINAE Bate, 1963

Genus EKTYPHOCYTHERE Bate, 1963

Ektyphocythere translucens (Blake, 1876)

(Plate 23, figs 1-4)

1876 *Cythere translucens* Blake, p. 432, 433, pl, 17, fig. 10.

1923 *Bairdia translucens* (Tate and Blake); Pratje, p. 253.

1971 *Klinglerella? translucens* (Blake); Lord, p. 656, pl. 123, figs. 4-5.

1985 *Klinglerella translucens* (Blake); Donze, p. 110-111, pl. 23, figs. 5-7.

1987 *Kinkelinella (Ektyphocythere) translucens* (Blake); Park, p. 59-60, pl. 2, figs. 1-6.

1989 *Kinkelinella translucens* (Blake); Ainsworth, p. 137, 138, 149, 154, pl. 4, fig. 1.

1991 *Ektyphocythere translucens* (Blake); Boomer, p. 213-214.

2009 *Ektyphocythere translucens* (Blake); Boomer & Ainsworth, p. 190-191, pl. 2, figs. 1-3.

Description: The lateral view of the test is elongate, sub-oval outline with highest point at anterior cardinal angle and the longest length exactly below mid-height. The linear dorsal margin exhibits low gradient until it reaches narrow well-rounded posterior end. The anterior margin has rounded margin too but broader than posterior margin. Both anterior and

posterior margins comprise bordering rim. The convex ventral margin can be either poorly or distinct inflated. This smooth valve are inflated entirely except for the flattened anterior-dorsal regions. From dorsal view, greatest width located behind the mid-length; posteriorly.

Variation: Most of examined specimens are frequently smooth, yet few tests contain weak longitudinal ribs near the ventral margin or weak reticulations at the mid-valve area. These types are found from mid Hettangian of Magilligan and Carnduff-1 boreholes only. These variations are very identical to the Paris Basin specimens; illustrated by Donze (1985).

Remark: *E. translucens* is common in Hettangian and normally exists together with *O. aspinata*.

Dimension: Ballinlea-1 Borehole (pl. 23, fig. 1) carapace: length 444 μm, height 283 μm; (pl. 23, fig. 2) left valve: length 531 μm, height 342 μm. Carnduff-1 Borehole (pl. 23, fig. 3) left valve: length 594 μm, height 361 μm; (pl. 23, fig. 4) left valve: length 553 μm, height 312 μm. Magilligan Borehole (pl. 23, fig. 5) carapace: length 470 μm, height 255 μm; (pl. 23, fig. 6) left valve: length 427 μm, height 241 μm; (pl. 23, fig. 7) carapace: length 484 μm, width 226 μm.

Material: Ballinlea-1 Borehole 25 carapaces, 23 right valves and 20 left valves; Magilligan Borehole 8 carapaces, 25 right valves and 24 left valves.; Carnduff-1 Borehole 30 carapaces, 103 right valves and 101 left valves; Tircrevan Burn 4 right valves and 5 left valves; Larne 1 right valves and 14 left valves; Ballygalley 50 right valves and 75 left valves.

Range: Total range: latest Triassic-early Sinemurian (Bucklandi Ammonite Chronozone, Boomer & Ainsworth, 2009). Range of studied samples: Hettangian-Early Sinemurian (Ballinlea-1 Borehole), Hettangian (Carnduff-1 Borehole), Hettangian (Magilligan Borehole), Early Sinemurian (Tircrevan Burn), end Hettangian (Larne), Hettangian (Ballygalley).

Suborder CYTHEROCOPINA Baird, 1850

Superfamily CYTHEROIDEA Baird, 1850

Family CYTHERURIDAE Müller, 1894

Genus ACROCYTHERE Neale, 1960

Acrocythere gassumensis (Michelsen, 1975)

(Plate 25, figs 4 & 5)

1975 *Acrocythere gassumensis* (Michelsen), p. 153, 154, pl. 7, figs. 97-100; pl. 8, figs. 117-119.

1989 *Acrocythere?* cf. *A? gassumensis* Michelsen; Ainsworth, p. 129, 147, 151, pl. 1, figs. 23, 24, 27.

Description: *Acrocythere* is a small sized ostracod with a sub-rectangular outline in lateral view. The anterior end is broadly rounded, whilst the posterior end is narrow obtuse angle. The greatest height located at anterior cardinal angle. The straight dorsal margin is gently slope exactly after the anterior cardinal angle until the obtuse posterior end. The ventral margin is also straight but horizontal. The inflated anterior and posterior lateral surface are

separated by concave median-dorsal surface. The elevated tests are heavily ornamented by coarse sub-ovate or sub-quadrate homogenous reticulations except for smooth flanged anterior and posterior marginals. Although mostly are utterly reticulated, few specimens bear faded or weak ornament at the median concave region of the valve surface. The eye spot is well-developed and situated near the anterior cardinal angle.

Remark: *A. gassumensis* closely resemble to *A. oeresundensis*. However, the lateral outline of former species is shorter and more rectangular than the latter elongate species. These small genera; *Acrocythere* and *Nanacythere* are both important stratigraphically.

Dimension: Ballinlea-1 Borehole (pl. 25, fig. 4) right valve: length 373 µm, height 188 µm; (pl. 25, fig. 5) right valve: length 278 µm, height 138 µm.

Material: Ballinlea-1 Borehole 13 carapaces, 2 right valves and 1 left valve; Tircrevan Burn 1 right valve.

Range: Total range: Early-Late Sinemurian (Michelsen, 1975). Range of studied samples: Early-Late Sinemurian (Ballinlea-1 Borehole), Early Sinemurian (Tircrevan Burn).

Chapter 4

Biostratigraphy, biozonation and palaeoenvironment of Ballinlea-1 Late Triassic-Early

Jurassic sequences

4.1 Introduction

A deep onshore borehole (TD 2683 m) in the Rathlin Basin; Ballinlea-1 [D 03765 39317] (Figure 4.1) drilled in 2008 by Rathlin Energy for hydrocarbon exploration. The borehole yielded thickest Waterloo Mudstone Formation (Early Jurassic age) sequences known from Northern Ireland. The discovery provides the opportunity to study Early Jurassic benthic microfauna of this region in detail.

4.2 Lithology

The thickest sequence of Waterloo Mudstone Formation known in Northern Ireland of approximately 605 m underlie relatively thin (15 m) Cretaceous Chalk of the Ulster White Limestone Group (UWLG) and a thicker (92 m) Paleogene Antrim Lava Group (ALG). Above these are a 238 m faulted, repeated section that comprises Jurassic Waterloo Mudstone Formation (47 m) and a further 51 m section of Cretaceous UWLG which overstepped by 140 m Paleogene Antrim Lava Group. Our study focuses on the largely continuous early Jurassic sequence underlying these sediments from about 345 m to 950 m.
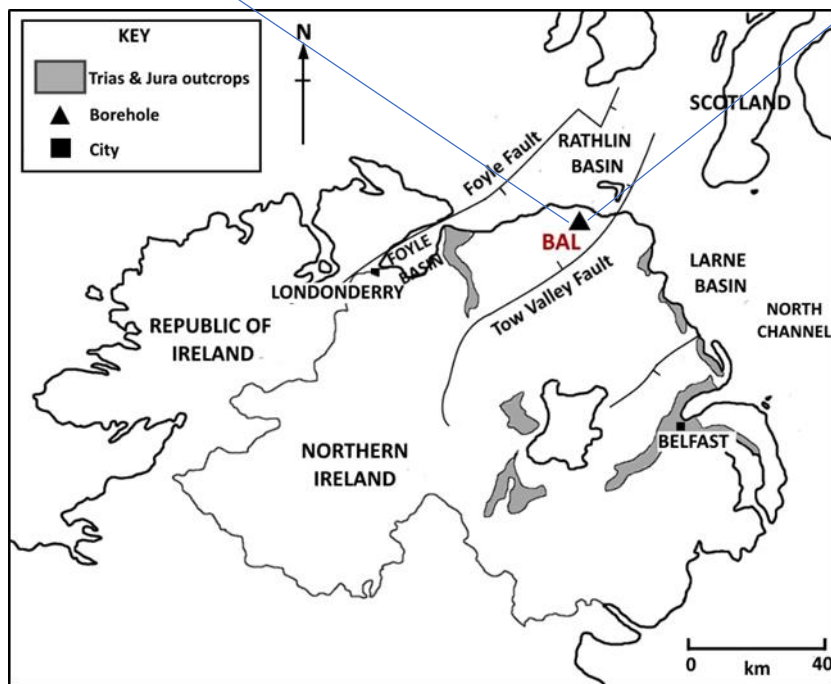
Figure 4.1: The location map of Ballinlea-1 Borehole (BAL) [D 03765 39317].

The Waterloo Mudstone Formation comprises principally grey calcareous mudstones with occasional thin grey limestones and silty mudstones. The colours are variable range of grey but common by blueish-grey and olive-grey. Mica and fossils such as foraminifera, ostracods, micro-bivalves, micro-gastropods, echinoderm fragments, ophiuroid fragments are prevalent, whilst pyrites, carbonaceous materials, iron nodules and quartz grains distributed irregularly throughout.

4.3 Biostratigraphy and Chronostratigraphic Age

Of the 70 cuttings samples from Ballinlea-1, only 4 are considered belong to the Late Triassic (Mercia Mudstone Group and Penarth Group) and remaining 69 samples are from the Early Jurassic Lias Group (Figure 4.2). A total of 10990 specimens were recovered consisting of 156 species of calcareous benthic foraminifera, 2 species of agglutinated foraminifera and 57 species of ostracods. Most of the samples yielded microfaunas of varying abundance (the highest is 576 specimens per 10 grams), however, some barren samples were noted. The microfaunas are very low (0.86 Fisher's alpha diversity) to highly diverse (27.36 Fisher's alpha diversity). The changing abundances and diversity of both ostracods and foraminifera are shown in Figure 4.2.

The oldest examined samples are upper part of the Late Triassic Collin Glen Formation, Mercia Mudstone Group. This interpretation is based on their lithologies; reddish-brown mudstone (BAL980) and greenish-grey mudstone (BAL970-BAL975) which according to Mitchell (2004)

as typical characteristics of the Collin Glen Formation. The microfaunas of this formation are impoverished, only exhibits ostracods *Lutkevichinella,* juvenile Metacopina, *Ektyphocythere moorei,* foraminifera *Paralingulina tenera tenera* and *Lenticulina varians varians.* Unfortunately, the existence of these species is questionable whether *in-situ* or caving.

The overlying beds are dark grey mudstone (BAL960-BAL965) and reddish grey siltsone (BAL950), most probably from the Penarth Group; Westbury Formation. The dark grey mudstone encompasses low abundance and diversity of marine foraminifera (Lagenida) and ostracods (Metacopina and Podocopina). While, the subsequent bed; reddish grey siltstone (BAL950) exhibits few white fine sandstone fragments with reddish stain. The sample has rare juvenile of Metacopina and very rare Podocopina with no foraminifera specimen. The assignation of age and lithostratigraphy are uncertain as no strong evidence from microfaunas that can provide biostratigraphical or environmental markers, plus author did not have access to additional data other than cutting samples and gamma ray log (Figure 4.2). The author just relies on lithologies and compared with the description of Penarth Group provided in Mitchell (2004).

The succeeding beds are grey mudstone (BAL945) of Waterloo Mudstone Formation, Lias Group. This based on bisaccate pollen information from Riding (2010), where he concluded BAL945 as Hettangian in age due to the occurrence of *Riccisporites tuberculatus* and the absence of Rhaetian markers such as *Rhaetipollis germanicus* and *Rhaetogonyaulax rhaetica.* His discovery means that probably the Lilstock Formation (Cotham Member and Langport Member) are missing. Hence, the unconformity possibly exists in between BAL950 and BAL945

strata. Furthermore, Delhaye *et al.* (2016) stated that within the Rathlin Basin, Jurassic Lias Group mudstone overlain unconformably on top of the Triassic Mercia Mudstone Group.

The Ballinlea-1 Early Jurassic (Waterloo Mudstone Formation) strata yield mainly of grey calcareous mudstone; interpreted from BAL345 to BAL945. The microfaunas are entirely benthic taxa where foraminiferal specific diversity is generally higher than for ostracods. Both groups show low diversity in Hettangian age (mostly below 5 Fisher's alpha diversity), to mid-part of the Early Sinemurian, but it then gradually increases for both groups starting from Early Sinemurian (1.83-26.56 Fisher's alpha diversity) to the Late Sinemurian (8.87-27.36 Fisher's alpha diversity). The diversity then slightly drops in the Early Pliensbachian interval (11.96-19.07 Fisher's alpha diversity), but still more diverse than during the Hettangian and Early Sinemurian stages.

For abundance, the low abundances are noted during the earliest Hettangian (19-61 specimens per 10 grams) but then increase in latter Hettangian sequence (73-490 specimens per 10 grams). Although the abundance is high during mid-latest Hettangian age, the assemblages are actually dominant by ostracods, specifically *Ogmoconchella aspinata*. Despite of ostracods dominance, the turnover recorded in BAL920 sample, where an influx of *Reinholdella planiconvexa* (210 specimens per 10 grams) takes place and it exceeds the number of *Ogmoconcehlla aspinata* (94 specimens per 10 grams). The abundance of earliest Early Sinemurian until mid Early Sinemurian are almost same pattern as in Hettangian sections. The microfossils abundances are very low during the earliest Early Sinemurian (4-41 specimens per 10 grams) but drastically increase when reach mid Early Sinemurian (10-576

specimens per 10 grams). These assemblages still dominant by ostracods especially *Ogmoconchella aspinata* and *Ogmoconcha hagenowi*. The younger beds; Late Sinemurian to Early Pliensbcahian recorded moderate to high abundance (24-270 specimens per 10 grams) and dominant by foraminifera.

The foraminifera assemblages mainly belong to the Order Lagenida but representatives of important accessory taxa assigned to the orders Miliolida, Buliminida and families Ceratobuliminidae and Spirillinidae are also recorded. The overall foraminiferal assemblages are abundance by the *Paralingulina tenera* plexus, followed by the *Lenticulina muensteri* plexus, the *Lenticulina varians* plexus and the *Marginulina prima* plexus. These genus particularly high amounts from the later part of the early Sinemurian onwards.

The ostracods mostly belong to the Order Metacopina which are present in almost every sample. There is an increasing abundance and diversity of the Order Podocopina noted from the mid-part of the Early Sinemurian onwards.
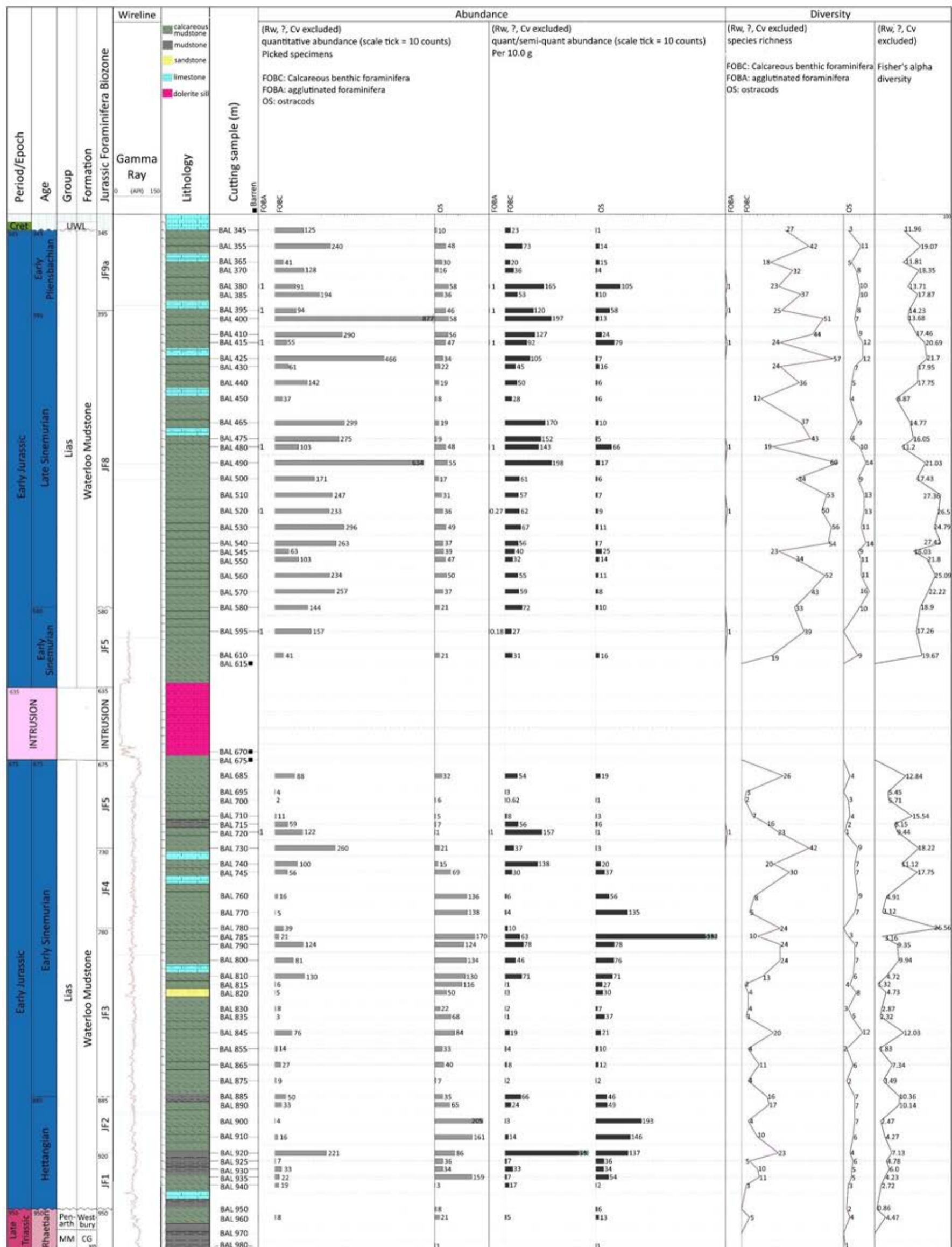
Figure 4.2: Sedimentary log, gamma ray log, relative abundance, species richness and Fisher's alpha diversity of microfaunas from Ballinlea-1 Borehole (MM: Mercia Mudstone Formation, CG: Collin Glen Formation).

4.4 Ballinlea-1 proposed biozonation

Ammonites form the basis for the chronostratigraphy of the Jurassic. As they are un-useable from cuttings wells, the age of the Ballinlea-1 core is established using the JF foraminiferal biozones of Copestake & Johnson (1989, 2014). The cuttings also demand that only the first downhole occurrences (FDO) of the marker species can be used, with a slightly modified approach taken for the interpretation of zones JF1 to JF3. The detail Ballinlea-1 Jurassic Foraminifera biozonations are discussed below together with microfossils range charts (Table 4.1 and Table 4.2).

Interval: 925 m- 950 m

Jurassic Foraminifera Biozone: JF1 (BAL925-BAL945)

Inferred age: earliest Hettangian

Ballinlea-1 indicator species: *Paralingulina tenera collenoti*, *Ogmoconchella aspinata* and *Ektyphocythere translucens*.

Riding (2010) determined the base of the Jurassic in this borehole as 945 m (BAL945) based on the presence of *Riccisporites tuberculatus* and the absence of distinctive Rhaetian markers such as *Rhaetipollis germanicus* and *Rhaetogonyaulax rhaetica*. No benthic microfauna data able to provide as this sample not in author's sample collections.

The bed above (BAL935) has impoverish marine assemblages; only *Paralingulina tenera tenera* and *Eoguttulina liassica* with the absence of JF1 marker; *Paralingulina tenera collenoti*.

However, common occurrence *of P. t. collenoti* is recorded at the top of JF1 biozone together with low numbers of *Reinholdella planiconvexa.* In the Mochras Borehole (Copestake & Johnson, 2014), *P. t. collenoti* appears commonly at the top of JF1 which they assigned as equivalent of Planorbis Chronozone (Planorbis Subchronozone); whereas *R planiconvexa* inception is near the base of JF1.

The Ballinlea-1 JF1 biozone also accompanied by the typical Early Hettangian ostracods taxa; *Ogmoconchella aspinata* and *Ektyphocythere translucens*.

Interval: 890 m-925 m

Jurassic Foraminifera Biozone: JF2 (BAL890-BAL920)

Inferred age: middle Hettangian

Ballinlea-1 indicator species: *Reinholdella planiconvexa, Paralingulina tenera collenoti, Planularia inaequistriata* and *Ogmoconchella aspinata*

Although events relating to the last downhole occurrence should be treated with caution in this borehole, the sudden flood of *Reinholdella planiconvexa* and common occurrence of *P. t. collenoti* in BAL920 depth strongly suggests that the JF2 biozone begins at about this depth. The influx of *R. planiconvexa* also occurs elsewhere in Britain such as the Blue Lias Formation of the Mochras Borehole (at the base of JF2; assigned as upper Planorbis Chronozone, Johnstoni Subchronozone) which is associated with development of widespread claystone units (e.g. Lavernock Shale and Saltford Shale; Copestake & Johnson, 2014).

At the end of JF2 biozone (BAL890), *Planularia inaequistriata* appears rare until bottommost JF3 (BAL885). Ballinlea-1 JF2 biozone is marked by high abundances and the consistent occurrence of the ostracod *O. aspinata.*

Interval: 785 m-900 m

Jurassic Foraminifera Biozone: JF3 (BAL785-BAL885)

Inferred age: Late Hettangian-earliest Sinemurian

Ballinlea-1 indicator species: *Paralingulina tenera substriata, Dentalina langi, Ichthyolaria terquemi barnardi, Ogmconchella aspinata* and *Ogmoconcha hagenowi*

The total range of the large and distinctive species; *Dentalina langi* is used to defined JF3 biozone (Copstake & Johnson, 2014). However, in Ballinlea-1, only 1 specimen of *Dentalina langi* is recorded (in BAL845). Therefore, the base of Ballinlea-1 JF3 biozone is proposed by the last occurrence (first downhole occurrence) of *Ichthyolaria terquemi barnardi* at 885 m and supported by the presence of *Paralingulina tenera substriata.* The sudden abundance of *Astacolus speciosus* appeared near the upper part of Ballinlea-1 JF3 (BAL810). Based on Copestake & Johnson (2014), this bioevent is particularly a diagnostic of the Sinemurian in Britain.

For ostracods, last downhole occurrence (first appearance) of common and consistent *Ogmoconcha hagenowi* appears within JF3 coincides with Ogmoconchella aspinata which abundant and consistent since JF1.

Riding (2010) examined two samples from this samples range (BAL875 and BAL825) and he observed the occurrence of consistent Hettangian-Early Sinemurian spore; *Kraeuseliporites reissingeri.* Thus, this supported the author's age interpretation of this succession.

Interval: 735 m- 785m

Jurassic Foraminifera Biozone: JF4 (BAL735-BAL780)

Inferred age: Early Sinemurian

Ballinlea-1 indicator species: *Paralingulina tenera substriata*, *Marginulina prima insignis* and *Marginulina prima incisa, Ogmoconhella aspinata* and *Ogmoconcha hagenowi.*

The base of JF4 in the Ballinlea-1 borehole is represented by the extinction of *Paralingulina tenera substriata* recorded at BAL780. The JF4 biozone is further characterised by continuation of *Marginulina prima insignis* and *Marginulina prima incisa* which reach their maximum numbers at the top of the biozone (BAL730). Near the top of the biozone, *Ogmoconcha hagenowi* and *Ogmoconchella aspinata* becomes less common and both disappear (first downhole occurrence) at the JF4-JF5 boundary. Boomer & Ainsworth (2009) record the *Ogmoconcha hagenowi* and *Ogmoconchella aspinata* extinction event as earliest and mid Semicostatum Ammonite Chronozone of Early Sinemurian respectively. Copestake & Johnson (1989, 2014) divided JF4 into two sub-biozones; JF4a and JF4b by using common to abundant *Involutina liassica* (top of the Bucklandi Chronozone) as an indicator for this boundary; e.g. Mendip High (Somerset; Barnard, 1949), Inner Hebrides well L134/5-1 (Ainsworth & Boomer, 2001) and Wessex Basin (Ainsworth *et al.*, 1998a). However, the absence of *I. liassica* in this core, makes this separation impossible.

Interval: 575 m-735 m

Jurassic Foraminifera Biozone: JF5 (BAL575-BAL730)

Inferred age: Early Sinemurian

Ballinlea-1 indicator species: *Neobulimina bangae, Vaginulina listi, Paralingulina tenera subprismatica, Marginulina turneri*

The base of JF5 biozone is defined by the common and consistent occurrence of foraminifera *Neobulimina bangae* (Early Sinemurian) from BAL720 to BAL730. Furthermore, based on palynological data from Riding (2010), the presence of pollen *Cerebropollenites macroverrucosus* in BAL700 inidicates Early Sinemurian age. While, the top of the biozone (BAL580 and BAL595) comprises few specimens of foraminifera marker; *Marginulina* aff. *turneri* which according to Copestake and Johnson (2014), *Marginulina turneri* only restricted to the Turneri Ammonite Chronozone of Early Sinemurian age. The ostracod assemblages are dominated by *Ogmoconchella danica* and *Ogmoconchella mouhersensis;* starting from the top of JF5 (BAL580). Boomer & Ainsworth (2009) ascribed inception of *Ogmoconchella danica* and *Ogmoconchella mouhersensis* appearing in the earliest Obtusum Chronozone. Alas, based on the presence of *Marginulina* aff. *turneri* from BAL580-BAL595, this means the last downhole occurrence (first appearance) of *Ogmoconchella danica* and *Ogmoconchella mouhersensis* recorded earlier (Turneri Ammonite Chronozone) than Boomer & Ainsworth (2009) proposed chronozone; Obtusum Ammonite Chronozone.

Table 4.1: Ranges of Ballinlea-1 stratigraphic and environmental benthic foraminifera markers in relation to proposed biozonation and stage.

Series	Substage	Jurassic Foraminifera biozone	Sample/Depth (m)	Lenticulina muensteri muensteri	Lenticulina varians varians	Paralingulina tenera pupa	Marginulina prima insignis	Marginulina prima interrupta	Lenticulina muensteri polygonata	Astacolus speciosus	Paralingulina tenera tenera	Marginulina prima rugosa	Paralingulina tenera tenuistriata	Vaginulina listi	Marginulina prima incisa	Marginulina prima spinata	Mesodentalina matutina	Lenticulina muensteri ssp. (A)	Ammodiscus siliceous	Mesodentalina varians haeusleri	Brizalina liasica	Ophthalmidium m. macfadyeni	Eoguttulina liassica	Nodosaria issleri	Planularia inaequistriata	Paralingulina tenera subprismatica	Vaginulinopsis denticulatocarinata	Reinholdella margarita margarita	Reinholdella robusta	Ichthyolaria terquemi squamosa	Spirillina infima	Ophthalmidium liasicum	Reinholdella pachyderma humilis	Reinholdella? planiconvexa	Marginulina turneri	Neobulimina bangae	Paralingulina tenera substriata	Haplophragmoides kingakensis	Reinholdella sp. A	Dentalina langi	Ichthyolaria terquemi barnardi	Paralingulina tenera collenoti
Early Jurassic	Early Pliensbachian	JF9a	BAL345	7	6	9	1	1	1	3	9	10	48	6																												
			BAL355	11	7	49		3	5	6	30	14	33		3	4	2																									
			BAL365		6	6	2	1	2		3				1		2																									
			BAL370	10	18	6	5		1	5	3	8	20		7	3	1	3	1																							
			BAL380	7	7	22				2	1	9	17		1				1																							
			BAL385	1	7	37				2	2	12	78		4	2	5			1	1	1	1																			
			BAL395	10	5	10			1	3	1	12	19		2	4	4		1																							
	Late Sinemurian	JF8	BAL400	7	14	236	3		5	1	33	9	141		2	5	4	1						116	33	4		6	1													
			BAL410	10	18	80	1			3	5	17	72		1		5								3			3	2													
			BAL415	8	4	9	2				5	1	5											1	1			1							1							
			BAL425	14	28	142		10	3	1	9	14	63		3	4	7							1	1	3		2		19	5			10	2							
			BAL430	7	2	7	3				3	1					1							2	4	1		1					16									
			BAL440	11	19	4			2	1	8	3	12	3		2	5							5	13	1	2			11			2		2							
			BAL450	1	1								3	1																2			21									
			BAL465	8	21	17	1		4	4	12		1		1		4							4	40	2				122			3		2							
			BAL475	7	31	21	1		1	8	8	3	17		3	5	3							7	11	5		9	1	77			1									
			BAL480	16	14	11		14			5		10		5	5	1						1	2	7									1								
			BAL490	21	43	50		8	14	6	73	9	18		4	9	21							5	3	5		2		112			20	5	1	67						
			BAL500	4	17	23		1	4		14		24		6	2	9							3	2					28			2		1							
			BAL510	9	8	49		2	8	5	35	4		1	11	4	10		1					4	1	3		1		30	4											
			BAL520	13	7	26	6		3	2	32	2	31		7	2	4	3				1	1		8					29	1	1										
			BAL530	11	9	33	3		8	2	45	8	27		1	2	8	7					1		12	3				16	1	2		9								
			BAL540	12	14	11	1	2	2	4	54	11	18		4	5	44	3				1	1		4	1				4	3		1									
			BAL545	4	2	1				5	2	12	5	4	1	2	3							1						2												
			BAL550	7	8	15	6			2	3	11	2	8	1		5							1							2	2										
			BAL560	16	16	34			5	1	13	4	36		1	3	17	2							2			4	1	7	1	1	1									
			BAL570	8	25	57	5			8	7	17	6	3	3	7	21	2												4												
	E. Sin	JF5	BAL580	19	13	9				3	16	6	15		1	20	2								1					1								5				
			BAL595	13	10	6			4	1	13	2	18	1		24	1													2								2				
			BAL610	2	8	3					4	3	6	1			3																									
			BAL615																																							
			BAL635-BAL673	INTRUSION																																					
	Early Sinemurian	JF5	BAL685	3	13					2		1	4		12	16												1	1													
			BAL695		1	2											1																									
			BAL700														1																									
			BAL710	1								1	1		1													1							4							
			BAL715	1	4	3					17				3																				16							
			BAL720		9	1	3			6	3	3			2																				65	1	1					
		JF4	BAL730		24	8	30				61				24		1								1	4							1			2						
			BAL740		17	2	1				46														1	1							6									
			BAL745		3						1	3	2		2										1	1							4									
			BAL760	1							6	1	1																				4									
			BAL770			1									1																											
		JF3	BAL780	1	1	2					7		2		1																		3				3	2				
			BAL785		1	5				2	4				1																		1									
			BAL790		11	2				1	1		2										8		1								7	7								
			BAL800		1	3				1	14		27					1					7										3						1	4		
			BAL810		8					91	16												1											1								
			BAL815							5																																
			BAL820		2																		1																			
			BAL830	1	3						3												1																			
			BAL835		1						1																															
			BAL845		4	3					32	17																					2				1	1		1		
			BAL855								1																												11			
			BAL865							1	16		2										1										1									
			BAL875	1							4																															
	Hettangian	JF2	BAL885		9						15							4							1								2			1	2	3			3	
			BAL890			1					3												1		2															1		
			BAL900		1						1																															
			BAL910	1	5					1	2																															
			BAL920		6	3					11		3										13													6			132		1	16
			BAL925								1																												3			
		JF1	BAL930		1						5												1													1			9	1		12
			BAL935								4																									1						4
			BAL940								16												2																			
Late Triassic	Rhaetian		BAL950																																							
			BAL960		2					1	3																															
			BAL970																																							
			BAL980		1						1						1																									

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Table 4.2: Ranges of Ballinlea-1 stratigraphic and environmental ostracods markers in relation to proposed biozonation and stage.

Series	Substage	Jurassic Foraminifera biozone	Sample/Depth (m)	Ogmoconchella aequalis	Ogmoconchella gruendeli	Ogmoconcha eocontractula	Ogmoconchella danica	Pleurifera harpa	Gammacythere foveolata	Gammacythere ubiquita	Ektyphocythere herrigi	Acrocythere michelseni?	Ogmoconchella mouhersensis	Acrocythere oeresundensis	Pleurifera plicata	Pleurifera vermiculata	Ektyphocythere frequens	Polycope pelta	Ektyphocythere sinemuriana	Polycope cerasia	Polycope cincinnata	Ektyphocythere exiloreticulata?	Ektyphocythere triebeli	Acrocythere gassumensis	Ektyphocythere perplexa	Ektyphocythere luxuriosa	Nanacythere aequdicostis	Ektyphocythere translucens	Ogmoconcha hagenowi	Ogmoconchella aspinata	Polycope minor	Ektyphocythere mooeri	Ektyphocythere cookiana	Ogmoconchella bristolensis	Lutkevichinella hortonae?
Early Jurassic	Early Pliensbachian	JF9a	BAL345	3																															
Early Jurassic	Early Pliensbachian	JF9a	BAL355	12	7	12	4	2	3	2	1																								
Early Jurassic	Early Pliensbachian	JF9a	BAL365	6	12	5		5		2	1?																								
Early Jurassic	Early Pliensbachian	JF9a	BAL370	2	1	1	3	5	1																										
Early Jurassic	Early Pliensbachian	JF9a	BAL380	9	24	4		3	7																										
Early Jurassic	Early Pliensbachian	JF9a	BAL385	10	5	5	5	6	1	1		1																							
Early Jurassic	Early Pliensbachian	JF9a	BAL395		10	14	3		4	3	1																								
Early Jurassic	Late Sinemurian	JF8	BAL400		11	16	11	6		6																									
Early Jurassic	Late Sinemurian	JF8	BAL410		6	10	12	5		8																									
Early Jurassic	Late Sinemurian	JF8	BAL415		6		8	2	4		1	1	6																						
Early Jurassic	Late Sinemurian	JF8	BAL425		2	5	3	3	9			1	2	2																					
Early Jurassic	Late Sinemurian	JF8	BAL430		2	6		3		4			2		1																				
Early Jurassic	Late Sinemurian	JF8	BAL440		5			3	3	3			5																						
Early Jurassic	Late Sinemurian	JF8	BAL450			4	1	1		1																									
Early Jurassic	Late Sinemurian	JF8	BAL465		1	5	2		3	1			1						1																
Early Jurassic	Late Sinemurian	JF8	BAL475		3	1		2					3																						
Early Jurassic	Late Sinemurian	JF8	BAL480		5		9	6		8	2		5						4																
Early Jurassic	Late Sinemurian	JF8	BAL490	3	2	8	2		1	6			3						11	2	2	4													
Early Jurassic	Late Sinemurian	JF8	BAL500	3		2			1	1			1						1			2	3					1							
Early Jurassic	Late Sinemurian	JF8	BAL510	2	4		1		3	1									3	3	2		3	3?											
Early Jurassic	Late Sinemurian	JF8	BAL520	3	4	4	5		4				1						5									3	1	1					
Early Jurassic	Late Sinemurian	JF8	BAL530	4		24			5				5	2					3										1						
Early Jurassic	Late Sinemurian	JF8	BAL540		1	7	4		4										4	1	2							3	4	1					
Early Jurassic	Late Sinemurian	JF8	BAL545		3	7	4												12										7	2					
Early Jurassic	Late Sinemurian	JF8	BAL550			17	1		2										10	1															
Early Jurassic	Late Sinemurian	JF8	BAL560		20	2			1										7	2	1								4						
Early Jurassic	Late Sinemurian	JF8	BAL570		3	2	1												2	3								2		6					
Early Jurassic	E. Sin	JF5	BAL580		1	4	1												3	2								1		2					
Early Jurassic	E. Sin	JF5	BAL595																																
Early Jurassic	E. Sin	JF5	BAL610																			1		2			3		1						
Early Jurassic	E. Sin	JF5	BAL615																																
			BAL635-BAL673	INTRUSION																														
Early Jurassic	Early Sinemurian	JF5	BAL685								3						16																		
Early Jurassic	Early Sinemurian	JF5	BAL695																																
Early Jurassic	Early Sinemurian	JF5	BAL700														2																		
Early Jurassic	Early Sinemurian	JF5	BAL710													1																			
Early Jurassic	Early Sinemurian	JF5	BAL715																																
Early Jurassic	Early Sinemurian	JF5	BAL720																																
Early Jurassic	Early Sinemurian	JF4	BAL730																			1	3		1			2	1						
Early Jurassic	Early Sinemurian	JF4	BAL740																	1	1					2			3						
Early Jurassic	Early Sinemurian	JF4	BAL745																										4						
Early Jurassic	Early Sinemurian	JF4	BAL760						1			1																2	10	85					
Early Jurassic	Early Sinemurian	JF4	BAL770																									2	54	61					
Early Jurassic	Early Sinemurian	JF3	BAL780																																
Early Jurassic	Early Sinemurian	JF3	BAL785																										88	72					
Early Jurassic	Early Sinemurian	JF3	BAL790																					11				4	22	35					
Early Jurassic	Early Sinemurian	JF3	BAL800																									2	57	60					
Early Jurassic	Early Sinemurian	JF3	BAL810																									2	48	64					
Early Jurassic	Early Sinemurian	JF3	BAL815																										50	53					
Early Jurassic	Early Sinemurian	JF3	BAL820																				7					10	12	11	1				
Early Jurassic	Early Sinemurian	JF3	BAL830																										12	7					
Early Jurassic	Early Sinemurian	JF3	BAL835																									2	6	58					
Early Jurassic	Early Sinemurian	JF3	BAL845																			1	1		1			4	5	39					
Early Jurassic	Early Sinemurian	JF3	BAL855																											28					
Early Jurassic	Early Sinemurian	JF3	BAL865																				4					3	6	19					
Early Jurassic	Early Sinemurian	JF3	BAL875																											6					
Early Jurassic	Hettangian	JF2	BAL885																									6	4	15		2			
Early Jurassic	Hettangian	JF2	BAL890																1										6	50		1			
Early Jurassic	Hettangian	JF2	BAL900																										3	161					
Early Jurassic	Hettangian	JF2	BAL910																1										1	151					
Early Jurassic	Hettangian	JF2	BAL920																										4	59					
Early Jurassic	Hettangian	JF1	BAL925																									4	1	21					
Early Jurassic	Hettangian	JF1	BAL930																										4	19					
Early Jurassic	Hettangian	JF1	BAL935																										1	103					
Early Jurassic	Hettangian	JF1	BAL940																										1						
Late Triassic	Rhaetian	JF1	BAL950																											6					
Late Triassic	Rhaetian	JF1	BAL960																										1	15			1		
Late Triassic	Rhaetian	JF1	BAL970																															1?	
Late Triassic	Rhaetian	JF1	BAL980																															1?	2

Interval: 395 m-575 m

Analysed sample: BAL400-BAL570

Jurassic Foraminifera Biozone: JF8

Inferred age: Late Sinemurian

Ballinlea-1 indicator species: *Marginulina prima spinata* and *Marginulina* aff. *turneri*

Although the usage of last downhole occurrence as marker should be avoided in this borehole, the consistent and common occurrence of *Marginulina prima spinata* indicates base of JF8 biozone. Thus, this shows that JF6 and JF7 are missing within Ballinlea (refer to palaeoenvironment for further explainations).

The JF8 biozone is also marked by the consistent occurrence of Late Sinemurian assemblages; foraminifera *Ichthyolaria terquemi squamosa, Marginulina prima spinata, Marginulina prima interrupta, Nodosaria issleri, Mesodentalina varians hauesleri, Paralingulina tenera subprismatica* and ostracods *Ogmoconchella danica, Ogmoconchella mouhersensis* and *Ogmoconcha eocontractula.* A sudden peak of *Reinholdella pachyderma humilis* occurs within this biozone (BAL490). Copestake & Johnson (2014) stated that this influx indicates the Raricostatum Ammonite Chronozone. Comprehensively, *P. t. subprismatica* occurs abundantly throughout the biozone.

Another important Late Sinemurian taxa is *Varginulinopsis denticulatacarinata* which occurs in significant numbers near the top of Ballinlea-1 JF8 biozone (BAL400-BAL425). The top of JF8 biozone (BAL400) is defined by the disappearance (first downhole occurrence) of *Nodosaria issleri* and abundant occurrence of *Brizalina liasica.* Based on the Early Jurassic British and northern Europe foraminifera biozonation scheme, the *Nodosaria issleri* extinction marks the end of Raricostatum Ammonite Chronozone (Aplantum Subchronozone); latest Late Sinemurian (Copestake & Johnson, 1989, 2014).

Interval: 345 m- 395 m

Jurassic Foraminifera Biozone: JF9a (BAL345-BAL395)

Inferred age: bottommost Early Pliensbachian

Ballinlea-1 indicator species: *Nodosaria issleri, Astacolus speciosus* and *M. p. spinata*

The JF8-JF9a boundary is defined by first downhole occurrence of *Nodosaria issleri* at BAL400. Therefore, the base of JF9 (Early Pliensbcahian) is suggested from BAL395 through to BAL345. Some species such as *Astacolus speciosus* and *Marginulina prima spinata* still occur commonly in this biozone. At Mochras, JF9 is classified into two sub-biozones; JF9a and JF9b by the last downhole occurrence of *Haplophragmoides lincolnensis* (Copestake & Johnson, 2014). This species has not been observed in Ballinlea-1, hence the youngest studied sample is interpreted as the JF9a biozone of Early Pliensbachian.

The occurrence of ostracods *Ogmoconchella danica, Ogmoconchella gruendeli* and *Ogmoconcha eocontractua* continue up to almost end of studied samples (BAL355). These taxa are known as Late Sinemurian and Early Pliensbachian species (Michelsen, 1975; Park, 1988).

4.5 Palaeoenvironmental analysis

In the following section, the palaeoenvironments are interpreted based on the full range of biotic components observed during the study and only Waterloo Mudstone Formation will be discussed.

4.5.1 Hettangian (BAL885 to BAL950)

The Lias Group was deposited during latest Rhaetian to earliest Jurassic eustatic sea level rise.

The microfauna of the Hettangian interval (885 m to 950 m) yields no evidence of freshwater or brackish ostracod genera like *Darwinula* or *Lutkevichinella* suggesting that the transgression was firmly established throughout this interval. The late Triassic mass extinction is slowly recovered in Hettangian towards earliest Sinemurian. Even though the faunas start to recover, the diversity is still too low (alpha diversity less than 5) and mostly dominated by ostracods especially adult Metacopina (*Ogmoconchella aspinata* and *Ogmoconcha hagenowi*) with subsidiary ostracod

species such as *Ektyphocythere translucens* and foraminifera *Paralingulina tenera collenoti* and *P. t. tenera*. This is probably because they are still in the recovery phase from Tr-Jr mass extinction. This lowermost Waterloo Mudstone Formation was deposited in a well-oxygenated, marine, inner shelf environment; reflected by the colonization of opportunistic and successful group of organisms that were able to tolerate a wide range of environment like *O. aspinata* (Boomer & Ainsworth, 2009).

Morphogroup		Test form	Life-style	Feeding strategy	Genera
Agglutinateds	C	Elongated uniserial or biserial	Shallow infaunal	Detritivores, bacterial scavengers	Ammobaculites Textularia
	D	Rounded planispiral	Epifaunal to shallow infaunal	Active herbivores, detritivores and bacterivores	Haplophragmoides
Calcareous	G	Plano-convex trochospiral	Epifaunal	Primary weed fauna grazing herbivores	Epistomina
	H	Discoidal flattened (planispiral)	Epifaunal	Primary weed fauna grazing herbivores/ phytodetritivores	Spirillina Involutina
	I	Discoidal flattened spiral, elongated	Epifaunal	Active deposit-feeders herbivores, detritivores	Ophthalmidium
	J	J1	Elongated uniserial	Shallow infaunal	Active deposit-feeders, herbivores, bacterial scavengers	Citharina Dentalina Ichtyolaria Lingulina Marginulina Nodosaria Pseudonodosaria Tristix Vaginulina
		J2	Elongated flattened	Shallow infaunal	Active deposit-feeders grazing omnivores	Astacolus Falsopalmula Marginulinopsis Planularia Saracenaria
		J3	Elongated with straight periphery	Shallow to deep infaunal	Active deposit-feeders grazing omnivores	Eoguttulina
	K	Biconvex (lenticular) planispiral	Epifaunal to deep infaunal	Active deposit-feeders, grazing omnivores	Lenticulina

Figure 4.3: Benthic foraminifera morphogroups (Reolid *et al.*, 2013).

Within the early part of Hettangian, both diversity of foraminifera and ostracods are low, however, the distinct peak of small aragonitic taxon; *Reinholdella planiconvexa* has been recorded at in BAL920, in association with moderate number of *O. aspinata*. *Reinholdella* is a primary seaweed epifaunal grazing herbivors (Reolid *et al.*, 2013) (Figure 4.3) and opportunistic species (Bernhard, 1986; Koutsoukos *et al*., 1990; Boutakiout & Elmi, 1996; Sagasti & Ballent, 2002; Ballent *et al*., 2006) that can adapt to biotic stress environments (Clémence & Hart, 2013) or stagnant sea-bottom (Brouwer, 1969; Johnson, 1976). According to (Johnson, 1976), *Reinholdella planiconvexa* lived at inner to middle shelf environment.

4.5.2 Early Sinemurian (BAL610 to BAL885)

A regressive episode is interpreted, within the overall marine transgression (Figure 4.4), in the earliest Sinemurian (Haq, 2017), this supported by the presence of common to abundant quartz grained between BAL820 to BAL845 associated with abundant micro-ironstone nodules at BAL820. The arenaceous material might be correlated with the Tircrevan Sandstone Member mentioned in Mitchell (2004) which is exposed in the Tircrevan Burn section (refer Chapter 6 in this study), therefore a shallower environment is envisaged. These unfavourable environments cause the decline of both foraminifera and ostracods numbers and diversity (BAL815 to BAL875 samples) especially the abundance of *O. aspinata,* and those that occur are mostly juvenile (possibly transported) and it's later replaced by slightly higher numbers of *Ogmoconcha*

hagenowi. Even though these intervals deposited in the shallower setting, no agglutinated foraminifera are recorded.

The microfaunas diversity are increase starting from BAL810 up to BAL740. As stated by Haynes (1981), the diversity is the highest in open marine conditions, while low diverse denoted shallowing environment (close to land) or due to other factors (for instance, stagnant of bottom water or change of salinity or turbulence). Moreover, Copestake & Johnson (1989) related the inception as association of transgression, whereas extinction linked to the regression. Therefore, this increases diversity can be associated with sea-level rise. Despite of this transgression, BAL810 might be deposited in the low-oxygen environment based on the abundant occurrence of *Astacolus speciosus*. According to Bernhard (1986), the high occurrence of ornamented flattened Lagenida such as *Astacolus speciosus* indicates low oxygen condition (Reolid *et al.,* 2012). The younger intervals above (785 m to 800 m) deposited in inner shelf environment with little or no oxygen depletion; inferred by the increase of foraminiferal and ostracods abundant and diversity (note that ostracods are still more numerous than foraminifera).

The fauna turnover is marked at BAL740 where the foraminifera become diverse and dominant the abundance. The dominance of foraminifera by Lagenida members happened towards Early Plienbachian. The dominance and diversity of Lagenida indicates a favourable environment with normal marine inner shelf (Nagy & Alve, 2010).

However, within these diverse assemblages, BAL615 and BAL675 samples are barren due to the intrusion (630 m-670 m) that cause contact metamorphism on adjacent beds and making fossil extraction impossible.

4.5.3 Late Sinemurian (BAL400 to BAL570)

Based on the biostratigraphic foraminifera, the Northern Ireland Late Sinemurian interval is missing of JF6 and JF7 (equivalent to Obtusum and Oxynotum Ammonite Chronozone). This can be highly correlated with the adjacent borehole; Port More Borehole where the Obtusum and Oxynotum Ammonite Chronozes are missing too (Wilson & Manning 1978). This event notably across NW Europe and according to Hallam (1978, 1981), this is the period of shallowing or regression.

Generally, the Late Sinemurian horizon (JF8) recorded the most diverse and abundance of both microfaunas especially foraminifera. The increasing calcareous benthic foraminifera are resulted from the consistent sea-level rise which gradually change the inner shelf to middle or outer shelf environment. Hallam (1978) and Copestake & Johnson (2014) mentioned that latest Sinemurian is a representative of major transgression in Europe. Hence, the sea-level rise not only occurred in Northern Ireland but other parts of Europe too. The faunas are still dominated by the abundance *Paralingulina* with increasing specimens of *Lenticulina*, while ostracods dominant by

Metacopina. The uncoiled form of *Lenticulina* began to appear in the earliest Late Sinemurian. This trend is indicative of their adaptations to live near the sediment or water interface (Haynes, 1981).

It is noted that an influx of *Reinholdella pachyderma humilis* occurs in 490 m samples accompanied with very high number of *Paralingulina*. Brouwer (1969) and Jones (2013) stated that abundant of *Reinholdella* is characteristic of deep, open-marine; middle bathyal environments but below the Aragonite Compensation Depth (approximately 2000 m). Other authors interpreted genus *Reinholdella* as deep water indicator too, but that this genus lived on middle to outer shelf open marine (Brouwer, 1969; Johnson 1976; Hylton & Hart, 2000) with the onset of low-oxygen condition (Hylton & Hart, 2000). However, the Lias Mochras borehole study by Johnson (1976) has discovered the different *Reinholdella* species preferred different environment settings. He described that *Reinholdella pachyderma* lived on the outermost middle shelf or outer shelf. Meanwhile, occurrence of very abundance and dominance *Paralingulina tenera* plexus in this level indicate them as opportunistic species. This is supported by the statement of Rey *et al.* (1994) which suggested the elongated early Jurassic Lagenida are specialist form that able to adapt in confined environments (Reolid *et al.*, 2012). Another distinctive fauna is from BAL465 sample; where the nonexistence of *Ophthalmidium* in below intervals is suddenly expand to moderate amounts. This species accompanied by very abundant of *Paralingulina tenera* plexus. Jones (2013) described *Ophthalmidium* as a genus restricted to deep marine environments.

Another deeper setting proven from BAL400, where the occurrence of abundant *Brizalina liassica* together with profuse *Paralingulina tenera* plexus and moderate numbers of *Ophthalmidium*. Both *Brizalina* and *Ophthalmidium* dominant on deeper setting; outer shelf (Haynes, 1981; Jones, 2013). Boltovskoy (1972) stated the successful of *Brizalina* is related to their ability to tolerate with lower oxygen conditions. The depletion of oxygen is supported by the evidences of the dwarf size of *Brizalina* and *Paralingulina*; these two species recovered mostly in smaller sizes (63 µm to 125 µm residue) together with common amount of pyrites.

The influx of deep marine species such as *Brizalina* and *Ophthalmidium* usually come together with very abundant of *Paralingulina tenera* plexus. Therefore, this proven Reolied *et al.* (2012) statement regarding the elongated Lagenida are specialist form that able to with-stand confined environments.

4.5.4 Early Pliensbachian (BAL345 to BAL400)

The microfaunas still diverse in Early Pliensbachian but slightly decrease. The decline may be due to the minor fall of sea level during Pliensbachian age.
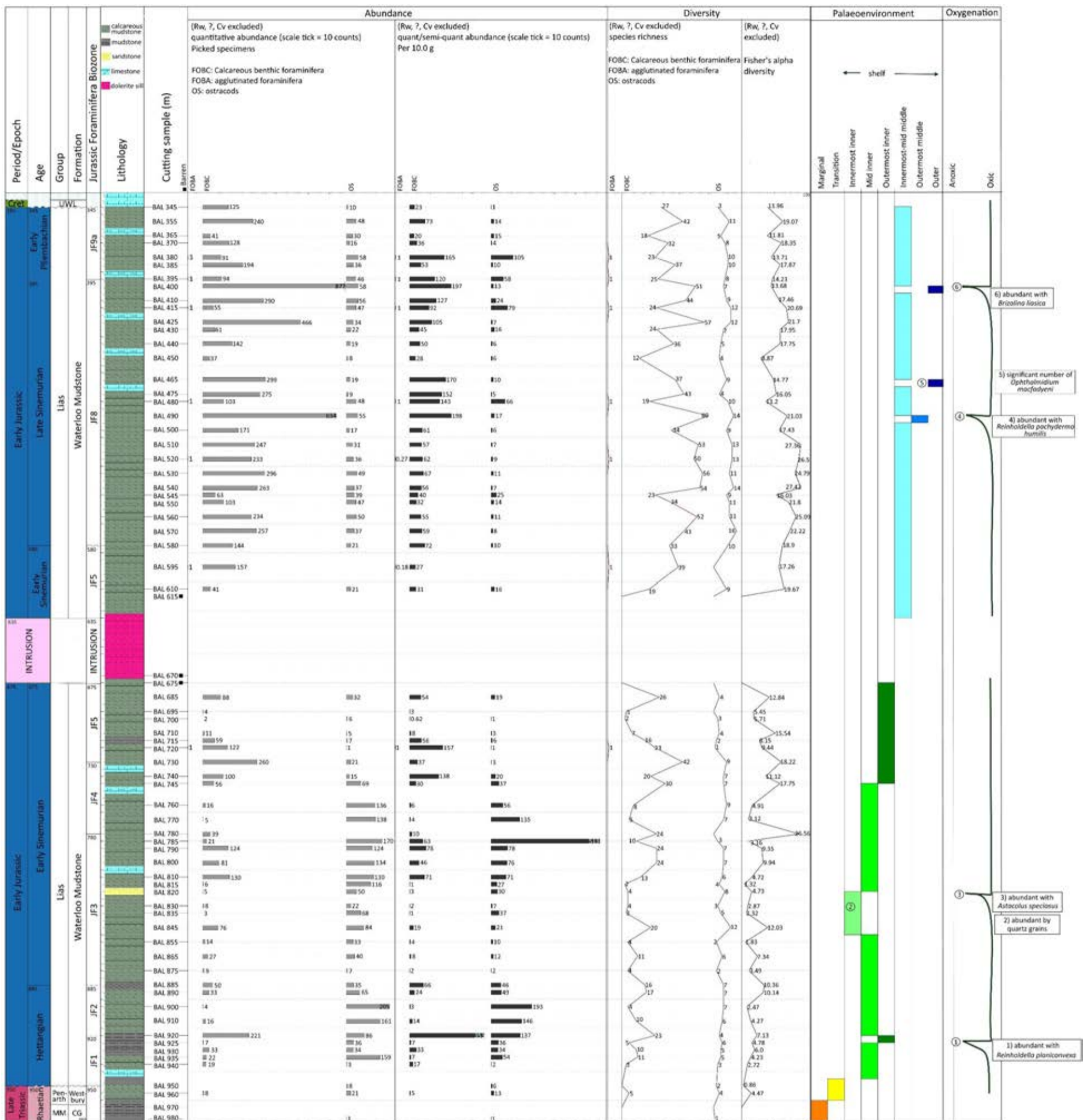
Figure 4.4: Stratigraphic summary, microfossils abundance, microfossils diversity, palaeoenvironment and oxygenation interpretation of the latest Triassic-Early Jurassic of Ballinlea-1 Borehole (MM: Mercia Mudstone Formation, CG: Colline Glen Formation).

Chapter 5:

Biostratigraphy, biozonation and palaeoenvironment of Carnduff-1 Late Triassic-Early Jurassic sequences

5.1 Introduction

The Carnduff-1 borehole (Figure 5.1) [D 40150 00983] was drilled within the Larne Basin, east Co. Antrim in 2013 by Gaelectric Energy Storage for salt exploration. The 8 cm diameter borehole of TD 922.7 m penetrated Waterloo Mudstone Formation from 163.9 m-320 m depth. The core samples from this borehole allows a detailed study of the Triassic-Jurassic boundary interval lithologies and microfaunas. The detailed studies of foraminifera and ostracod groups also allows an interpretation of the age and palaeoenvironment of the Late Triassic - Early Jurassic interval in the Larne Basin. These aspects are discussed in this chapter together with materials, lithology and biostratigraphy descriptions.

5.2 Lithology

The Carnduff-1 core samples are stored in GSNI samples room and during the visit, only Late Triassic to Early Jurassic sequences are observed. We then selected 28 samples from 170 m to 326 m depth; upper part of Penarth Group (Late Triassic) up to the uppermost Lias Group (Early Jurassic).
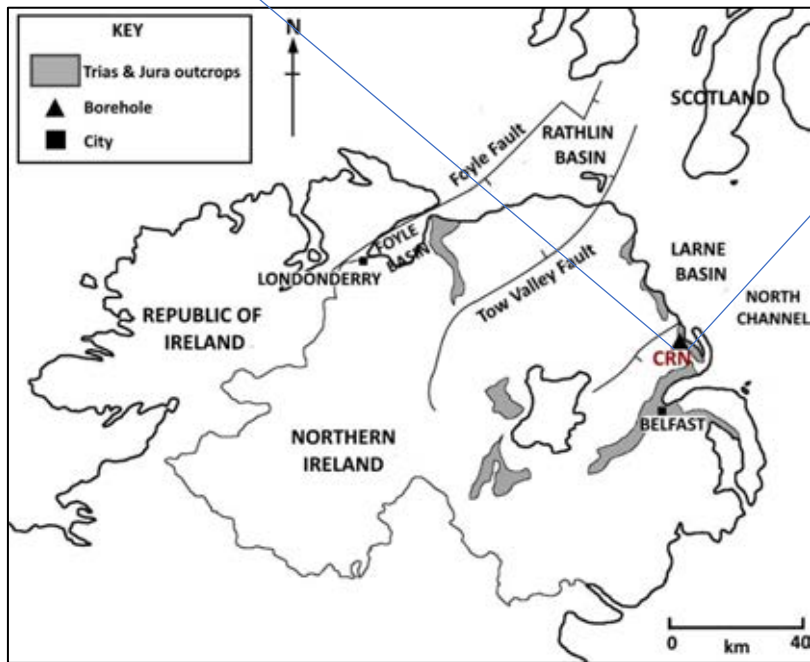
Figure 5.1: The location map of Carnduff-1 Borehole (CRN) [D 40150 00983].

The observed Penarth Group only limited to the Lilstock Formation. The lower part of Lilstock Formation; Cotham Member facies is very distinctive; the lamination of white siltstones with grey mudstone. Further up, the fine lamination gradually disappears as the siltstone become thicker and interbedded with mudstone. The distinct change of silt dominant to mud-dominant sediments began at 327 m depth, this marks the boundary of Cotham Member-Langport Member. The base of Langport Member comprises dominant dark grey micaceous mudstone with few laminations in between until upper part of the member but about the mid of Langport Member, 2 m thick slumping bed, noticeable in CRN322. Then, the upper half of Langport Member is coarsening upwards where relatively thick (approximately 1 m) white siltstones occur at the top.

Based on Simms & Jeram's (2007) study on the Waterloo Bay section, at Larne (just 4 km to the north east of Carnduff-1), they observed the Waterloo Mudstone Formation (Lias Group) resting conformably on the Lilstock Formation (Penarth Group). They marked the dark grey mudstone as the bottommost part of Lias Group which overlain the white bed of Langport Member. These interpretations have been applied in Carnduff-1 Borehole too, where the transition of white siltstone to dark grey mudstone at 320 m depth marks the Lilstock Formation (Penarth Group)-Waterloo Mudstone Formation (Lias Group) boundary.

The Waterloo Mudstone Formation in Carnduff-1 borehole is 156.1 m thick and intruded by Palaeogene dolerite sill at 224 m-230 m depth. The formation made up of varies colour of grey calcareous mudstone with occasional grey limestone and mudstone. They are commonly fossiliferous, micaceous with some pyrite and carbonaceous materials recorded. Commonly,

the beds contain ammonites (Figure 5.2-5.4), bivalves (Figure 5.5), micro-gastropods, echinoderm fragments, ophiuroid fragments, foraminifera and ostracods. The macrofossils observed in the cores is ammonites in 313.4 m (Figure 5.2) and 312.9 m (Figure 5.3) and bivalves such as in *Modiolus minimus* (Figure 5.5) and *Gryphaea arcuate* in several horizons.

Figure 5.2: The first occurrence of ammonite; *Psiloceras* sp. observed at 313.4 m depth (CRN313.4) of Carnduff-1 Borehole. This marks the base of Jurassic.

Figure 5.3: *Psiloceras* sp. observed at 312.9 m (CRN312.9) of Carnduff-1 Borehole.

Figure 5.4: Ammonite observed in younger section of Carnduff-1 Borehole

Figure 5.5: *Modiolus minimus* at 309.7 m (CRN309.7) of Carnduff-1 Borehole

5.3 Biostratigraphy

The 28 processed samples yielded 6940 microfossils comprising 5000 calcareous benthic foraminifera and 1940 marine ostracods. These specimens are from 89 species of calcareous benthonic foraminifera and 18 species of ostracods. In general, the abundance of both foraminifera and ostracods are vary from low (17 specimens per 10 grams) to extremely abundant (1288 specimens per 10 grams). While the diversity still considered as low (most samples have Fisher's alpha diversity below than 5) but moderate to high diversity (6.03-13.37 Fisher's alpha diversity) do occurred occasionally. Throughout much of the core the order

Lagenida dominates the foraminifera abundance and diversity, whilst the ostracod assemblage rich with Metacopina but the greatest diversity belongs to the Podocopina. Basically, foraminifera fauna is more diverse than the ostracods except for samples at CRN186 and CRN191.3 where the ostracods demonstrate greater diversity.

From these 28 core samples, only two Late Triassic samples (CRN324.35 and CRN326) from the Lilstock Formation are included in the research, unfortunately, both of them barren with microfossils but from Jim Fenton observations (unpublished report, 2017), CRN326 is abundant with algal cysts, whereby in CRN324.35 recorded occurrence of *Ricciisporites tuberculatus,* common *Todisporites minor,* abundant *Deltoidospora* spp., base *Cerebropollenites thiergartii.*

The first observed microfossils marks in CRN319.50, belongs to the Waterloo Mudstone Formation. This sample is low diverse (1.34 Fisher's alpha diversity) but profuse with *Eoguttulina liassica* (862 specimens per 10 grams). Then in subsequent bed (CRN314.9), the assemblage are still very abundant (1288 specimens per 10 grams) by low diverse fauna (1.27 Fisher's alpha diversity). This extremely abundant resulted from the influx of *Reinholdella planiconvexa* which continue up to the younger section (CRN296.2). Albeit of this continuation flood, the *R. planiconvexa* amounts literally decrease from 1232 specimens (per 10 grams) in CRN314.9 into 203 specimens (per 10 grams) in CRN296.2. This bioevent is a characteristic of Hettangian age (Planorbis Ammonite Chronozone; Copestake & Johnson, 2014). However, the ammonite (Figure 5.2) initially observed in CRN313.4, thus this marks the boundary of Triassic-Jurassic. Therefore, the flood of *R. planiconvexa* in Carnduff-1 Borehole occurred earlier than

most of adjacent regions. These floods are normally accompanied by abundant *Ogmoconchella aspinata* but still lower numbers than *Reinholdella planiconvexa*.

After end of the Robertinida floods, the foraminifera assemblages predominant by members of Lagenida particularly *Paralingulina tenera* plexus until the youngest sections of Carnduff-1 Waterloo Mudstone Formation. Another important occurrence of Lagenida members are moderate numbers of *Marginulina prima incisa* and *Marginulina prima insignis* in CRN211. These species indicate base of Sinemurian. Despite of Lagenida dominance, contrast appear at the top of Carnduff-1 Waterloo Mudstone Formation successions; in CRN182.9, CRN191.3 and CRN198.6, when localised peaks of Miliolida (*Cornuspira liasina*) occurred. The *Cornuspira* flood (111-383 specimens per 10 grams) only happened when *Paralingulina* is absent or rare; the change of infaunal (*Paralingulina*) to epifaunal (*Cornuspira*) are resulted from change of environment setting (discussed in section 5.5). Meanwhile in ostracods assemblages, *Ogmoconchella aspinata* is the most abundant among it group especially in the earliest Hettangian. Alas, the richness declines once *Ektyphocythere translucens* and *Ogmoconcha hagenowi* appeared but *Ogmoconchella aspinata* still dominant in mostly horizons. These three species start to disappear in the Waterloo Mudstone Formation youngest sections (CRN170.7-CRN182.9) when *Bairdia molesta*, *Isobythocypris tatei* and *Nanacythere aequalicostis* become significant in numbers. Figure 5.6 plots the picked abundance, relative abundance, species richness and Fisher's alpha diversity of Carnduff-1 microfossils.
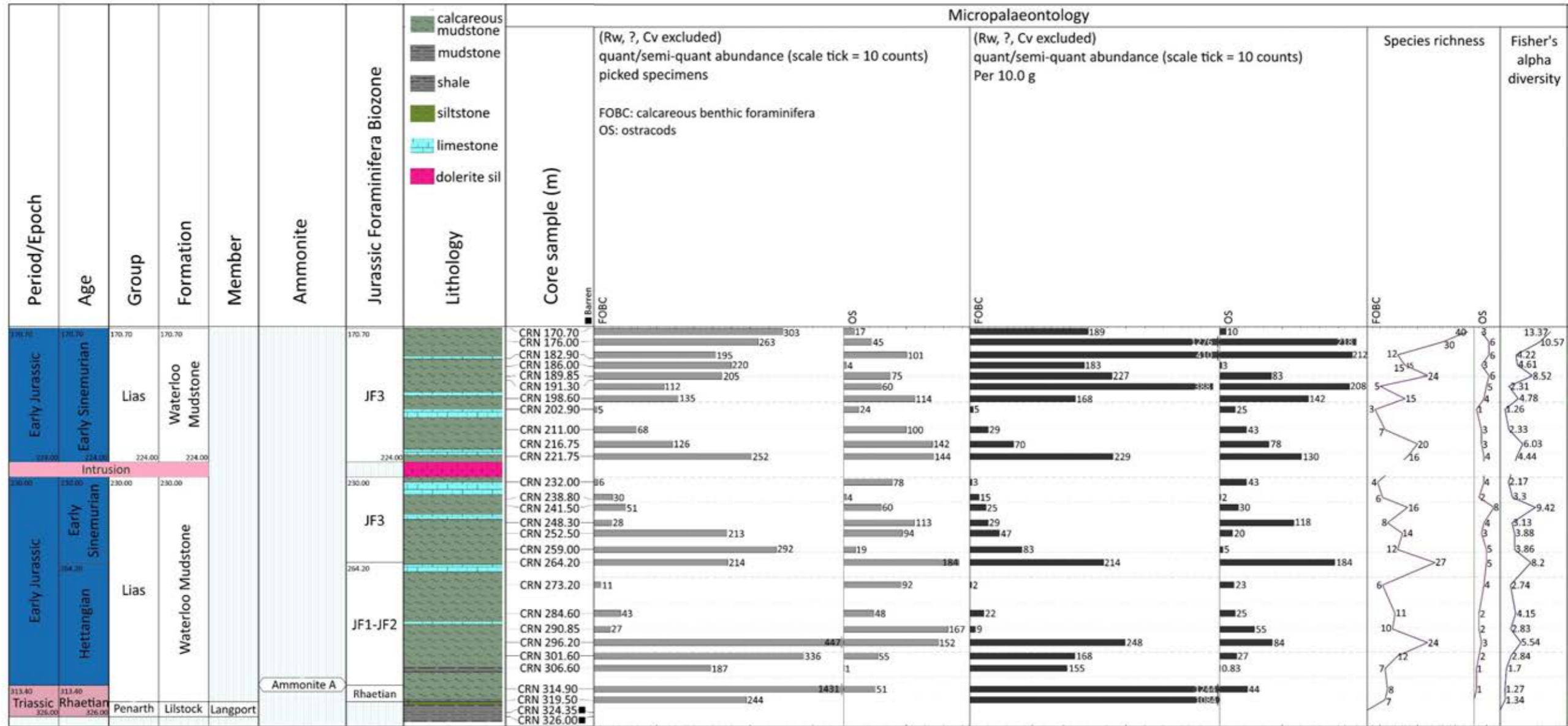
Figure 5.6: Sedimentary log, relative abundance, species richness and Fisher's alpha diversity of microfaunas from Carnduff-1 Borehole.

5.4 Carnduff-1 proposed biozonation

The Late Triassic and Early Jurassic biozonations of the Carnduff-1 borehole are proposed using the important foraminifera biozone markers with addition of key ostracods events (Table 5.1). Since these materials are from core samples, emphasis is placed on first appearance (last downhole occurence) and last occurrence (first downhole occurrence) of marker taxa. The Carnduff-1 Waterloo Mudstone Formation yields three biozones; Rhaetian, JF1-JF2 and JF3 (Table 5.1). The biozones determination only on Waterloo Mudstone Formation of latest Triassic to Early Jurassic age. Below are details of the Carnduff-1 biozonation:

Interval: 313.4 m-320 m

Analysed sample: CRN314.9-CRN319.5

Jurassic Foraminifera Biozone: Rhaetian

Inferred age: Latest Rhaetian

Carnduff-1 indicator species: *Eoguttulina liassica* and *Reinholdella planiconvexa*

The oldest Waterloo Mudstone Formation strata analysed are CRN314.9 and CRN319.5 which both contain microfossil. Two important both biostratigraphical and environmental markers appear in each section. The CRN319.5 sample is abundant with *Eoguttulina liassica* which Copestake & Johnson (2014) ascribed as typical event in Late Rhaetian due to begin of the sea-level rise. In younger bed (CRN314.9), the flood of thousands aragonitic taxa; *Reinholdella planiconvexa* documented. This event is recorded elsewhere, in Ballinlea and Magilligan

boreholes, even across the NW Europe. The last donwhole occurence (first appearance) of this influx is used as marker for base JF2 (Copestake & Johnson, 2014). However, in Carnduff-1 Borehole, the last downhole occurrence of this event happened earlier, in latest Rhaetian rather than Hettangian. This age proven by the discovery of the first occurrence of ammonite (Figure 5.2) found at the overlying bed; CRN313.4. Thus, the boundary of Triassic-Jurassic marks at CRN313.4. Refer to the section 4.5 for detailed explanation regarding relationship of *Reinholdella planiconvexa* with environment.

Analysed sample: CRN264.2-CRN306.6

Jurassic Foraminifera Biozone: JF1-JF2

Inferred age: Hettangian-mid Hettangian.

Carnduff-1 indicator species: *Reinholdella planiconvexa* and *Paralingulina tenera collenoti*

The base of JF1 is marked at the first occurrence of ammonite in CRN313.4. The latest Rhaetian *Reinholdella planiconvexa* flood continue in this biozones up to CRN296.2 but their numbers drops drastically to hundreds. This flood coincides with common occurrence of *Paralingulina tenera collenoti* from CRN296.2-CRN306.6. According to Copestake & Johnson (2014) these common and consistent occurrence ends before mid of JF2 biozone. However, because of the *Reinholdella planiconvexa* floods appear earlier than other part of NW Europe which commonly happened within JF2, hence the usage of last downhole occurrence (first appearance) of *Reinholdella planiconvexa* influx as the base JF2 marker is not applicable in this borehole. This cause the Carnduff-1 JF1-JF2 boundary uncertain, therefore author includes both biozones as one range.

The ostracod assemblages in this range are dominated by *Ogmoconchella aspinata* throughout the biozone, whereas the at the top of biozone; *Ogmoconcha hagenowi* and *Ektyphocythere translucens* appear frequent. These species are also representative of Hettangian stage (Boomer & Ainsworth, 2009).

Analysed sample: CRN170.7-CRN259

Biozone: JF3

Inferred age: latest Hettangian

Carnduff-1 indicator species: *Paralingulina tenera substriata*, *Marginulina prima incisa*, *Mesodentalina matutina*

The first appearance and abundance of *Paralingulina tenera substriata* are used to denote the base of the JF3 biozone which starts at sample CRN259 continuing through to the youngest studied sample (CRN170.7). This part of the sequence is assigned to the JF3 biozone due to the presence of *Paralingulina tenera substriata* as this species only range up to the JF3 biozone. Meanwhile, other two important JF3 index markers; *Marginulina prima incisa* and *Marginulina prima insignis* observed in CRN252.5 and CRN241.5 respectively. These two species reach their maximum abundance and dominate the foraminifera assemblage in the CRN211 sample. The ostracod assemblages are dominated by smooth Metacopina such as *Ogmoconchella aspinata* which decreases in abundance as *Ogmoconcha hagenowi* increases.

Table 5.1: Range chart of Carnduff-1's biostratigraphical and environmental important taxa (foraminifera and ostracods) in relation to proposed biozonation.

						Foraminifera																	Ostracods										
Group	Formation	Period	Stages/Substages	Jurassic Foraminifera biozonation	Sample/depth (m)	Eoguttulina liassica	Paralingulina tenera tenera	Paralingulina tenera tenuistriata	Paralingulina tenera substriata	Reinholdella planiconvexa	Paralingulina tenera pupa	Paralingulina tenera collenoti	Spirillina tenuissima	Ophthalmidium macfadyeni macfadyeni	Cornuspira liasina	Astacolus speciosus	Marginulina prima incisa	Marginulina prima praerugosa	Mesodentalina matutina	Marginulina prima rugosa	Marginulina prima insignis	Reinholdella sp. A	Ogmoconchella aspinata	Nanacythere elegans	Nanacythere paracostata	Ekthypocythere translucens	Ogmoconcha hagenowi	Bairdia molesta	Polycope cerasia	Nanacythere aequalicostis	Isobythocypris tatei	Polycope cincinnata	Polycope minor
Lias	Waterloo Mudstone	Early Jurassic	Early Sinemurian		CRN170.7		61	103	12		3		6			5	2			7	6									1	15		2
					CRN176		126		8				18		25	4											18			2	21		2
					CRN182.9	1									182												45	4		25	24	2	
					CRN186		14	153	5	4												18					1	1			2		
					CRN189.85		60	31								1	8	16	1		2		23				40	2		7		2	
					CRN191.3										109						1		38				4						
					CRN198.6										104		8				3		58				30						
				JF3	CRN202.9																													
					CRN211		1										17			1	45		62				36						
					CRN216.75		37	13									4	7	3		1		85	1			56						
					CRN221.75		166	44	6				2								1		81	2	1		60						
		Early Jurassic	Hettangian		CRN232	2																	32				41	2					
					CRN238.8		3						1																3				
					CRN241.5		2						5				3	5	4		7		30					6	9	4	8	1	
					CRN248.3		12											2	9				55					23	32				
					CRN252.5		100	82	2										3?				11				67	16					
					CRN259		124	150					1										8	2			4						
					CRN264.2	4	48	19							44	1							60					35	61	19	9		
					CRN273.2	1																	66					21					
				JF1-JF2	CRN284.6	17		8	7		2												44	4									
					CRN290.85					7	2												166										
					CRN296.2	4	29			367	17	9	3										149										
					CRN301.6		84	4		220	15	1											54										
					CRN306.6	1				147	19	15											1										
		Late Triassic	Rhaetian		CRN314.9	2	2	2		1417													51										
					CRN319.5	196																											
Penarth					CRN324.35																												
					CRN326																												

5.5 Palaeoenvironmental analysis

The progressive transgression during latest Triassic allowed the deposition of the epicontinental sea sediments (Penarth Group) which then gradually change to deeper setting that resulted on the development of dominant calcareous mudstone facies, Lias Group. This continues transgression enable the colonisation of infaunal *Eoguttulina liassica* in CRN319.5 sample. This species is a shallow marine genus (Jones, 2013) and their dominance in low

diversity microfaunas described it as opportunistic species (Nocchi & Bartolini, 1994). This reflects the beginning of transgression as the sea-level progressively increase but still relatively shallow.

The profuse of epifaunal grazing herbivors (Reolid. *et al*, 2012) *Reinholdella planiconvexa* in the younger sections (Figure 5.7), suggested inner to middle shelf environment (Johnson, 1976) with confined setting as this species is opportunistic species (Bernhard, 1986; Koutsoukos *et al*., 1990; Boutakiout & Elmi, 1996; Sagasti & Ballent, 2002; Ballent *et al*., 2006) that can with-stand biotic stress environments (Clémence & Hart, 2013) or stagnant sea-bottom (Brouwer, 1969; Johnson, 1976). Furthermore, the *Reinholdella* flood occurred earlier in Carnduff-1 compared to other two boreholes. This show that sea-level rapidly increase in Larne Basin compared to Rathlin and Foyle Basin. This may be due to the local setting of the Larne Basin.

Clémence & Hart (2013) stated that the restoration of stable environments causes the absence of *Reinholdella* yet trigger the appearance of other species. For instance, drop of *Reinholdella* numbers in Carnduff-1 allowed other opportunist species like *Paralingulina* and *Ogmoconchella* to colonise the ecology.

The assemblages then dominated by *Cornuspira liasina* within earliest Sinemurian (CRN198.6, CRN191.3, CRN182.9). This species is interpreted as shallow marine type based on the studies in Persian Gulf (Murray, 1965, 1970; Evans *et al*., 1973; Seibold *et al*., 1973; Hughes Clarke & Keij, 1973) and in the Caribbean (Murray 1965, 1970; Evans *et al*., 1973; Seibold *et al*., 1973;

Hughes Clarke & Keij, 1973) shown that smaller porcelaneous foraminifera dominant and achieve utmost diversity in tropical carbonate settings (Haynes, 1981). In addition, Jones (1994) stated that the smaller type of Miliolida such as family Cornuspiridae reach their maximum diversity in shallow marine, inner neritic environments. Based on the research of Bock (1969) and Brasie (1975) on relationship of seagrass (*Thalassia*) with epiphytic foraminifera in Caribbean, Haynes (1981) concluded that the success of small or large porcelaneous foraminifera in shallow water carbonate environments are because of seagrass role in providing the habitat to this group. The dominance of this shallow marine species also supported by the sea-level fall that is recorded at end Hettangian to earliest Sinemurian.

The overall palaeoenvironmental changes throughout Late Triassic to Early Jurassic are plotted in Figure 5.7.
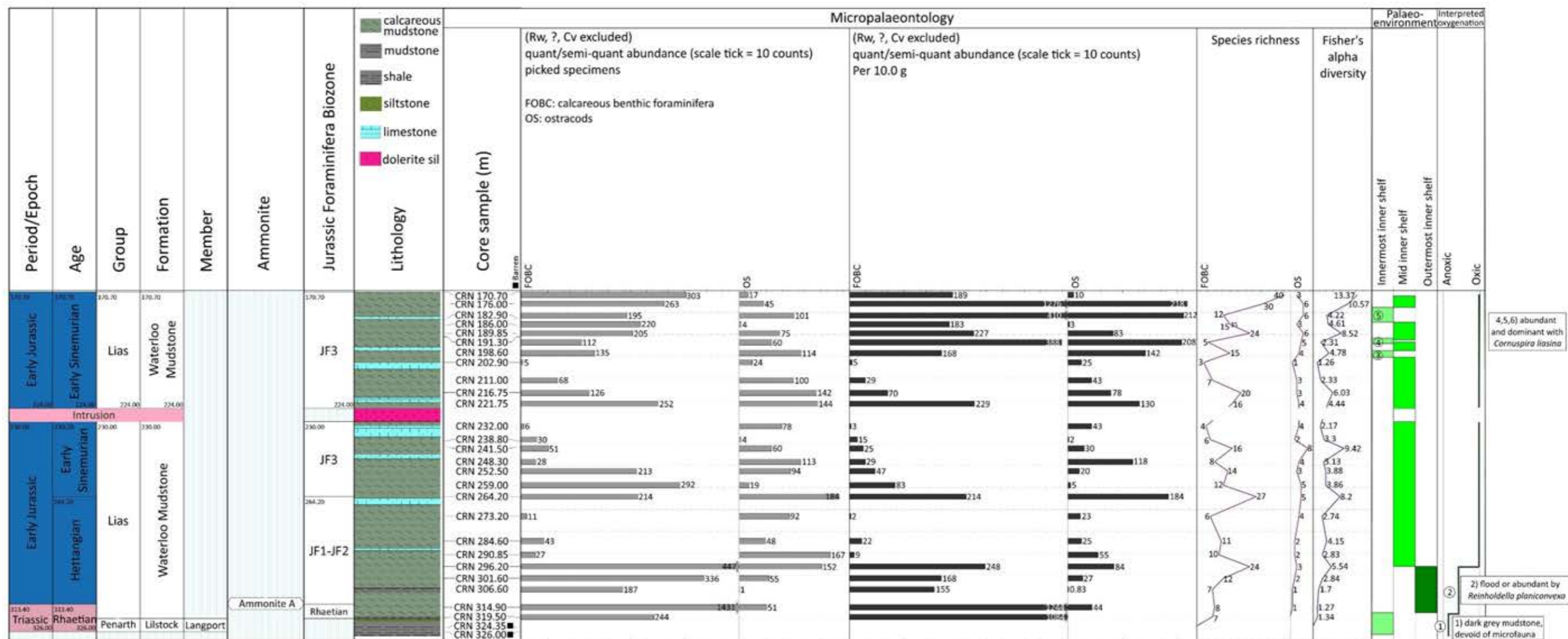
Figure 5.7: Stratigraphic summary, microfossils abundance, microfossils diversity, palaeoenvironment and oxygenation interpretation of the latest Triassic-Early Jurassic of Carnduff-1 Borehole.

Chapter 6

Biostratigraphy, biozonation and palaeoenvironment of Late Triassic-Early Jurassic

sequences of Magilligan Borehole and Tircrevan Burn

6.1 Introduction

The Co. Londonderry Waterloo Mudstone Formation (Waterloo Mudstone Formation) were investigated from a borehole at Magilligan [C 70039 33251] (Figure 6.1); Geological Society Northern Ireland (GSNI) onshore coal exploration borehole drilled within Lough Foyle Basin in 1963-1964 and with TD of 1346 m. Younger sequences of sediments are exposed at the Tircrevan Burn [C 70126 32552]; 6 km to the SE of Magilligan Borehole. Therefore, the results of these two localities will be included together in this chapter.

This chapter presents biostratigraphy, biozonations and palaeo-environmental interpretations based on the foraminifera and ostracods of the Magilligan Borehole and Tircrevan Burn exposures. The microfaunas are studied in detail as these sections have not previously been studied for their micropalaeontological remains.
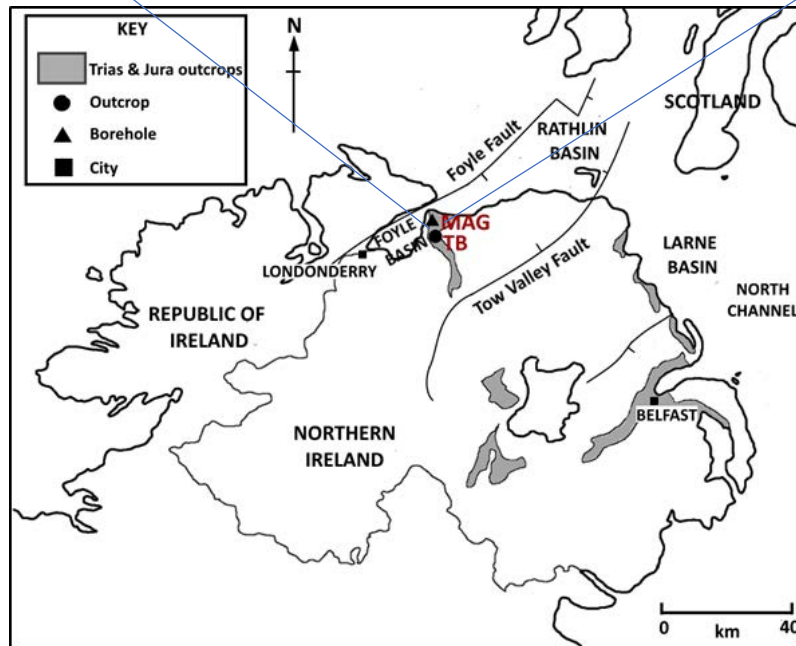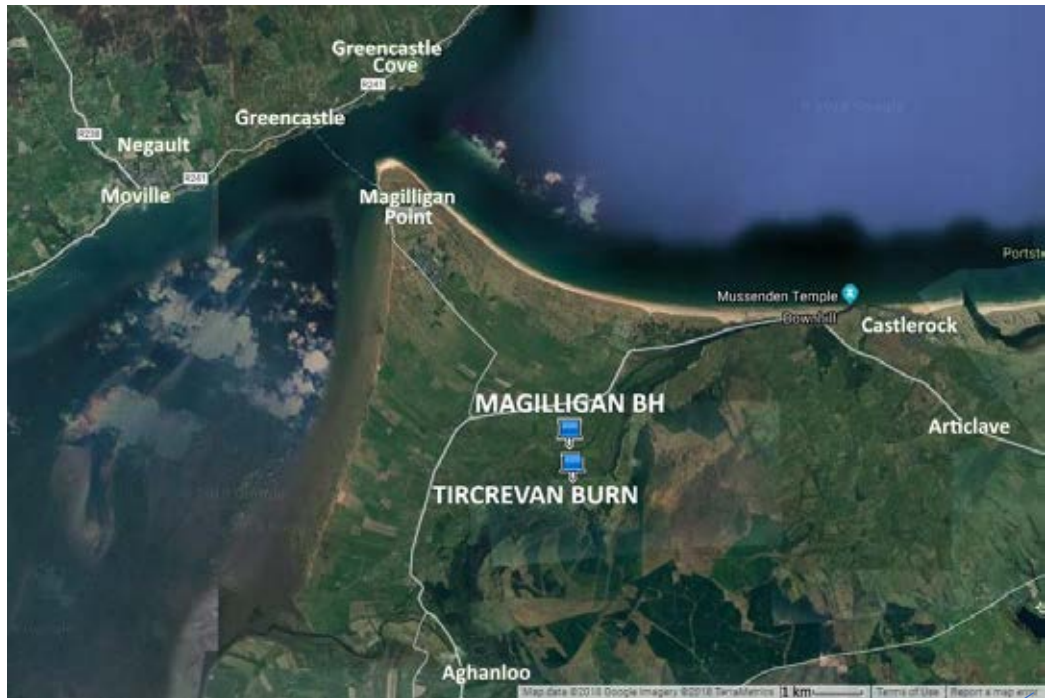
Figure 6.1: The location map of Magilligan Borehole (MAG) [C 70039 33251] and Tircrevan Burn (TB) exposure [C 70126 32552].

6.2 Lithology

6.2.1 Magilligan Borehole

A total of 35 core samples from Waterloo Mudstone Formation and Westbury Formation with 2-7m intervals were provided by Geological Survey of Northern Ireland. From these core samples, only 28 were processed for this study. The Waterloo Mudstone deposited in Magilligan Borehole is overlain conformably on top of Lilstock Formation which rest on top of the Westbury Formation.

The Westbury Formation of Penarth Group made up of alternating black to dark grey shales with mudstone and calcareous mudstone consisting silty laminae. The formation is rich with bivalve fossils and common with iron nodules. Meanwhile, the lithology description for Lilstock Formation cannot be explain in detail due to the absence of this formation in author's sample collection. Yet in general Lilstock Formation exhibits distinctive facies of grey mudstone laminae with white or light grey siltstones.

The Waterloo Mudstone Formation herein is about 163 m thick comprised mainly calcareous mudstone in association with infrequent mudstones and thin limestones in several horizons. The lithologies are often micaceous and subordinate with pyrite, iron nodules and carbonaceous material (see Appendix H and I for details).

6.2.2 Tircrevan Burn exposure

The continuation of Magilligan Borehole Waterloo Mudstone Formation sequences is display at Tircrevan Burn (Figure 6.2) which is one of the best Northern Ireland Waterloo Mudstone Formation exposures. However, the Tircrevan Burn Waterloo Mudstone Formation beds do not appear to overlap Magilligan Borehole but the gap between them is not large, about 50 m.

The Tircrevan Burn Waterloo Mudstone Formation sections are exposed along the stream which approximately 52 m thick (Bazley *et al*, 1997; Mitchell, 2004) which yields 13 m thick of Tircrevan Sandstone Member (Mitchell, 2004).

During fieldtrip, we were able to access several outcrop localities (Figure 6.2) and collected few samples for microfaunas study. The first observed bed was a part of Tircrevan Burn Member; thick white fine-grained quartz sandstone with black mud drapes on top of the facies (TB1 and TB2). Later, this arenaceous facies grades into blueish grey calcareous mudstone (TB3). Towards southeast, another two samples were collected, both are blueish grey calcareous mudstone. These are the youngest exposures that we able to access during our fieldtrip.

Figure 6.2: The locations of Tircrevan Burn sampling; TB1-TB2 [C 70126 32552], TB3 [C 70131 32531], TB4 [C 70218 32321] and TB5 [C 70292 32167].

6.3 Biostratigraphy

6.3.1. Magilligan Borehole

Total of 1552 specimens of microfossils were picked from 28 core samples, with resolution of 4 m to 10 m intervals. The specimens consist of 784 calcareous benthic foraminifera, 121 agglutinated foraminifera and 647 marine ostracods. In addition, 9080 specimens of foraminifera, *Reinholdella planiconvexa* have been observed and counted but it proved impossible to picked all of these as they are time consuming. Thus, the total number of microfossils found in 28 core samples were 10,632 specimens.

From the studied samples, only 21 samples have microfossils yet another 7 samples barren.

The predominantly black shales with silty laminae (MAG179.43-MAG175.1) belong to the

Westbury Formation of Penarth Group are devoid of microfaunas except for the oldest sample

that comprises an impoverished foraminiferal assemblage (six specimens of two species at

MAG179.43). the absence of microfossils continues up to the top section of the Westbury

Formation (MAG173.54). Lilstock Formation samples from 163.95m-172m interval are not in

author's sample collection, hence no biostratigraphy analysis is able to conduct.

The microfauna assemblages from Waterloo Mudstone Formation sediments are generally

low to moderate (20-45 specimens per 10 grams) and decline to very low (barren to 13

specimens per 10 grams) towards the upper part of the Magilligan Borehole (Figure 6.3). Yet,

few peaks of high (149-333 specimens per 10 grams) to very high abundance (1515-47430

specimens per 10 grams) are documented. These high abundances are resulted from the

dominance of certain species, for instance, the very high abundance at the lower part of the

sequences (MAG146 and MAG158) are due to the flood of aragonitic species *Reinholdella*

planiconvexa, whereas about the mid of the sequences, the high abundance is caused by the

dominance of *Ogmoconchella aspinata* or by the low diverse of Lingulina members.

Almost entirely analysed samples contain low diversity; Fisher's alpha diversity less than 5.

Alas, within these low diversities, there are two samples recorded alpha diversity greater than

5 which are MAG146 and MAG131.1. The assemblages with low diversity are typical

characteristic of latest Rhaetian-earliest Early Sinemurian age.
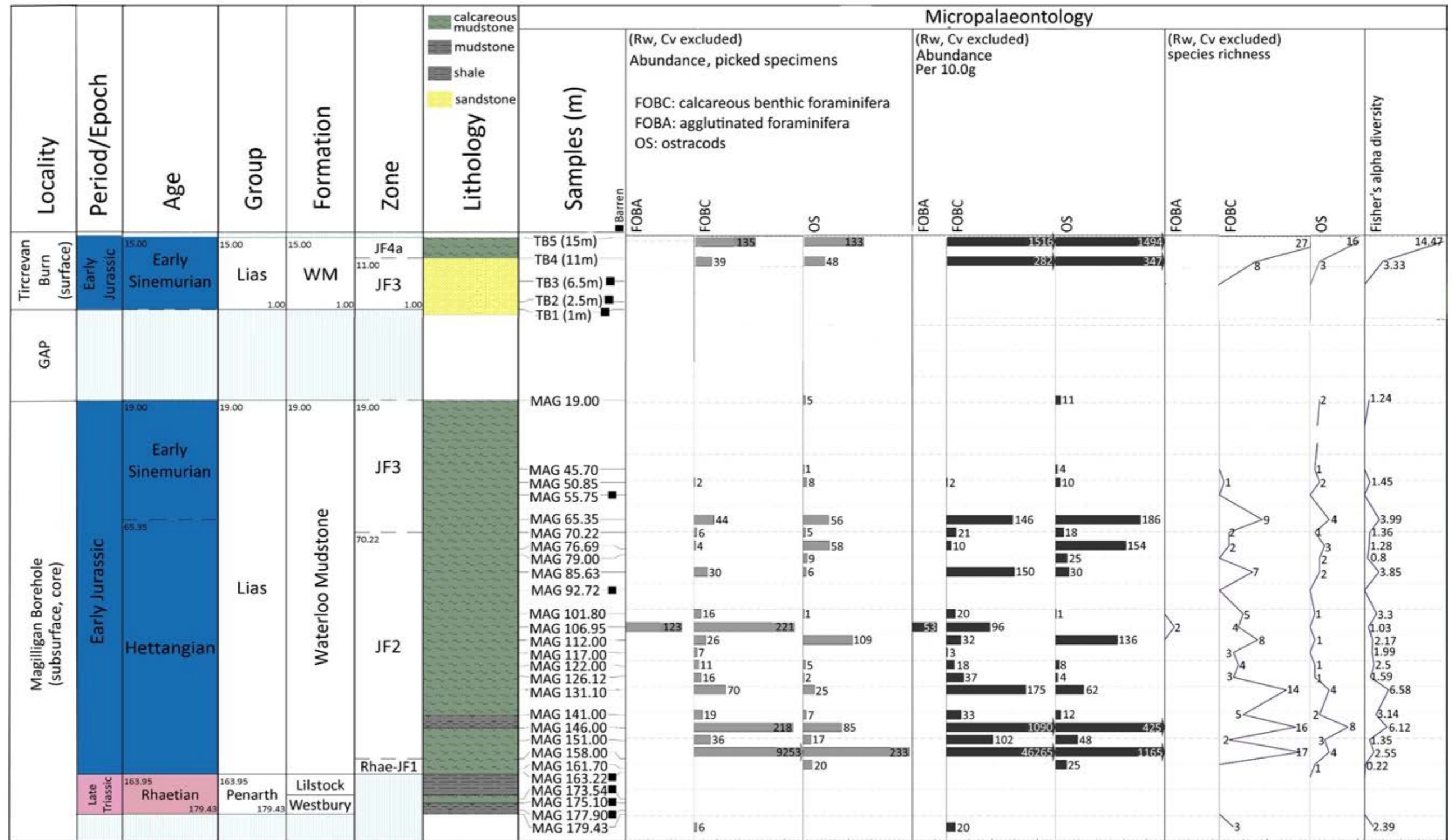
Figure 6.3: Sedimentary log, relative abundance, species richness and Fisher's alpha diversity of microfaunas from Magilligan Borehole and Tircrevan Burn exposure.

6.3.2 Tircrevan Burn

Total of 175 foraminifera specimens and 178 ostracods specimens are extracted from two collected samples (TB4 and TB5); both are calcareous mudstones. Another three samples belong to the Tircrevan Sandstone Member are barren. These samples exhibit low to high diversity (3.33 to 14.47 Fisher's alpha diversity); the foraminifera assemblages are more diverse (3.05-10.15 Fisher's alpha diversity) than ostracods (0.71-4.75 Fisher's alpha diversity). TB4 sample dominant by ostracods (347 specimens per 10 g) particularly from *O. aspinata* whereas the younger bed (TB5) abundant by foraminifera (1516 specimens per 10 grams) which numerous by *Cornuspira liasina.*

6.4 Magilligan Borehole and Tircrevan Burn proposed biozonation

6.4.1 Magilligan Borehole

The biozones of the Waterloo Mudstone Formation in the Magilligan Borehole are interpreted based on first appearance (last downhole occurrence) and last occurrence (first downhole occurrence) of the index species (Table 6.1). Downhole contamination is not an issue in these samples as they are core material. The details of Magilligan biozonations are shown below:

Interval: 158 m-163.95 m

Analysed sample: MAG161.7-MAG163.9

Jurassic Foraminifera Biozone: cannot be assigned due to the absent of foraminifera

Inferred age: latest Rhaetian-earliest Hettangian

Magilligan indicator species: *Ogmoconchella aspinata*

The oldest analysed samples from this interval are devoid of microfossils. The microfauna only observed in MAG161.7 sample where occurrence of monospecific is recognised; juveniles of *Ogmoconchella aspinata*. According to Boomer & Ainsworth (2009), *Ogmoconchella aspinata* ranges from latest Rhaetian (Late Triassic) to Early Sinemurian (Early Jurassic). In this study, the author interpreted the interval of being latest Rhaetian to very earliest Hettangian due to the typical characteristic of these age; very low diversity yet dominant by *Ogmocnchella aspinata*.

The foraminifera absence cause the identification of JF biozone uncertain. However, the biozone perhaps Rhaetian-JF1 because it overlie by JF2 biozone.

Interval: 76.69 m-158 m

Analysed sample:

Jurassic Foraminifera Biozone: JF2 (MAG76.69-MAG158)

Inferred age: middle Hettangian

Magilligan indicator taxa: *Reinholdella planiconvexa, Paralingulina tenera collenoti* and *Ogmoconchella aspinata*

The base of JF2 is defined by the inception (last downhole occurrence) of super-abundant *Reinholdella planiconvexa*. Copestake & Johnson (2014) described this important event as base of JF2 biozone (Planorbis Ammonite Chronozone). Magilligan JF2 is also marked by the common occurrence and consistency of *Paralingulina tenera collenoti* recorded from early to mid-part of JF2 biozone. For ostracods, *Ogmoconchella aspinata* remains present throughout this biozone. JF2 of Magilligan borehole is interpreted until MAG76.69; making this biozone 81.31 m thickness.

Interval: 19 m?- 76.69 m

Analysed sample: MAG19-MAG70.22

Jurassic Foraminifera Biozone: JF3 (MAG19-MAG70.22)

Inferred Age: latest Hettangian-earliest Early Sinemurian

Magilligan indicator species: *Marginulina prima incisa, Mesodentalina matutina*, *Paralingulina tenera substriata* and *Ektyphocythere*

JF3 biozone lies between latest Hettangian-earliest Sinemurian age (Copestake & Johnson, 2014). They stated that total range of *Dentalina langi* and common occurrence of *Paralingulina tenera substriata* determine the JF3 biozone but due to the absence of *Dentalina langi* in the Mochras Borehole, thus they used first appearance of *Mesodentalina matutina* as a marker of the base JF3 (Hettangian). The same approach applied in the Magilligan Borehole due to non-existence of distinctive *Dentalina langi.* Furthermore, another important JF3 indicators such as *Involutina liassica* and *Marginulina prima insignis* also absent.

Table 6.1 — Ranges of Magilligan Borehole stratigraphic and environmental foraminifera and ostracods species in relation to proposed biozonation.

Group	Formation	Period	Stage/Substage	Jurassic Foraminifera Biozone	Sample/depth (m)	Paralingulina tenera collenoti	Paralingulina tenera tenera	Paralingulina tenera pupa	Paralingulina tenera substriata	Paralingulina tenera tenuistriata	Dentalina pseudocommunis	Spirillina tenuissima	Reinholdella? planiconvexa	Eugottulina liassica	Nodosaria metensis	Prodentalina bicornis	Ophthalmidium macfadyeni tenuiloculare	Trochammina canningensis	Reophax sp. A	Marginulina prima incisa	Mesodentalina matutina	Planularia inaequistriata	Ogmoconchella aspinata	Ektyphocythere translucens	Ektyphocythere triebeli	Ektyphocythere retia	Ektyphocythere mooeri	Ogmoconcha hagenowi
Lias	Waterloo Mudstone	Early Jurassic	Early Sinemurian	JF3	MAG19																		3					2
Lias	Waterloo Mudstone	Early Jurassic	Early Sinemurian	JF3	MAG45.7																							
Lias	Waterloo Mudstone	Early Jurassic	Early Sinemurian	JF3	MAG50.85			2																	2			
Lias	Waterloo Mudstone	Early Jurassic	Early Sinemurian	JF3	MAG55.75																							
Lias	Waterloo Mudstone	Early Jurassic	Early Sinemurian	JF3	MAG65.35	18		7	9	1					1							2	17	9		11	12	
Lias	Waterloo Mudstone	Early Jurassic	Early Sinemurian	JF3	MAG70.22															1	5		5					
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG76.69								2										47	3	8			
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG79																		8	1				
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG85.63								9			3	10						4	2				
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG92.72																							
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG101.8										1	5												
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG106.95									105	101			82	40									
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG112								2			2	11						109					
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG117											3												
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG122								1			3	6						5					
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG126.12		4							5	7									2				
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG131.1	2	3	1			2	1	38	9	2	3	1						18	4				
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG141		4						12	1										2				
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG146	9	38	5	2		1	3	136	7									65	9				
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG151	4							32										12	2				
Lias	Waterloo Mudstone	Early Jurassic	Hettangian	JF2	MAG158	15	32	5	1	7	2	4	9173										229					
Penarth	Westbury	Late Triassic	Rhaetian		MAG161.7																		20					
Penarth	Westbury	Late Triassic	Rhaetian		MAG163.22																							
Penarth	Westbury	Late Triassic	Rhaetian		MAG163.9																							
Penarth	Westbury	Late Triassic	Rhaetian		MAG163.95																							
Penarth	Westbury	Late Triassic	Rhaetian		MAG172																							
Penarth	Westbury	Late Triassic	Rhaetian		MAG173.54																							
Penarth	Westbury	Late Triassic	Rhaetian		MAG175.1																							
Penarth	Westbury	Late Triassic	Rhaetian		MAG175.58																							
Penarth	Westbury	Late Triassic	Rhaetian		MAG177.9																							
Penarth	Westbury	Late Triassic	Rhaetian		MAG179.43						5																	

Table 6.1: Ranges of Magilligan Borehole stratigraphic and environmental foraminifera and ostracods species in relation to proposed biozonation.

Consequently, the base of Magilligan Borehole JF3 biozone is indicated by the first appearances (last downhole occurrences) of *Mesodentalina matutina* and *Marginulina prima incisa* at MAG70.22. The useful marker *Paralingulina tenera substriata* observed too, but they appear infrequent since JF2 (mid Hettangian) and common within JF3 of Early Sinemurian age. The increases in abundance and diversity of the ostracod genus *Ektyphocythere* are recorded in this biozone particularly *Ektyphocythere retia*. The most significant appearance of this genus is marked in MAG65.35 and based on Boomer & Ainsworth (2009), *Ektyphocythere retia* only began to appear at the earliest Early Sinemurian. Thus, this concluded the Early Sinemurian age start from 65.35 m towards the top.

6.4.2 Tircrevan Burn

The continuation of the Early Jurassic sedimentary sequence recorded in the Magilligan Borehole can be observed at the Tircrevan Burn exposures approximately 1 km to the southeast of the Magilligan Borehole. From five collected samples, only two exhibit microfossils (Table 6.2).

Analysed sample: TB4 and TB5

Biozone: JF4

Inferred age: early Sinemurian

Tircrevan Burn indicator taxa: *Marginulina prima incisa*, *Marginulina prima insignis*

The samples observed are assigned to the bottommost part of the JF4 biozone and the *Marginulina prima* plexus are the only significant JF indicator recognised. These are determined by the common occurrence of *Marginulina prima incisa* and *Marginulina prima insignis*. Other important indicator taxa for JF4 such as *Neobulimina bangae, Paralingulina tenera substriata* and *Involutina liassica* are absent in above samples. Both species coincide with biostratigraphical important ostracods, *Ogmoconcha hagenowi* and *Ogmoconchella aspinata*. These osracods range up to Semicostatum Ammonite Chronozone of Early Sinemurian age (Boomer & Ainsworth, 2009). Both occurrences of foraminifera and ostracods biostratigraphy markers confirm the Early Sinemurian age; younger than those deposited in the Magilligan Borehole.

Period	Stage/substage	Formation	Member	Jurassic Foraminifera Biozone	Sample	Foraminifera							Ostracods										
						Marginulina prima insignis	*Marginulina prima incisa*	*Paralingulina tenera tenera*	*Mesodentalina matutina*	*Ichthyolaria terquemi bicostata*	*Cornuspira liasina*	*Prodentalina sinemuriensis*	*Ogmoconchella aspinata*	*Ogmoconcha hagenowi*	*Metacopina (juvenile)*	*Acrocythere gassumensis*	*Polycope cerasia*	*Polycope minor*	*Paracypris redcarensis*	*Paracypris semidisca*	*Isobythocypris tatei*	*Isobythocypris elongata*	*Ektyphocythere translucens*
Early Jurassic	Early Sinemurian	Waterloo Mudstone		JF4	TB 05	1		1	1	1	54	1	29	16	38	1	1	2	12	1	12	2	5
					TB 04	19	11	2	1				23	9	14								
			Tircrevan Sandstone	JF3?	TB 03																		
					TB 02																		
					TB 01																		

Table 6.2: Ranges of stratigraphic and environmental indicators of Tircrevan Burn in relation with proposed biozonation.

6.5 Palaeoenvironmental analysis

6.5.1 Magilligan Borehole

The basal sample analysed (MAG179.43); dark grey mudstone contains only two species of foraminifera (*Eoguttulina liassica* and *Paralingulina lanceolata*) and most of the specimens are recorded from *Eoguttulina liassica*. Jones (2013) interpreted *Eoguttulina* as shallow marine genus. In addition, Nocchi and Bartolini (1994) described *Eoguttulina liassica* from Early Toarian sediments in Umbria Marhe Basin, Italy as opportunist species too. The absence of ostracods fauna and very sparse diversity of foraminifera in MAG197.43 proved *Eoguttulina liassica* as an opportunist species.

The overlain beds (MAG175.1-MAG177.9) are Westbury Formation comprise fossiliferous black shales or mudstones with silty laminae. This succession was deposited during the continuing Rhaetian marine transgression (Warrington & Ivimey-Cook, 1992; Ainsworth & Riley, 2010) and formed due to the accumulation of organic matter under the dysaerobic conditions (Nichols 2009). Specifically, Allington-Jones *et al*. (2010) interpreted this formation as the product of anoxic lagoonal environment with some episodic storms based on trace fossils, sedimentary and geochemical evidences. As studied by Ainsworth & Riley (2010) based on the Westbury Formation of Kerr McGee 97/12-1 exploration well in offshore southern England, the organic-rich nature of the sediments with the presence of abundant dinocyst but devoid of microfossils demonstrated low energy and anoxic environment. The salinity changes in this shallow epeiric sea resulted on the mass mortality of bivalves and fish faunas in the

Westbury Formation beds (Mitchell, 2004). These explain the nonexistence of microfauna yet abundant with bivalve fossils and presence of fish tooth fossils (Appendix H and I) in these observed interval (MAG175.1-MAG177.9). The absence of microfossils continues in the younger beds; olive grey calcareous mudstone (MAG173.54) of the Westbury Formation.

The younger sections (MAG163.95-MAG172) are the epicontinental sea deposition of Lilstock Formation which divided into two members; Cotham Member and Langport Member. Unfortunately, no core sample provided for this research.

The continuation of sea-level rise during latest Triassic-Early Jurassic (Figure 6.4) resulted on the deposition of predominantly calcareous mudstone succession known as the Waterloo Mudstone Formation of the Lias Group. The oldest examined samples of this formation (MAG163.22 and MAG 163.9) are barren with microfauna. The microfossils only begin to discover in MAG161.7 yet has only low abundance (25 specimens per 10 grams) of ostracods, *Ogmoconchella aspinata*. The presence of *Ogmoconchella aspinata* reveals the extension of Late Triassic marine transgression (Boomer & Ainsworth, 2009), particularly inner shelf setting (Ainsworth, 1989). The colonisation of this taxon also indicates *Ogmoconchella aspinata* as an opportunistic species (Ainsworth 1989; Ainsworth & Boomer, 2001; Ainsworth & Riley, 2010).

The sudden flood of thousands *Reinholdella planiconvexa* (45865 specimens per 10 grams) is noted from MAG158 (Figure 6.4). They are accompanied by abundant specimens of *Ogmoconchella aspinata* (1145 specimens per 10 grams) and moderate numbers of *Paralingulina tenera* plexus too (300 specimens per 10 grams). According to (Johnson, 1976),

Reinholdella planiconvexa lived at inner to middle shelf environment and the dominance of *Reinholdella* in low diverse assemblages reflected marine stagnant environment. Haynes (1981) and Hylton & Hart (2000) also described *Reinholdella* as a genus which can withstand poorly-oxygenated environments. This proved by the influx of this small foraminifera *Reinholdella planiconvexa* and the dominance of juvenile of *Ogmoconchella aspinata* in ostracods assemblage. Although *Reinholdella planiconvexa* documented until MAG126.12 sample, their abundances decrease drastically (12-682 specimens per 10 grams) indicates the oxygen-level recovery.

The microfossils abundances then drop starting from MAG122 until the youngest section MAG19 either caused by sea-level fall or unfavourable environment. However, among these low abundances, there are few samples abundant with microfaunas such as MAG112, MAG106.95, MAG85.63, MAG76.69 and MAG 65.35. Although these samples are abundant by microfaunas, the diversty still low diverse (less than 5 Fisher's alpha index diversity) as the assemblages dominant by few taxa only. For instance, the dominance of *Ogmoconchella aspinata* in MAG112 and MAG76.69, which according to Ainsworth & Boomer (2001), Boomer & Ainsworth (2009) and Ainsworth & Riley (2010) this taxon is opportunistic and can tolerate in wide range environment. Even the foraminifera assemblages in MAG112 reflected the unfavourable setting based on the dominance of *Nodosaria metensis* among its group. *Nodosaria* is one of the genus that capable in having tolerant with suboxic environment (Jones, 2014).

The most distinctive assemblage can be observed in olive grey calcareous mudstone MAG106.95, where the assemblage only encompasses foraminifera, both calcareous and agglutinated benthic. The fauna is dominant by *Spirillina tenuissima*, *Eoguttulina liassica* and simple agglutinated taxa (*Reophax* sp. A and *Trochammina canningensis*). Simple agglutinated foraminifera are known as shallow marine taxa (Gordon, 1970). The dominance of *Sprillina* (Copestake & Johnson, 1981; Shipp & Murray, 1981) and *Eoguttulina* (Jones, 2013) also suggested shallow marine setting. Whereas, the abundant of opportunistic taxa; *Eoguttulina* (Nocchi & Bartolini, 1994) indicates oxygen shortage. This resulted on impoverish diversity.

The abundant yet low diverse of Lagenida in MAG65.3 is an evidence of inner neritic environment (Brooke & Braun, 1972). Whereas the dominance of *Ektyphocythere* in ostracods fauna marks the improvement of bottom water conditions (Ainsworth & Boomer, 2001).

These shallow marine setting also continue until the earliest Sinemurian (MAG19-MAG65.35) as their abundance and diversity decrease when the arenaceous materials increase (Appendix I). This phenomenon not just observed in the Magilligan samples but also from Ballinlea-1 earliest Snemurian sample.

6.5.2 Tircrevan Burn

The shallow marine deposition continues to observe in the surface section from Tircrevan Burn. This anrenaceous bed are Tircrevan Sandstone Member, the only significant thick of

arenaceous sediment. (13 m) in the Waterloo Mudstone Formation Ths fine quartz-grained sandstone yield mud-drapes which indicates inter-tidal depositional setting. The overlying bed are typical Waterloo Mudstone facies, calcareous mudstones comprise mcirofaunas. The younger samples studied; blueish calcareous mudstone encompasses rare diverse of microfaunas where the ostracods specimens recovered are greater than foraminifera. Low diversity of foraminifera (Brooke & Braune, 1972) and the dominant of *Ogmoconchella aspinata* implied marine inner neritic environment (Ainsworth 1989; Boomer & Ainsworth 2009). The microfaunas assemblages then increasing rapidly in the youngest sample collected; blueish calcareous mudstone (5th sample). The foraminifera are dominant by moderate number of *Cornuspira liasina*, while ostracods by Metacopina. This again indicates shallow marine environment which defined by the dominance of *Cornuspira liasina* which represents shallow marine environment, inner neritic (Jones, 1994). Therefore, the transgression continues gradually after the deposition of the Tircrevan Sandstone Member.

Figure 6.4: Stratigraphic summary, microfossils abundance, microfossils diversity, palaeoenvironment interpretation and oxygenation interpretation of the latest Triassic-Early Jurassic of Magilligan Borehole and Tircrevan Burn outcrop.

CHAPTER 7:

Biostratigraphy, biozonation and palaeoenvironment of Northern Ireland Early Jurassic exposures

7.1 Introduction

Outcrop sampling was undertaken in Co. Antrim and Co. Londonderry to understand the distribution of Waterloo Mudstone Formation exposures across these counties. The selected localities (Figure 7.1) are Tircrevan Burn [C 70126 32552], Portrush [C 85725 41021], White Park Bay [D 02271 44184**]**, Ballintoy Harbour [D 03625 45177], Kinbane Head [D 08951 43354], Minnis [D 33835 13695], Ballygalley [D 37901 07956] and Waterloo Bay [D 40786 03768]. Among these, White Park Bay (the youngest exposure of Early Jurassic sediments in Northern Ireland), Tircrevan Burn (the continuation of Early Jurassic sequence from subsurface beds; Magilligan boreholes) and Larne (the oldest exposure of Early Jurassic in Northern Ireland) are the most important exposures. Most of the observed sections yielded microfaunas for this study except for Minnis (absence of in-situ early Jurassic beds) and Portrush (sediments have been metamorphosed). The studied exposures discussed below except for Tircrevan Burn which is included together with the Magilligan borehole in Chapter 6.
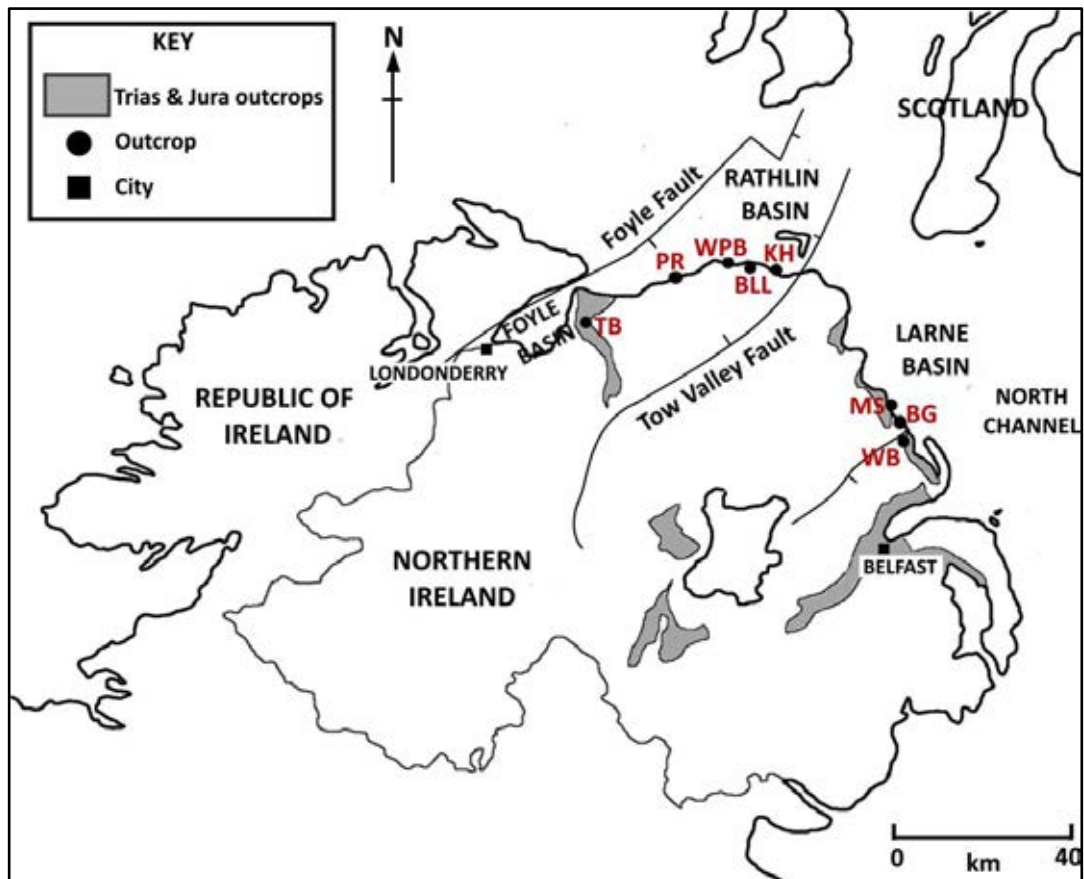
Figure 7.1: Location of observed Waterloo Mudstone Formation exposures (TB: Tircrevan Burn [C 70126 32552], PB: Portrush [C 85725 41021], WPB: White Park Bay [D 02271 44184], BLL: Ballintoy Harbour [D 03625 45177], KH: Kinbane Head [D 08951 43354], MS: Minnis [D 33835 13695], BG: Ballygalley [D 37901 07956] and WB: Waterloo Bay [D 40786 03768]).

7.2 Materials and Lithologies

The localities descriptions below are discussed in ascending stratigraphic order; from oldest to the youngest sections.

7.2.1 Waterloo Bay, Larne

The foreshore at Waterloo Bay [D 40786 03768], east coast Co. Antrim exposes Rhaetian to Sinemurian (Bucklandi Ammonite Chronozone) successions through the transition of the late Triassic Penarth Formation to the late Triassic Waterloo Mudstone Formation and Triassic-Jurassic boundary (Mitchell, 2004; Simms & Jeram, 2007).

However, during our fieldtrip, only Early Jurassic strata from northern part of Waterloo section is able to collect (LRN1). The sample is taken from a 2 m thick blueish-grey calcareous mudstone bed, the location is marked in Figure 7.2. Another best exposure in Waterloo Bay is the alternating beds of mudstones and limestones (Figure 7.3).
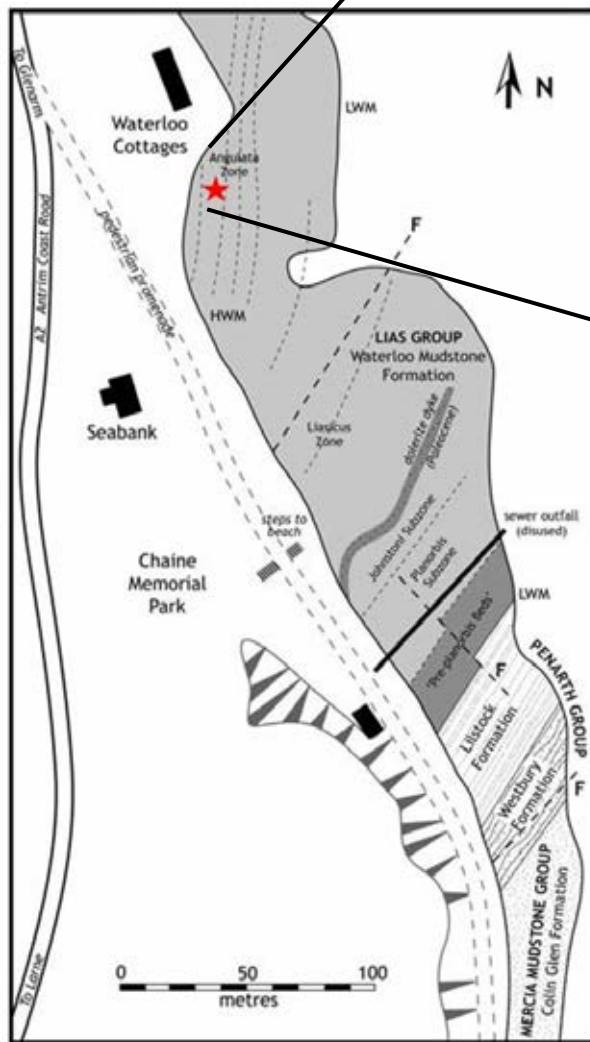
Figure 7.2: Sketch map of Late Triassic-Early Jurassic sections (dipping to the northwest at 20o-30o) crop out on the foreshore at Waterloo Bay, Larne (after Ivimey-Cook, 1975 in Simms & Jeram, 2007). The red star is LRN1 sample location (Blueish grey calcareous mudstone).

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Figure 7.3: The alternating of limestone with mudstone at Waterloo Bay. Some part of the mudstone had been eroded.

7.2.2 Ballygalley

The exposure at Ballygalley [D 37901 07956] is poor and very limited (Figure 7.4); just 2 m of blueish-grey calcareous mudstones (Figure 7.5) was recorded, yielding fossils of ammonites (Figure 7.6), bivalve (Figure 7.7), crinoid stems and reptile bone (Figure 7.8). Only a single sample is taken for further study (BLG1).

Figure 7.4: The dark grey rocks on the foreshore are Waterloo Mudstone Formation, while the lighter rocks are Ulster White Limestone Formation.

Figure 7.5: Ballygalley outcrops.

Figure 7.6: Jurassic ammonite found at Balleygalley, probably belongs to the Johnstoni Ammonite subchronozone.

Figure 7.7: Jurassic bivalve fossil (*Gryphaea* sp.) found at Ballygalley.

Figure 7.8: Reptile bone discovered at Ballygalley.

7.2.3 Kinbane Head

Very limited and poor outcrops (less than 1 m thick) exposed at the down cliff of Kinbane Head [D 08951 43354], not far from Ballycastle. The beds of blueish-grey mudstone (Figure 7.9) are soft and humid due to the contact of the sea water, thus just a sample bag was taken (KH1).

Figure 7.9: Grey mudstone of Waterloo Mudstone Formation exposed at Kinbane Head.

7.2.4 Ballintoy Harbour

Early Jurassic outcrops yield ammonite and bivalve fossils are observed at the foreshore of Ballintoy Harbour [D 03625 45177]. The exposure just 1 m thick of bluiesh-grey mudstone, overlain by recent beach deposits (Figure 7.10), only a single sample was collected; BLT1.

Figure 7.10: Exposure of Waterloo Mudstone Formation at the foreshore of Ballintoy Harbour. The bed thickness is approximately 0.5 m.

7.2.5 Portrush

At Portrush [C 85725 41021], the Early Jurassic sediments have been metamorphised to hornfels facies by the Portrush Sill (Figure 7.11). No sample was taken from this locality, only few images of ammonites are captured during the visit (Figure 7.12-7.14).

Figure 7.11: Lateral view of Waterloo Mudstone Formation at Portrush.

Figure 7.12: Ammonites from Raricostatum Ammonite Chronozone, Portrush.

Figure 7.13: Ammonites from Raricostatum Ammonite Chronozone, Portrush.

Figure 7.14: Ammonites from Raricostatum Ammonite Chronozone, Portrush.

7.2.6 White Park Bay

The best-known, and youngest Early Jurassic sequences in Northern Ireland crop out at White Park Bay [D 02271 44184**]** (Figure 7.16), north Co. Antrim. The east sections are younger than west and dipping to the north-east, hence the samples are initially taken from west to the east with approximately every 20 m- 40 m distance (Figure 7.15). These successions are thin (less than 0.5 m thick) and discontinuously crop out as they are scattered along the intertidal zone. The Early Jurassic sections represent primarily by blueish-grey calcareous mudstone (Figure 7.17) with occasional olive-grey calcareous mudstone (Figure 7.18) and blueish-grey mudstone. Some parts of the exposure (close to the WPB4 bed of N312°E/7) are intruded by a Paleogene dolerite sill (Figure 7.19); baked and chill zones are clearly observed herein. The

youngest Early Jurassic bed in WPB; 0.06 m thick of blueish grey calcareous mudstone is displayed at the Oweynamuck cliff (the end of east White Park Bay) and lies unconformably beneath (N330°E/48 boundary) 0.5 m thick Late Cretaceous Hibernian Greensands Formation which is overlain by about 10 m thick Late Cretaceous Ulster White Limestone Formation (Figure 7.20). The greensand bed is rich in phosphatised pebbles with glauconite and prevalent bivalve fossils, crinoid stem fragments and some re-worked Jurassic pebbles, while the chalks above have numerous flints.

Figure 7.15: the localities of collected sample from White Park Bay; WPB1 [D 02271 44184], WPB2 [D 02396 44276], WPB3 [D 02607 44429], WPB4 [D 02708 44491], WPB5 [D02805 44624], WPB6 [D02870 44783], WPB7 [D 02890 44824].

Figure 7.16: lateral view of White Park Bay captured from eastern end of the bay.

Figure 7.17: Thin blueish-grey calcareous mudstone bed crops out on the beach floor (WPB3 locality, White Park Bay).
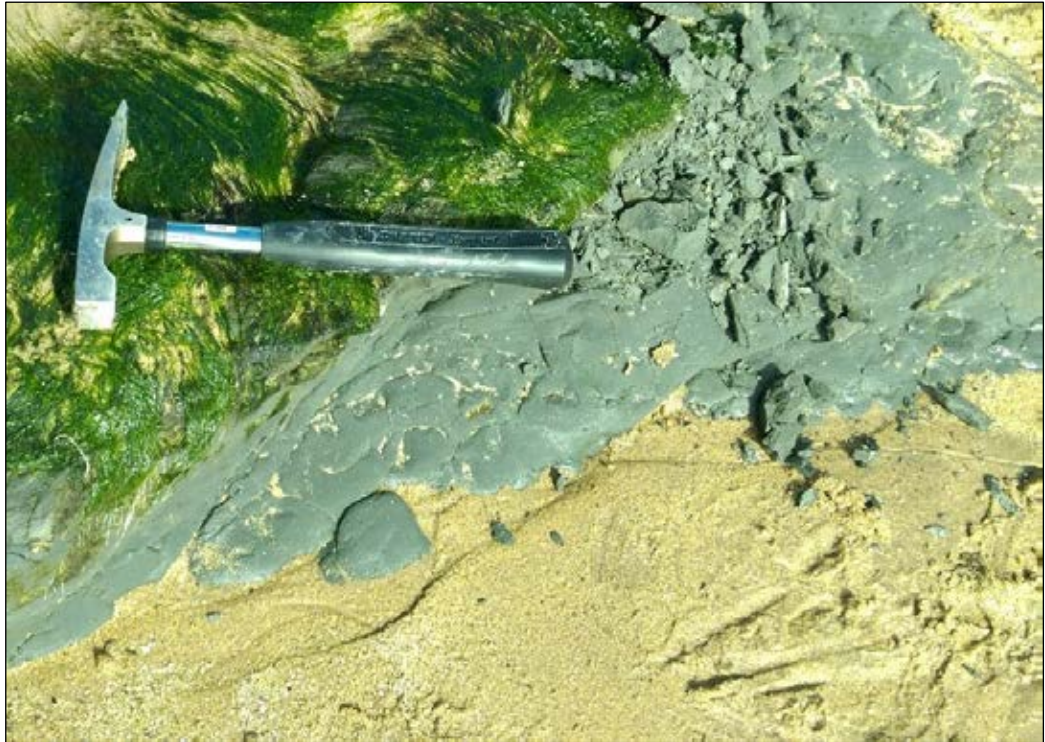
Figure 7.18: Thin olive-grey calcareous mudstone bed crops out on the beach floor (WPB5 locality, White Park Bay).

Figure 7.19: Dolerite sills intruded Waterloo Mudstone Formation (WPB4 locality, White Park Bay).
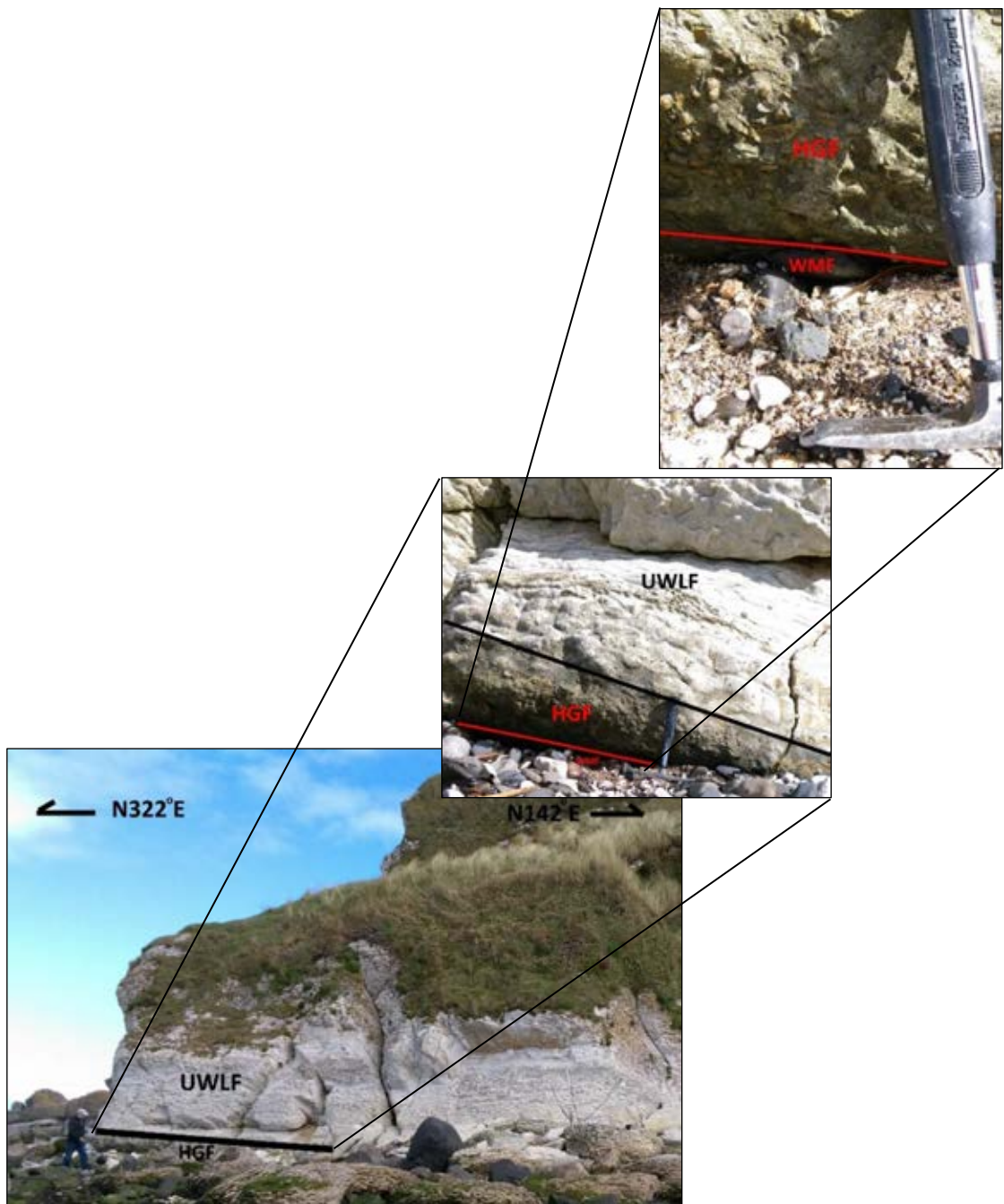
Figure 7.20: The unconformable boundary of Early Jurassic Waterloo Mudstone Formation-Late Cretaceous Hibernian Greensands Formation at Oweynamuck, eastern end of White Park Bay (see figure 7.16 for locality). HGF: Hibernian Greensands Formation, UWLF: Ulster White Limestone Formation, WMF: Waterloo Mudstone Formation.

7.3 Biostratigraphy

7.3.1 Waterloo Bay, Larne

The only Larne sample included is a blueish grey calcareous mudstone situated at the north of the Waterloo Bay. The sample reveals 71 microfossil specimens (Figure 7.21) from 8 calcareous benthonic foraminifera taxa and 6 marine ostracods species. The assemblages are moderate in abundance with ostracods approximately four times higher (83 specimens per 10 grams) than foraminifera specimens (17 specimens per 10 gram). Even though, the ostracods numbers are greater than foraminifera, the foraminifera diversity (2.71 Fisher's alpha diversity) is relatively higher than ostracods (1.59 Fisher's alpha diversity) (Figure 7.22). Overall assemblages are dominated by *Isobythocypris tatei* (18 specimens) followed by almost the same number of *Ogmoconchella aspinata* and *Ektyphocythere translucens.* Meanwhile, foraminifera are dominant by low numbers of *Lenticulina varians varians* (just 4 specimens found).
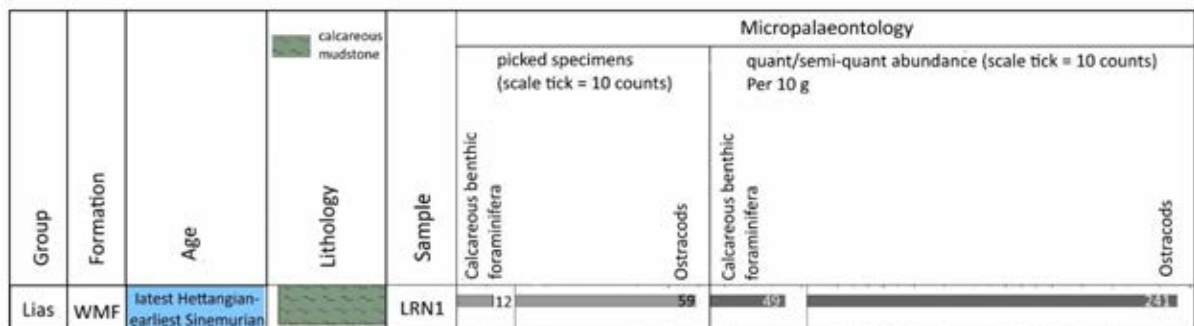
Figure 7.21: Abundance of foraminifera and ostracod recovered from the Larne outcrop sample. (WMF: Waterloo Mudstone Formation, L: Late, E: Early).

Group	Formation	Age	Lithology	Sample	Micropalaeontology		
					species richness		
					Calcareous benthic foraminifera	Ostracods	Fisher's alpha diversity (Total foram and ostra)
Lias	WMF	latest Hettangian-earliest Sinemurian	calcareous mudstone	LRN1	8	8	3.64

Figure 7.22: The species richness of Larne is plotted separately according to the groups, whilst the Fisher's alpha diversity is displayed in total. (WMF: Waterloo Mudstone Formation, L: Late, E: Early).

7.3.2 Ballygalley

A total of 106 specimens (Figure 7.23), comprising 4 calcareous benthonic foraminifera species in association of 3 ostracods species was picked from a single sample. In this sample, the ostracods are more numerous than the foraminifera. Almost 98% (170 specimens per 10 g) of recovered microfossils belong to Podocopid ostracods; (mainly *Ektyphocythere translucens*) three times greater than Metacopina (*Ogmoconchella aspinata).* The foraminifera specimens discovered (6 specimens per 10 g) are entirely Lagenida members. Meanwhile, the diversity of both group is low, even the Fisher's alpha diversity is just 1.68 (Figure 7.24)
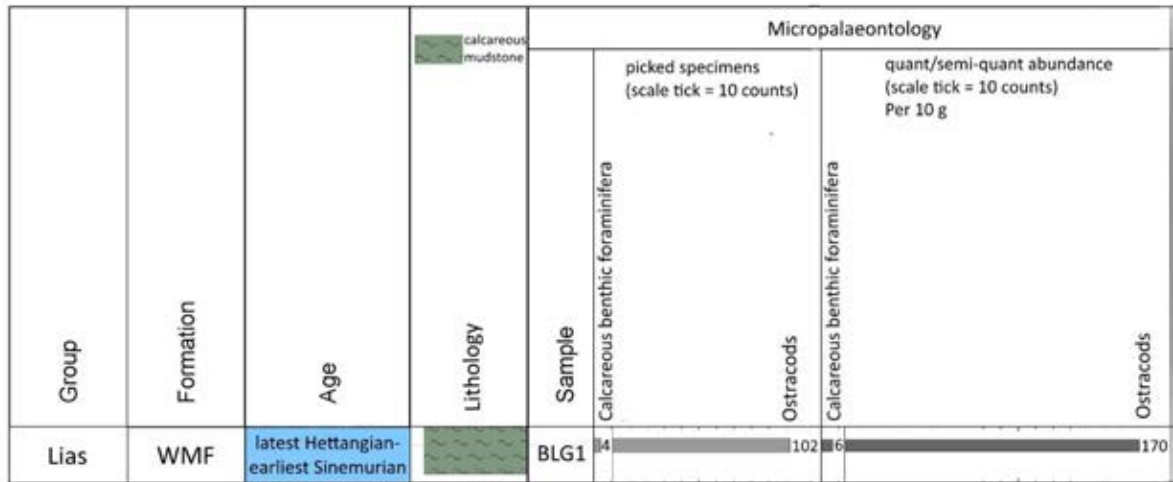
Figure 7.23: Foraminifera and ostracod abundance recovered from the Ballygalley outcrop sample. (WMF: Waterloo Mudstone Formation).
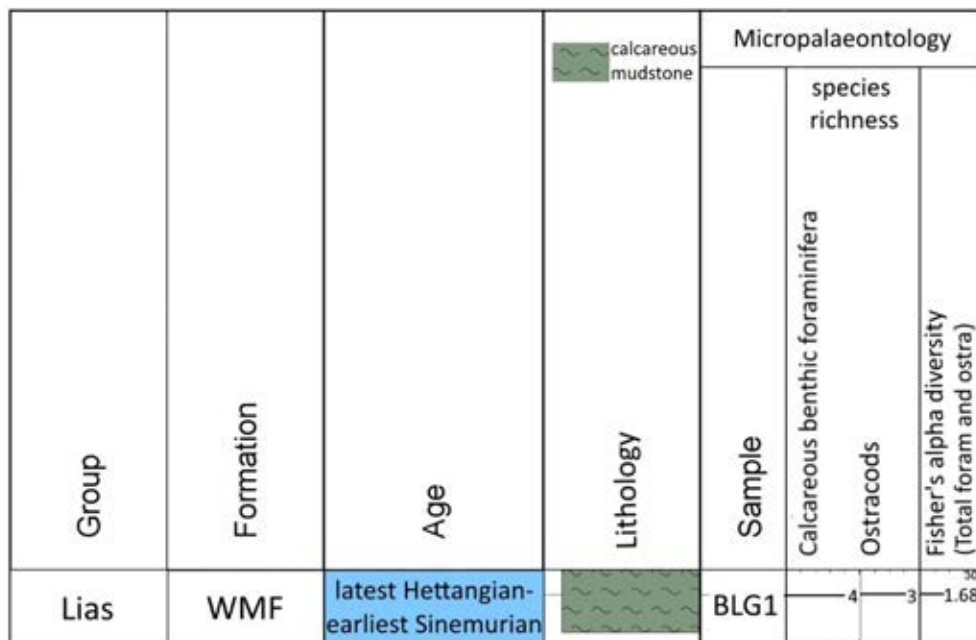
Figure 7.24: The species richness of foraminifera and oistracods recovered from Ballygalley sample and the total of Fisher's alpha diversity. (WMF: Waterloo Mudstone Formation).

7.3.3 Kinbane Head

Kinbane Head Early Jurassic sediment contains 117 microfossils (Figure 7.25) belong to 26 calcareous benthic foraminifera taxa and 6 ostracods species. The moderate diverse (14.61 Fisher's alpha diversity) is noticed from the collected sample (Figure 7.26). These foraminifera dominance (five times greater than ostracods) in association with low diversity and abundance of ostracods specimens. The foraminifera recovered are mostly from order Lagenida with *Lenticulina muensteri* ssp. A as the highest specimens recorded, followed by *Paralingulina tenera tenuistriata*. The ostracod fauna is dominated by *Ogmoconchella danica* and *Gammacythere ubiquita*.

Figure 7.25: Foraminifera and ostracod abundance recovered from the Kinbane Head outcrop sample. (WMF=Waterloo Mudstone Formation).

Group	Formation	Age	Zone	Lithology	Sample	Micropalaeontology		
						species richness		Fisher's alpha diversity
						Calcareous benthic foraminifera	Ostracods	Total foram and ostra
Lias	WMF	Late Sinemurian	JF8		KH1	26	6	14.61

Figure 7.26: The species richness (number of species observed in the Kenbane Head studied section) is plotted separately according to the groups, whilst the Fisher's alpha diversity is displayed in total. (WMF: Waterloo Mudstone Formation).

7.3.4 Ballintoy Harbour

Eighteen calcareous benthonic foraminifera species and 8 ostracod species of total 81 specimens were observed from collected sample (Figure 7.27). The abundances of picked foraminifera and ostracods in this sample are almost equal but the foraminifera diversity is two times higher than ostracods. The foraminifera fauna is typically from the order Lagenida which rich by *Lenticulina varians varians* (10 specimens recovered); while ostracods mostly denoted by Podocopida; with the highest abundance of *Pleurifera vermiculata* (12 specimens recovered). The assemblage is diverse by foraminifera (species richness of 19) and total Fisher's alpha of the microfaunas is quite high (Figure 7.28).

Figure 7.27: Foraminifera and ostracod abundances recovered from the Ballintoy outcrop sample. (WMF: Waterloo Mudstone Formation)

Figure 7.28: Foraminifera and ostracods species richness together with Fisher's alpha diversity recovered from Ballintoy examined sample. (WMF: Waterloo Mudstone Formation).

7.3.5 White Park Bay

Examination of 7 outcrops samples resulted in recovery of 877 microfaunal specimens from 64 calcareous benthonic foraminifera species and 22 ostracods species (Figure 7.29). Generally, the abundances of foraminifera are moderate to abundant (64-140 specimens per 10 g) throughout the samples except for WPB1 and WPB5 where both are very abundant; 332 specimens (per 10 g) and 335 specimens (per 10 g) respectively. By contrast, ostracods abundances are lower than foraminifera as they are only low to moderate abundance (1-35 specimens per 10 g). Similar to the foraminifera abundance in WPB1 and WPB5, ostracod abundance was recorded as 213 specimens per 10 g for the former and 264 specimens per 10 g for the latter. The total diversity for both groups are relatively diverse (9.32-18.11 Fisher's alpha diversity) except for low diversity in sample WPB7 (3.47 Fisher's alpha diversity) (Figure 7.30).

The foraminifera assemblages are almost entirely from the Order Lagenida; The most diverse genus is *Prodentalina* but abundant by *Paralingulina*. Less than 5% of foraminifera species are from other orders such as Spirillinida (genera *Spirillina*), Robertinida (genus *Reinholdella*) and Buliminida (genus *Brizalina)*. Overall, the total foraminifera specimens recovered are almost three times higher than ostracods.

Of the ostracod fauna, the Podocopina is the most diverse and abundant, more so than the Metacopina, yet the differences are not significant. The highest number of ostracods

specimens is recorded from *Ogmoconchella danica, Gammacythere faveolata* and *Ektyphocythere perplexa*.
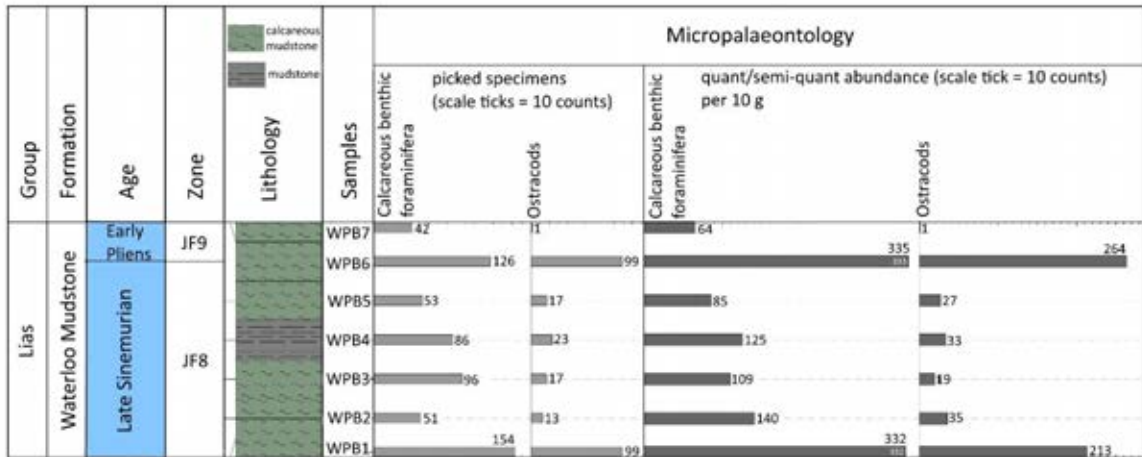
Figure 7.29: Foraminifera and ostracod abundances identified from the White Park Bay samples. (Pliens: Pliensbachian).
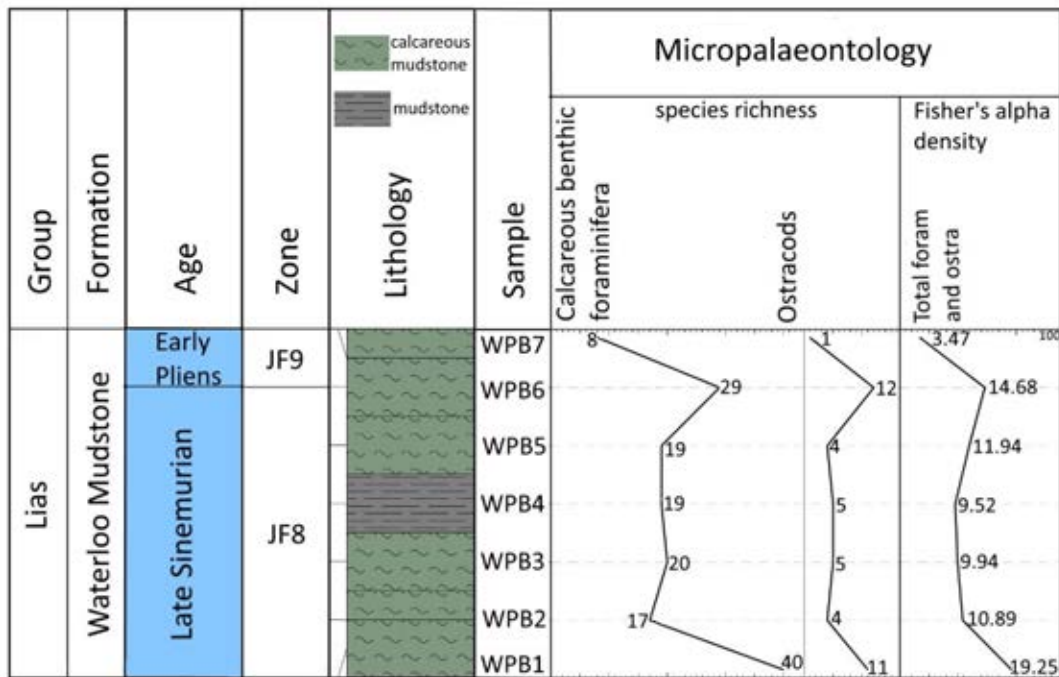
Figure 7.30: The species richness and Fisher's alpha diversity of White Park Bay microfossils. (Pliens: Pliensbachian).

7.4 Outcrops proposed biozonation

7.4.1 Waterloo Bay, Larne

Sample: LRN1

Jurassic Foraminifera Biozone: cannot be assigned due to the absence of index foraminifera.

Inferred age: latest Hettangian- Early Sinemurian

Larne indicator species: *Ektyphocythere translucens, Ogmoconchella aspinata* and *Ogmoconcha hagenowi*

The Larne sample did not yield any Jurassic foraminifera biozone indicators (Table 7.1). However, a broad age can be assigned based on the existence of biostratigraphically important ostracods; dominant *Ektyphocythere translucens* and common *Ogmoconchella aspinata* and rare occurrence of *Ogmoconcha hagenowi.* According to Boomer & Ainsworth (2009), *Ogmoconcha hagenowi* first appears within the early Angulata Ammonite Chronozone (latest Hettangian), whereas *Ektyphocythere translucens* becomes extinct within the Bucklandi Chronozone (earliest Early Sinemurian). Therefore, these suggest an age from latest Hettangian to earliest Early Sinemurian.

Stage	Sample ID	Foraminifera								Ostracods				
		Paralingulina tenera tenera	*Paralingulina cernua*	*Lenticulina varians varians*	*Spirillina tenuissima*	*Prodentalina subsiliqua*	*Prodentalina aff. mucronata*	*Prodentalina terquemi*	*Prodentalina sinemuriensis*	*Ogmoconchella aspinata*	*Ogmoconcha hagenowi*	*Isobythocypris tatei*	*Isobythocypris elongata*	*Ektyphocythere translucens*
latest Hettangian-Early Sinemurian	LRN1	1	1	4	1	1	2	1	1	16	7	18	4	14

Table 7.1: Biostratigraphy data of examined Larne sample.

7.4.2 Ballygalley

Sample: BLG1

Jurassic Foraminifera Biozone: cannot be assigned due to the absence of index foraminifera

Inferred age: latest Hettangian-Early Sinemurian

Ballygalley indicator species: *Ogmoconchella aspinata* and *Ektyphocythere translucens*

The Ballygalley sample has very low diversity (Table 7.2); only 7 species (3 ostracod, 4 foramininfera), abundant *Ektyphocythere translucens* with supplementary *Ogmoconchella aspinata*. The absence of Hettangian foraminifera markers, such as *Paralingulina tenera collenoti* (JF1 marker, earliest Hettangian) or *Reinholdella planiconvexa* (JF2 marker, mid Hettangian) cause the foraminifera biozonation assignation impossible. Yet, the age can be determined by the presence of *Ektyphocythere translucens* and *Ogmoconchella aspinata,* the former ranges from the Planorbis Ammonite Chronozone (very earliest Hettangian) to the middle Bucklandi Ammonite Chronozone (very earliest Sinemurian), whilst the latter ranges from the latest Rhaetian (Late Triassic) to uppermost Semicostatum Ammonite Chronozone

(Early Sinemurian; Boomer & Ainsworth, 2009). The sample mostly likely from latest Hettangian to earliest Sinemurian.

		Foraminifera				Ostracods		
Stage	Sample ID	*Ichthyolaria terquemi sulcata*	*Prodentalina arbuscula*	*Lagena liasica*	*Spirillina tenuissima*	*Ogmoconchella aspinata*	*Ektyphocythere translucen*	*Polycope cerasia*
latest Hettangian-earliest Sinemurian	BLG1	1	1	1	1	26	75	1

Table 7.2: Biostratigraphy data of examined Ballygalley sample.

7.4.3 Kinbane Head

Sample: KH1

Jurassic Foraminifera Biozone: JF8

Inferred age: Late Sinemurian

Kinbane Head indicator species: *Marginulina prima aspinata, Marginulina prima interrupta, Mesodentalina matutina, Astacolus speciosus, Ogmoconchella danica, Ogmoconchella mouhersensis* and *Ogmoconcha eocontractula.*

The foraminifera assemblage of Kinbane Head is relatively abundant but mostly long-ranging species (Table 7.3). Of the 16 species present, 4 foraminifera species are JF biozone markers;

Marginulina prima interrupta, *Marginulina prima spinata*, *Mesodentalina matutina* and *Astacolus speciosus*. The occurrences of *Marginulina prima spinata* and *Marginulina prima interrupta* suggested the sample to be JF8 biozone as the inception of these taxa is at the base JF8. Meanwhile, the common occurrence of *Astacolus speciosus* and *Mesodentalina matutina* reflect that this sample must not be younger than Late Sinemurian because, based on Copestake & Johnson (2014), the last occurrence of these species are at the top of JF8 (Late Sinemurian-Early Pliensbachian boundary). Therefore, the sample range within JF8.

The occurrence of Late Sinemurian ostracods; *Ogmoconchella danica*, *Ogmoconchella mouhersensis, Ogmoconcha eocontractula* supports this age definition.

Stage	JF biozone	Sample ID	Foraminifera								Ostracods					
			Paralingulina tenera tenuistriata	*Paralingulina tenera pupa*	*Paralingulina paranodosaria*	*Astacolus speciosus*	*Marginulina prima interrupta*	*Marginulina prima spinata*	*Mesodentalina matutina*	*Lenticulina muensteri* ssp. A	*Ogmocnchella danica*	*Ogmoconchella mouhersensis*	*Ogmoconcha eocontractula*	*Gammacythere ubiquita*	*Ektyphocythere triebeli*	*Pleurifera harpa*
Late Sinemurian	JF8	KH1	14	13	1	6	1	2	4	16	5	2	2	5	2	3

Table 7.3: Range chart of studied Kinbane Head sample.

7.4.4 Ballintoy Harbour

Sample: BLT1

Jurassic Foraminifera Biozone: JF8

Inferred age: latest Late Sinemurian

Ballintoy indicator species: *Ichthyolaria terquemi squamosa, Marginulina prima spinata, Pleurifera plicata* and *Ektyphocythere perplexa*

The Ballintoy section is interpreted as JF8 biozone based on the presence of *Marginulina prima spinata* and *Ichthyolaria terquemi squamosa* (Table 7.4). Both species first appear at the base of JF8 biozone (Copestake & Johnson, 2014). The co-occurrence of typical Late Sinemurian ostracods especially *Pleurifera plicata* and *Ektyphocythere perplexa* supported the inferred age.

Furthermore, Reid & Bancroft (1986) described and corrected *Ammonite macdonnelli* from Portlock's Larne fossils collection as *Leptechiosceras macdonnelli* from Ballintoy and this species defined the Macdonnelli Ammonite Subchronozone of Raricostatum Ammonite Chronozone. In particular, JF8 ranges from end Oxynotum Ammonite Chronozone to Raricostatum Ammonite Chronozone and Macdonnelli Ammonite Subchronozone of the Raricostatum Ammonite Chronozone is equivalent to the mid JF8 (Copestake & Johnson, 2014), hence this supports author suggestion of the age and biozonation of the Ballintoy sample.

Stage	JF biozone	Sample ID	Foraminifera													Ostracods					
			Lenticulina varians varians	*Lenticulina muensteri muensteri*	*Lenticulina muensteri ssp. A*	*Lenticulina muensteri polygonata*	*Paralingulina tenera tenuistriata*	*Paralingulina tenera pupa*	*Ichthyolaria terquemi squamosa*	*Mesodentalina matutina*	*Planularia inaequistriata*	*Marginulina prima spinata*	*Vaginulina listi*	*Pleurifera vermiculata*	*Ogmoconchella danica*	*Ogmoconchella mouhersensis*	*Ogmoconcha eocontractula*	*Isobythocypris elongata*	*Ektyphocythere perplexa*	*Acrocythere oeresundensis*
Late Sinemurian	JF8	BLT1	10	3	2	1	6	2	2	2	2	1	1	12	10	5	3	3	4	1

Table 7.4: Range chart of Ballintoy studied sample.

7.4.5 White Park Bay

Samples: WPB1-WPB5

Jurassic Foraminifera Biozone: JF8

Inferred age: latest Late Sinemurian

WPB indicator species: *Nodosaria issleri, Ichthyolaria terquemi squamosa, Marginulina prima spinata, Marginulina prima interrupta, Mesodentalina matutina* and *Gammacythere faveolata*

Nodosaria issleri is restricted to the Late Sinemurian, ranges from JF6 upwards into top JF8 biozone (Obtusum Ammonite Chronozone-Raricostatum Ammonite Chronozone; Copestake & Johnson, 2014). The last occurrence of *Nodosaria issleri* in White Park Bay documented in WPB3 defined top JF8 (Table 7.5). However, in younger bed (WPB5) is notable in containing

another top JF8 marker; last occurrence of common *Mesodentalina matutina*. Consequently, the definition of top JF8 marked at WPB5. The co-occurrence of other JF8 representatives; *Ichthyolaria terquemi squamosa, Marginulina prima spinata* and *Marginulina prima interrupta* supported this conclusion as these species first appear at the base of JF8.

The ostracod fauna comprises Late Sinemurian taxa such as *Ogmoconchella danica, Ogmoconchella mouhersensis, Ogmoconcha eocontractula* and *Ektyphocythere perplexa* throughout the biozone. The most distinctive occurrence noted in WPB5 as *Gammacythere foveolata* is recorded abundantly and dominates throughout the samples. In Boomer & Ainsworth (2009) range chart, *Gammacythere foveolata* ranges from very latest Sinemurian to Early Pliensbachian.

Wilson and Manning (1978) stated that at the western end of WPB (a small stream called Lemnagh Burn) exhibits representative of the Raricostatum Ammonite Chronozone such as *Crucilobiceras* sp., *Gemmellaroceras* (*Tubellites*) *tubellus* (Simpson), *Leptechioceras* sp., *Paltechioceras boehmi* (Hug), and *Paltechioceras* sp. In particular, *Leptechioceras* indicates the *Leptechioceras macdonnelli* Subzone. The Raricostatum Ammonite Chronozone faunas include *Gemmellaroceras tubellus* (Simpson) and *Gemmellaroceras* sp**.** recorded towards the eastern end of WPB; at the base of a small waterfall (Wilson & Manning, 1978). Even Mitchell (2004) described mid WPB to eastern end of the bay (right before Oweynamuck) belong to the Macdonnelli Subchronozone of the Raricostatum Ammonite Chronozone. No older chronozone had been mentioned by Wilson & Manning (1978) or Mitchell (2004), hence the

WPB1-WPB5 sections discussed above only confined to the Raricostatum Ammonite Chronozone (range from mid to end JF8 biozone).

A microfaunal study of WPB had been conducted by McGugan (1965). The sample he examined was collected from small east-facing stream bank located almost at the centre of WPB and not precisely *in-situ*. The sample recovered was dominated by members of the Lagenida such as *Marginulina bergquisti* Tappan and *Marginulina* spp. (=uncoiled form of *Lenticulina muensteri muensteri*), *Frondicularia lustrata* Tappan (=*Ichthyolaria terquemi bicostata*), *F. sulcata* Bornemann (=*Ichthyolaria terquemi sulcata*) and *Lingulina tenera* Bornemann (=*Paralingulina tenera tenera*). McGugan concluded this to be Angulata chronozone based on Barnard (1956, 1957) claimed that the occurrences of variants *Frondicularia sulcata* Bornemann and *Lingulina tenera* Bornemann as representative of Angulata Ammonite Chronozone. This proposed chronozone by McGugan is definitely wrong as no older bed found in WPB by any authors.

Stage	JF biozone	Sample ID	*Paralingulina tenera tenera*	*Paralingulina tenera tenuistriata*	*Paralingulina tenera pupa*	*Lenticulina varians varians*	*Lenticulina muensteri muensteri*	*Ichthyolaria terquemi squamosa*	*Astacolus speciosus*	*Nodosaria issleri*	*Mesodentalina matutina*	*Mesodentalina varians varians*	*Marginulina prima spinata*	*Spirillina tenuissima*	*Brizalina liasica*	*Paralingulina tenera subprismatica*	*Lenticulina muensteri polygonata*	*Mesodentalina varians haeusleri*	*Ophthalmidium macfadyeni macfadyeni*	*Reinholdella robusta*	*Ogmoconcha eocontractula*	*Ogmoconchella danica*	*Ogmoconchella mouhersensis*	*Ogmoconchella gruendeli*	*Ektyphocythere perplexa*	*Isobythocypris elongata*	*Nanacythere firma*	*Acrocythere oeresundensis*	*Polycope cerasia*	*Pleurifera vermiculata*	*Gammacythere faveolata*
			Foraminifera																		Ostracods										
Early Pliens.	JF9	WPB 07	15			11	6		2		2	1					3	2					1								
		WPB 06	21			1	6				2	2	2				1				2				7	6					2
Late Sinemurian	JF8	WPB 05	30	10	16	5	1	1			9	3					5	2		3	11			1	7	3				25	42
		WPB 04	34	1		5	7				6	1	15				1	2	1			5	5		11			1	1		
		WPB 03	33		7	3	3	3	6		12	1	1			2	4	1				3	6	2	5				1		
		WPB 02	12		4	1	3	2			5		2				2					2	5	1	5						
		WPB 01	13	13	12	3	2	2	2	1	5	2	1	1	1						40	13	9	12	10	6					

Table 7.5: Range chart of stratigraphic and environmental markers of examined White Park Bay samples. (Pliens: Pliensbachian).

Samples: WPB6-WPB7

Jurassic Foraminifera Biozone: JF9

Inferred age: earliest Early Pliensbachian

WPB indicator species: *Mesodentalina matutina, Marginulina prima spinata, Ogmoconchella gruendeli*

The base JF9 indicator; consistent or common occurrence of *Vaginulinopsis denticulatacarinata* (Copestake & Johnson, 2014) is absent in two youngest WPB studied samples. This biozone can only be suggested based on the low occurrence of *Mesodentalina matutina* (only 2 specimens discovered in each sample). The Late Sinemurian-Pliensbachian species; *Marginulina prima spinata*, and ostracods *Ogmoconchella gruendeli* and *Gammacythere faveolata* continue to occur in this biozone. Moreover, the decline in abundance and diversity of both microfauna groups are typical events of Early Pliensbachian observed in Ballinlea-1 Borehole to the east.

The thin exposure of Early Jurassic sediments at the base of the cliff under Cretaceous strata at the eastern end of WPB (Oweynamuck, a small promontory) encompasses ammonites and bivalve faunas which probably belong to the Raricostatum Chronozone (Wilson & Manning, 1978). However, this chronozone is not confirmed due to the presence of ammonite *Gemmellaroceras tubellum* and *Oxynoticeras* sp. juv which range up into the Jamesoni Chronozone (Wilson & Manning, 1978). Contrary to Wilson & Manning's (1978) chronozone proposal, Charlesworth (1935, 1963) stated that the Early Jurassic beds (Waterloo Mudstone Formation) at White Park Bay reaches as high as the Davoei Ammonite Chronozone (Early

Pliensbachian). Whilst, Mitchell (2004) documented the youngest chronozone as Valdani Subchronozone of the Ibex chronozone which is situated about 60 m NNW from Early Jurassic-Late Cretaceous boundary (WPB7). This Ibex Chronozone mentioned by Mitchell (2004) was not collected during our fieldtrip.

7.5 Palaeoenvironmental analysis

The Hettangian samples from Ballygalley and Larne have abundant ostracods but are low diversity in both ostracods and forminifera, similar to Hettangian strata in studied boreholes. The Hettangian microfaunal diversity is still relatively low compared to the Sinemurian due to the recovery from Tr-Jr mass extinction . In Larne sample, *Isobythocypris elongata* and *Ogmoconchella aspinata* dominate the assemblages. The dominance of *Isobythocypris* may have denoted slightly lower oxygen level on the sea floor of shallow marine setting (Ainsworth & Boomer, 2001), whereas *Ogmoconchella aspinata* which is commonly abundant throughout NW Europe Hettangian sediments are opportunistic species and often occur in very high abundance in newly established niches (Boomer & Ainsworth, 2009). However, at Ballygalley, the abundance and dominance of *Ektyphocythere translucens* indicates the improvement of bottom water conditions (Ainsworth & Boomer, 2001).

The dominance and diversity of Lagenida in the Kinbane Head and Ballintoy Late Sinemurian samples and the White Park Bay Late Sinemurian-Early Pliensbachian sequences are ascribed wider range of normal marine settings; both in oxygenation and salinity (Nagy *et al.,* 1990,

Ainsworth & Boomer, 2001, Nagy *et al.,* 2010) and also contain typical constituents of inner shelf environments (Barnard, 1948; Ainsworth & Boomer, 2001).

Albeit these are diverse faunas, the youngest WPB Early Jurassic bed (WPB7) exhibits low diversity in both foraminifera and ostracods; only 3.47 alpha diversity. In modern faunas, an alpha diversity less than 5 suggests a restricted setting, either low salinity or low oxygen (Nagy *et al*., 2010). The sparse microfaunal abundance and diversity observed in the Early Pliensbachian facies of offshore Ireland too (Ainsworth, 1987, 1990; Boomer & Ainsworth, 2009) which are described as shallow marine facies particularly nearshore shelf with dysaerobic bottom waters conditions. The remarkable drop of both abundance and diversity in Early Pliensbachian sediments, also noted from the offshore Inner Hebrides, west Scotland by Ainsworth & Boomer (2001) which are interpreted as inner to mid shelf depositional settings with confined water circulation.

Chapter 8

Microfaunas comparison

8.1 Introduction

At north Co. Antrim, the Ballinlea-1 boreholes is situated in the Rathlin Basin near to the Tow Valley Fault, whilst Magilligan Borehole was drilled within Lough Foyle Basin next to the Foyle Fault. The Carnduff-1 borehole is situated in the Larne Basin; eastern Northern Ireland.

Of these, Ballinlea-1 proved the thickest sequence of the Waterloo Mudstone Formation (600 m), while Magilligan and Carnduff-1 are about 163 m and 156 m respectively (Figure 8.1). The stratigraphical ranges involved vary; Ballinlea-1 ranges from the earliest Hettangian to earliest Lower Pliensbachian, Magilligan and Carnduff-1 from the Rhaetian to earliest Lower Sinemurian. Although the Waterloo Mudstone Formation at Magilligan is thinner than at Ballinlea, the thickest Hettangian strata belong to the former (Figure 8.1).

In the Magilligan and Carnduff-1 boreholes, the Waterloo Mudstone Formation conformably overlies the Lilstock Formation, Penarth Group. However, at Ballinlea this differentiation is less clear due to the nature of the cuttings but it is thought that the Waterloo Mudstone Formation may rests unconformably on top of a short Penarth Group interval which overlies the Mercia Mudstone Group. The latest Rhaetian to early Jurassic facies in these three boreholes are basically the same; rhythmically alternating calcareous mudstone and limestone with variable amounts of mudstone; typical of the Waterloo Mudstone Formation.
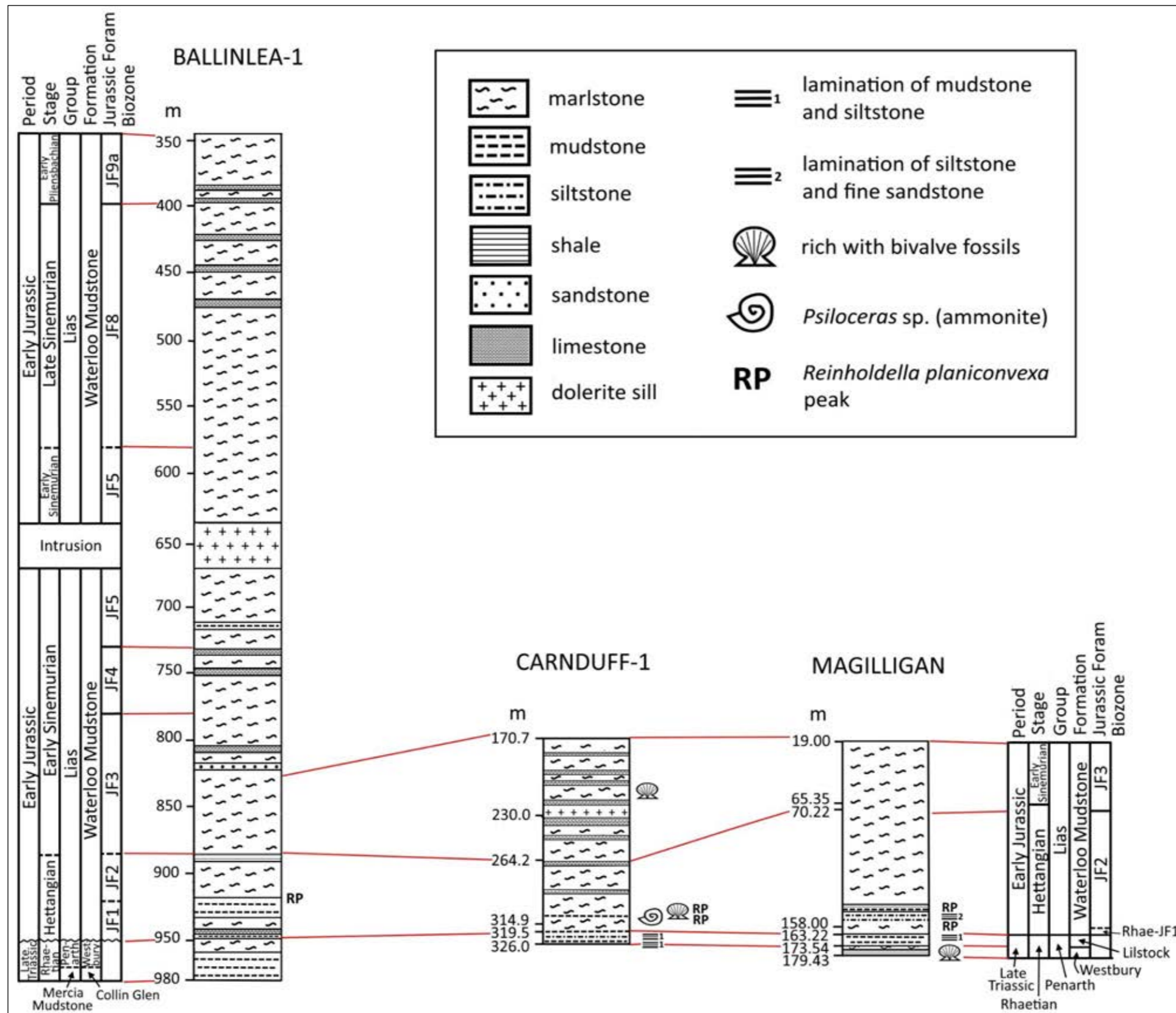
Figure 8.1: Correlation of lithostratigraphic logs of Late Triassic and Early Jurassic sequences of Ballinlea-1, Magilligan and Carnduff-1 boreholes.

8.2 Microfaunas of Waterloo Mudstone Formation, Lias Group

The microfaunas assemblages are mostly calcareous benthonic foraminifera and ostracods; dominant by Lagenida and Metacopina members respectively. The agglutinated foraminifera are rarely recovered from the Northern Ireland Waterloo Mudstone Formation. However, a sample from Magilligan Borehole (MAG106.95) has the greatest agglutinated foraminifera specimens compared to other boreholes (refer to Table 6.1).

8.2.1 Latest Triassic to Hettangian events

The latest Rhaetian-Hettangian microfossil assemblages from Ballinlea-1, Magilligan and Carnduff-1 have dominant representatives of the Order Lagenida (except for abundant Robertinida, Miliolida and Spirillinida in some sections) and ostracods of the Metacopina (particularly the *Ogmoconchella aspinata* and *Ogmoconcha hagenowi*). The similarities and dissimilarities between these boreholes are discussed further below.

The influx of thousands of *Reinholdella planiconvexa* (1231 specimens per 10 grams) at Carnduff-1 can be correlated with the Magilligan borehole (45865 specimens per 10 grams). Although this flood is continued in younger beds of Carnduff-1 (Figure 5.7), the numbers decrease to hundreds (110-200 specimens per 10 grams). Even though Ballinlea-1 does not have these high abundances, hundreds of specimens (210 specimens per 10 grams) are documented. The influx of *Reinholdella* is a typical bioevent in the Northwest Europe Hettangian sediments, in which Copestake & Johnson (2014) used as biostratigraphical

marker; JF2 base indicator (Johnstoni Subchoronoze of Planorbis Ammonite Chronozone). Hence, the inception (last downhole occurrence) of common *Reinholdella planiconvexa* in Ballinlea-1 and Magilligan boreholes mark the base of JF2 biozone. However, the records of *Psiloceras* sp. in CRN313.4 (which above the first appearance of abundant *R. planiconvexa)* suggests the first appearance of influx *R. planiconvexa* at Carnduff-1 occur earlier; in the latest Rhaetian, not within Hettangian as in Ballinlea-1 and Magilligan boreholes. This shows that this may not be synchronous across Northern Ireland nor may it be the same as age as Copestake & Johnson (2014) event as their abundant and dominance occurred due to the confined environment. The earlier flood of the *Reinholdella planiconvexa* is most likely due to the local environmental change in the Larne Basin (Carnduff-1).

Another distinctive event in Hettangian strata of those boreholes are the occurrence of agglutinated foraminifera. Among these three boreholes, only Magilligan contains a significant number of agglutinated foraminifera (53 specimens per 10 grams), however they are just from a single sample (MAG106.95). This kind of abundance not been observed from any age of any analysed localities.

8.2.2 Comparison of Early Sinemurian records

The Early Sinemurian sediments were deposited in all three boreholes, but the complete sequence only documented in Ballinlea-1. The Magilligan and Carnduff-1 only exhibit the earliest Early Sinemurian successions.

Faunal dissimilarities between Carnduff-1 and another two boreholes are noted in the earliest Early Sinemurian beds; the dominance of *Cornuspira liasina* in the low diverse fauna only occurs in Carnduff-1. The dominance of this species denotes shallow marine; inner neritic environment (Jones, 1994). Even though this shallow marine taxon is not found in the equivalent age of Ballinlea and Magilligan Boreholes, this shallow marine taxon was dentified from the examined Tircrevan Burn exposure (continuation sequence of subsurface Magilligan).

8.3 Comparisons of biostratigraphical microfossils with adjacent region

The youngest Northern Ireland Early Jurassic strata are earliest Early Pliensbachian in age, recovered from the Ballinlea-1 Borehole (Figure 8.3). Many of the nearest records from adjacent basins reach Mid-late Toarcian age such as the Cardigan Bay Basin (Copestake & Johnson, 2014), Portland-Wight Basin (Ainsworth *et al.,* 1998a, 1998b; Ainsworth & Riley, 2010), and West Ireland basins; Porcupine, Slyne, Erris and Donegal (Ainsworth, 1990) (Figure 8.2). Yet, shorter age found in the Fastnet Basin, southwest Ireland (only up to Early Toarcian, Ainsworth, 1986) and offshore Inner Hebrides, west Scotland (up to Late Pliensbachian; Ainsworth & Boomer, 2001). The comparisons of microfaunas only limited to the Great Britain and Ireland sites as listed below (Table 8.1).

Figure 8.2: Location map of studied sites and their adjacent boreholes, outcrops and basins. (M: Magilligan Borehole; B: Ballinlea-1 Borehole; C: Carnduff-1 Borehole; 1: Tircrevan Burn; 2: White Park Bay; 3: Ballintoy; 4: Kinbane Head, 5: Ballygalley; 6: Waterloo Bay, Larne (this study). 7: Redcar. 8: North Cliffe, 9: Hotham (Lord, 1971); 10: Holwell Quarry, 11: Cloford Quarry (Copestake, 1982); 12: East Quantoxhead (Hylton, 1998); 13: Doniford Bay (Clémence *et al.,* 2010; Clémence & Hart, 2013); 14: Lyme Regis (Macfadyen, 1941; Barnard, 1949); MF: Mochras Farm Borehole (Copestake & Johnson, 1981, 1989, 2014); W: Wilkesley Borehole, PL: Platt Lane Borehole, SP: Stowell Park Borehole, HL: Hill Lane Borehole, BR: Burton Row Borehole (Copestake & Johnson, 1981, 1989); Kerr McGee 97/12-1 (Ainsworth & Riley, 2010); English Channel (Ainsworth *et al*., 1998a, 1998b); L135/4-1 (Ainsworth & Boomer, 2001); Elf 55/30-1 (Ainsworth & Horton, 1986); Fastnet Basin (Ainsworth, 1989); Donegal, Porcupine, Slyne and Erris Basins (Ainsworth, 1990)).

Site	Country	Author
Mochras Borehole, Stowell Park Borehole, Burton Row Borehole, Hill Lane Borehole, Wikesley Borehole, Plate Lane Borehole	Wales and England	Copestake & Johnson, 1981, 1989
Mochras Borehole (Cardigan Bay Basin)	Wales	Copestake & Johnson, 2014
L134/5-1 well (Offshore Inner Hebrides)	Scotland	Ainsworth & Boomer, 2001
Kerr McGee 97/12-1 well (Portland-Wight Basin)	English Channel, England	Ainsworth & Riley, 2010
Lyme Regis (Dorset coast)	South West England	Macfadyen, 1941
Lyme Regis (Dorset coast)	South West England	Barnard, 1949
North Cliffe, Hotham and Redcar (Yorkshire)	Northern England	Lord, 1971
East Quantoxhead (West Somerset)	South West England	Hylton, 1998
Doniford Bay (West Somerset)	South West England	Clémence *et al.,* 2010; Clémence & Hart, 2013
Cloford quarry and Holwell quarry (Somerset)	South West England	Copestake, 1982
98/6-7, 98/6-8, 98/7-2, 98/11-1, 98/11-2, 98/11-3, 98/11-4, 98/13-1, 98/16-2A, 98/16-1, 98/18-1, 98/22-2, 98/23-1, 99/16-1, 99/18-1, 99/12-1, Lulworth Banks (Portland-Wight Basin) and Seabarn Farm, Radipole-1, Winterborne Kingston, Wytch Farm, Sandhills-1, Bottom Copse-1, Marchwood-1, Southampton-1, Chilworth-1, Hoe-1, Crocker Hill-1, Portsdown-1, Portsdown-2, Horndean-1, Middleton-1, Humbly Groove (adjacent onshore)	English Channel, England	Ainsworth *et al.,* 1998a, 1998b

Elf 55/30-1 well (Fastnet Basin)	Offshore Southwest Ireland	Ainsworth & Horton, 1986
BP 56/26-1, BP 56/26-2, Cities Service 63/4-1, Cities Service 63/10-1, Deminex 56/21-1, Deminex 56/21-2, Elf 55/30-1, Elf 64/2-1, Ranger 63/8-1, Texaco 56/22-1 (Fastnet Basin)	Offshore Southwest Ireland	Ainsworth, 1989
Amoco 12/13-1A (Donegal Basin), Amoco 19/5-1 (Erris Trough), BP 26/22-1A (North Porcupine Basin), Elf 27/13-1 (Slyne Trough), Gulf 26/21-1 (Porcupine Bank)	Offshore West Ireland	Ainsworth, 1990

Table 8.1: The adjacent boreholes and outcrops involved in microfaunas comparison discussed in this chapter

8.3.1 Foraminifera bioevents

The Ballinlea-1 yields a typical European Boreal Atlantic foraminiferal fauna which is dominated by calcareous benthic taxa and very scarce agglutinated taxa. These show very close affinities with Ireland and Great Britain boreholes Hettangian to Early Pliensbachian foraminifera especially from Mochras Borehole (Copestake & Johnson, 2014) and offshore Inner Hebrides (Ainsworth & Boomer, 2001). Similarities and differences are discussed below. Note that only stratigraphically and environmentally important markers are emphasized in this discussion.

The latest Rhaetian to Early Pliensbachian biostratigraphical indicators proposed by Copestake & Johnson (2014) are widely occurred in NW Europe especially from the adjacent areas of

Mochras Borehole, Cardigan Bay Basin. The presence of these species in adjacent borehole,

basins or exposures are summarised in Table 8.2 below.

Indicator species of foraminifera biozonation	Age, ammonite chronozone and ammonite subchronozone (based on Copestake & Johnson, 2014)	Great Britain and Ireland boreholes, basins and exposures	Northern Ireland sections (this study)
Paralingulina tenera collenoti	Late Rhaetian-Hettangian (Angulata Chronozone, Complanata-Depressa Subchronozone)	Mochras, Stowell Park, Burton Row, Hill Lane, Wilkesley, Plate Lane boreholes (Copstake & Johnson, 1981, 1989).	Ballinlea-1 Borehole, Carnduff-1 Borehole, Magilligan Borehole.
Reinholdella planiconvexa	Rhaetian-Early Pliensbachian (Jamesoni Chronozone, Taylori Chronozone)	Mochras Borehole (Copestake & Johnson, 2014); Offshore Inner Hebrides (named as *Reinholdella* spp. with *Oberhausella*; Ainsworth & Boomer, 2001); Fastnet Basin (Ainsworth & Horton, 1986); Doniford Bay exposure (Clemence *et al.*, 2010; Clemence & Hart, 2013)	Ballinlea-1 Borehole, Carnduff-1 Borehole, Magilligan Borehole.
Ichthyolaria terquemi barnardi	Hettangian (Planorbis Chronozone, Johnstoni Subchronozone-Angulata Chronozone, Depressa Subchronozone)	Mochras Borehole (Copestake & Johnson, 2014); Portland-Wight Basin (English Channel; Ainsworth *et al.*, 1998a).	Ballinlea-1 Borehole.
Planularia ineaquistriata	Hettangian (Liasicus Chronozone, Portlocki Subchronozone)-Late	Mochras Borehole (Copestake & Johnson, 2014);	Ballinlea-1 Borehole,

	Sinemurian (Raricostatum Chronozone, Aplanatum Subchronozone)	Portland-Wight Basin (named as Zone FJ3 in this basin; Ainsworth *et al.,* 1998a); Kerr McGee 97/12-1, Portland Wight Basin (Ainsworth & Riley, 2010); East Quantoxhead exposure (West Somerset; Hylton, 1998); Dorset exposures (Macfadyen, 1941; Barnard, 1949);	Magilligan Borehole, Carnduff-1 Borehole, Ballintoy exposure.
Dentalina langi	Hettangian (Angulata Chronozone, Complanata Subchronozone)	Portland-Wight Basin (English Channel; Ainsworth *et al.,* 1998a); Dorset exposure (Barnard, 1949).	Ballinlea-1 Borehole.
Marginulina prima insignis	Hettangian (Angulata Chronozone, Complanata Subchronozone)-Late Pliensbachian (Spinatum Chronozone, Hawskerense Subchronozone)	Mochras Borehole (Copestake & Johnson, 1989, 2014); Eastern Mendips exposures (Somerset, Copestake 1982).	Ballinlea-1 Borehole, Carnduff-1 Borehole, Tircrevan Burn exposure.
Marginulina prima incisa	Hettangian (Angulata Chronozone, Complanata Subchronozone)-Late Pliensbachian (Spinatum Chronozone, Hawskerense Subchronozone).	Mochras Borehole (Copestake & Johnson, 1989, 2014);	Ballinlea-1 Borehole, Carnduff-1 Borehole, Magilligan Borehole, Tircrevan Burn exposure.
Mesodentalina matutina	Hettangian (Angulata Chronozone, Complanata Subchronozone)-Late Pliensbachian (Spinatum	Mochras Borehole (Wales, Copesake & Johnson, 2014); East Quantoxhead	Ballinlea-1 Borehole, Carnduff-1 Borehole,

	Chronozone, Hawskerense Subchronozone)	exposures (West Somerset; Hylton, 1998); Eastern Mendips (West Somerset; Copestake, 1982); Dorset (Barnard, 1949)	Magilligan Borehole, White Park Bay exposure, Kinbane Head exposure, Ballintoy exposure, Tircrevan Burn exposure.
Involutina liassica	Rhaetian-Toarcian (Tenuicostatum Chronozone, Semicelatum Subchronozone)	Mochras Borehole (Copestake & Johnson, 2014); Portland-Wight Basin (named as Zone FJ3 in this basin; Ainsworth *et al.,* 1998a); Kerr McGee 97/12-1 (Portland-Wight Basin; Ainsworth & Riley, 2010); offshore Inner Hebrides (Ainsworth & Boomer, 2001).	Absent
Paralingulina tenera substriata	Hettangian (Planorbis Chronozone, Planorbis Subchronozone)–Lower Sinemurian (Bucklandi Chronozone, Conybeari Subchronozone)	Mochras Borehole (Copestake & Johnson, 2014); East Quantoxhead exposures (West Somerset; Hylton, 1998).	Ballinlea-1 Borehole, Carnduff-1 Borehole, Magilligan Borehole.
Neobulumina bangae	Latest Hettangian (Angulata Chronozone, Complanata Subchronozone)-Late Sinemurian (Obtusum Chronozone, Obtusum Subchronozone)	Mochras Borehole (Copestake & Johnson, 2014); Portland-Wight Basin (named as *Neobulimina* sp. 2 in this basin; Ainsworth *et al.,* 1998a).	Ballinlea-1 Borehole.

Astacolus speciosus	Hettangian (Liasicus Chronozone, Portlocki Subchronozone)-Late Jurassic	Mochras Boreholes (Copestake & Johnson, 2014); East Quantoxhead exposures (West Somerset; Hylton, 1998);	Ballinla-1 Borehole, Carnduff-1 Borehole, White Park bay exposure, Kinbane Head exposure.
Marginulina turneri	Early Sinemurian (Turneri Chronozone)	Mochras Borehole (Copestake & Johnson, 2014).	Ballinlea-1 Borehole.
Vaginulina listi	Hettangian (Angulata Chronozone, Complanata Subchronozone)-Early Bajocian	Mochras Borehole (Copestake & Johnson, 2014); Fastnet Basin (Ainsworth et al., 1989); Eastern Mendips exposure (Somerset, Copestake, 1982).	Ballinlea-1 Borehole; Ballintoy exposure.
Paralingulina tenera subprismatica	Early Sinemurian (Semicostatum Chronozone, Sauzeanum Subchronozone)-Late Pliensbachian (Margaritatus Chronozone, Gibbosus Subchronozone)	Mochras Borehole (Copestake & Johnson).	Ballinlea-1 Borehole; White Park Bay exposure.
Astacolus semireticulatus	Early Sinemurian (Semicostatum Chronozone, Scipionianum Subchronozone-Turneri Chronozone, Birchi Subchronozone)	Mochras (Copestake & Johnson, 2014); Portland-Wight Basin (Ainsworth *et al.*, 1998a); Kerr McGee 97/12-1 (Portland-Wight Basin, Ainsworth & Riley, 2010); Fastnet Basin (Ainsworth & Horton, 1986).	Absent

Reinholdella margarita margarita	Sinemurian (upper Semicostatum Chronozone, Sauzeanum Subchronozone–lower Obtusum Chronozone, Stellare Subchronozone)	Mochras Borehole (Copestake & Johnson, 2014); Portland-Wight Basin (named as Zone FJ3 in this basin; Ainsworth *et al.,* 1998a).	Ballinlea-1 Borehole.
Vaginulinopsis exarata	Hettangian-Late Pliensbachian	Mochras Borehole (Copestake & Johnson, 2014); Inner Hebrides (Ainsworth & Boomer, 2001).	Absent
Brizalina liasica	Late Sinemurian (Obtusum Chronozone, Obtusum Subchronozone)-Early Toarcian (Serpentinum Chronozone, Exaratum Subchronozone)	Mochras Borehole (Copestake & Johnson, 2014).	Ballinlea-1 Borehole, White Park Bay exposure.
Ichthyolaria terquemi squamosa	Late Sinemurian (Oxynotum Chronozone, Oxynotum Subchronozone)–Early Toarcian (Tenuicostatum Chronozone, Semicelatum Subchronozone)	Mochras Borehole (Copestake & Johnson); Dorset exposures (Macfadyen, 1941; Barnard, 1949)	Ballinlea-1 Borehole, White Park Bay exposure, Ballintoy exposure.
Marginulina prima spinata	Late Sinemurian (Raricostatum Chronozone, Raricostatum Subchronozone)-Early Toarcian (Serpentinum Chronozone, Exaratum Subchronozone)	Mochras Borehole (Copestake & Johnson, 2014); Lyme Regis exposure (Dorset, Macfadyen, 1941)	Ballinlea-1 Borehole, Ballintoy exposure, Kinbane Head exposure.
Marginulina prima interrupta	Late Sinemurian (Raricostatum Chronozone, Raricostatum Subchronozone)-Early Toarcian (Tenuicostatum Chronozone, Semicelatum Subchronozone).	Mochras Borehole (Copestake & Johnson, 2014).	Ballinlea-1 Borehole, Kinbane Head exposure.

Reinholdella pachyderma humilis	Late Sinemurian (Raricostatum Chronozone, Aplanatum Subchronozone)-Early Pliensbachian (Jamesoni Chronozone, Jamesoni Subchronozone)	Mochras Borehole (Copestake & Johnson, 2014).	Ballinlea-1 Borehole.
Mesodentalina varians hauesleri	Early Sinemurian (Turneri Chronozone, Birchi Subchronozone)-Middle Toarcian (Bifrons Chronozone, Crassum Subchronozone)	Mochras Borehole (Copestake & Johnson, 1989, 2014), Fastnet Basin (Ainsworth, 1989), Portland-Wight Basin (Ainsworth *et al.,* 1998a), offshore Inner Hebrides Basin (Ainsworth & Boomer, 2001) and Kerr McGee 97/12-1 (Portland-Wight Basin, Ainsworth & Riley, 2010); Dorset exposure (Barnard, 1949).	Ballinlea-1 Borehole, White Park bay exposure.
Nodosaria issleri	Late Sinemurian (Obtusum Chronozone, Obtusum Subchronozone-Raricostatum Chronozone, Aplanatum Subchronozone)	Mochras Borehole (Copestake & Johnson, 1989, 2014), Fastnet Basin (Ainsworth, 1989), Portland-Wight Basin (Ainsworth *et al.,* 1998a), offshore Inner Hebrides Basin (Ainsworth & Boomer, 2001) and Kerr McGee 97/12-1 (Portland-Wight Basin, Ainsworth & Riley, 2010).	Ballinlea-1 Borehole, White Park Bay exposure.
Paralingulina tenera occidentalis	Late Sinemurian (Raricostatum Chronozone, Macdonnelli Subchronozone)-Early	Mochras Borehole (Copestake & Johnson, 2014).	Absent

	Toarcian (Serpentinum Chronozone, Exaratum Subchrnozone).		
Vaginulinopsis denticulatacarinata	Late Sinemurian (Obtususm Chronozone, Obtusum Subchronozone)-Early Pliensbachian (Davoei Chronozone, Figulinum Subchronozone)	Mochras Borehole (Copestake & Johnson, 2014).	Ballinlea-1
Verneuilinoides mauritii	Late Sinemurian? - Lower Pliensbachian? (Davoei Chronozone)	Mochras Borehole (Copestake & Johnson, 1989, 2014); offshore Inner Hebrides (Ainsworth & Boomer, 2001).	Absent

Table 8.2: The important biostratigraphical taxa in Great Britain, Ireland and this study

Although in general, the Northern Ireland Early Jurassic microfaunas are similar to adjacents region, there are still some obvious difference recorded between them. One of them is the first appearance of flood *Reinholdella planiconvexa* in the Carnduff-1 Borehole, which came earlier than other places, this confirmed by the first occurrences of *Planorbis* sp. on it top bed. Copestake & Johnson (2014) described this bioevent as typical in the Northwest Europe Hettangian sediments (Johnstoni Subchoronoze of Planorbis Ammonite Chronozone). Due to the absence of ammonite data in Ballinlea-1 and Magilligan boreholes, the first appearance of flood *Reinholdella planiconvexa* in both boreholes are interpreted as proposed by Copestake & Johnson (2014); base JF2 biozone of Johnstoni Ammonite Subchronozone, Hettangian.

Another distinctive difference is the absent of important JF biozone markers in studied boreholes such as *Involutina liassica, Astacolus semireticulatus, Vaginulinopsis exarata* and *Paralingulina tenera occidentalis*.

At the upper part of JF3 biozone (Angulata to Bucklandi Ammonite Chronozones), *Involutina liassica* occurs commonly or consistent in the Mochras Borehole (Copestake & Johnson, 1989, 2014) but infrequent in the Portland-Wight Basin (named as Zone FJ3 in this basin; Ainsworth *et al.,* 1998a), Kerr McGee 97/12-1 (Portland-Wight Basin; Ainsworth & Riley, 2010) and offshore Inner Hebrides (Ainsworth & Boomer, 2001). Unfortunately, not a single specimen of *I. liassica* is found in Ballinlea-1 or any other of examined Northern Ireland sections. This absence may be cause by unsuitable habitat or dissolution of their tests as they are aragonitic.

The occurrence of important JF5 biozone marker; *A. semireticulatus* that described from the Mochras Borehole (Cardigan-Bay Basin; Copestake & Johnson, 2014), Portland-Wight Basin (Ainsworth *et al.*, 1998a), Kerr McGee 97/12-1 (Portland-Wight Basin, Ainsworth & Riley, 2010) and the Fastnet Basin (Ainsworth & Horton, 1986) are devoid in any Northern Ireland analysed samples. The other important JF5 marker is *Vaginulinopsis exarata* which numerous in the early of Semicostatum Ammonite Chronozone of Mochras Borehole (Copestake & Johnson, 2014) and very rare in offshore Inner Hebrides (Ainsworth & Boomer, 2001) also absence in Ballinlea-1. The cause for the absence of these two stratigraphic markers are uncertain.

The important Early Pliensbachian stratigraphic marker; *P. t. occidentalis* which recovered from Mochras Borehole (Copestake & Johnson, 2014) is not found from Ballinlea-1. This is probably due to the thin sequence of Ballinlea Early Pliensbachian sediments. However, the intermediate form of *P. t. occidentalis* and *P. t. tenera* does occur within Ballinlea ranges from the latest Sinemurian up to earliest Plienbachian sections.

8.3.2 Ostracods bioevent

The Ballinlea-1 latest Triassic ostracods fauna shows no direct correlation with Fastnet Basin, North Celtic Sea, Porcupine, Slyne, Erris and Donegal Basins due to the assemblage of marginal ostracods; *Darwinula* and *Lutkevichinella* in these Ireland basins (Ainsworth & Horton, 1986; Ainsworth *et al.* 1989; Ainsworth, 1989, 1990) being absent from the northern Irish sequences*.* These taxa are recorded throughout Hettangian of the Ireland basins above, whereas in Rathlin Basin (Ballinlea-1 borehole), *Darwinula* has not been found in any samples and only two specimens of *Lutkevichinella hortonae* have been recovered in the non-marine Ballinlea-1 Collin Glen Formation (Mercia Mudstone Group).

The latest Rhaetian to lowermost Early Sinemurian sediments of Northern Ireland Borehole (Ballinlea-1, Carnduff-1 and Magilligan) possess low diversity ostracod assemblage but abundant by *Ogmoconchella aspinata*, *Ektyphocythere translucens* and *Ogmoconcha hagenowi.* These taxa have a widespread geographical distribution, occurring throughout northwest Europe from strata of similar age. The nearest basins that can be highly correlated with this occurrence are Inner Hebrides (Ainsworth & Boomer, 2001), Cardigan Bay Basin

(Mochras Borehole) (Boomer, 1991), Kerr McGee 97/12-1 (Portland-Wight Basin, Ainsworth & Riley, 2010) and Portland-Wight Basin (Ainsworth *et al.*, 1998a). There is a slightly contradictory fauna noticed from offshore west and southwest Ireland; recovered with abundant of *O. serratostriata* at Hettangian age together with high number of marginal genera such as *Darwinula* and *Lutkevichinella* (Ainsworth & Horton, 1986; Ainsworth, 1989, 1990). The existence of non-marine taxa in the Ireland Hettangian sediments indicates that Ireland was still apart of land during latest Rhaetian, contrary to the Northern Ireland and much of UK which shallow-marine environment was already developing. The marine ostracods *O. ellipsoidea* (*O. aspinata* synonym) only start to appear during latest Hettangian to the earliest Sinemurian (offshore west and southwest Ireland; Ainsworth & Horton, 1986; Ainsworth, 1989, 1990).

The diverse but declining abundance of Late Sinemurian ostracods assemblages at Ballinlea are still dominated by the Metacopina (typical NW Europe species) but different taxa; *Ogmoconcha eocontractula*, *Ogmoconchella danica*, *Ogmoconchella mouhersensis*, and *Ogmoconchella gruendeli*. The assemblages also become diverse by Podocopina such as genera *Ektyphocythere*, *Gammacythere*, *Pleurifera, Isobythocypris, Paracypris* and *Nancythere.* The similar occurences recorded in the offshore Inner Hebrides (Ainsworth & Boomer, 2001), Mochras Borehole (Boomer, 1991), Fastnet Basin (Ainsworth & Horton, 1986). Meanwhile in and the Kerr McGee 97/12-1, Portland-Wight basin, the Late Sinemurian has very low abundance and diversity of ostracods fauna (Ainsworth & Riley, 2010). The only

Locality	Author & Year	Tr Rh	Hettangian	E. Sine	L. Sine	E. Pliens	L. Pliens	E. Toarcian	L. Toarcian
Ballinlea-1 Borehole, Co. Antrim	This study								
Carnduff-1 Borehole, Co. Antrim									
Magilligan Borehole, Co. Londonderry									
Ballygally, Co. Antrim									
Larne, Co. Antrim									
Tircrevan Burn, Co. Londonderry									
Portrush, Co. Antrim									
Kinbane Head, Co. Antrim									
Ballintoy, Co. Antrim									
White Park Bay, Co. Antrim									
Doniford Bay, Somerset	Clémence et al. (2010)								
	Clémence & Hart (2013)								
Hotham, Yorkshire	Lord (1971)								
Cliffe, Yorkshire									
Redcar, Yorkshire									
East Quantoxhead, West Somerset	Hylton, 1998								
Holwell, Eastern Mendips	Copestake, 1982								
Cloford, Eastern Mendips									
Dorset coast	Barnard, 1949								
Dorset coast	Macfadyen, 1940								
Offshore Inner Hebrides, Scotland	Ainsworth & Boomer, 2001								
Mochras Boreholes, Wales	Copestake & Johnson, 2014								
Portland-Wight Basin, England	Ainsworth et al., 1998								
Offshore southwest Ireland Basin	Ainsworth & Horton, 1986								
Offshore southern England	Ainsworth & Riley, 2010								

Figure 8.3: Latest Rhaetian to Early Jurassic sequences in Northern Ireland and England (Tr=Triassic; RH=Rhaetian; E. Sine=Early Sinemurian; L. Sine= Late Sineurian; E. Plien=Early Pliensbachian; L. Pliens=Late Pliensbachian; E. Toarcian=Early Toarcian; L. Toarcian=Late Toarcian).

contrast is the presence of *Lophodentina striata* in the Mochras Borehole (Boomer, 1991) that is not found in Ballinlea-1 or even anywhere else.

The Ballinlea-1 Early Pliensbachian ostracod abundance and diversity slightly drops due to relatively sea-level fall in the earliest Pliensbachian. The assemblages comprise common Metacopina such as rare *Ogmoconchella danica*, common and consistent of *Ogmoconchella eocontractula* and *Ogmoconchella gruendeli*. The Podocopina is diverse but occur sporadically. The similar pattern and Early Pliensbachian assemblages documented in the

Portland-Wight Basin (Ainsworth *et al.*, 1998a), Kerr McGee 97/12-1 (Portland-Wight Basin, Ainsworth & Riley, 2010), offshore Inner Hebrides (Ainsworth & Boomer, 2001), Fastnet Basin and North Celtic Sea (Ainsworth & Horton, 1986).

Chapter 9

Palaeogeography and palaeobiogeography summaries

Gordon (1970) classified Early to Late Jurassic foraminifera into five types of assemblages which develop based on temperature controls and broad geotectonic-sedimentary environment. Three of these types are boreal shelf type assemblages, while the remaining two are Tethyan type assemblages.

The Boreal Realm includes northern two-thirds of Europe, western interior region of North America, Russian platform, Sinai, Somaliland and few places in the southern hemisphere (Gordon, 1970). Despite this, both Boreal and Tethyan assemblages do occur in border zones like Mexico, Switzerland and Austria (Gordon, 1970). The shelf assemblages indicate a shelf sea setting are close to the land that supplies coarse to fine terrigenous sediments and where the progression of carbonate deposition occur (Gordon, 1970). The three types shelf assemblages (Gordon, 1970) are summarised below:

1) Nodosariid (now called as Lagenida) and Nodosariid-mixed assemblage (Nodosariid not less than one-fifth of all specimens and no other apparent calcareous foraminifera present).

2) Calcareous benthonic species other than nodosariids (at least one quarter of all specimens).

3) Dominant of simple agglutinated assemblages such as *Ammodiscus, Trochammina*, and *Reophax* (agglutinated taxa at least four-fifths of overall specimens).

Another two assemblages; complex agglutinated species assemblage and planktonic assemblage belong to the Tethyan Zone, associated with the Tethys Ocean. The Tethyan type assemblage is recorded from the Mediterranean, Middle East, Himalayas and Indonesian archipelago (Gordon, 1970). These two assemblages populated since Early Jurassic but are best known from the Middle Jurassic to Late Jurassic. The Tethyan assemblages described by Gordon (1970) are:

1) Dominant of complex agglutinated species such as *Pseudopfenderina, Everticyclammina* and *Lituosepta.*

2) Planktonic assemblage. Even though Gordon (1970) proposed this assemblage, he was doubting whether they are completely planktonic (holoplanktonic) or not. Previously Fuchs (1967, 1971, 1973, 1975, 1977) claimed that Triassic *Oberhauserella* as planktonic foraminifera origin, unfortunately after careful examinations by F. Rögl (Natural History Museum, Vienna), A. Görög (Budapest, Hungary), Hart *et al.* (2002) and Hudson *et al.* (2009), they decided that this genus is a benthonic species which has flattened umbilical sides and entirely lack of the inflated chambers (Hart *et al.*, 2002; Hudson *et al.*, 2009). Nonetheless, based on Hart *et al.* (2002, 2003), *Oberhauserella quadrilobata* (one of planktonic taxa proposed by Fuchs and also association of *Praegubkinella* spp. from Wernli (1995) study) probably planktonic ancestor as they are more inflated yet remains benthic (or quasi-planktic) throughout their life. The morphological change in *O. quadrilobata*

prompted by early Toarcian oceanic anoxic event (Hart *et al.*, 2002, 2003). In addition, Hudson *et al.* (2009) stated that the planktonic foraminifera first evolved on the shelf edge of the western Tethys after the global extinction of early Toarcian and right after a dysaerobic event in the Exaratum Subzone, the sea level highstand and the δ^{13}C excursion. Later in Bajocian-Bathonian, the meroplanktonic (partially planktic) *Conoglobigerina* appeared, which possibly from evolution of *Praegubkinella racemosa* (Wernli, 1995) and *Conoglobigerina* are restricted to the northern side of the Tethys (Hart *et al.*, 2002). Gordon (1970) stated that possibly Tethys was the homeland of the globigerinids in Late Bajocian-Lower Bathonian. He also concluded that later the planktonic migrated to the shelf of northern two-thirds of Europe based on Bignot and Guyader (1966) observation of 5% *Globigerina* within dominant benthic taxa from Oxfordian sediments in Le Havre constitute, northern France. The first appearance of planktonic foraminifera also discovered from the Oxfordian sections of Furzedown Clays, Dorset Coast, the species are *Globuligerina oxfordiana, Haeuslerina helvetojurassica* and *Compactogerina* sp. cf. C. *stellapolaris* (Oxford *et al.*, 2002). Gordon (1970) suggestion about the migration of planktonic had supported by the evidence that *Globigerina balakhmatovae* in Late Bajocian-Early Bathonian, northeastern Caucasus is very resembled to *Globigerina oxfordiana* from the northern France (Bignot & Guyader, 1966) and Britain (Oxford *et al.*, 2002).

Different foraminiferal assemblage divisions were established by Basov & Kuznetsova (2000). They categorised Hettangian-Tithonian (Jurassic) foraminiferal assemblages into three divisions; Tethyan, Boreal-Atlantic and Arctic. The only difference of Basov & Kuznetsova (2000) classification with Gordon (1970) is the Boreal Realm assemblages (shelf type assemblage) which Basov & Kuznetsova (2000) recognised as two subdivisions; Boreal Atlantic Realm (e.g. Mochras Borehole, UK; Copestake & Johnson, 2014) and Boreal Arctic Realm (e.g. Barents Sea shelf, Russia; Basov *et al.*, 2009). The Boreal Atlantic Realm is located at the south of Boreal Realm with the dominance of Lagenida and epistominiid association, whereas in the north, Boreal Arctic Realm yields Lagenida and ammodiscid association (agglutinated foraminifera as the dominant type). According to Nikitenko (2008), the deposition of sands, silts and clay in arctic sea resulted on predominant occurrence of agglutinated taxa (e.g. *Ammodiscus, Glomospira, Glomospirella, Saccammina,* and *Trochammina*) with occasional benthic foraminifera (e.g. *Astacolus, Lenticulina, Pseudonodosaria,* and *Nodosaria*). The arctic sea (such as middle Siberia, northern Alaska, Arctic Canada) have very contrast foraminifera assemblage to the Boreal Atlantic Realm because the former dominant by simple agglutinated form while the latter rich by benthonic calcareous form (Nikintenko, 2008).

In the present study, the Northern Ireland Jurassic foraminifera are typical shelf assemblages, to be specific the European Boreal Atlantic Realm (situated at the northern hemisphere (Figure 9.1). This classification based on the predominant occurrence of Lagenida members (type one assemblage) throughout most of the studied sections. Yet, the type two shelf assemblage;

''calcareous benthonic species other than nodosariids'' also recorded in several horizons. These non-nodosariid taxa such as Miliolida and Robertinida are sometimes notably abundant; for example, the flood of Robertinida (*R. planiconvexa*) in Hettangian of all three boreholes and the richness of Miliolida (*Cornuspira liasina*) in the earliest Sinemurian sections of Carnduff-1 Borehole. Throughout this study, no samples showed ''dominant simple agglutinated assemblages'' although a single sample from Magilligan Borehole (MAG106.96) has abundant simple agglutinated foraminifera. Yet they only constituted one third of the entire sample because the agglutinated species in MAG106.95 appeared together with abundant calcareous taxa such as *Eoguttulina liassica* and *Cornuspira liasina*.

The Northern Ireland ostracod assemblages are mostly dominated by Metacopina such as *Ogmoconchella aspinata*, *Ogmoconcha hagenowi*, *Ogmoconchella danica* and *Ogmoconcha eocontractula* with additional diversity provided by the Podocopina particularly *Ektyphocythere*. These species occur at similar levels throughout the northwest Europe, such as in western Germany (Drexler, 1958); Yorkshire (England; Lord, 1971), Danish embayment (Denmark; Michelsen, 1975), Paris Basin (France; Donze, 1985) and Mochras Borehole (Wales; Boomer, 1991). Furthermore, these species are not just common in NW Europe but also in few parts of southern hemisphere, Arias (2006) suggests the frequent occurrence of *Ogmoconchella aspinata* in Australian Hettangian, while Boomer & Ballent (1996) conclude that the northern hemisphere (Mochras Borehole) is linked with southern hemisphere (Argentina) through a proto-Atlantic rather than Tethyan seaway. This is also supported by the hypothesis of Arias (2006) which
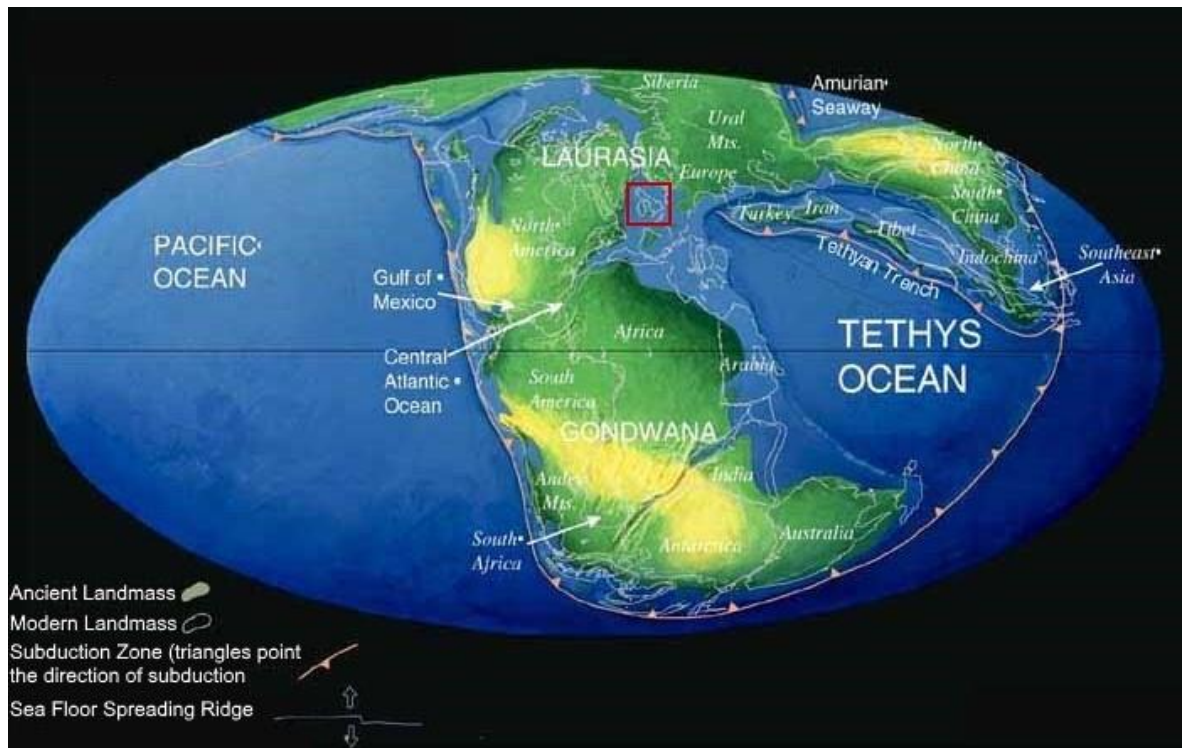
Figure 9.1 the Palaeogeographic map during Early Jurassic together with location of Britain and Ireland (red box). (Scotese, 1997)

suggested that throughout the Hettangian to Late Pliensbachian, the high degree of similarity between European ostracods assemblages and Argentina is high especially in the Early Pliensbachian.

Moreover, northern Tethyan Late Triassic (latest Rhaetian)-Early Jurassic ostracods assemblages such as in Portugal, Spain, Turkey and Himalayas are not much different with northwest Europe (Lord, 1988). This close similarity also noticed within the Tethyan and the southern hemisphere. Within these three divisions, only arctic sea comprises contrast ostracods assemblage. This

proved by Nikintenko (2008) study; the ostracod assemblages in the Arctic (known from mid Siberia, northern Alaska and Arctic Canada) are very sparse compared to the abundant ostracods fauna in the Boreal Atlantic Realm; this rarity is likely due to unfavourable environments (Nikitenko, 2008).

Chapter 10

Conclusion

10.1 Introduction

The examination of 142 samples from 9 different localities resulted in the recovery of 24,530 foraminifera and 6,410 ostracods specimens. The specimens belong to 7 orders, 16 families, 29 genera and 167 species of benthic foraminifera, whilst 69 ostracods species are from 4 suborders, 14 families, 19 genera and 5 unknown affinity. The foraminifera assemblages consist almost exclusively calcareous benthic foraminifera dominated by the Lagenida, albeit a single sample from the Magilligan Borehole exhibits localised peaked agglutinated foraminifera. While, the most abundant ostracod specimens belong to the smooth-shelled Metacopina. The most abundant species throughout the study is *Paralingulina tenera* plexus, but the profusion and dominance of other groups was also observed particularly within Hettangian strata. For example, Miliolida (*Cornuspira liasina*), Robertinida (*Reinholdella planiconvexa*) and agglutinated (*Reophax* sp. and *Trochammina canningensis*).

The picking process was undertaken throughout 63 µm to 500 µm fractions but chiefly the microfossils found from 125 -250 µm fraction. Smaller size fractions are crucial for the identification of small species and recognition of juvenile forms, especially in the discovery of important biostratigraphically taxa such as *Reinholdella planiconvexa*, *Ichthyolaria terquemi*

barnardi, Brizalina liasica, Paralingulina tenera plexus and the ostracod *Nanacythere* together with environmental markers like *Ophthamlidium* spp., *Cornuspira liasina* and *Spirillina infima*. The tests of microfossils are excellent to moderately well-preserved throughout most samples including aragonitic types. The only exception being those tests extracted from Carnduff-1 as they are often poorly preserved due to calcite overgrowth. This makes species classification difficult, especially *Paralingilina tenera* plexus as this group needs careful ribs examinations to differentiate them.

10.2 Biostratigraphy and age of sediments

The biostratigraphically valuable foraminifera permitted determination of Jurassic Foraminifera Biozones following the Copestake & Johnson (2014) scheme. The youngest biozone encountered is JF9a, recorded from two localities in North Co. Antrim, Ballinlea-1 Borehole and White Park Bay exposures. In this study, the most complete Northern Ireland Waterloo Mudstone Formation is from Ballinlea-1 which yields biozone JF1 to JF9a (Hettangian-Early Pliensbachian); followed by both shorter successions from Magilligan and Carnduff-1 boreholes (Rhaetian-JF3 of the latest Rhaetian to Early Sinemurian age). Even though WPB exposures (Mitchell, 2004) and Port More Borehole (Wilson & Manning, 1978; Warrington, 1997) had previously been considered to have their youngest sediments from Ibex Ammonite Chronozone (equivalent to the end JF9a-basal JF9b) of Early Pliensbachian age, the youngest sections interpreted in this research are of the

Jamesoni Ammonite Chronozone (JF9a biozone) of Early Pliensbachian age documented from WPB and Ballinlea-1 Borehole (see Chapter 4 and 7 for detailed discussions). Therefore, the Waterloo Mudstone Formation (Lias Group) in Northern Ireland spans the time range from the Late Rhaetian (Late Triassic) to Early Pliensbachian (Early Jurassic) and this study proved that Ballinlea has the most complete and thickest Early Jurassic strata.

The investigation of Northern Ireland Waterloo Mudstone Formation exposures brings to the conclusion that younger sections; Late Sinemurian (Raricostatum Ammonite Chronozone) onwards are scattered in north Co. Antrim, whilst older sections (latest Rhaetian-Early Sinemurian) crop out along the eastern margin of Co. Antrim. In northern Co. Londonderry, to the west of Co. Antrim, this area composed exposures of Early Sinemurian age. Variations in the completeness of Early Jurassic beds preserved at the surface and subsurface resulted from structural events occurred between Pliensbachian and Cenomanian (Warrington, 1997) which included faulting (George, 1976; Fletcher, 1997 in Warrington, 1997), uplift (Simms & Jeram, 2007), and pre-Cretaceous erosion (Broughan *et al.*, 1989; Simms & Jeram, 2007). This is evident in boreholes sections represented by variable thickness and age.

While Ballinlea-1 possesses the thickest succession of the Waterloo Mudstone Formation, the thickest documented Hettangian strata comes from the adjacent Magilligan Borehole. The Hettangian beds from Magilligan, Carnduff-1 and Ballinlea-1 are about 93 m, 90 m and 65 m thick respectively. The differences in thickness are presumably due either differential sedimentation

rates because of slightly palaeodepth settings or greater degree of post-depositional compaction of the sediments.

The widespread mudstone deposition cause by the Late Triassic progressive transgression permits the recovery of benthic microfauna following on from the global Triassic-Jurassic boundary mass extinction. Throughout latest Rhaetian to Hettangian, the microfauna diversity in the region of the UK and Ireland is generally low (alpha diversity usually less than 5), often monospecific or colonised by shallow marine species; *Eoguttulina liassica* or opportunistic taxa; *Ogmoconchella aspinata*. The profuse occurrence of the small aragonitic taxon *Reinholdella planiconvexa* during the mid Hettangian reflects a stagnant marine environment as they are prone to low-oxygen condition at the sea-floor.

10. 3 Palaeoenvironments

The most widespread poor-oxygenated environments in Northern Ireland occurred during Hettangian age (Figure 10.1) and allowed the opportunistic species such as *Reinholdella planiconvexa* (Haynes, 1981; Bernhard 1986; Koutsoukos et al 1990; Boutakiout & Elmi, 1996; Hylton & Hart, 2000; xnSbbagasti & Ballent, 2002; Ballent et al., 2006) to colonise the ecology. However, local environmental conditions also affected the microfaunal assemblages, for instance, the abundant occurrence of simple agglutinated foraminifera (*Reophax* sp. and *Trochammina*

canningensis) and shallow type calcareous benthic foraminifera (*Eoguttulina liassica* and *Cornuspira liasina*) within latest Hettangian strata of Magilligan borehole denotes low sea-levels (Gordon, 1970; Jones, 1994; Jones, 2013). This significant numbers of simple agglutinated foraminifera only appeared in the Magilligan Borehole.

During earliest Sinemurian, a shallow setting of deposition can be seen from the Tircrevan Burn exposure, Magilligan and Ballinlea-1 boreholes. The exposure comprises 13 m of the Tircrevan Sandstone Member; fine sandstone with mud drapes which indicates the marginal setting , tidal to sub-tidal (Nichols, 2009). While in Ballinlea-1 and Magilligan, the increase of quartz grains in the earliest Sinemurian cutting samples results from the influence of a shallow setting. This regional picture of lowstand at this time correlates with global relative sea-level drop in the earliest Sinemurian (refer to Figure 1.2 and Figure 1.3 from Chapter 1).

From the mid Early Sinemurian to Early Pliensbachian, the relatively higher diversity of the microfaunas (the alpha index diversity greater than 5) particularly represented by members of the Lagenida indicates well-oxygenated outermost-inner to middle shelf, open marine environments (Nagy & Alve, 2010). However, during the Late Sinemurian some sediments indicate deeper environments, from outermost-middle to outer shelf. These are suggested by the abundant and dominance of deep water taxa such as *Reinholdella pachyderma humilis* (Johnson, 1976)*, the* genus *Ophthalmidium* (Jones, 2013) and species *Brizalina liasica* (Haynes, 1981; Jones, 2013)*.

Another important event within Late Sinemurian is the hiatus and absence of the Oxynotum Ammonite Chronozone in southern England (Cope *et al.* 1980 in Boomer & Ainsworth, 2009) which is also reflected in this study where the Obtusum-Oxynotum Ammonite Chronozone (JF6-JF7) are missing within the Ballinlea-1. Another Northern Ireland locality exhibits this event is in the Port More Borehole where the Obtusum and Oxynotum Ammonite Chronozes are missing within the borehole (Wilson & Manning 1978). Hallam (1978, 1981) describes this event as regressive phase which prevailed throughout NW Europe. The species used to interpret the palaeoenvironments in this study are listed in Table 10.1

Microfossil	Abundant or dominant by species/genus	Oxygen-level/Palaeoenvironment	Reference
Foraminifera	*Reinholdella planiconvexa*	Opportunistic species	Bernhard 1986 Koutsoukos *et al* 1990 Boutakiout & Elmi, 1996 Sagasti & Ballent, 2002 Ballent *et al.*, 2006
		Biotic stress	Clémence & Hart, 2013
		Stagnant sea-bottom	Brouwer, 1969 Johnson, 1976
		Withstand poorly-oxygenated environments	Haynes, 1981 Hylton & Hart, 2000
		Inner to middle shelf environment	Johnson, 1976
	Reinholdella	Deep, open-marine, middle to outer shelf (below Aragonite Compensation Depth)	Brouwer, 1969 Johnson, 1976 Hylton & Hart, 2000 Jones, 2013

	Reinholdella pachyderma	Outermost middle shelf or outer shelf	Johnson, 1976
	Diverse of Lagenida members	Favourable environment and normal marine inner-mid shelf	Nagy & Alve, 2010
	Low diverse of Lagenida member	Inner neritic environment	Brooke & Braun, 1972
	Paralingulina tenera plexus or elongated form of Lagenida	Opportunistic species, adapt in confined environment	Rey et al., 1994 Reolid *et al*, 2012
	Astacolus speciosus	Low-oxygen condition	Reolid *et al*., 2012
	Uncoiled *Lenticulina*	Adaptations to live near the sediment or water interface	Haynes, 1981
	Nodosaria	Tolerant with suboxic environment	Jones, 2014
	Ophthalmidium	Deep marine	Jones, 2013
	Brizalina liassica	Deep marine, outer shelf	Haynes, 1981 Jones, 2013
		Ability to tolerate lower oxygen conditions	Boltovskoy, 1972
	Eoguttulina liassica	Shallow marine	Jones, 2013
		Opportunistic species	Nocchi & Bartolini, 1994
	Cornuspira liasina	Shallow marine (tropical carbonate setting), inner neritic	Jones, 1994 Haynes, 1981
	Spirillina	Shallow marine	Copestake & Johnson, 1981 Shipp & Murray, 1981
	Reophax	Shelf sea setting	Gordon, 1970

	Trochammina canningensis	Sehlf sea setting	Gordon, 1970
Ostracods	*Ogmoconchella aspinata*	Tolerate wide range environment	Boomer & Ainsworth, 2009
		Opportunistic species	Ainsworth, 1989 Ainsworth & Boomer,2001 Ainsworth & Riley, 2010
		Inner shelf	Ainsworth, 1989
	Isobythocypris	Slightly lower oxygen level, shallow marine	Ainsworth & Boomer, 2001
	Ektyphocythere translucens	Improvement of bottom water	Ainsworth & Boomer, 2001

Table 10.1 The Early Jurassic foraminifera and ostracods palaeoenvironmental indicators recovered from Northern Ireland analysed samples.

Figure 10.1: Summary and correlation of lithostratigraphy logs, Fisher's alpha diversities, palaeoenvironment interpretations and oxygenation interpretations of studied localities; both boreholes and outcrops. MM: Mercia Mudstone Formation, CG: Collin Glen Formation. (the bigger version of this figure is folded inside the envelop attached).

10.4 Recommendation for further study:

- The detailed study of ammonites from Carnduff-1 (in progress) and Magilligan core samples together with exposures are necessary to resolve the problem in the biozonation or age assignation either cause by early appearance or absence of biostratigraphical benthic micro-organism.

- Conducted higher resolution (every 2 m or 5 m depending on the samples avaibility) microfaunas analysis to fill in gaps in the data especially the Triassic-Jurassic boundary and age or biozonation transition.

- Conducted bulk isotopes of core samples; Carnduff-1 Borehole (in progress for publication) and Magilligan Borehole.

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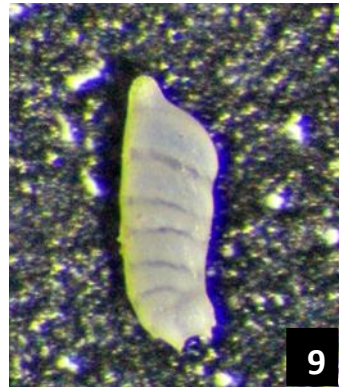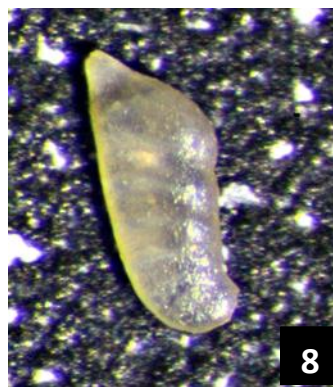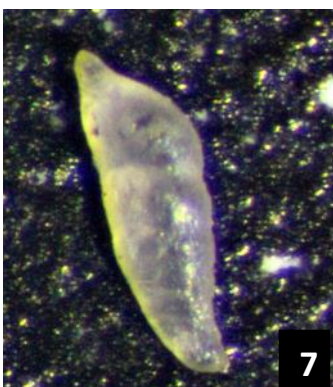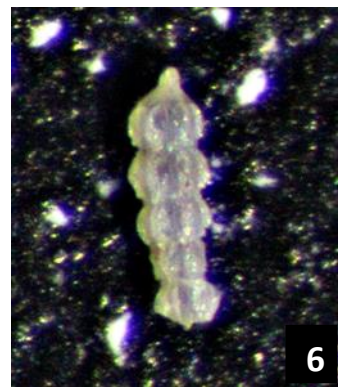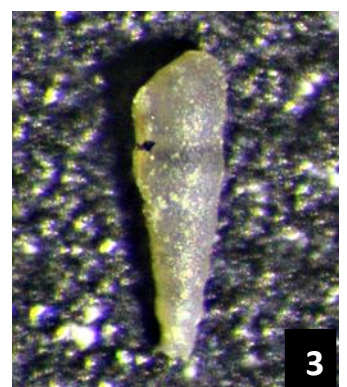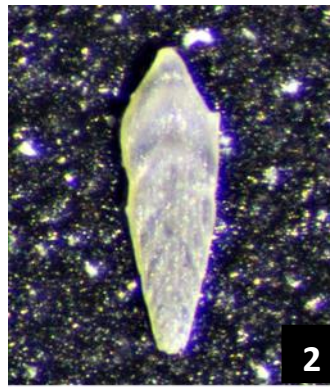
Figure A

1. *Dentalina langi* Barnard, Ballinlea-1 Borehole BAL845, lateral view, height 1540 μm, width 310 μm, diameter of aperture 90 μm.

2. *Ichthyolaria terquemi squamosa* (Terquem & Berthelin), Ballinlea-1 Borehole BAL425, lateral view, height 559 μm, width 178 μm.

3. *Marginulina* aff. *turneri* Copestake & Johnson, Ballinlea-1 Borehole BAL580, lateral view, height 626 μm, width 198 μm.

4. *Marginulina sherborni* Franke, Ballinlea-1 Borehole BAL425, lateral view, height 889 μm, width 230 μm.

5. *Marginulina prima incisa* Franke, Ballinlea-1 Borehole BAL540, lateral view, height 622 μm, width 156 μm.

6. *Marginulina prima interrupta* Terquem, Ballinlea-1 Borehole BAL530, lateral view, height 378 μm, width 111 μm, thickness 111 μm.

7, 8. *Vaginulina listi* (Bornemann)*.* G, Ballinlea-1 Borehole BAL595, lateral view, height 515 μm, width 152 μm; H, Ballinlea-1 Borehole BAL570, lateral view, height 626 μm, width 236 μ.

9. *Vaginulinopsis denticulatacarinata* (Franke), Ballinlea-1 Borehole BAL410, lateral view, height 526 μm, width 193 μm.
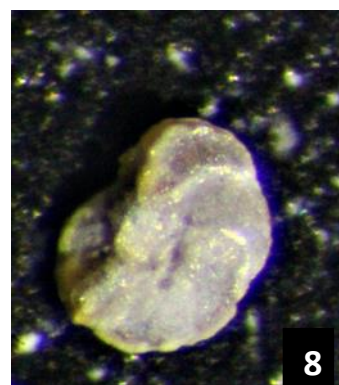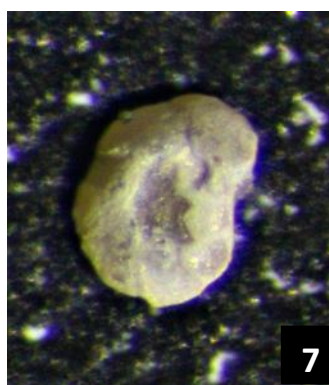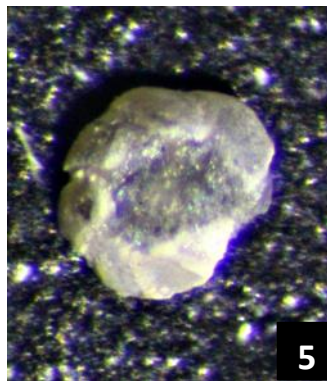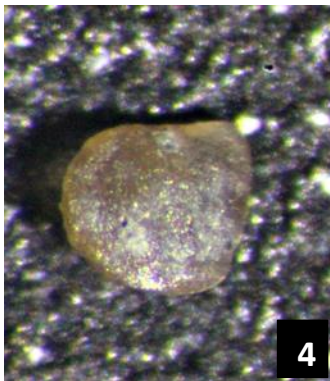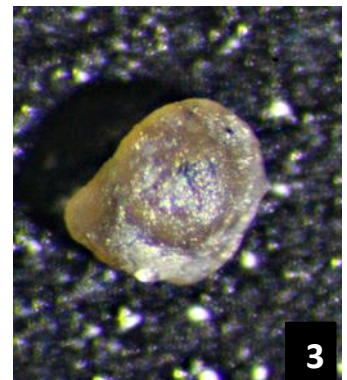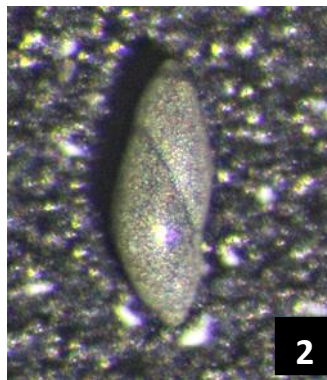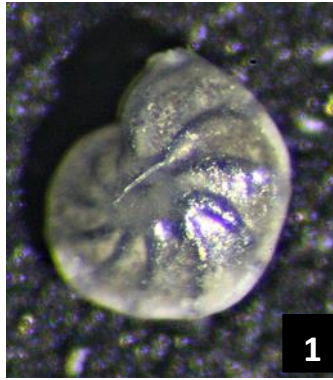
Figure B

1. *Lenticulina muensteri* ssp. A, Ballinlea-1 Borehole BAL490, lateral view, diameter of coil 575 μm.

2. *Eoguttulina liassica* (Strickland), Ballinlea-1 Borehole BAL465, lateral view, height 511 μm, width 200 μm, thickness 156 μm.

3, 4. *Reinholdella* sp. A, Ballinlea-1 Borehole BAL855, dorsal view and ventral view respectively, 454 μm.

5, 6, 7, 8. *Reinholdella margarita margarita* (Terquem). E, F. Ballinlea-1 Borehole BAL430, dorsal view and ventral view respectively, diameter 454 μm; G, H. Ballinlea-1 Borehole BAL430, dorsal view and ventral view respectively, diameter 441 μm.
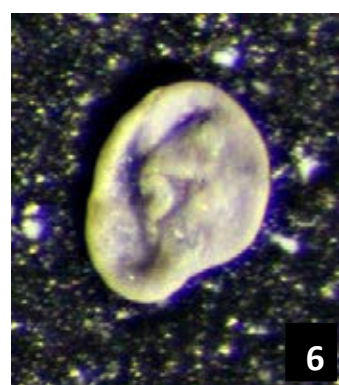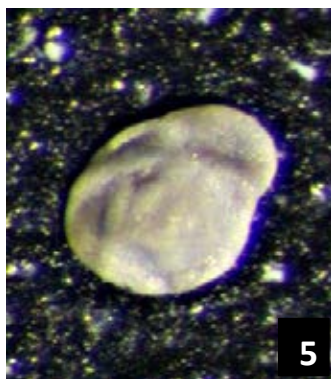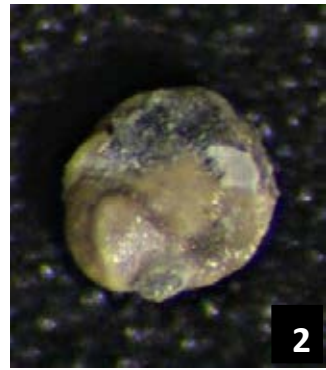
Figure C

Figure C

1, 2. *Reinholdella robusta* Copestake & Johnson, Ballinlea-1 Borehole BAL430, dorsal view and ventral view respectively, diameter 441 µm.

3, 4. *Reinholdella dreheri* (Bartenstein), Ballinlea-1 Borehole BAL570, dorsal view and ventral view respectively, diameter 379 µm.

5, 6. *Reinholdella* sp. B, Ballinlea-1 Borehole BAL545, dorsal view and ventral view repectively, diameter 219 µm.
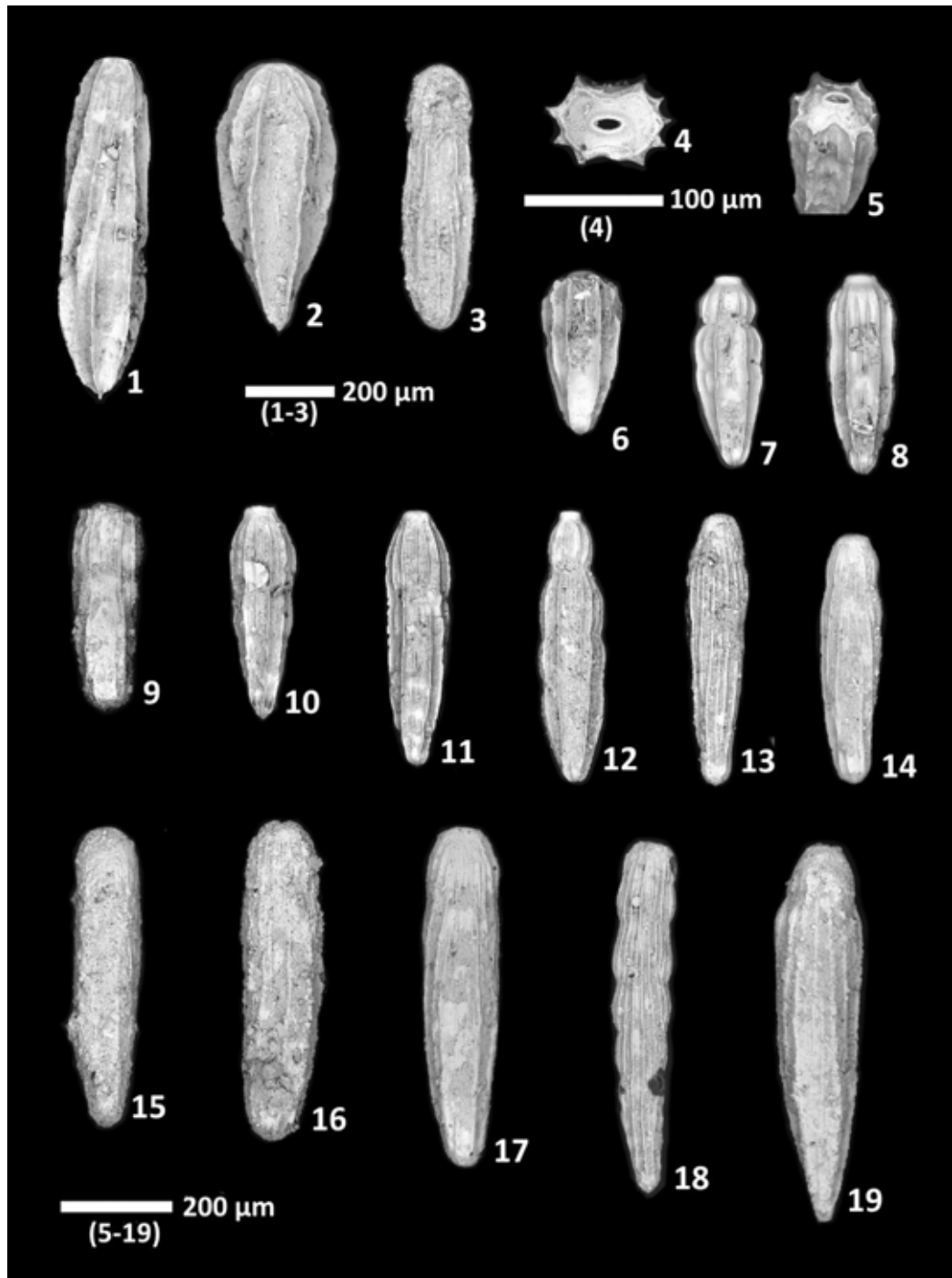
Plate 1

Plate 1

1-3. *Paralingulina tenera substriata* (Nørvang). 1, Carnduff-1 Borehole CRN176, lateral view x240; 2, Carnduff-1 Borehole CRN176, lateral view x240; 3, Carnduff-1 Borehole CRN 186, lateral view x260.

4-8. *Paralingulina tenera tenuistriata* (Nørvang).4, Ballinlea-1 Borehole BAL400, aperture view x940; 5, Ballinlea-1 Borehole BAL385, aperture view x860; 6, Ballinlea-1 Borehole BAL425, lateral view x400; 7, Ballinlea-1 Borehole BAL530, lateral view x310; 8, Ballinlea-1 Borehole BAL560, lateral view x430.

9-13, 18, 19. *Paralingulina tenera pupa* (Terquem)*.* 9, Magilligan Borehole MAG146, lateral view x275; 10, Ballinlea-1 Borehole BAL410, lateral view x370; 11, Ballinlea-1 Borehole BAL530, lateral view x350; 12, Ballinlea-1 Borehole BAL425, lateral view x320; 13, Carnduff-1 Borehole CRN306.6, lateral view x310; 18, Carnduff-1 Borehole CRN306.6, lateral view x250; 19, Magilligan Borehole MAG131.1, lateral view x250.

14-17. *Paralingulina tenera collenoti* (Terquem).14, Magilligan Borehole MAG146, lateral view x250; 15, Ballinlea-1 Borehole BAL935, lateral view x290; 16, Carnduff-1 Borehole CRN301.6, lateral view x275; 17, Magilligan Borehole MAG151, lateral view x250.
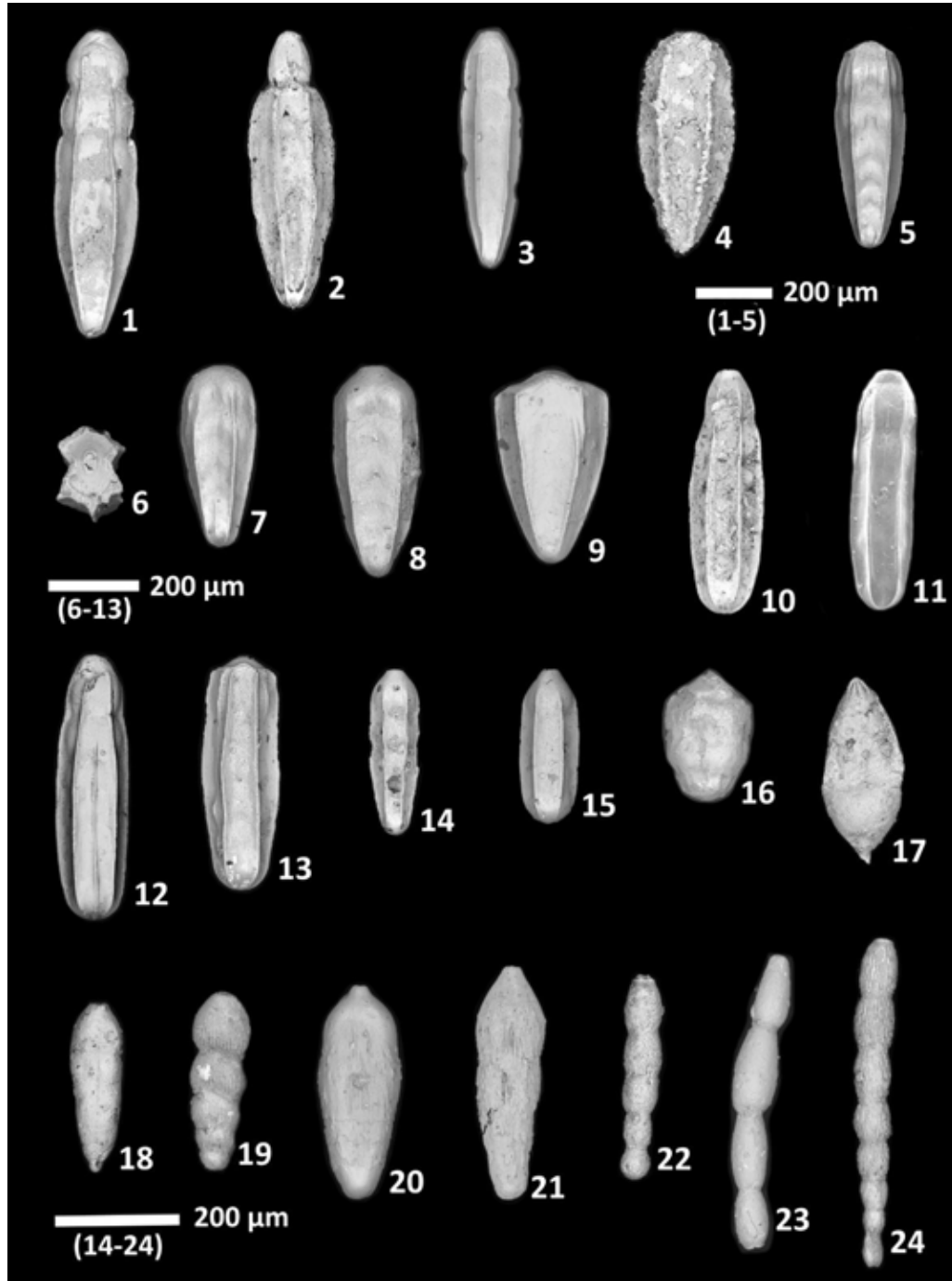
Plate 2

Plate 2

1-9. *Paralingulina tenera tenera* (Bornemann). 1, Ballinlea-1 Borehole BAL580, lateral view x255; 2, Ballinlea- 1 Borehole BAL490, lateral view x245; 3, 3, Ballinlea-1 Borehole BAL520, lateral view x290; 4, Carnduff-1 Borehole CRN259, lateral view x300; 5, Ballinlea-1 Borehole BAL845, lateral view x300; 6, Ballinlea-1 Borehole BAL400, aperture view x670; 7, Ballinlae-1 BAL845, lateral view x340; 8, Ballinlea-1 Borehole BAL610, lateral view x380; 9, Ballinlea-1 Borehole BAL550, lateral view x310.

10-15. *Paralingulina tenera subprismatica* (Franke). 10, Ballinlea-1 Borehole BAL500, lateral view x370; 11, Ballinlea-1 Borehole BAL465, lateral view x100; 12, Ballinlea-1 Borehole BAL520, lateral view x285; 13, Ballinlea-1 Borehole BAL530, lateral view x380; 14, Ballinlea-1 Borehole BAL425, lateral view x470; 15, Ballinlea-1 Borehole BAL425, lateral view x580.

16. *Paralingulina esseyana* (Deecke), Ballinlea-1 Borehole BAL490, lateral view x600.

17. *Paralingulina minuta* (Franke)*,* Ballinlea-1 Borehole BAL595, lateral view x700.

18-20. *Paralingulina lanceolata* (Haeusler)*.* 18, Magilligan Borehole MAG178.43, lateral view x590; 19, Magilligan Borehole MAG146, lateral view x470; 20, Ballinlea-1 Borehole BAL520, lateral view x410.

21. *Paralingulina longiscata longiscata* (Terquem)*.* Ballinlea-1 Borehole BAL510, lateral view x400.

22, 23. *Paralingulina cernua* (Berthelin)*.* 22, Carnduff-1 Borehole CRN176, lateral view x450; 23, Ballinlea-1 Borehole BAL730, lateral view x360.

24. *Paralingulina paranodosaria* (Copestake & Johnson)*,* Ballinlea-1 Borehole BAL595, lateral view x370.

Plate 3
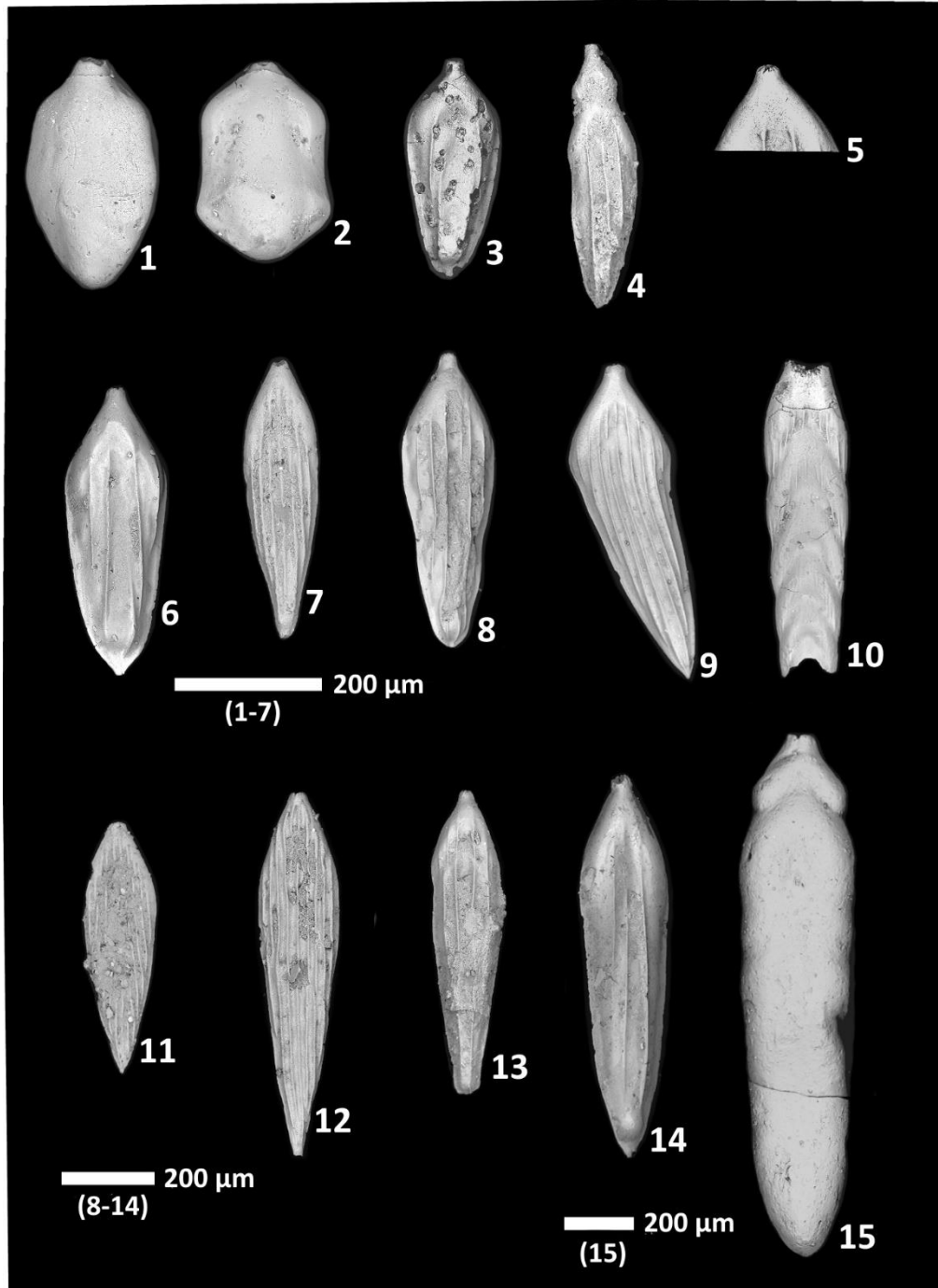
Plate 3

1, 2, 15. *Ichthyolaria brizaeformis* (Bornemann)*.* 1, Ballinlea-1 Borehole BAL425, lateral view x520; 2, Ballinlea-1 Borehole BAL425, lateral view x510; 15, Ballinlea-1 Borehole BAL570, lateral view x210.

3. *Ichthyolaria terquemi terquemi* (d'Orbigny)*,* Ballinlea-1 Borehole BAL520, lateral view x530.

4. *Ichthyolaria terquemi barnardi* (Copestake & Johnson)*,* Ballinlea-1 Borehole BAL885, lateral view x500.

5, 6, 13, 14. *Ichthyolaria terquemi bicostata* (d'Orbigny)*.* 5, Ballinlea-1 Borehole BAL400, lateral view x800; 6, Ballinlea-1 Borehole BAL425, lateral view x520; 13, Ballinlea-1 Borehole BAL730, lateral view x 290; 14, Ballinlea-1 Borehole BAL380, lateral view x250.

7-10. *Ichthyolaria terquemi sulcata* (Bornemann)*.* 7, Ballinlea-1 Borehole BAL570, lateral view x480; 8, Ballinlea-1 Borehole BAL715, lateral view x300; 9, Magilligan Borehole MAG76.69, lateral view x270; 10, Ballinlea-1 Borehole BAL410, lateral view x250.

11, 12. *Ichthyolaria terquemi squamosa* (Terquem & Berthelin)*.* 11, Ballinlea-1 Borehole BAL490, lateral view x290; 12, White Park Bay WPB2, lateral view x240.

Plate 4

50 μm
(1-2)

200 μm
(3-4)

200 μm
(5-13)

200 μm
(14-18)

293
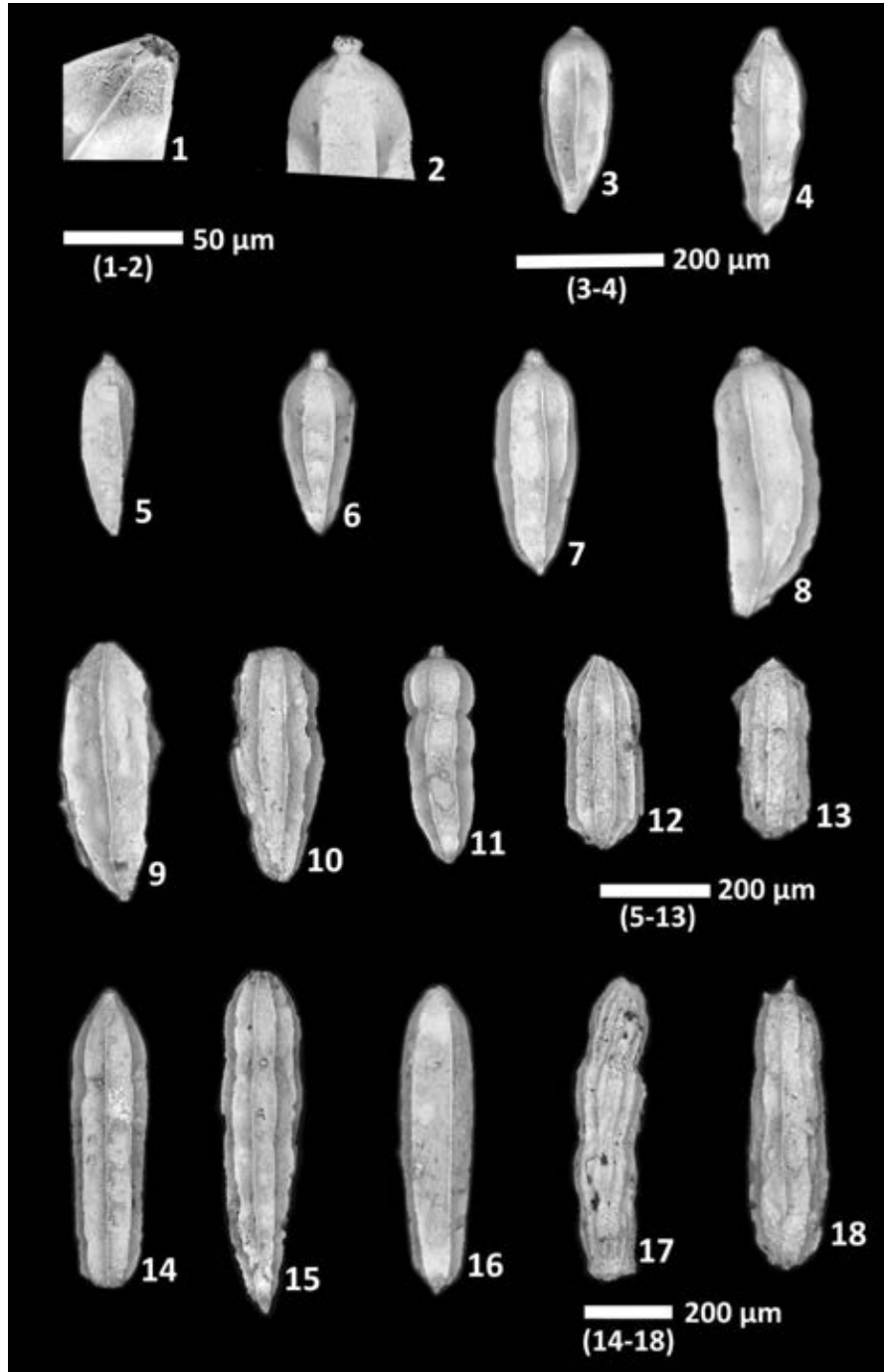
Plate 4

1, 4, 9, 14. *Nodosaria mitis* (Terquem & Berthelin). 1, Ballinlea-1 Borehole BAL425, aperture view x3700; 4, Ballinlea-1 Borehole BAL560, lateral view x530; 9, Ballinlea-1 Borehole BAL685, lateral view x360; 14, Ballinlea-1 Borehole BAL595, lateral view x250.

2, 3, 5-8. *Nodosaria issleri* Franke. 2, Ballinlea-1 Borehole BAL400, aperture view x740; 3, Ballinlea-1 Borehole BAL430, lateral view x600; 5, Ballinlea-1 Borehole BAL560, lateral view x320; 6, White Park Bay WPB3, lateral view x400; 7, Ballinlea-1 Borehole BAL540, lateral view x350; 8, Ballinlea-1 Borehole BAL490, lateral view x330.

10. *Nodosaria prima* d'Orbigny, Ballinlea-1 Borehole BAL715, lateral view x390.

11. *Nodosaria radiata* (Terquem), Ballinlea-1 Borehole BAL530, lateral view x440.

12. *Nodosaria columnaris* Franke, Ballinlea-Borehole BAL475, lateral view x520.

13. *Nodosaria kuhni* Franke, Ballinlea-1 Borehole BAL790, lateral view x440.

15. *Nodosaria novemcostata* Bornemann, Carnduff-1 Borehole CRN189.85, lateral view x250.

16. *Nodosaria sexcostata* Terquem, Ballinlea-1 Borehole BAL580, lateral view x260.

17. *Nodosaria porrecta* Terquem, Carnduff-1 Borehole CRN170.7, lateral view x240.

18. *Nodosaria tenera* Franke, Ballinlea-1 Borehole BAL745, lateral view x275.

Plate 5
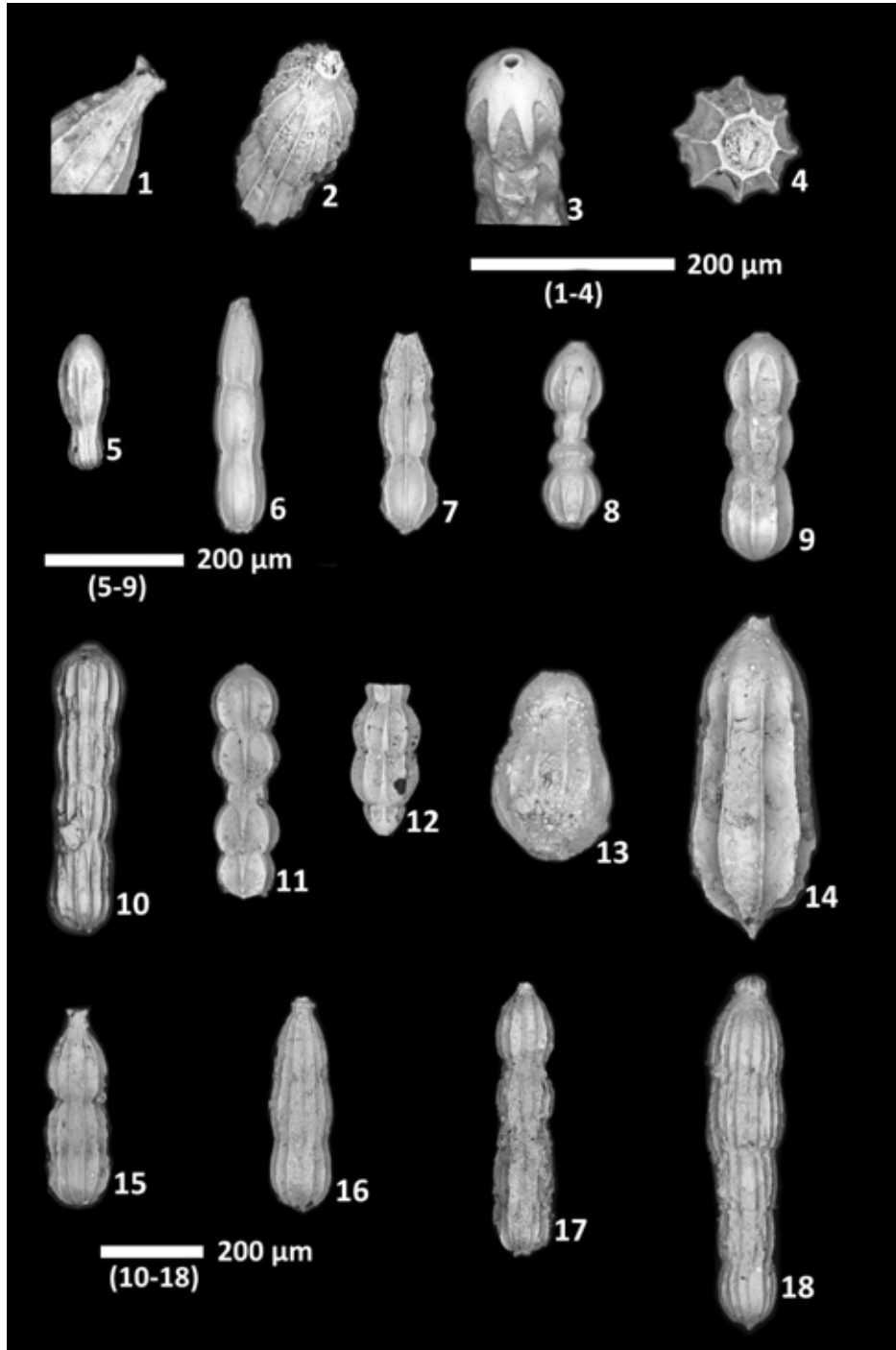
Plate 5

1, 2, 14-18. *Nodosaria metensis* Terquem*.* 1, Carnduff-1 Borehole CRN216.75, aperture view x1450; 2, Carnduff-1 Borehole CRN216.75, aperture view x660; 14, Ballinlea-1 Borehole BAL595, lateral view x280; 15, Carnduff-1 Borehole CRN216.75, lateral view x450; 16, Magilligan Borehole MAG122, lateral view x360; 17, Magilligan Borehole MAG112, lateral view x410; 18, Magilligan Borehole MAG131.1, lateral view x210.

3, 8-11. *Nodosaria fontinensis* Terquem*.* 3, Ballinlea-1 Borehole BAL395, aperture view x640; 8, Ballinlea-1 Borehole BAL540, lateral view x480; 9, Ballinlea-1 Borehole BAL395, lateral view x430; 10, Ballinlea-1 Borehole BAL570, lateral view x255; 11, Ballinlea-1 BAL425, lateral view x380.

4, 12. *Nodosaria rara* Franke*.* 4, Ballinlea-1 Borehole BAL425, aperture view x910; 12, Ballinlea-1 Borehole BAL490, lateral view x420.

5. *Nodosaria* cf. *kunzi* Paalzow, Ballinlea-1 Borehole BAL400, lateral view x730.

6, 7. *Nodosaria hortensis* Terquem*.* 6, Ballinlea-1 Borehole BAL695, lateral view x420; 7, Ballinlea-1 Borehole BAL935, lateral view x490.

13. *Nodosaria lagenoides* Wisniówskim, Ballinlea-1 Borehole BAL785, lateral view x370.

Plate 6
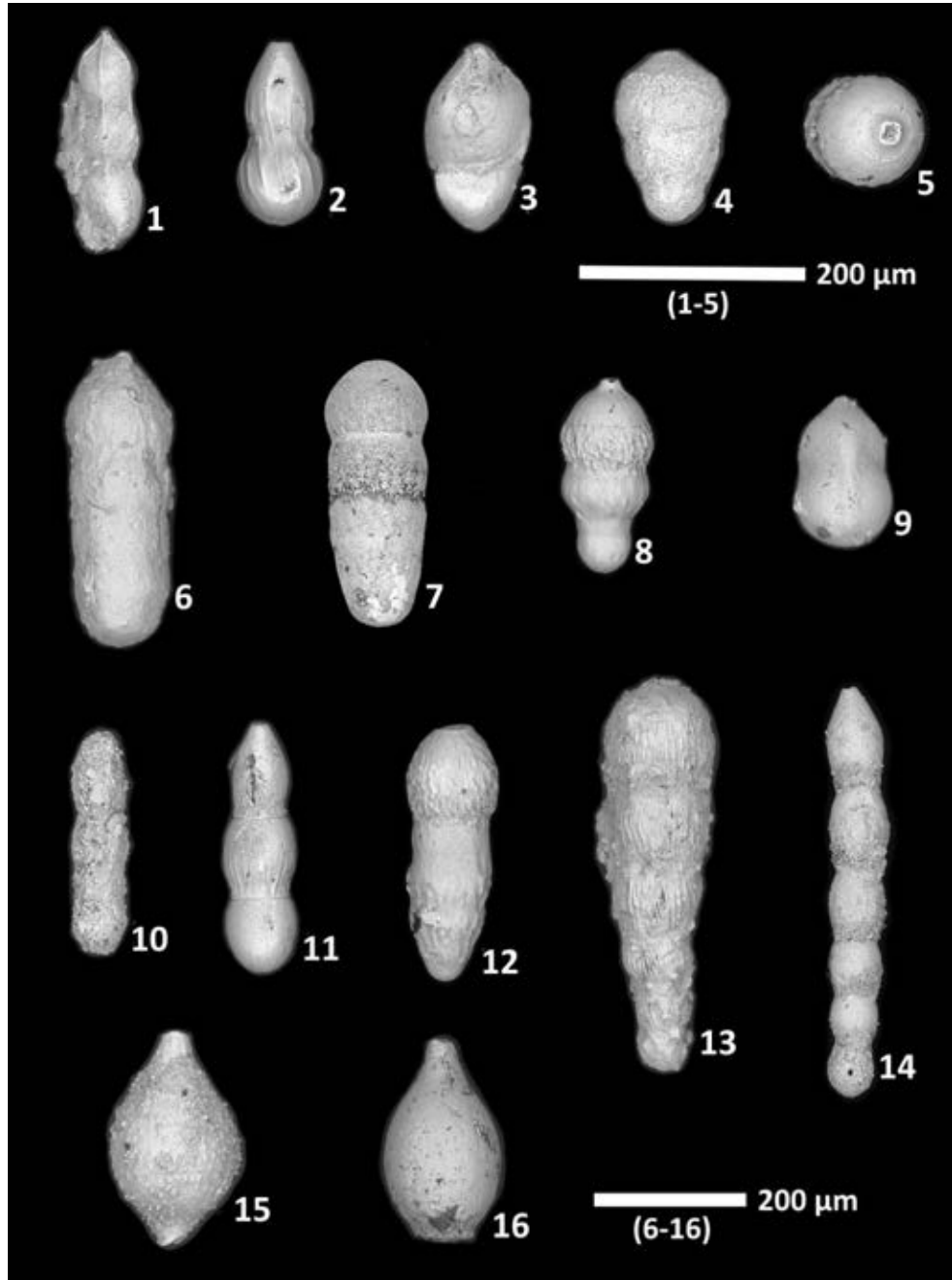
Plate 6

1*. Nodosaria* sp. A, Ballinlea-1 Borehole BAL530, lateral view x690.

2*. Nodosaria* sp. B, Ballinlea-1 Borehole BAL400, lateral view x890.

3. *Nodosaria crispata* Terquem, ballinlea-1 Borehole BAL730, lateral view x700.

4-7. *Nodosaria nitidana* Brand. 4, Ballinlea-1 Borehole BAL400, lateral view x790; 5, Ballinlea-1 Borehole BAL400, aperture view x740; 6, Ballinlea-1 Borehole BAL530, lateral view x410; 7, Ballinlea-1 Borehole BAL500, lateral view x510.

8. *Nodosaria pseudoclaviformis* (Copestake & Johnson), Ballinlea-1 Borehole BAL400, lateral view x500.

9. *Nodosaria germanica* Franke, Ballinlea-1 Borehole BAL510, lateral view x580.

10, 11. *Nodosaria primitiva* Kübler & Zwingli.10, Carnduff-1 Borehole CRN241.5, lateral view x570; 11, Ballinlea-1 Borehole BAL440, lateral view x540.

12, 13. *Nodosaria claviformis* Terquem. 12, Ballinlea-1 Borehole BAL425, lateral view x500; 13, Ballinlea-1 Borehole BAL520, lateral view x450.

14. *Nodosaria simplex* (Terquem), White Park Bay WPB1, lateral view x280.

15. *Nodosaria apheiloloculla* Tappan, Ballinlea-1 Borehole BAL685, lateral view x480.

16. *Nodosaria pseudoregularis* Canales, Ballinlea-1 Borehole BAL540, lateral view x540.

Plate 7
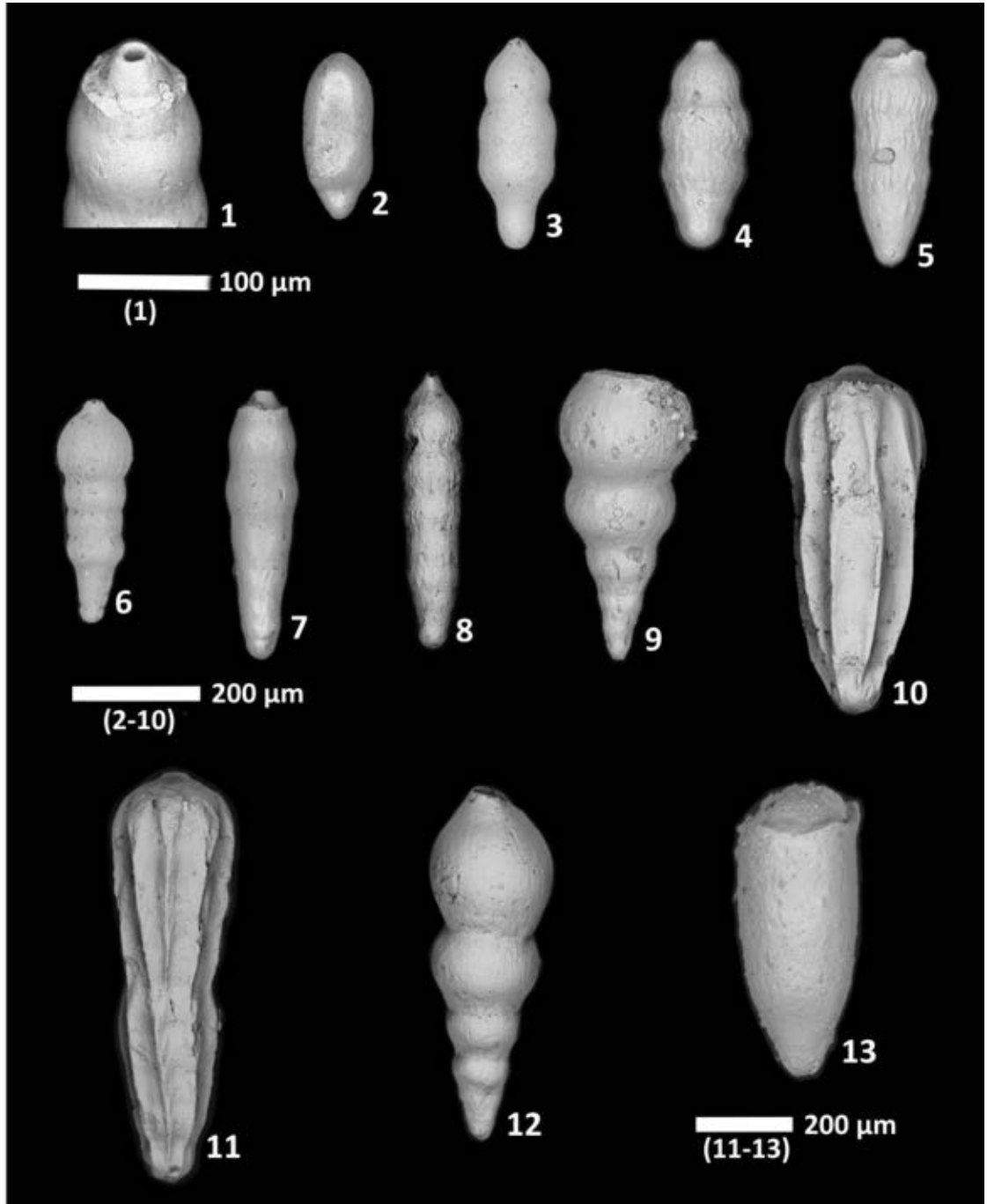
Plate 7

1-8, 13. *Pseudonodosaria vulgata.* 1, Ballinlea-1 Borehole BAL385, aperture view x390; 2, Magilligan Borehole MAG179.43, lateral view x610; 3, Ballinlea-1 BAL490; lateral view x410; 4, Ballinlea-1 Borehole BAL410; lateral view x420; 5, Ballinlea-1 Borehole BAL560, lateral view x410; 6, Ballinlea-1 Borehole BAL490, lateral view x400; 7, Ballinlea-1 Borehole BAL385, lateral view x390; 8, Ballinlea-1 Borehole BAL570, lateral view x350; 13, Ballinlea-1 Borehole BAL845, lateral view x280.

9, 12. *Pseudonodosaria dubia.* 9, Ballinlea-1 Borehole BAL510, lateral view x340; 12, Ballinlea-1 Borehole BAL520, lateral view x250.

10, 11. *Pseudonodosaria multicostata.* 10, Ballinlea-1 Borehole BAL530, lateral view x295; 11, Ballinlea-1 Borehole BAL560, lateral view x205.

Plate 8

303
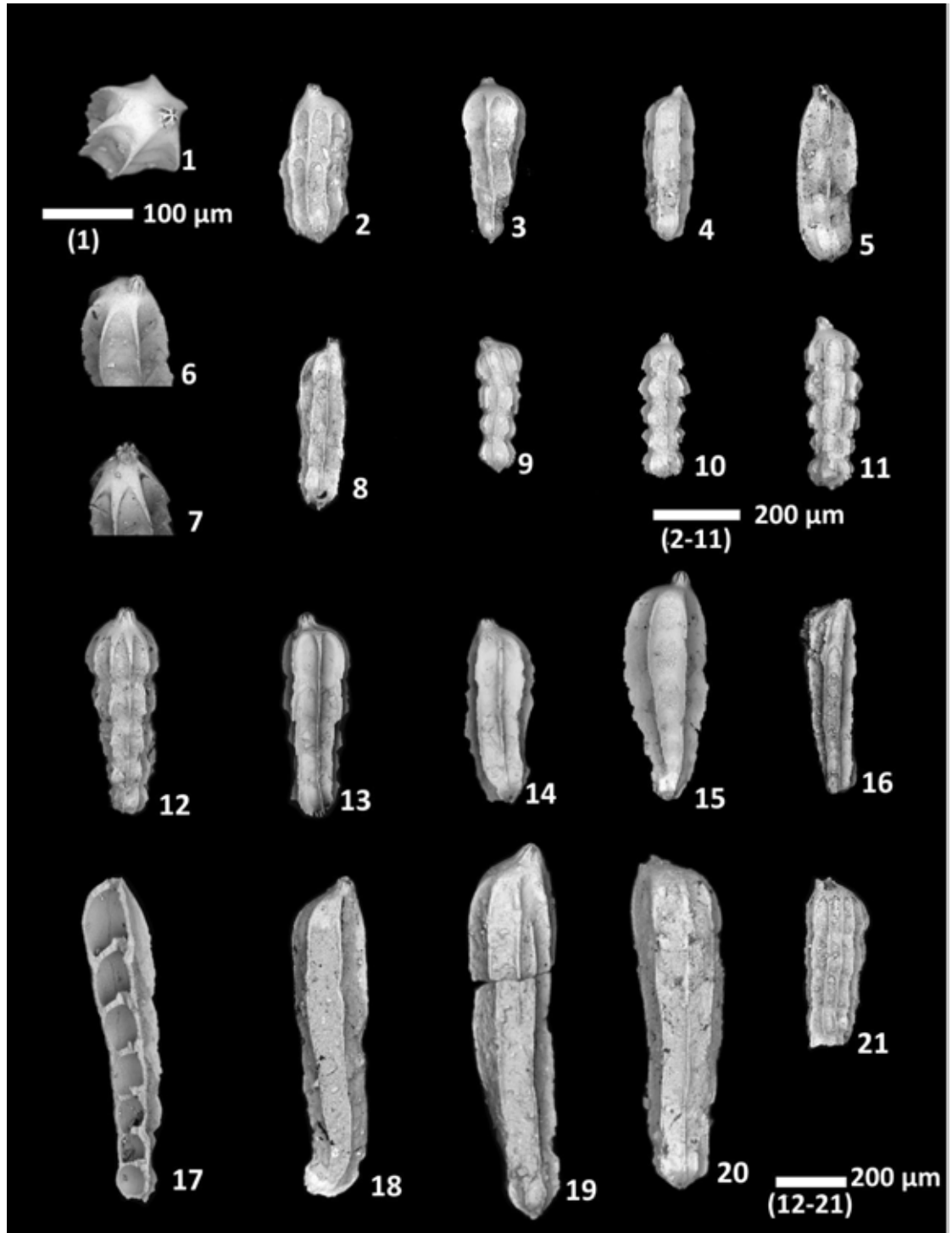
Plate 8

1, 6, 14, 15. *Marginulina prima rugosa* Bornemann. 1, Ballinlea-1 Borehole BAL400, aperture view x710; 6, Ballinlea-1 Borehole BAL385, aperture view x580; 14, Ballinlea-1 Borehole BAL550, lateral view x290; 15, Ballinlea-1 Borehole BAL385, lateral view x295.

2, 3. *Marginulina prima prima* d'Orbigny. 2, Ballinlea-1 Borehole BAL385, lateral view x500; 3. Ballinlea-1 Borehole BAL425, lateral view x410.

4, 5. *Marginulina prima praerugosa* Nørvang. 4, Ballinlea-1 Borehole BAL400, lateral view x450; 5, Ballinlea-1 Borehole BAL500, lateral view x410.

7-9, 13. *Marginulina prima spinata* (Terquem). 7, Ballinlea-1 Borehole BAL400, aperture view x520; 8, Ballinlea-1 Borehole BAL400, lateral view x440; 9, Ballinlea-1 Borehole BAL510, lateral view x550; 13, White Park Bay WPB4, lateral view x290.

10-12. *Marginulina prima interrupta* Terquem. 10, Ballinlea-1 Borehole BAL425, lateral view x400; 11, Ballinlea-1 Borehole BAL540, lateral view x520; 12, Ballinlea-1 Borehole BAL510, lateral view x285.

16-18. *Marginulina prima incisa* Franke. 16, Carnduff-1 Borehole CRN211, lateral view x250; 17, Ballintoy BLT1, lateral view x240; 18, Ballinlea-1 Borehole BAL685, lateral view x275.

19-21. *Marginulina prima insignis* (Franke). 19, Ballinlea-1 Borehole BAL730, lateral view x180; 20, Ballinlea-1 Borehole BAL730, lateral view x260; 21, Carnduff-1 Borehole CRN211, lateral view x320.

Plate 9

200 μm
(1-5)

200 μm
(6-11)

200 μm
(12-14)

306
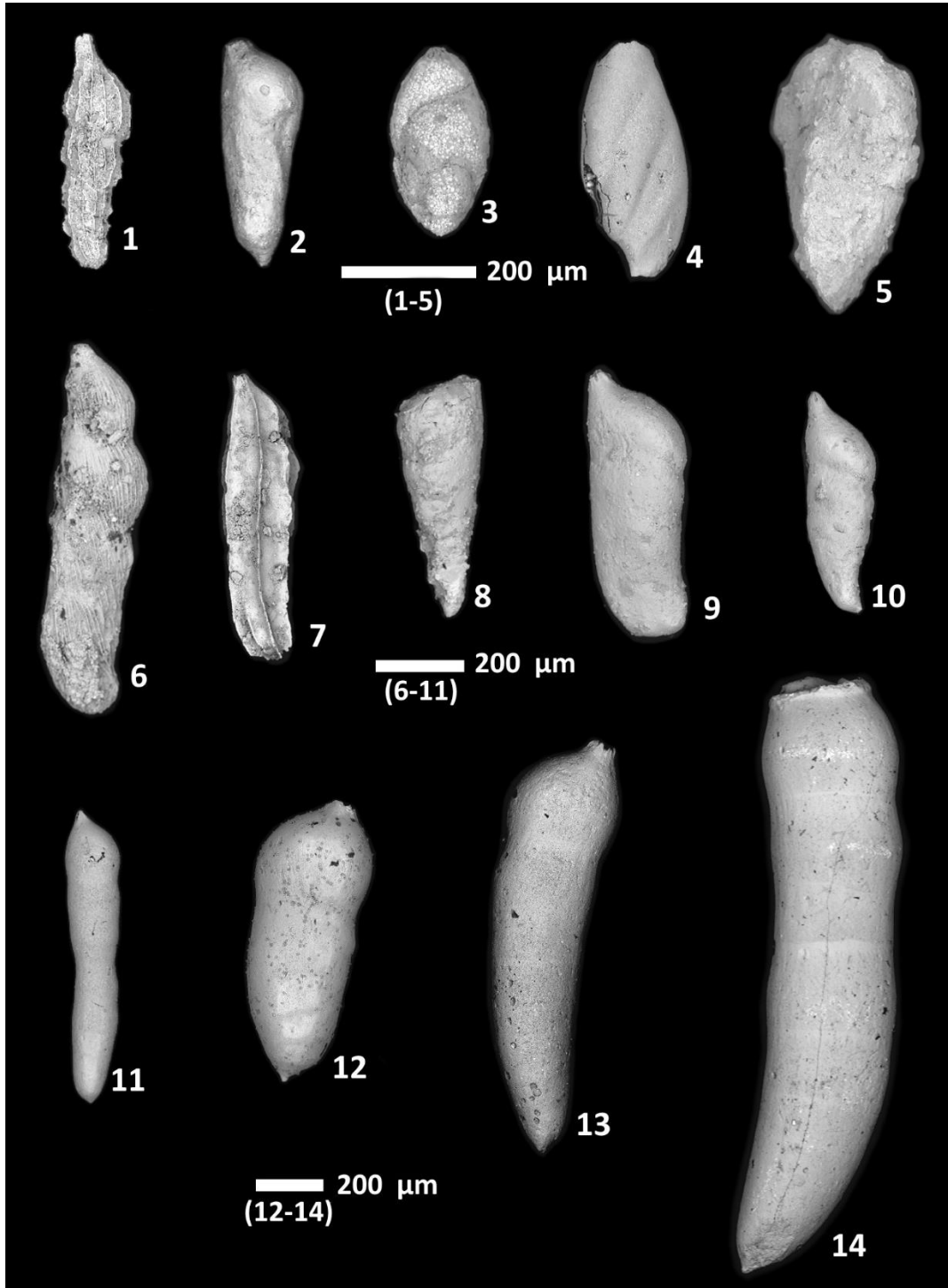
Plate 9

1. *Marginulina picturata* (Terquem & Berthelin), Ballinlea-1 Borehole BAL425, lateral view x610.

2. *Marginulina hamus* (Terquem), Ballinlea-1 Borehole BAL570, lateral view x490.

3, 4. *Vaginulina parva* Franke. 3, Carnduff-1 Borehole CRN284.6, lateral view x550; 4, Ballinlea-1 Borehole BAL440, lateral view x440.

5. *Saracenella mochrasensis* Johnson, Copestake & Herrero, Ballinlea-1 Borehole BAL920, lateral view x440.

6. *Vaginulina neglecta* Terquem, Carnduff-1 Borehole CRN170.7, lateral view x240.

7. *Vaginulina curva* Franke, Ballinlea-1 Borehole BAL595, lateral view x285.

8. *Marginulina* aff. *turneri* Copestake & Johnson, Ballinlea-1 Borehole BAL580, lateral view x265.

9, 10. *Vaginulina listi* (Bornemann). 9, Ballinlea-1 Borehole BAL580, lateral view x260; 10, Ballinlea-1 Borehole BAL595, lateral view x286.

11-14. *Marginulina sherborni* Franke. 11, Ballinlea-1 Borehole BAL410, lateral view x250; 12, Ballinlea-1 Borehole BAL395, lateral view x240; 13, Ballinlea-1 Borehole BAL400, lateral view x190; 14, Ballinlea-1 Borehole BAL530, lateral view x104.

Plate 10

200 μm
(1-18)
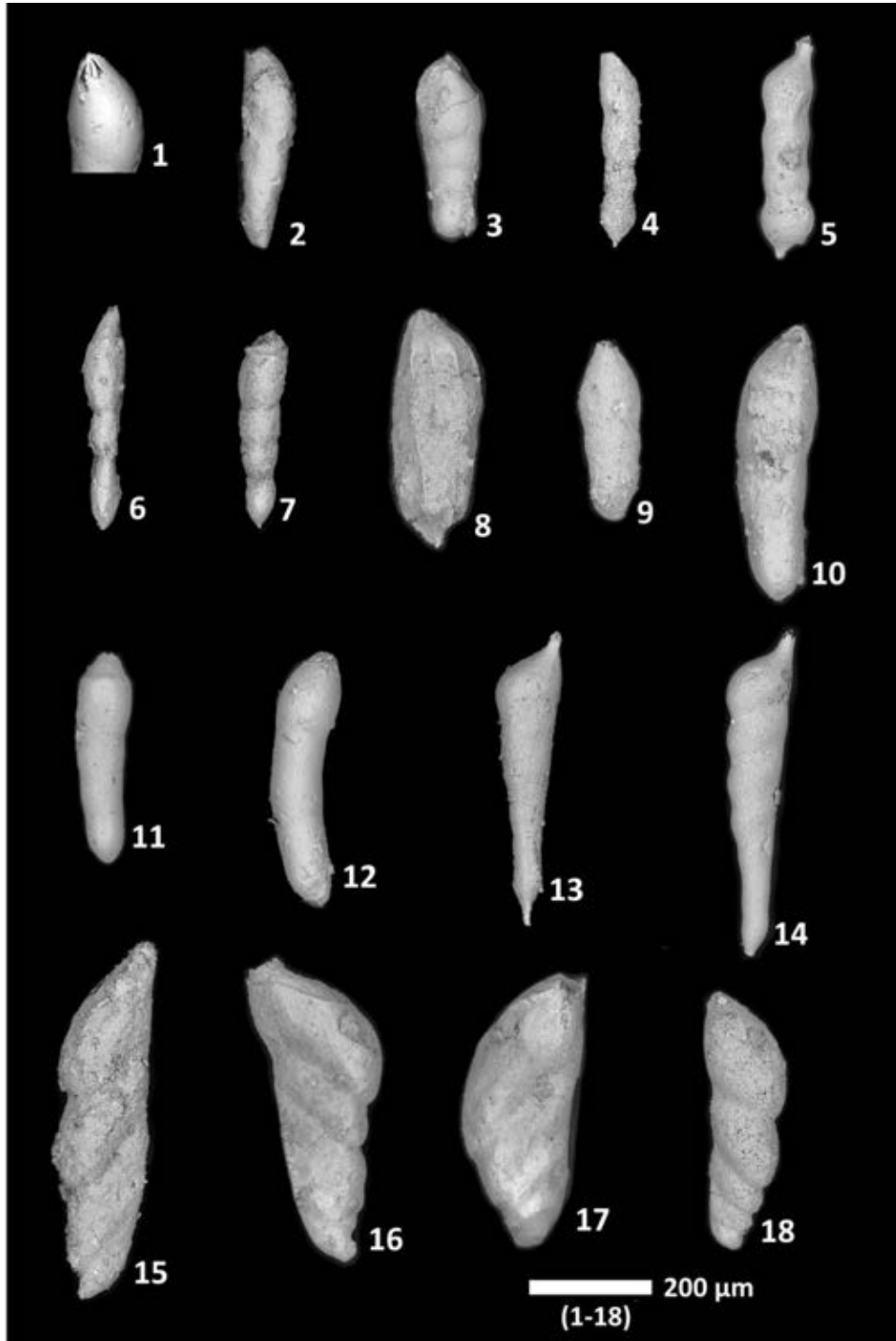
Plate 10

1, 2. *Prodentalina subsiliqua* (Franke). 1, Ballinlea-1 Borehole BAL400, aperture view x800; 2, Ballinlea-1 Borehole BAL530, lateral view x420.

3. *Prodentalina sinemuriensis* (Terquem), Ballinlea-1 Borehole BAL730, lateral view x480.

4, 5. *Prodentalina tortilis* (Franke)*.* 4, Carnduff-1 Borehole CRN176, lateral view x540; 5, Ballinlea-1 Borehole BAL355, lateral view x490.

6, 7. *Prodentalina crenata* (Schwager). 6, Magilligan Borehole MAG146, lateral view x460; 7, Magilligan Borehole MAG146, lateral view x430.

8. *Prodentalina paucicosta* (Terquem)*.* Ballinlea-1 Borehole BAL920, lateral view x460.

9, 10. *Prodentalina paucicurvata* (Franke). 9, Ballinlea-1 Borehole BAL745, lateral view x350; 10, Carnduff-1 Borehole CRN301.6, lateral view x420.

11, 12. *Prodentalina terquemi* (d'Orbigny). 11, Ballinlea-1 Borehole BAL440, lateral view x460; 12, Ballinlea-1 Borehole BAL845, lateral view x290.

13, 14. *Prodentalina clavata* (Terquem)*.* 13, White Park Bay WPB1, lateral view x400; 14, White Park Bay WPB3, lateral view x295.

15-18. *Prodentalina parvula* (Franke). 15, Carnduff-1 Borehole CRN296.2, lateral view x360; 16, Carnduff-1 Borehole CRN319.5, lateral view x360; 17, Carnduff-1 Borehole CRN319.5, lateral view x500; 18, Carnduff-1 Borehole CRN319.5, lateral view x430.

Plate 11

200 μm
(1-15)

200 μm
(16-20)
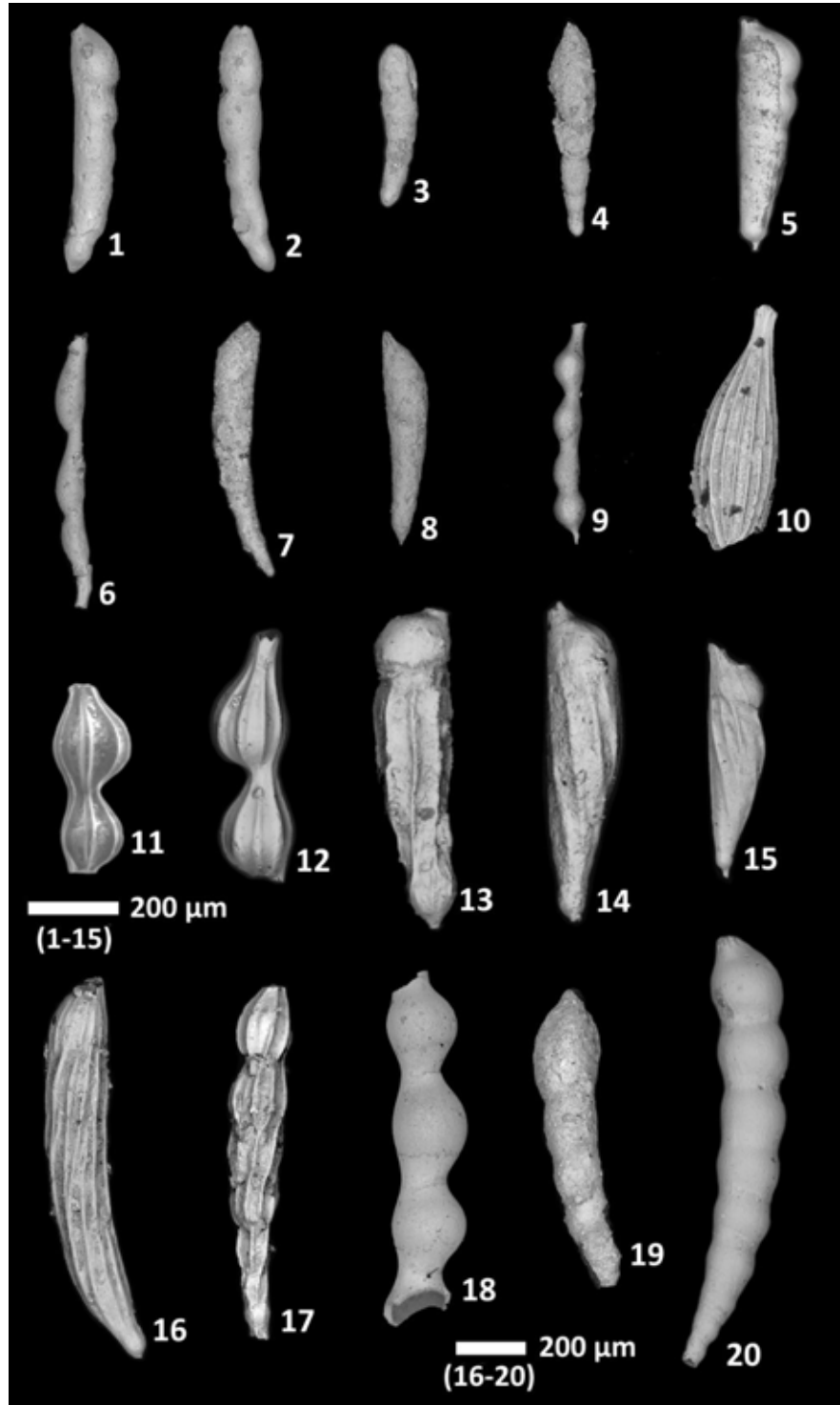
Plate 11

1, 19. *Dentalina pseudocommunis* Franke*.* 1, Ballinlea-1 Borehole BAL890, lateral view x295; 19, Ballinlea-1 Borehole BAL935, lateral view x290.

2, 3. *Prodentalina vetutissima* (d'Orbigny). 2, Magilligan Borehole MAG112, lateral view x290; 3, Carnduff-1 Borehole CRN319.5, lateral view x510.

4. *Prodentalina bicornis* (Terquem), Carnduff-1 Borehole CRN314.9, lateral view x360.

5. *Prodentalina arbuscula* (Terquem)*,* Ballinlea-1 Borehole BAL520. Lateral view x310.

6. *Prodentalina nodigera* (Terquem & Berthelin), White Park Bay WPB1, lateral view x380.

7. *Prodentalina* cf. *perlucida* (Terquem), Carnduff-1 Borehole CRN264.2, lateral view x295.

8. *Prodentalina* aff. *mucronata* (Neugeboren)*,* Carnduff-1 Borehole CRN176, lateral view x265.

9, 18. *Mesodentalina varians varians* (Terquem). 9, Ballinlea-1 Borehole BAL400, lateral view x370; 18, Ballinlea-1 Borehole BAL490, lateral view x190.

10. *Mesodentalina tenuistriata* (Terquem), Ballinlea-1 Borehole BAL400, lateral view x270.

11, 12. *Mesodentalina varians haeusleri* (Schick). 11, Ballinlea-1 Borehole BAL500, lateral view x150; 12, Ballinlea-1 Borehole BAL530, lateral view x290.

13-17. *Mesodentalina matutina* (d'Orbigny). 13, Ballinlea-1 Borehole BAL560, lateral view x260; 14, Ballinlea-1 Borehole BAL570, lateral view x260; 15, White Park Bay WPB3, lateral view x240; 16, Ballinlea-1 Borehole BAL475, lateral view x250; 17, Ballinlea-1 Borehole BAL580, lateral view x260.

20. *Prodentalina torta* (Terquem), Ballinlea-1 Borehole BAL475, lateral view x190.

Plate 12
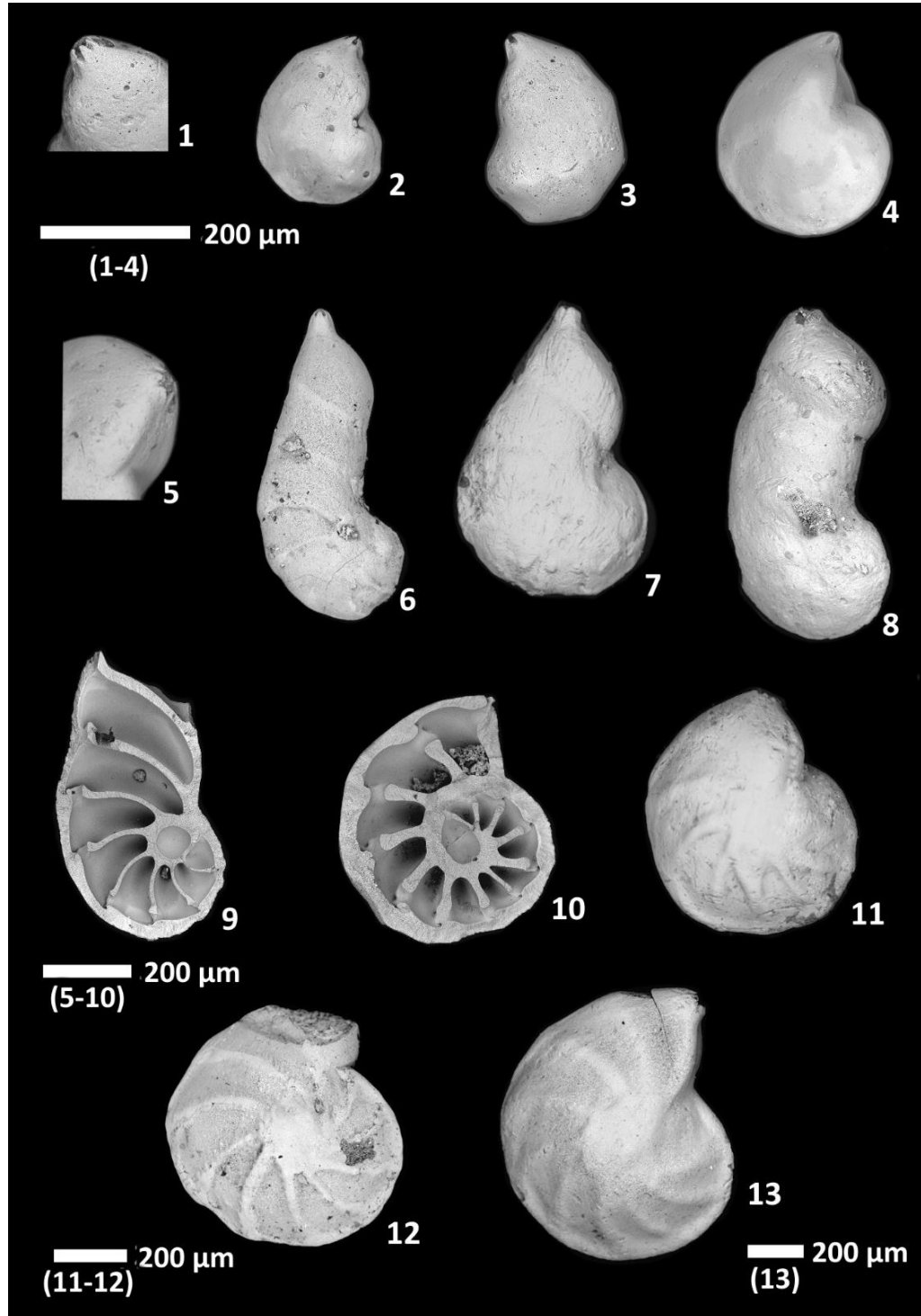
Plate 12

1-3. *Lenticulina muensteri polygonata* (Franke)*. 1, Ballinlea-1 Borehole BAL355, lateral view x900; 2, Ballinlea-1 Borehole BAL400, lateral view x570; 3, Ballinlea-1 Borehole BAL355, lateral view x500.

4-10. *Lenticulina muensteri muensteri* (Roemer)*. 4, Ballinlea-1 Borehole BAL440, lateral view x390; 5, Kenbane Head KB1, aperture view x700; 6, Ballinlea-1 Borehole BAL510, lateral view x295; 7, Ballinlea-1 Borehole BAL540, lateral view x205; 8, Ballinlea-1 Borehole BAL570, lateral view x260; 9, White Park Bay WPB6, internal view x275; 10, Ballintoy BLT1, internal view x340.

11-13. *Lenticulina muensteri* ssp. A. 11, Ballinlea-1 Borehole BAL490, lateral view x260; 12, Ballinlea-1 Borehole BAL510, lateral view x260; 13, Ballintoy BLT1, lateral view x245.

Plate 13
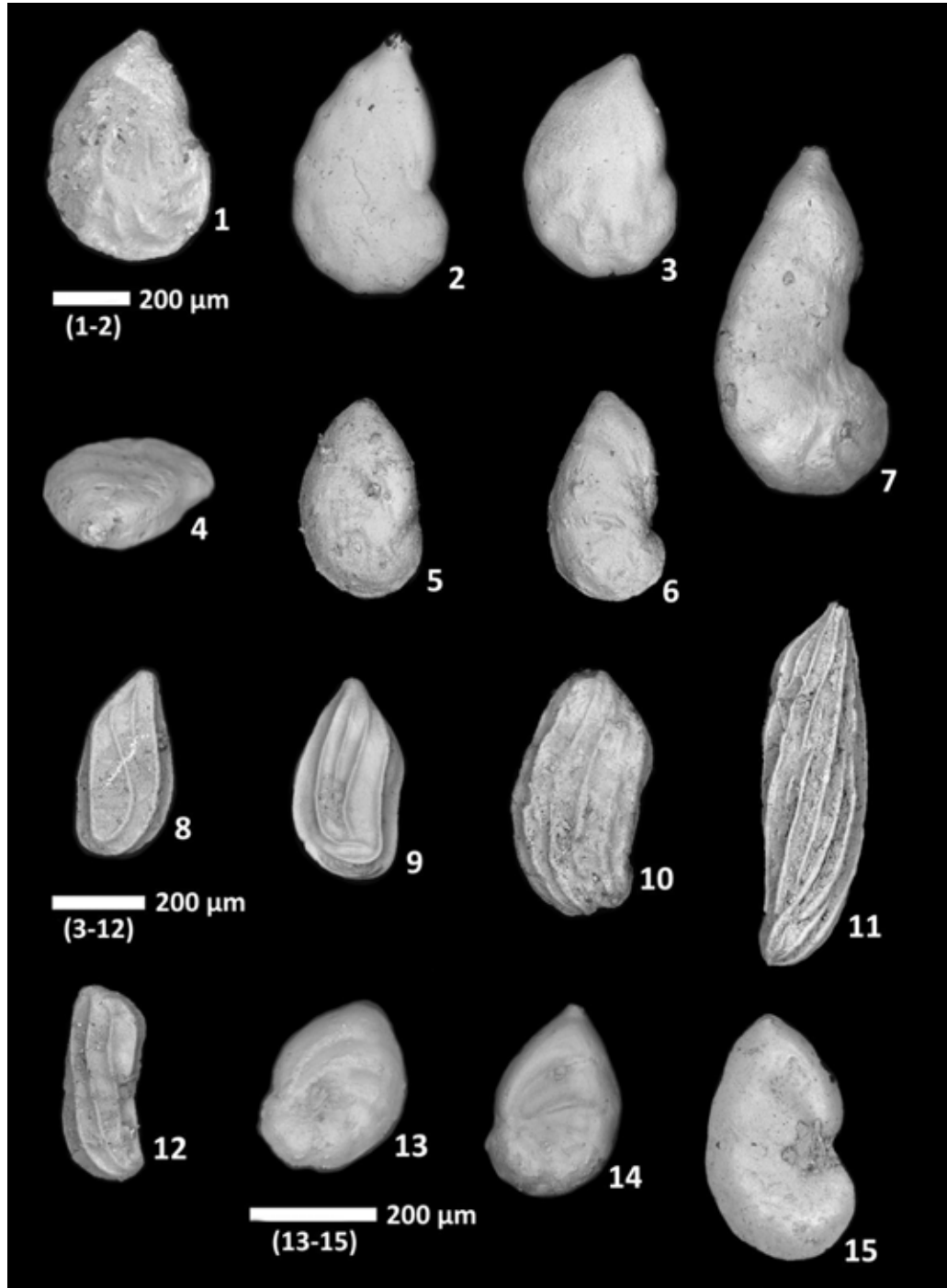
Plate 13

1. *Lenticulina* sp. A, Ballinlea-1 Borehole BAL465, lateral view x280.

2-7. *Lenticulina varians varians* (Bornemann)*. 2, White Park Bay WPB3, lateral view x296; 3, Ballinlea-1 Borehole BAL540, lateral view x320; 4, White Park Bay WPB7, aperture view x710; 5, Ballinlea-1 BAL960, lateral view x350; 6, Ballinlea-1 Borehole BAL730, lateral view x360; 7, Ballinlea-1 Borehole BAL580, lateral view x250.

8-12. *Astacolus speciosus* (Terquem)*. 8, Ballinlea-1 Borehole BAL685, lateral view x300; 9, Ballinlea-1 Borehole BAL560, lateral view x320; 10, Ballinlea-1 Borehole BAL580, lateral view x280; 11, Ballinlea-1 Borehole BAL845, lateral view x290; 12, Ballinlea-1 Borehole BAL410, lateral view x360.

13, 14. *Astacolus scalptus* (Franke)*. 13, Ballinlea-1 Borehole BAL490, lateral view x520; 14, Ballinlea-1 Borehole BAL720, lateral view x450.

15. *Astacolus primus* (d'Orbigny)*, Ballinlea-1 Borehole BAL490, lateral view x460.

Plate 14
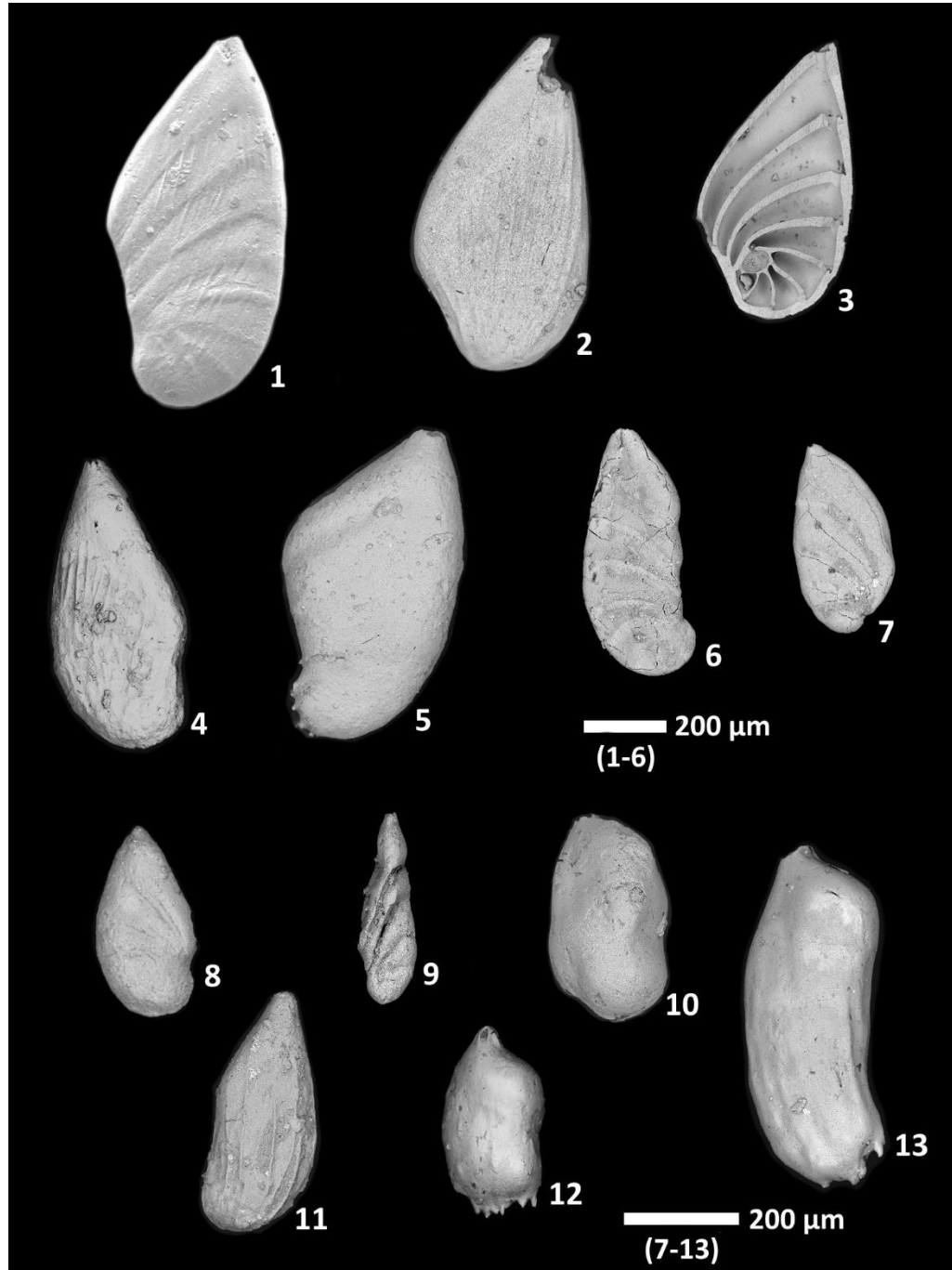
Plate 14

1-4. *Planularia inaequistriata* (Terquem). 1, Ballinlea-1 Borehole BAL730 x75; 2, Ballintoy BLT1, lateral view x275; 3, Ballintoy BLT1, internal view x275; 4, Ballinlea-1 BAL560, lateral view x250.

5. *Planularia pulchra* (Terquem), Ballinlea-1 Borehole BAL570, lateral view x275.

6, 9. *Planularia protracta* (Bornemann). 6, Ballinlea-1 Borehole BAL400, lateral view x290; 9, Ballinlea-1 Borehole BAL730, lateral view x440.

7, 8. *Planularia pauperata* Jones & Parker. 7, Ballinlea-1 Borehole BAL465, lateral view x570; 8, Ballinlea-1 Borehole BAL730, lateral view x440.

10. *Bullopora globulata globulata* Barnard, Ballinlea-1 Borehole BAL355, lateral view x480.

11. *Vaginulinopsis erzingensis* (Neuweiler), Ballinlea-1 Borehole BAL720, lateral view x390.

12, 13. *Vaginulinopsis denticulatacarinata* (Franke). 12, Ballinlea-1 Borehole BAL415, lateral view x630; 13, Ballinlea-1 Borehole BAL425, lateral view x300.

Plate 15
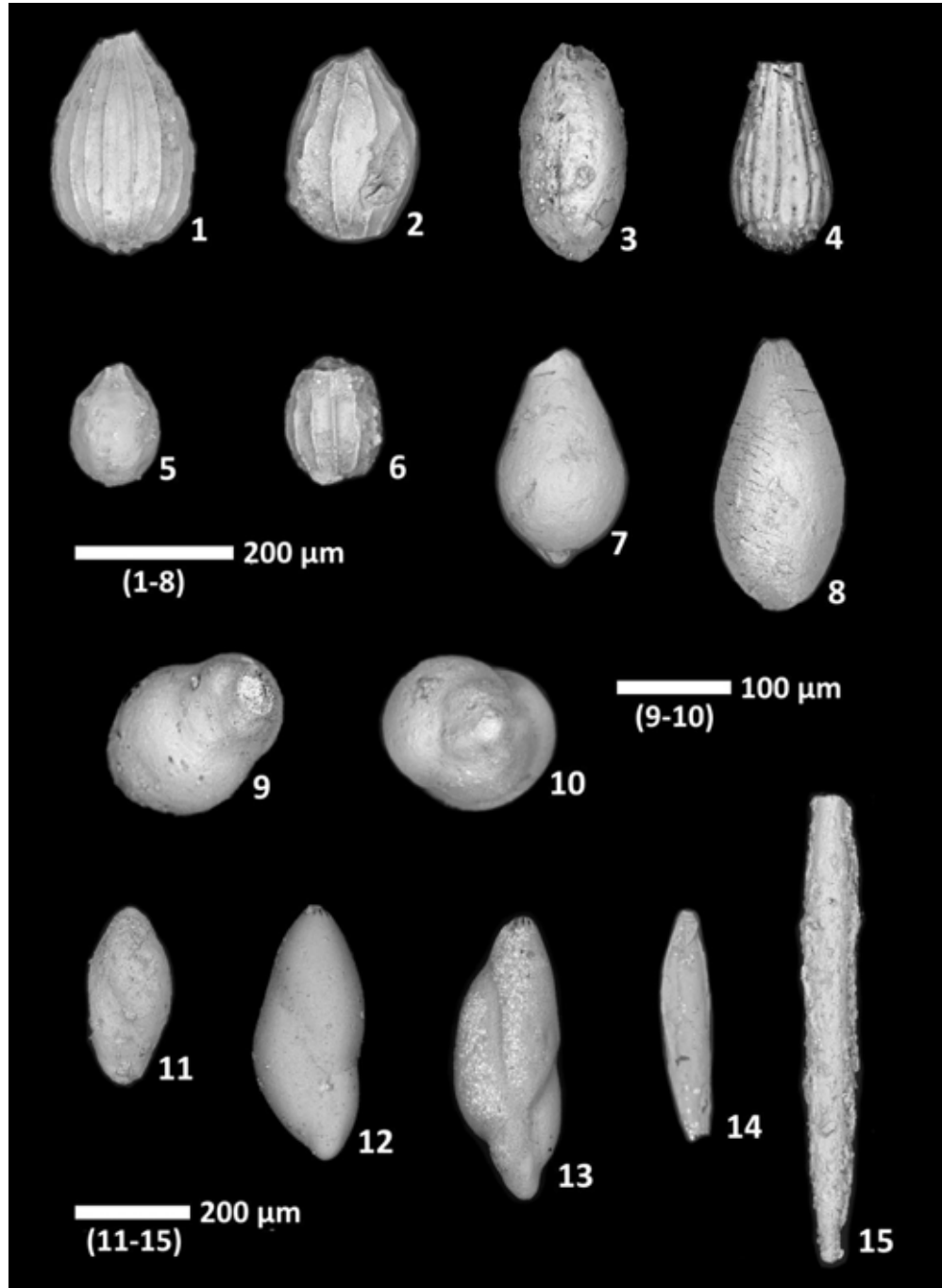
Plate 15

1, 2. *Lagena natrii* Blake. 1, Carnduff-1 Borehole CRN284.6, lateral view x560; 2, Ballinlea-1 Borehole BAL730, lateral view x510.

3. *Lagena liasica* (Kübler & Zwingli), Ballinlea-1 Borehole BAL790, lateral view x440.

4. A, Magilligan Borehole MAG158, lateral view x690.

5. *Lagena semisulcata* Copestake & Johnson, Ballinlea-1 Borehole BAL730, lateral view x700.

6. *Reussoolina laticosta* (Terquem & Berthelin), Magilligan Borehole MAG146, lateral view x690.

7. *Reussoolina minutissima* (Kübler & Zwingli), Ballinlea-1 Borehole BAL550, lateral view x480.

8. *Reussoolina*? *lacrimaforma* (Copestake & Johnson), Ballinlea-1 Borehole BAL865, lateral view x510.

9-13. *Eoguttulina liassica* (Strickland). 9, Magilligan Borehole MAG126.12, aperture view x710; 10, Magilligan Borehole MAG106.95, aperture view x880; 11, Carnduff-1 Borehole CRN319.5,

lateral view x500; 12, Ballinlea-1 Borehole BAL465, lateral view x320; 13, Magilligan Borehole MAG106.95, lateral view x340.

14, 15. *Procerolagena lanceolata* (Terquem). 14, Ballinlea-1 Borehole BAL490, lateral view x360; 15, Carnduff-1 Borehole CRN290.85, lateral view x250.

Plate 16
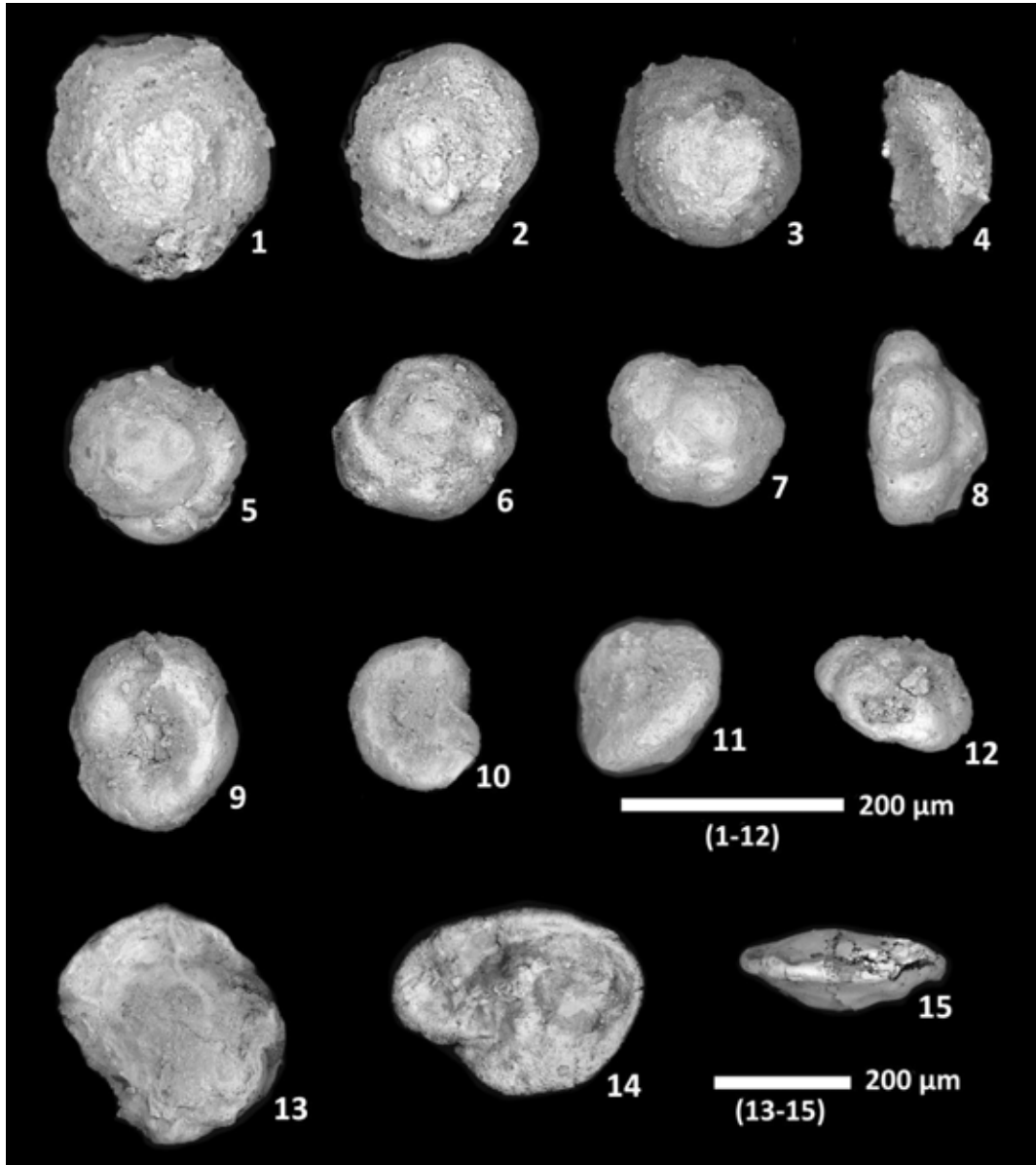
Plate 16

1-12. *Reinholdella planiconvexa* (Fuchs)*.* 1, Ballinlea-1 Borehole BAL920, dorsal view x550; 2, Ballinlea-1 Borehole BAL920, dorsal view x460; 3, Magilligan Borehole MAG158, dorsal view x870; 4, Magilligan Borehole MAG158, side view x840; 5, Magilligan Borehole MAG126.12, dorsal view x860; 6, Magilligan Borehole MAG126.12, dorsal view x930; 7, Magilligan Borehole MAG126.12, dorsal view x1000; 8, Magilligan Borehole MAG126.12, side view x1150; 9, Magilligan Borehole MAG126.12, ventral view x780; 10, Magilligan Borehole MAG146, ventral view x900; 11, Ballinlea-1 Borehole BAL920, ventral view x580; 12, Magilligan Borehole MAG158, side view x840.

13-15. *Reinholdella mochrasensis* Copestake & Johnson. 13, Ballinlea-1 Borehole BAL450, dorsal view x480; 14, Ballinlea-1 Borehole BAL545, ventral view x380; 15, White Park Bay WPB1, side view x440.

Plate 17
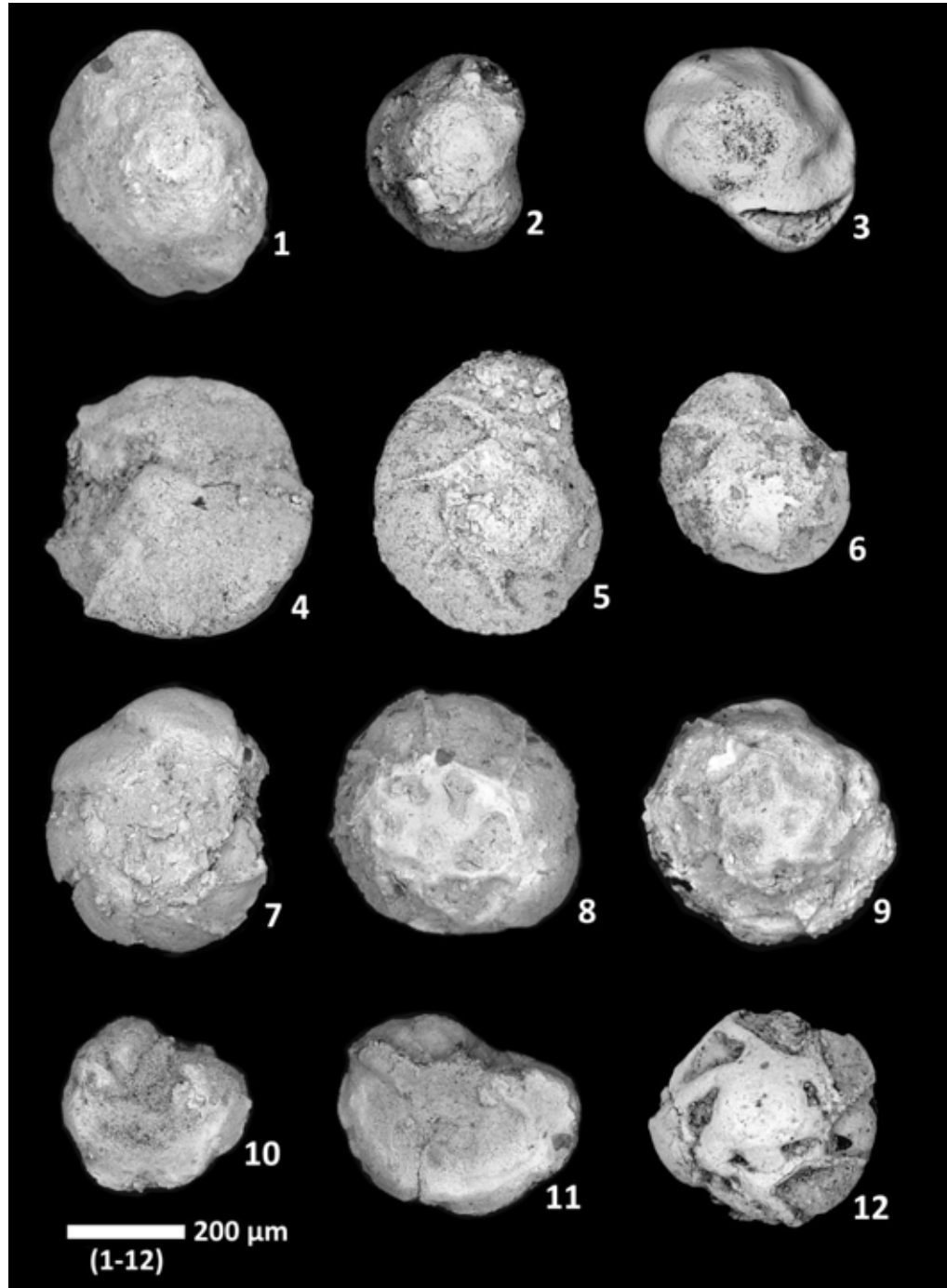
Plate 17

1, 2. *Reinholdella* sp. A. 1, Ballinlea-1 Borehole BAL855, dorsal view x340; 2, Ballinlea-1 Borehole BAL890, dorsal view x470.

3. *Reinholdella dreheri* (Bartenstein), Ballinlea-1 Borehole BAL570, dorsal view x290.

4-6. *Reinholdella pachyderma humilis* Copestake & Johnson*.* 4, Ballinlea-1 Borehole BAL490, ventral view x320; 5, Ballinlea-1 Borehole BAL490, dorsal view x400; 6, Ballinlea-1 Borehole BAL490, dorsal view x410.

7-11. *Reinholdella robusta* Copestake & Johnson. 7, Ballinlea-1 Borehole BAL430, dorsal view x320; 8, Ballinlea-1 Borehole BAL430, dorsal view x360; 9, Ballinlea-1 Borehole BAL415, dorsal view x320; 10, Ballinlea-1 Borehole BAL425, ventral view x610; 11, Ballinlea-1 borehole BAL425, ventral view x350.

12. *Reinholdella margarita margarita* (Terquem), Ballinlea-1 Borehole BAL510, dorsal view x350.

Plate 18
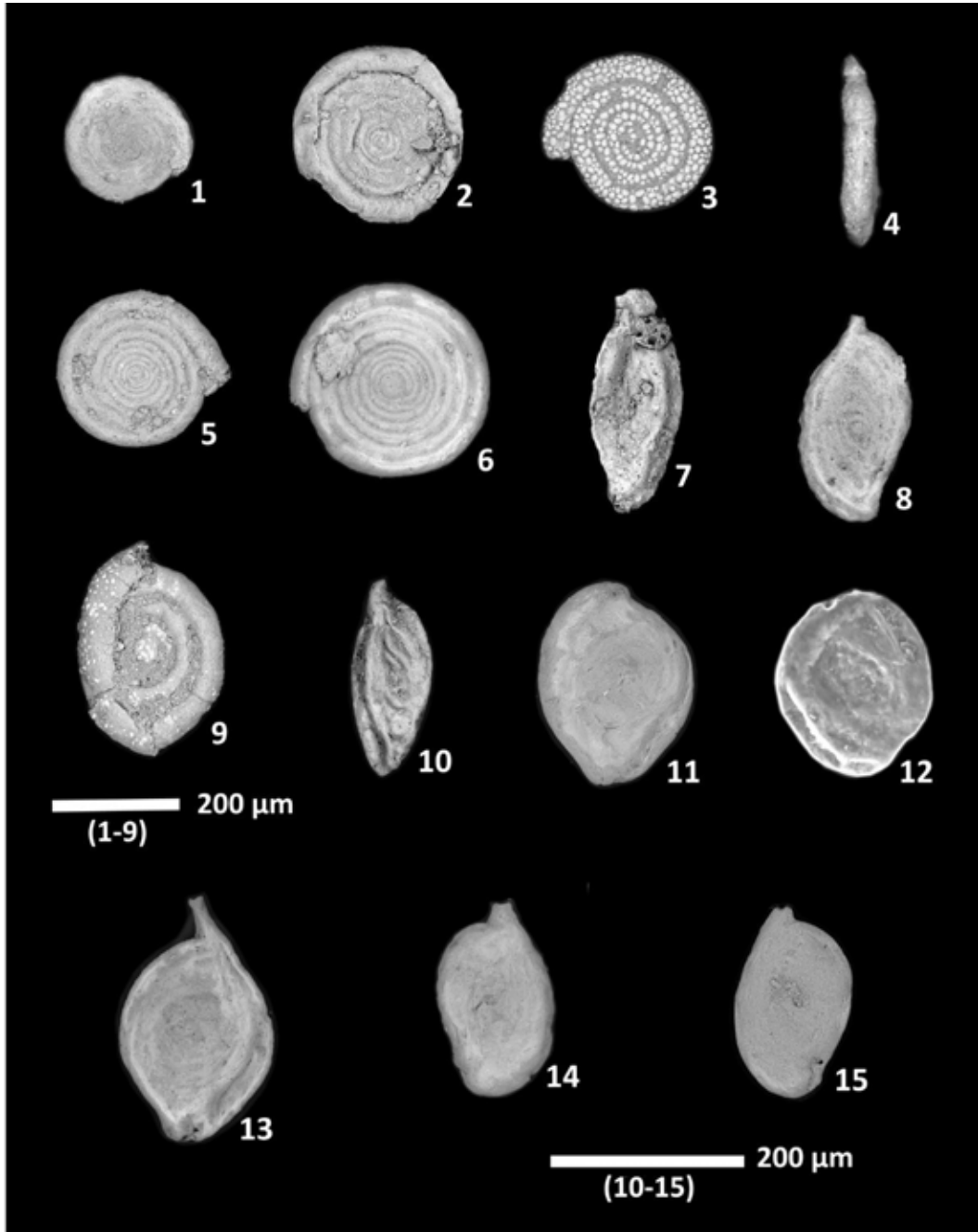
Plate 18

1, 2. *Spirillina tenuissima* Gümbel. 1, Carnduff-1 Borehole CRN198.6, lateral view x520; 2, Magilligan Borehole MAG146, lateral view x680.

3, 4. *Spirillina infima* (Strickland). 3, Ballinlea-1 Borehole BAL845, lateral view x490; 4, Magilligan Borehole MAG106.95, lateral view x790.

5, 6. *Cornuspira liasina* Terquem. 5, Carnduff-1 Borehole CRN191.3, lateral view x540; 6, Carnduff-1 Borehole CRN182.9, lateral view x580.

7, 10. *Spiroloculina concentrica* Terquem & Berthelin. 7, Ballinlea-1 Borehole BAL790, lateral view x390; 10, Ballinlea-1 Borehole BAL540, lateral view x680.

9, 11, 12. *Ophthalmidium liasicum* (Kübler & Zwingli). 9, Magilligan Borehole MAG131.1, lateral view x520; 11, Ballinlea-1 Borehole BAL400, lateral view x750; 12, Ballinlea-1 Borehole BAL520, lateral view x200.

13. *Ophthalmidium macfadyeni tenuiloculare* Copestake & Johnson, Ballinlea-1 Borehole BAL490, lateral view x500.

8, 14, 15. *Ophthalmidium macfadyeni macfadyeni* Wood & Barnard. 8, Ballinlea-1 Borehole BAL465, lateral view x510; 14, Ballinlea-1 Borehole BAL400, lateral view x880; 15, Ballinlea-1 Borehole BAL400, lateral view x770.

Plate 19
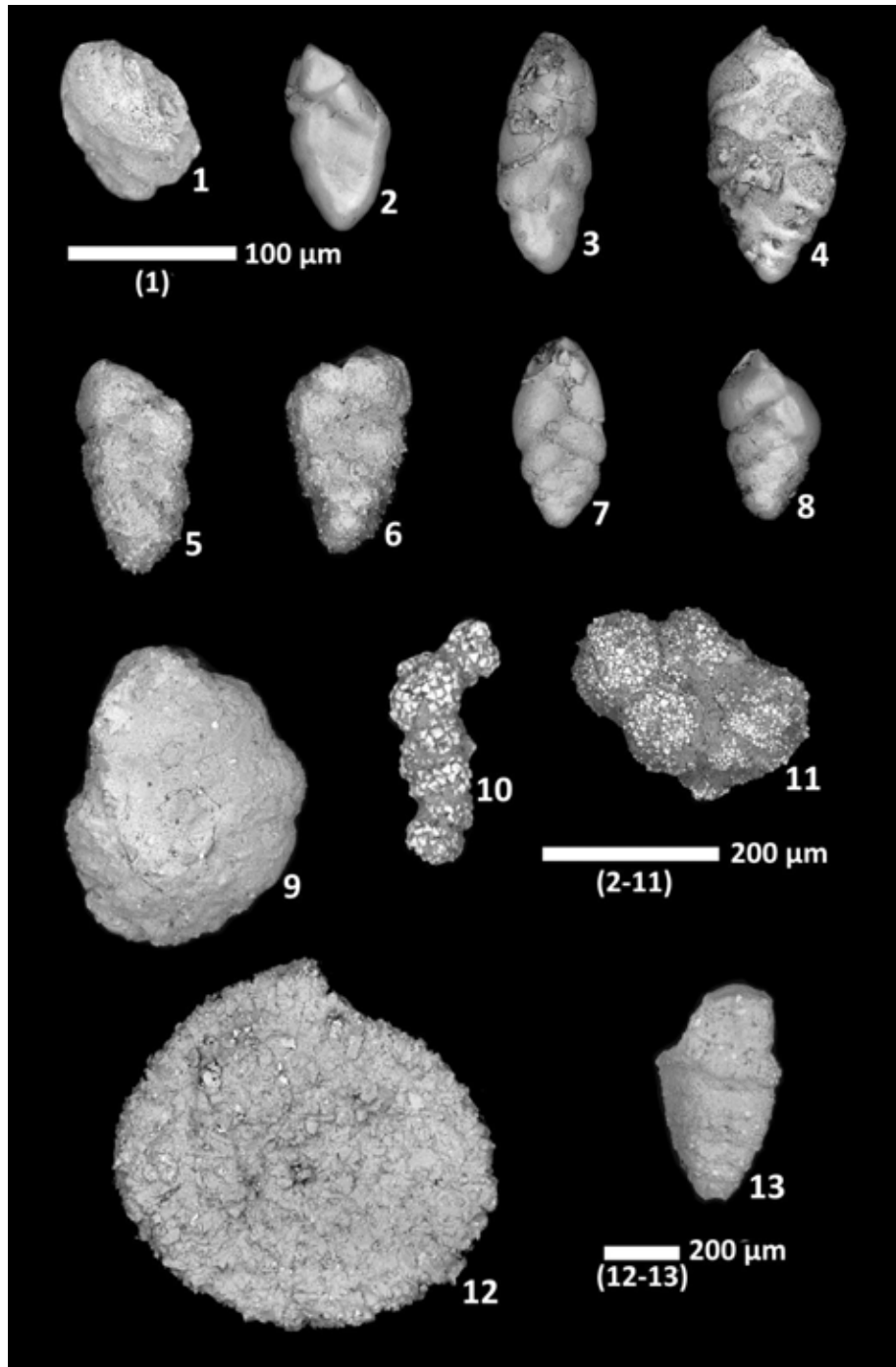
Plate 19

1-4. *Brizalina liasica* Terquem. 1, Ballinlea-1 Borehole BAL425, aperture view x1600; 2, Ballinlea-1 Borehole BAL400, lateral view x700; 3, Ballinlea-1 Borehole BAL385, lateral view x550; 4, Ballinlea-1 Borehole BAL490, lateral view x490.

5-8. *Neobulimina bangae* (Copestake & Johnson). 5, Ballinlea-1 Borehole BAL885, lateral view x520; 6, Ballinlea-1 Borehole BAL730, lateral view x620; 7, Ballinlea-1 Borehole BAL530, lateral view x600; 8, Ballinlea-1 Borehole BAL410, lateral view x710.

9. *Haplophragmoides kingakensis* Tappan, Ballinlea-1 Borehole BAL720, dorsal view x720.

10. *Reophax* sp. A, Magilligan Borehole MAG106.95, lateral view x810.

11. *Trochammina canningensis* Tappan, Magilligan Borehole MAG106.95, dorsal view x810.

12. *Ammodiscus siliceous* (Terquem), Ballinlea-1 Borehole BAL595, lateral view x260.

13. *Textularia* sp. A, Ballintoy BLT1, lateral view x295.

Plate 20
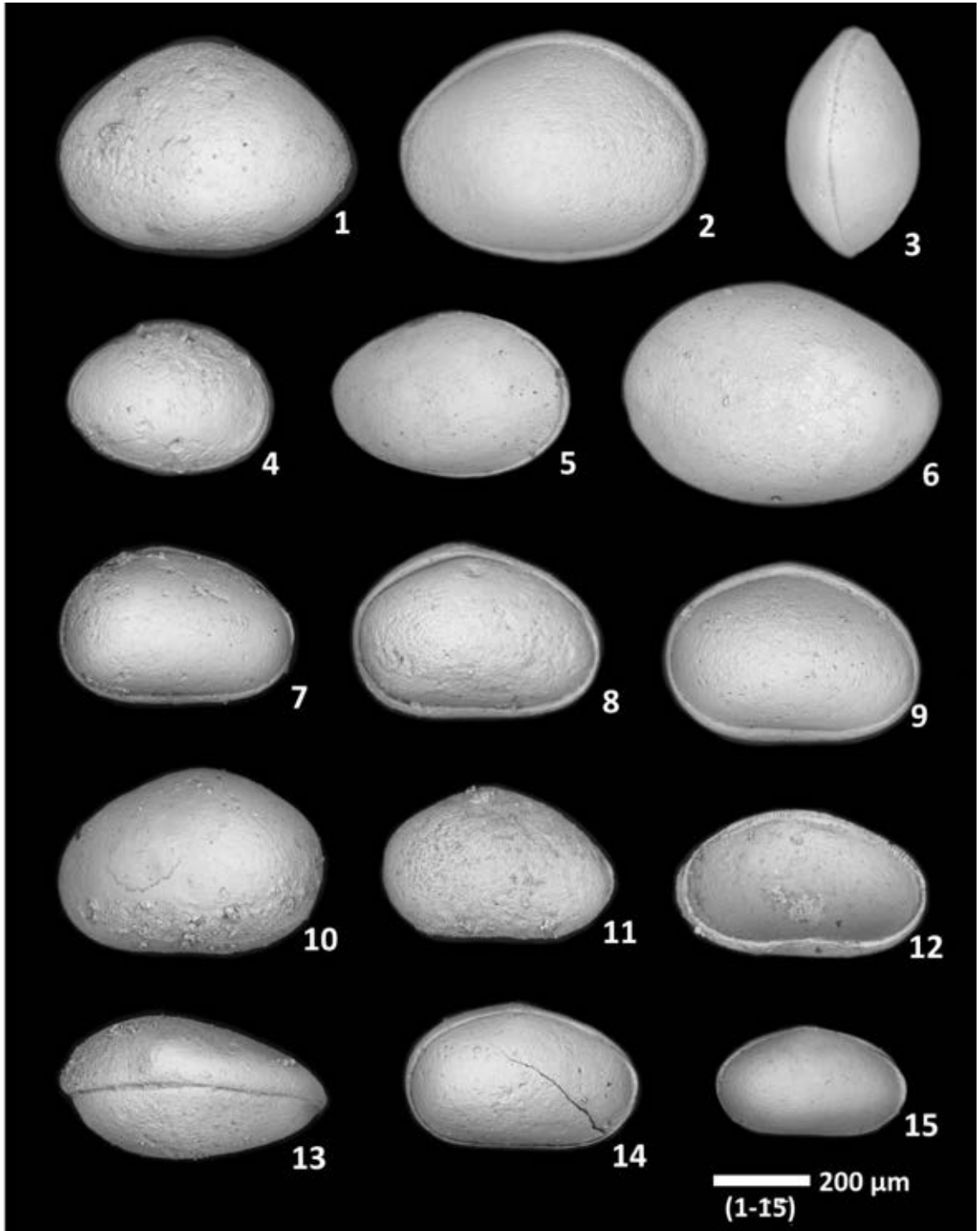
Plate 20

1-4. *Ogmoconcha hagenowi* Drexler. 1, Carnduff-1 Borehole CRN264.2, lateral view x225, right valve; 2, Magilligan Borehole MAG19, lateral view x310, carapace (LV>RV); 3, Ballinlea-1 Borehole BAL845, dorsal view x360, carapace (LV>RV); 4, Ballinlea-1 Borehole BAL820, lateral view x260, carapace (LV>RV).

**5, 6.** *Ogmoconcha eocontractula* Park. 5, Ballinlea-1 Borehole BAL410, lateral view x360, carapace; 6, Ballinlea-1 Borehole BAL465, lateral view x340, left valve.

7-15. *Ogmoconchella aspinata* (Drexler). 7, Ballinlea-1 Borehole BAL920, lateral view x245, carapace (LV>RV); 8, Carnduff-1 Borehole CRN296.2, lateral view x245, carapace (LV>RV); 9, Magilligan Borehole MAG122, lateral view x290, carapace; 10, Magilligan Borehole MAG158, lateral view x255, left valve; 11, Carnduff-1 Borehole CRN296.2, lateral view x270, right valve; 12, Magilligan Borehole MAG112, internal view x330, right valve; 13, Magilligan Borehole MAG122, dorsal view x235, carapace (LV>RV); 14, Ballinlea-1 Borehole BAL845, lateral view x275, carapace (LV>RV); 15, *Ogmoconchella* sp. B, Magilligan Borehole MAG50.85, lateral view x410, carapace (LV>RV).

Plate 21
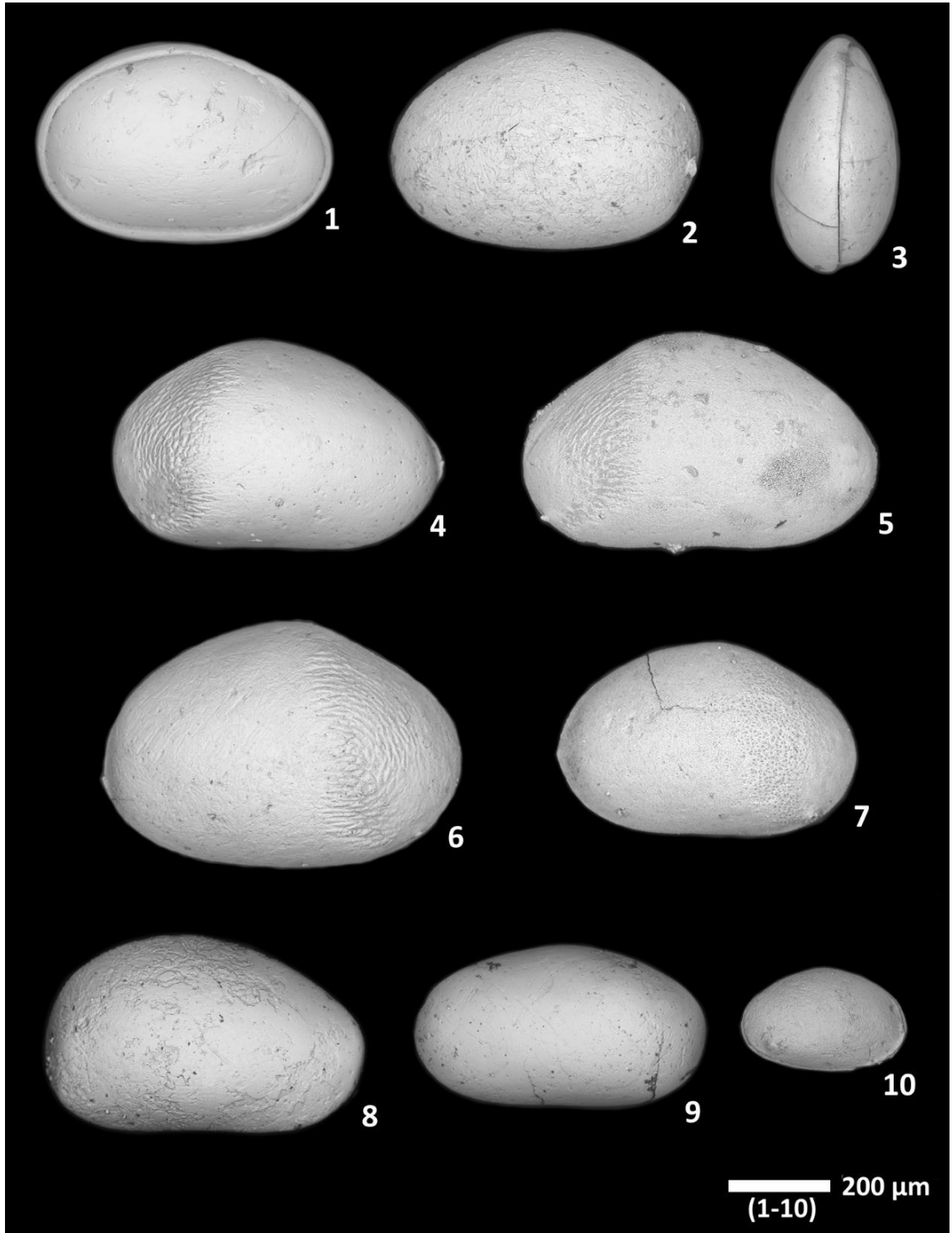
Plate 21

1-3, 10. *Ogmoconchella danica* Michelsen. 1, Ballinlea-1 Borehole BAL490, lateral view x310, carapace (LV>RV); 2, Ballinlea-1 Borehole BAL410, lateral view x275, left valve; 3, Ballinlea-1 Borehole BAL480, dorsal view x410, carapace (LV>RV); 10, Ballinlea-1 Borehole BAL490, lateral view x530, carapace of juvenile (LV>RV).

4-7. *Ogmoconchella mouhersensis* (Apostolescu). 4, White Park Bay WPB4, lateral view x275, right valve; 5, White Park Bay WPB7, lateral view x240, right valve; 6, White Park Bay WPB2, lateral view x260, left valve; 7, White Park Bay WPB1, lateral view x245, left valve.

8, 9. *Ogmoconchella gruendeli* (Malz, 1971). Ballinlea-1 Borehole BAL400, lateral view x245, right valve; 9, Ballinlea-1 Borehole BAL400, lateral view x270, left valve.

Plate 22

200 μm
(1-11)

200 μm
(12-16)
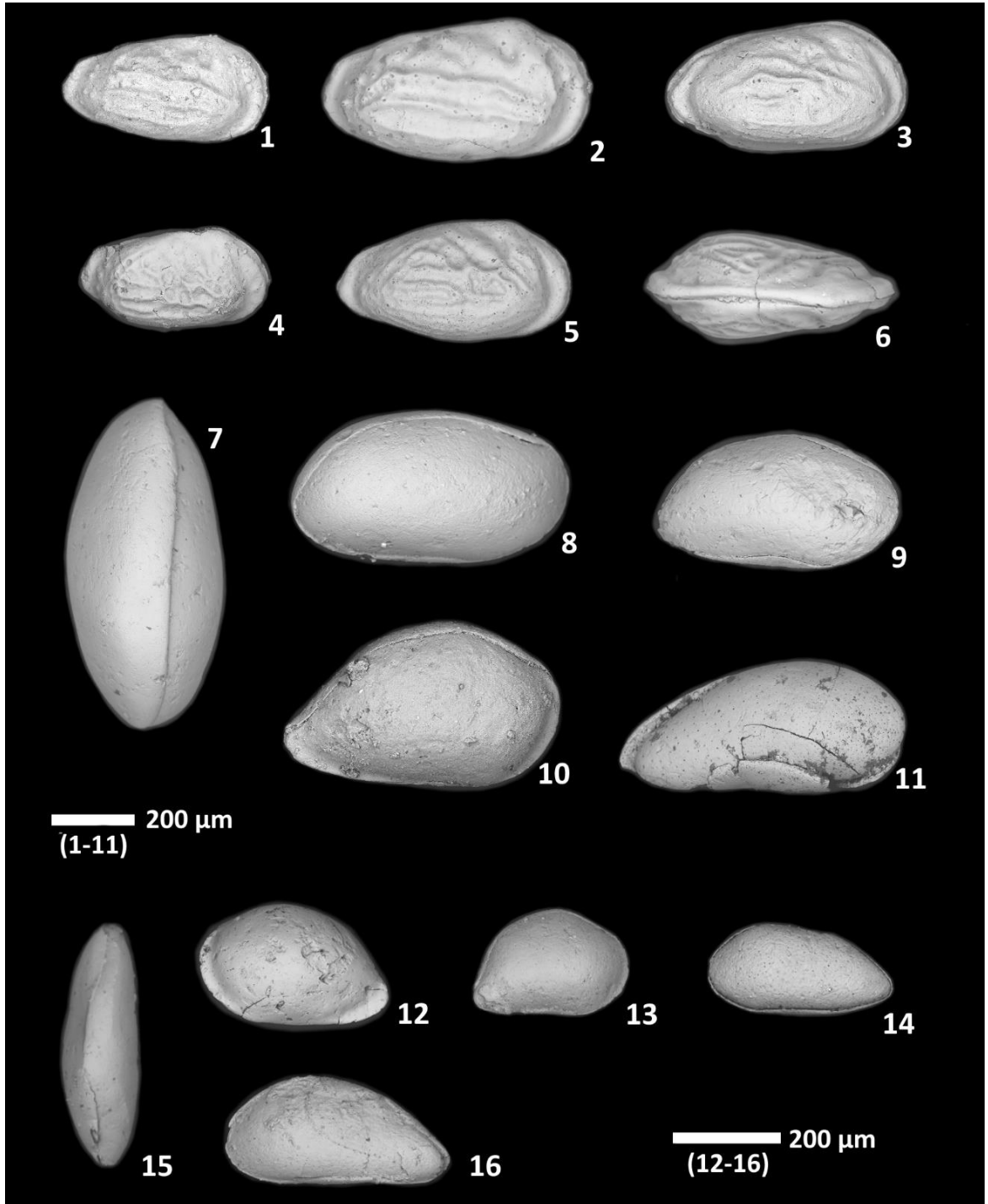
Plate 22

1, 2. *Pleurifera harpa* (Klingler & Neuweiler). 1, Ballinlea-1 Borehole BAL480, lateral view x470, right valve; 2, Ballinlea-1 Borehole BAL400, lateral view x310, right valve.

**3.** *Pleurifera plicata* (Apostolescu), Ballinlea-1 Borehole BAL540, lateral view x430, carapace (LV>RV).

4-6. *Pleurifera vermiculata* (Apostolescu). 4, White Park Bay WPB5, lateral view x470, right valve; 5, Bsllinlea-1 Borehole BAL510, lateral view x510, right valve; 6, Ballinlea-1 Borehole BAL490, dorsal view x295, carapace (LV>RV).

7, 8. *Isobythocypris tatei* Coryell. 7, Ballinlea-1 Borehole BAL960, dorsal view x360, carapace (LV>RV); 8, Ballinlea-1 Borehole BAL845, lateral view x295, carapace (LV>RV).

9, 13. *Isobythocypris* sp. A. 9, Ballinlea-1 Borehole BAL560, lateral view x290, carapace; 13, Ballinlea-1 Borehole BAL745, lateral view x530, carapace of juvenile (LV>RV).

10. *Bairdia molesta* Apostolescu, Carnduff-1 Borehole CRN182.9, lateral view x   295,   carapace (LV>RV).

11. *Liasina lanceolata* (Apostolescu), Ballinlea-1 Borehole BAL410, lateral view x330, carapace (LV>RV).

12. *Bairdia donzei* Herrig, White Park Bay WPB5, lateral view x295, left valve.

14. *Paracypris semidisca* Drexler, Ballinlea-1 BAL425, lateral view x530, carapace (RV>LV).

15, 16. *Paracypris redcarensis* Blake. 15, Ballinlea-1 Borehole BAL790, dorsal view x410, carapace (RV>LV); 16 Ballinlea-1 Borehole BAL910, lateral view x360, carapace (RV>LV).

Plate 23
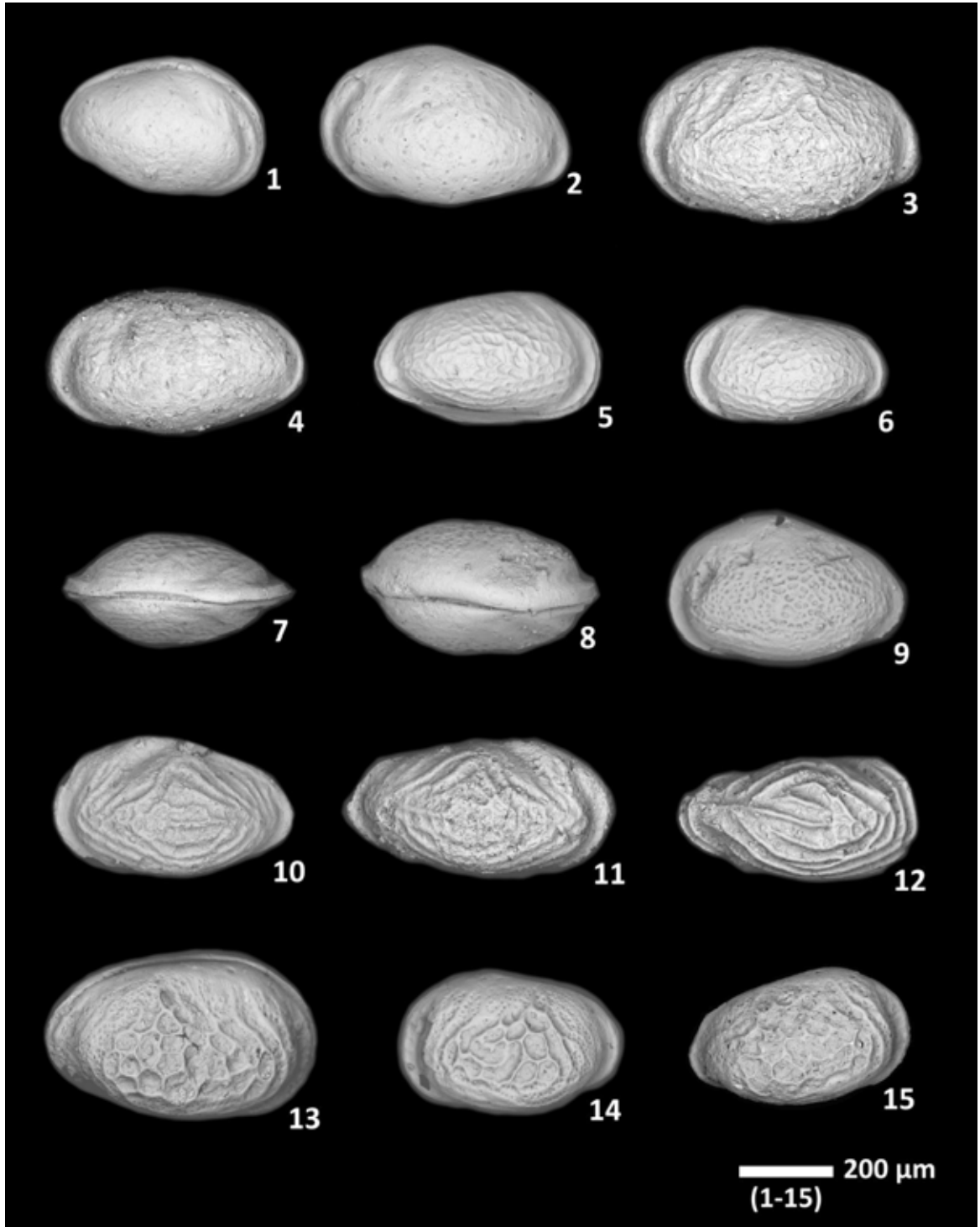
Plate 23

1-7. *Ektyphocythere translucens* (Blake). 1, Ballinlea-1 Borehole BAL820, lateral view x330, carapace (LV>RV); 2, Ballinlea-1 Borehole BAL845, lateral view x310, left valve; 3, Carnduff-1 Borehole CRN264.2, lateral view x285, left valve; 4, Carnduff-1 Borehole CRN273.2, lateral view x235, left valve; 5, Magilligan Borehole MAG126.12, lateral view x320, carapace (LV>RV); 6, Magilligan Borehole MAG131.1, lateral view x340, left valve; 7, Magilligan Borehole MAG131.1, dorsal view x350, carapace (LV>RV).

8, 9. *Ektyphocythere retia* (Ainsworth). 8, Magilligan Borehole MAG65.35, dorsal view x420, carapace (LV>RV); 9, Magilligan Borehole MAG65.35, lateral view x240, left valve.

10, 11. *Ektyphocythere mooeri* (Jones). 10, Magilligan Borehole MAG65.35, lateral view x350, left valve. 11, Magilligan Borehole MAG65.35, lateral view x340, right valve.

12. *Ektyphocythere luxuriosa* (Apostolescu), Ballinlea-1 Borehole BAL845, lateral view x330, right valve.

13-15. *Ektyphocythere triebeli* (Klingler & Neuweiler). 13, Ballinlea-1 Borehole BAL685, lateral view x330, carapace (LV>RV); 14, Ballinlea-1 Borehole BAL845, lateral view x300, right valve; 15, Ballinlea-1 Borehole BAL510, lateral view x285, left valve.

Plate 24
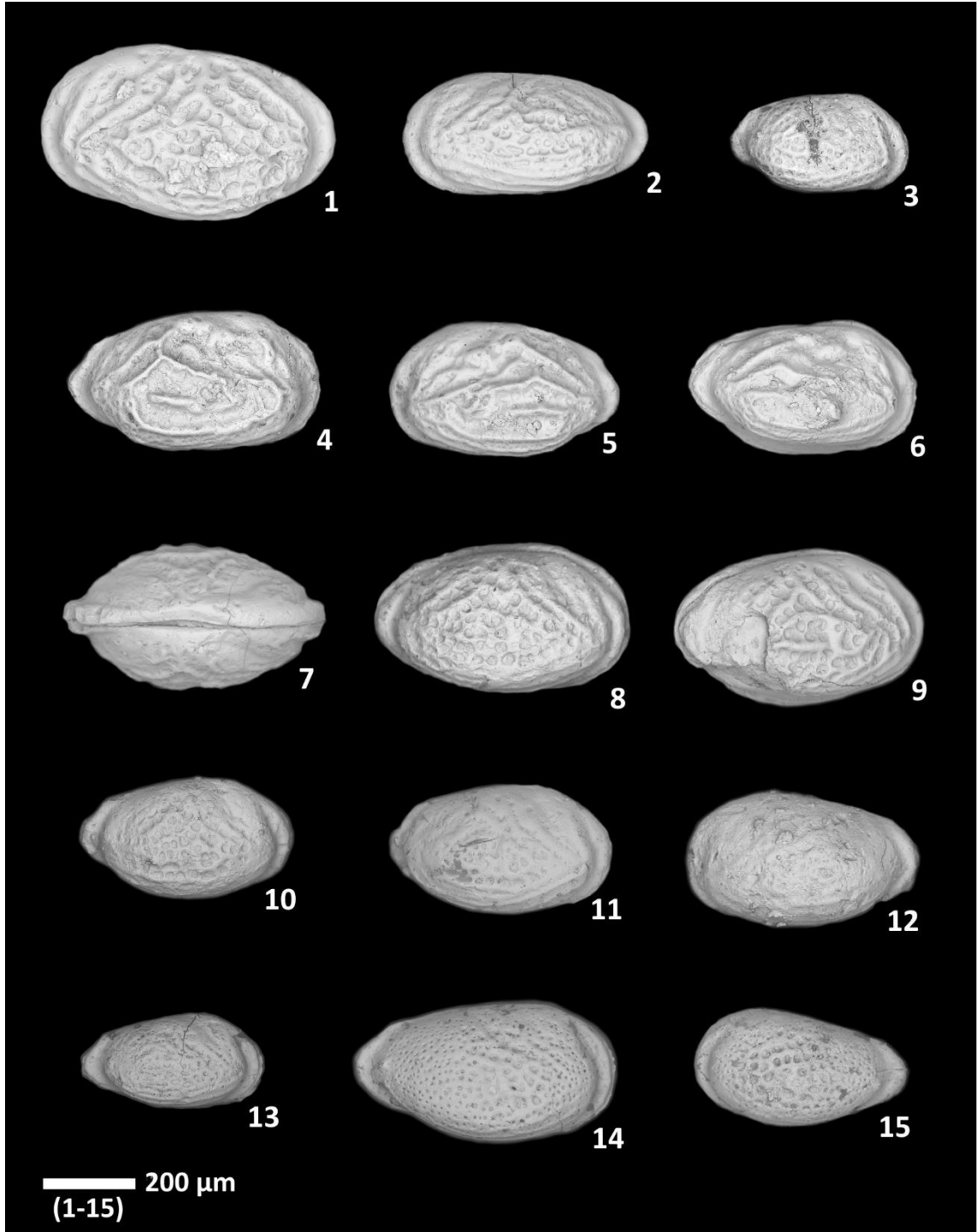
Plate 24

1, 7, 9. *Ektyphocythere* sp. A. White Park Bay WPB5, lateral view x320, left valve; 7, Ballinlea-1 Borehole BAL530, dorsal view x280, carapace (LV>RV); 9, Ballinlea-1 Borehole BAL490, lateral view x320, carapace (LV>RV).

2, 11. *Ektyphocythere herrigi* (Ainsworth). 2, White Park Bay WPB5, lateral view x360, left valve; 11, Ballinlea-1 Borehole BAL490, lateral view x360, right valve.

3, 8. *Ektyphocythere lacunosa* (Ainsworth). 3, Ballinlea-1 Borehole BAL580, lateral view x320, right valve; 8, Ballinlea-1 Borehole BAL510, lateral view x380, carapace (LV>RV).

4-6. *Ektyphocythere vitiosa* (Apostolescu). 4, White Park Bay WPB3, lateral view x420, right view; 5, White Park Bay WPB2, lateral view x290, left view; 6, Ballinlea-1 Borehole BAL545, lateral view x280, carapace (LV>RV).

10. *Ektyphocytheres sinemuriana* (Ainsworth). 10, Ballinlea-1 Borehole BAL510, lateral view x380, right valve.

12. *Ektyphocythere exiloreticulata* (Ainsworth), Ballinlea-1 Borehole BAL510, lateral view x285, left valve.

13. *Gammacythere faveolata* Michelsen, White Park Bay WPB5, lateral view x540, right valve.

14, 15. *Gammacythere ubiquita* Malz & Lord. 14, Ballinlea-1 Borehole BAL410, lateral view x300, right valve; 15, Ballinlea-1 Borehole BAL480, lateral view x310, left valve.

Plate 25
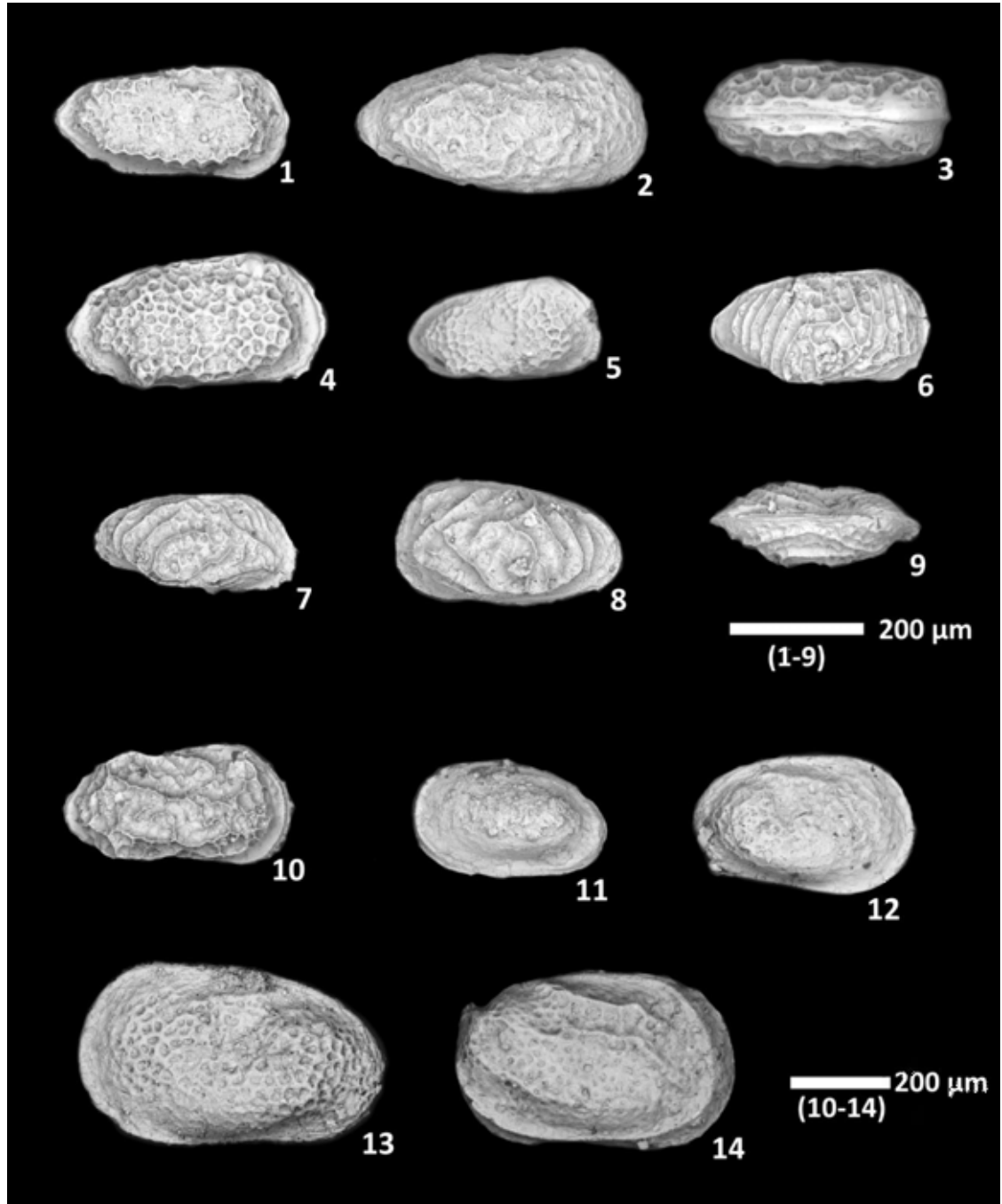
Plate 25

1-3. *Acrocythere oeresundensis* (Michelsen). 1, Ballinlea-1 Borehole BAL425, lateral view x540, right valve; 2, Ballinlea-1 Borehole BAL540, lateral view x350, right valve; 3, Ballinlea-1 Borehole BAL425, dorsal view x560, carapace (LV>RV).

4, 5. *Acrocythere gassumensis* (Michelsen). 4, Ballinlea-1 Borehole BAL845, lateral view x470, right valve; 5, Ballinlea-1 Borehole BAL580, lateral view x680, right valve.

6. *Nanacythere paracostata* Michelsen, 1975, Carnduff-1 Borehole CRN221.75, lateral view x600, right valve.

7-9 *Nanacythere elegans* (Drexler). 7, Carnduff-1 Borehole CRN259, lateral view x520, right valve; 8, Carnduff-1 Borehole CRN216.75, lateral view x570, left valve; 9, Carnduff-1 Borehole CRN284.6, dorsal view x470, carapace.

10. *Nanacythere aequalicostis* Park, Carnduff-1 Borehole CRN241.5, lateral view x420, right valve.

11-14. Cytherella sp. A. 11, Magilligan Borehole MAG146, lateral view x470, left valve; 12, Carnduff-1 Borehole CRN241.5, lateral view x280, right valve; 13, Carnduff-1 Borehole CRN241.5, lateral view x230, left valve; 14, Magilligan Borehole MAG146, lateral view x340, right valve.

Plate 26

200 μm
(1-6)

200 μm
(7-10)
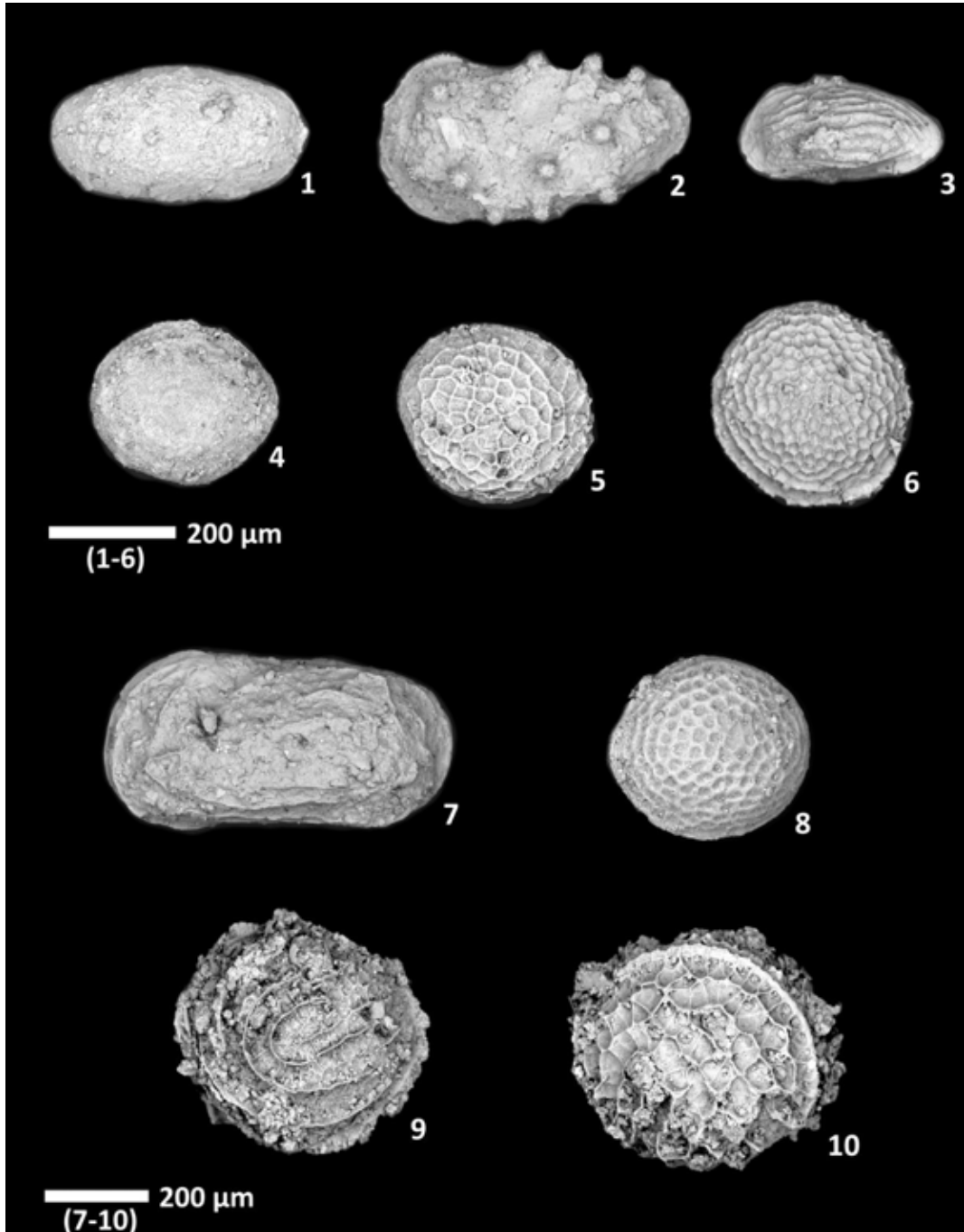
Plate 26

1. *Paradoxostoma pusillum* (Michelsen), Carnduff-1 Borehole CRN259, lateral view x480, left valve.

2. *Trachycythere tubulosa tubulosa* Triebel & Klingler, Ballinlea-1 Borehole BAL410, lateral view x500, left valve.

3. *Ektyphocythere* sp. C, White Park Bay WPB5, lateral view x790, carapace.

4. *Polycope minor* Michelsen, Carnduff-1 Borehole CRN176, lateral view x510, carapace.

5. *Polycope pumicosa* Apostolescu, Carnduff-1 Borehole 176, lateral view x500, valve.

6, 8. *Polycope cerasia* Blake. 5, Carnduff-1 Borehole CRN241.5, lateral view x470, valve; 7, Carnduuf-1 Borehole CRN182.9, lateral view x350, valve.

7. *Laphodentina lacunosa* Apostolescu, Ballinlea-1 BAL790, lateral view x280, left valve.

9. *Polycope cincinnata* Apostolescu, Carnduff-1 Borehole CRN182.9, lateral view x270, valve.

10. *Polycope* sp. A Carnduff-1 Borehole CRN182, lateral view x240, valve.

Plate 27
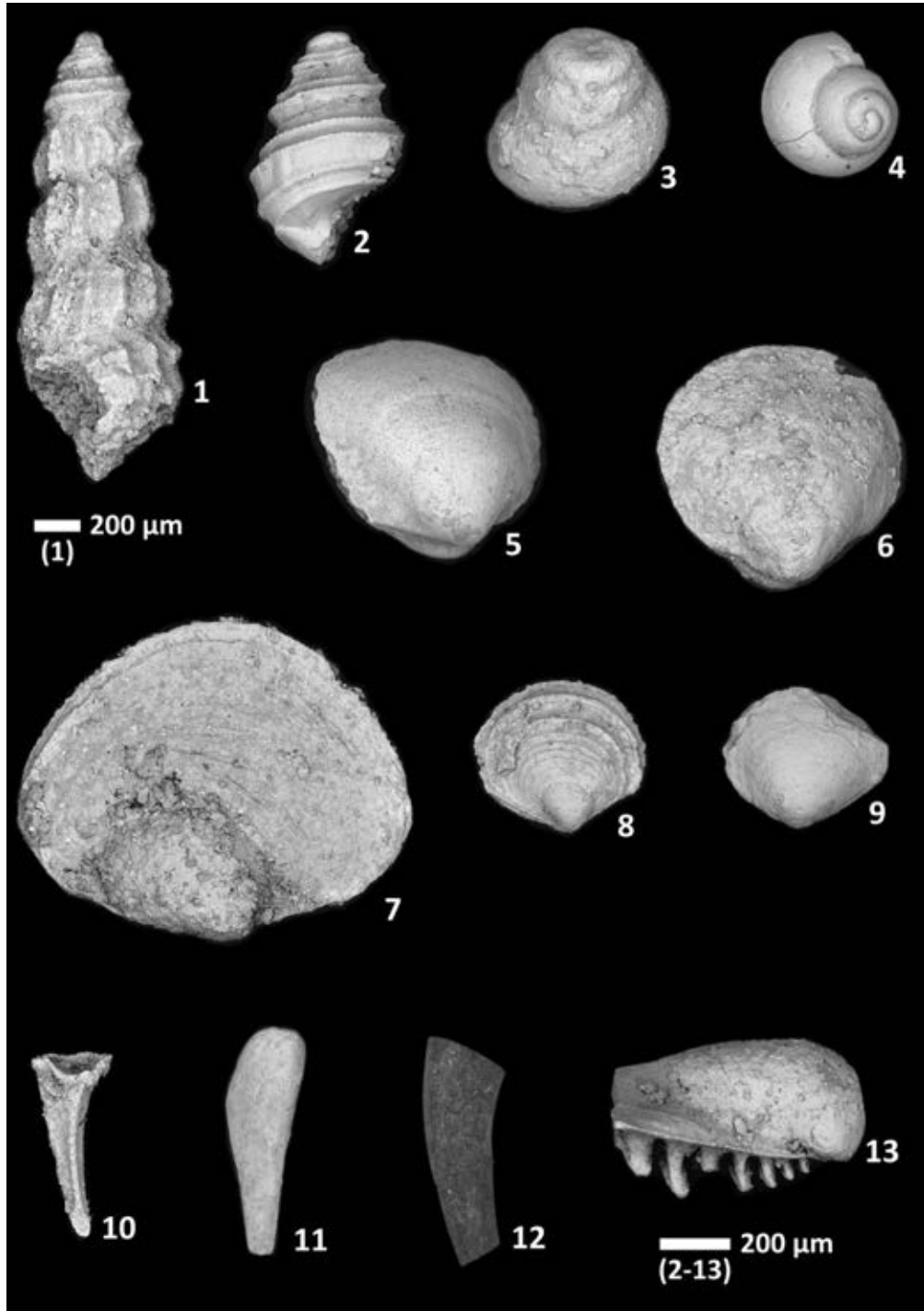
Plate 27

1. *Cryptaulax abcisum* Terquem & Piette (microgastropod), Carnduff-1 Borehole CRN301.6, lateral view x 225.

2. *Tricariida* sp. **(**microgastropod), Ballinlea-1 Borehole BAL520, lateral view x 220.

3, 4. *Gyrodes* sp. (microgastropod). 3, Ballinlea-1 Borehole BAL875, lateral view x 280; 4, Ballinlea-1 Borehole BAL510, lateral view x 350.

5, 6, 9. *Plagiostoma giganteum* Sowerby (microbivalve). 5, Ballinlea-1 Borehole BAL920, lateral view x 165; 6, Carnduff-1 Borehole CRN290.85, lateral view x 220; 9, Ballinlea-1 Borehole BAL760, lateral view x 340.

7. *Entolium* sp. **(**microbivalve), Carnduff-1 Borehole CRN296.2, lateral view x 215.

8. *Cardinia* sp. (microbivalve), Carnduff-1 Borehole CRN301.6, lateral view x 255.

10, 11, 12. Fish tooth. 10, Carnduff-1 Borehole CRN264.2, lateral view x 280; 11, Magilligan Borehole MAG173.54, lateral view x 295; 12, Magilligan MAG151, lateral view x 225.

13. Bivalve umbo, Carnduff-1 Borehole CRN290.85, lateral view x 250.

Plate 28
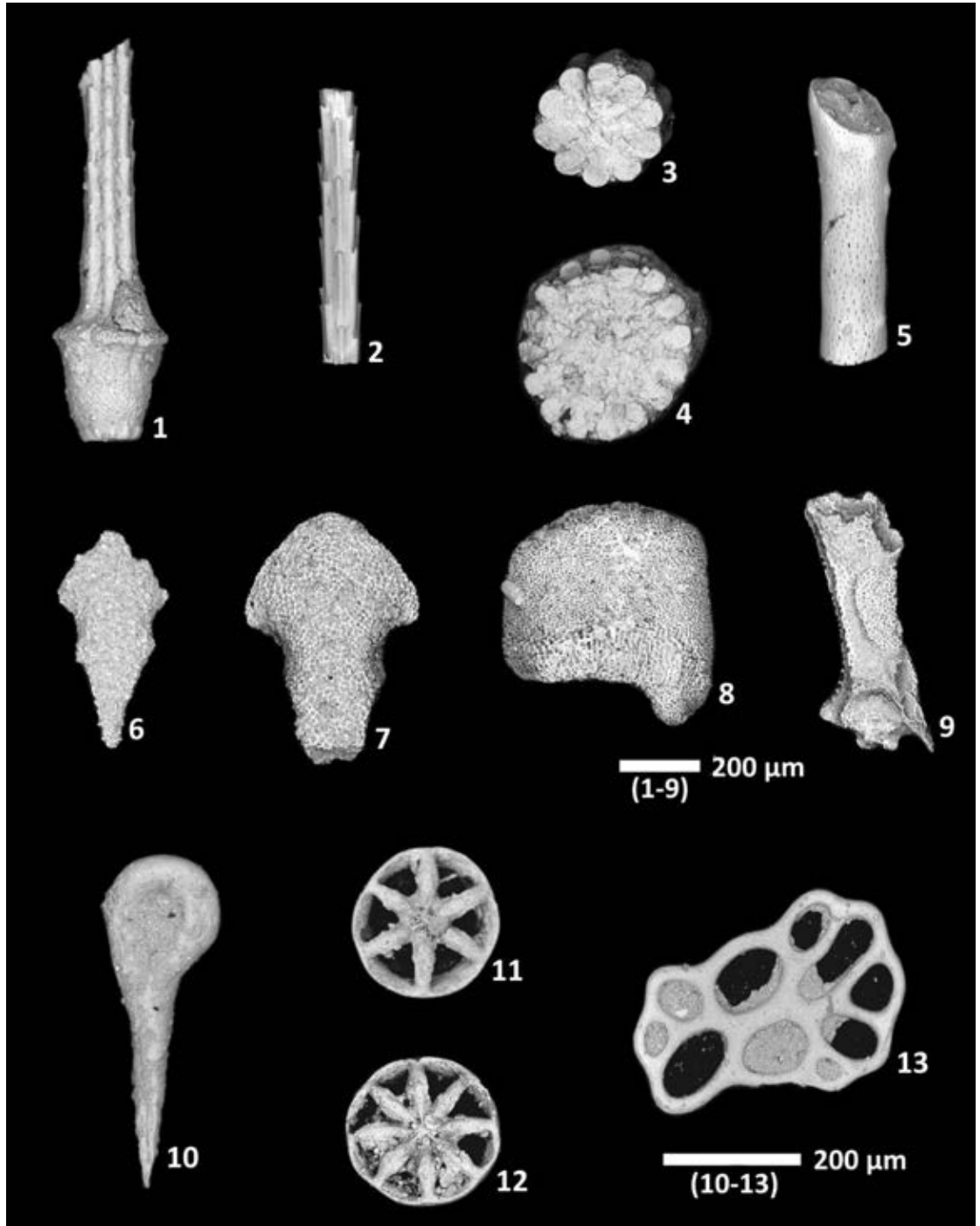
Plate 28

1. Echinoderm spine and base, Ballinlea-1 Borehole BAL730, lateral view x 150.

2. *Diademopsis* spine **(**Echinoderm). 2, Ballinlea-1 Borehole BAL465, lateral view x 275.

3, 4. Echinoderm spine. 3, Ballinlea-1 Borehole BAL760, cross-section x 450; 4, Ballinlea-1 Borehole BAL940, cross-section x 260.

5. Echinoderm part, Ballinlea-1 Borehole BAL465, lateral view x 220.

6, 7, 8, 9. Ophiuroid parts. 6, Magilligan Borehole MAG70.22, lateral view x 300; 7, Magilligan Borehole MAG122, lateral view x 220; 8, Carnduff-1 Borehole CRN176, lateral view x 230; 9, Magilligan Borehole MAG76.69, lateral view x 225.

10. *Achistrum bartensteini* Frizzell & Exline (Holothurian), Magilligan Borehole MAG131.1, lateral view x 320.

11, 12. *Theelia* sp. (Holothurian sclerites). 11, Carnduff-1 Borehole CRN176, top view x 650; 12, Carnduff-1 Borehole CRN176, top view x 760.

13. *Binoculites terquemi* Deflandre-Rigaud (Holothurian), Magilligan Borehole MAG106.95, lateral

view x 460

TAXONOMIC INDEX

(page numbers in bold refer to the main descriptions of the taxonomy and their plates)

Foraminifera

Ostracods

Macrofossils

Tricariida sp.(microgastropod); **351**

APPENDIX B

Recorded Northern Ireland Late Triassic-Early Jurassic foraminifera species and subspecies

(All species and subspecies identified in this study)

Ammodiscus siliceous

Astacolus primus

Astacolus scalptus

Astacolus speciosus

Berthelinella involuta involuta

Berthelinella involuta striata

Berthelinella sp. A

Brizalina liasica

Bullopora globulata globulata?

Cornuspira liasina

Dentalina dentaliniformis

Dentalina langi

Dentalina pseudocommunis

Eoguttulina liassica

Haplophragmoides kingakensis

Ichthyolaria brizaeformis

Ichthyolaria lignaria

Ichthyolaria pupiformis

Ichthyolaria terquemi barnardi

Ichthyolaria terquemi bicostata

Ichthyolaria terquemi squamosa

Ichthyolaria terquemi sulcata

Ichthyolaria terquemi terquemi

Lagena liasica

Lagena natrii

Lagena semisulcata

Lagena? *hausleri*

Lenticulina muensteri muensteri

Lenticulina muensteri polygonata

Lenticulina muensteri ssp. A

Lenticulina varians varians

Loxostomum liasicum liasicum

Loxostomum liasicum teres

Marginulina hamus

Marginulina lamellosa

Marginulina obliquecostulata

Marginulina picturata

Marginulina prima incisa

Marginulina prima insignis

Marginulina prima interrupta

Marginulina prima praerugosa

Marginulina prima prima

Marginulina prima rugosa

Marginulina prima spinata

Marginulina sherborni

Marginulina terquemi

Mesodentalina matutina

Mesodentalina tenuistriata

Marginulina aff. *turneri*

Mesodentalina varians haeusleri

Mesodentalina varians varians

Neobulimina bangae

Nodosaria apheilolocula

Nodosaria claviformis

Nodosaria columnaris

Nodosaria crispata

Nodosaria denticulatacostata

Nodosaria fontinensis

Nodosaria germanica

Nodosaria globulata

Nodosaria hortensis

Nodosaria issleri

Nodosaria cf. *kunzi*

Nodosaria kuhni

Nodosaria lagenoides

Nodosaria metensis

Nodosaria mitis

Nodosaria nitidana

Nodosaria novemcostata

Nodosaria porrecta

Nodosaria prima

Nodosaria primitiva

Nodosaria pseudoclaviformis

Nodosaria pseudoregularis

Nodosaria radiata

Nodosaria rara

Nodosaria sexcostata

Nodosaria simplex

Nodosaria sp. A

Nodosaria sp. B

Nodosaria sp. C

Nodosaria sp. D

Nodosaria sp. E

Nodosaria tenera

Nodosaria whittakeri

Ophthalmidium liasicum

Ophthalmidium macfadyeni macfadyeni

Ophthalmidium macfadyeni tenuiloculare

Paralingulina cernua

Paralingulina esseyana

Paralingulina lanceolata

Paralingulina longiscata longiscata

Paralingulina minuta

Paralingulina paranodosaria

Paralingulina sp. A

Paralingulina tenera collenoti

Paralingulina tenera pupa

Paralingulina tenera subprismatica

Paralingulina tenera substriata

Paralingulina tenera tenera

Paralingulina tenera tenuistriata

Planularia breoni

Planularia inaequistriata

Planularia pauperata

Planularia protracta

Planularia pulchra

Procerolagena lanceolata

Prodentalina arbuscula

Prodentalina bicornis

Prodentalina breoni

Prodentalina cf. *breoni*

Prodentalina clavata

Prodentalina crenata

Prodentalina cf. *guembeli*

Prodentalina integra

Prodentalina aff. *mucronata*

Prodentalina nodigera

Prodentalina parvula

Prodentalina paucicosta

Prodentalina paucicurvata

Prodentalina cf. *paucicurvata*

Prodentalina cf. *perlucida*

Prodentalina pyriformis

Prodentalina cf. *radicula*

Prodentalina simplex

Prodentalina sinemuriensis

Prodentalina sp. A

Prodentalina cf. *subulata*

Prodentalina subsiliqua

Prodentalina terquemi

Prodentalina teutoburgensis

Prodentalina torta

Prodentalina tortilis

Prodentalina vetustissima

Pseudonodosaria dubia

Pseudonodosaria multicostata

Pseudonodosaria oviformis

Pseudonodosaria vulgata

Reinholdella dreheri

Reinholdella margarita margarita

Reinholdella? mochrasensis

Reinholdella pachyderma humilis

Reinholdella robusta

Reinholdella sp. A (*Reinholdella ''praemacfadyeni''*)

Reinholdella planiconvexa

Reophax sp. A

Reussolina laticosta

Reussoolina aphela

Reussoolina minutissima

Reussoolina ovata

Reussoolina? *lacrimaforma*

Saracenella mochrasensis

Spirillina infima

Spirillina tenuissima

Spiroloculina concentrica

Trochammina canningensis

Vaginulina curva

Vaginulina listi

Vaginulina cf. *neglecta*

Vaginulina parva

Vaginulinopsis mediomatricorum

Vaginulinopsis denticulatacarinata

Vaginulinopsis pauperata

APPENDIX C

Recorded Northern Ireland Late Triassic-Early Jurassic ostracods species

(All species identified in this study)

Acrocythere gassumensis

Acrocythere michelseni?

Acrocythere oeresundensis

Bairdia molesta

Bairdia sp. A

Bairdiacypris? sartriensis

Bairdiocopina sp.

Cardobairdia sp.

Cytherella sp. A

Cytherelloidea sp. A

Ekthypocythere retia

Ektyphocythere betzi?

Ektyphocythere cookiana

Ektyphocythere exiloreticulata

Ektyphocythere frequens

Ektyphocythere herrigi

Ektyphocythere lacunosa

Ektyphocythere luxuriosa

Ektyphocythere mooeri

Ektyphocythere perplexa

Ektyphocythere retia

Ektyphocythere sinemuriana

Ektyphocythere sp. A

Ektyphocythere translucens

Ektyphocythere triebeli

Gammacythere faveolata

Gammacythere ubiquita

Isobythocypris elongata

Isobythocypris sp. A

Isobythocypris tatei

Laphodentina lacunosa

Liasina lanceolata

Lophodentalina cf. *pulchella*

Lutkevichinella hortonae

Nanacythere aequalicostis

Nanacythere elegans

Nanacythere firma

Nanacythere paracostata

Ogmocnchella danica

Ogmoconcha eocontractula

Ogmoconcha hagenowi

Ogmoconchella aequalis

Ogmoconchella aspinata

Ogmoconchella bispinosa

Ogmoconchella bristolensis

Ogmoconchella danica

Ogmoconchella gruendeli

Ogmoconchella mouhersensis

Paracypris redcarensis

Paracypris semidisca

Paracypris sp. A

Paracypris? semidisca

Paradoxostoma pusillum

Paradoxostoma sp. A

Pleurifera harpa

Pleurifera plicata

Pleurifera vermiculata

Polycope cerasia

Polycope cincinnata

Polycope minor

Polycope pelta

Polycope pumicosa

Polycope sp. A

Trachycythere tubulosa seratina

Trachycythere tubulosa tubulosa

Ballinlea-1 Borehole processed samples

Colour index:
1: white
2: light grey
3: olive grey
4: blueish grey
5: dark grey
6: black

Processed by Azrin
Proccessed by Mark
HP: Hydrogen peroxide
FT: Freeze-thaw

Sample/Depth (m)	Lithology	Colour index	Method	Weight undergo processed (g)	Weight after washed and dried (g)	Fraction picked	weight picked (g) (initial weight x fraction)
BAL 345	Calcareous mudstone	2	HP	54	8	1	54.00
BAL 355	Calcareous mudstone	2	HP	65	6	1/2	32.50
BAL 365	Calcareous mudstone	2.5		79	21	1/4	19.75
BAL 370	Calcareous mudstone	2.5	HP	70	9	1/2	35.00
BAL 380	Calcareous mudstone	2.5		44	18	1/8	5.50
BAL 385	Calcareous mudstone	2.5	HP	72	8	1/2	36.00
BAL 395	Calcareous mudstone	2.5		78	36	1/10	7.80
BAL 400	Calcareous mudstone	2.5	HP	89	12	1/2	44.50
BAL 410	Calcareous mudstone	2.5	HP	91	7	1/4	22.75
BAL 415	Calcareous mudstone	2.5		95	54	1/16	5.94
BAL 425	Calcareous mudstone	3	HP	88	8	1/2	44.00
BAL 430	Calcareous mudstone	3		81	47	1/6	13.50
BAL 440	Calcareous mudstone	3	HP	56	7	1/2	28.00
BAL 450	Calcareous mudstone	3		78	48	1/6	13.00
BAL 465	Calcareous mudstone	3.5	HP	70	9	1/4	17.50
BAL 475	Calcareous mudstone	3.5	HP	72	9	1/4	18.00
BAL 480	Calcareous mudstone	3.5		72	8	1/10	7.20

Ballinlea-1 Borehole processed samples

Colour index:							
1: white		Processed by Azrin					
2: light grey		Proccessed by Mark					
3: olive grey		HP: Hydrogen peroxide					
4: blueish grey		FT: Freeze-thaw					
5: dark grey							
6: black							

Sample/Depth (m)	Lithology	Colour index	Method	Weight undergo processed (g)	Weight after washed and dried (g)	Fraction picked	weight picked (g) (initial weight x fraction)
BAL 490	Calcareous mudstone	3	HP	64	9	1/2	32.00
BAL 500	Calcareous mudstone	3	HP	56	7	1/2	28.00
BAL 510	Calcareous mudstone	3	HP	86	14	1/2	43.00
BAL 520	Calcareous mudstone	3	FT	75	14	1/2	37.50
BAL 530	Calcareous mudstone	4	HP	88	15	1/2	44.00
BAL 540	Calcareous mudstone	4	HP	93	14	1/2	46.50
BAL 545	Calcareous mudstone	4		77	45	1/5	15.40
BAL 550	Calcareous mudstone	4	HP	64	17	1/2	32.00
BAL 560	Calcareous mudstone	4	HP	84	17	1/2	42.00
BAL 570	Calcareous mudstone	4	HP	87	16	1/2	43.50
BAL 580	Calcareous mudstone	4.5	HP	79	16	1/4	19.75
BAL 595	Calcareous mudstone	4.5	FT	57		1	57.00
BAL 610	Calcareous mudstone	5		65	35	1/5	13.00
BAL 615	Calcareous mudstone	5	FT	60			
BAL630-BAL668	Calcareous mudstone	6					
BAL 670	Calcareous mudstone	3		64	54		
BAL 675	Calcareous mudstone	5		66	51		

APPENDIX D (continued)

Ballinlea-1 Borehole processed samples

Colour index:
1: white
2: light grey
3: olive grey
4: blueish grey
5: dark grey
6: black

Processed by Azrin
Proccessed by Mark
HP: Hydrogen peroxide
FT: Freeze-thaw

Sample/Depth (m)	Lithology	Colour index	Method	Weight undergo processed (g)	Weight after washed and dried (g)	Fraction picked	weight picked (g) (initial weight x fraction)
BAL 685	Calcareous mudstone	4.5	FT	65		1/4	16.25
BAL 695	Calcareous mudstone	3	FT	51	15	1/4	12.75
BAL 700	Calcareous mudstone	2.5	FT	65		1/2	32.50
BAL 710	Calcareous mudstone	4	FT	54		1/4	13.50
BAL 715	Mudstone	3		84	31	1/8	10.50
BAL 720	Calcareous mudstone	3	FT	62	29	1/8	7.75
BAL 730	Limestone	4	FT	69	27	1	69.00
BAL 740	Limestone	4	FT	72	37	1/10	7.20
BAL 745	Limestone	3	FT	74	36	1/4	18.50
BAL 760	Limestone	4	FT	48	22	1/2	24.00
BAL 770	Calcareous mudstone	2.5		102	69	1/10	10.20
BAL 780	Limestone	3.5	FT	71	31	1/2	35.50
BAL 785	Limestone	3.5		106	63	1/32	3.31
BAL 790	Limestone	5.5	FT	63	29	1/4	15.75
BAL 800	Limestone	3.5	FT	70	35	1/4	17.50
BAL 810	Calcareous mudstone	4		73	29	1/4	18.25
BAL 815	Calcareous mudstone	3.5		84	33	1/2	42.00
BAL 820	Calcareous mudstone & sandstone	3.5	FT	66	29	1/4	16.50
BAL 830	Calcareous mudstone	3	FT	62	23	1/2	31.00

APPENDIX D (continued)

Ballinlea-1 Borehole processed samples

Colour index:			Processed by Azrin				
1: white							
2: light grey			Proccessed by Mark				
3: olive grey			HP: Hydrogen peroxide				
4: blueish grey			FT: Freeze-thaw				
5: dark grey							
6: black							

Sample/Depth (m)	Lithology	Colour index	Method	Weight undergo processed (g)	Weight after washed and dried (g)	Fraction picked	weight picked (g) (initial weight x fraction)
BAL 835	Calcareous mudstone	3.5	FT	72	22	1/4	18.00
BAL 845	Calcareous mudstone	2.5	FT	78	40	1/2	39.00
BAL 855	Calcareous mudstone	3	FT	62		1/2	31.00
BAL 860	Calcareous mudstone	3		59	31		
BAL 865	Calcareous mudstone	2.5	FT	66	38	1/4	16.50
BAL 875	Calcareous mudstone	3	FT	64	45	1/2	32.00
BAL 885	Mudstone	2		60	38	1/8	7.50
BAL 890	Calcareous mudstone	3.5	FT	53	28	1/4	13.25
BAL 900	Calcareous mudstone	2.5		53	37	1/5	10.60
BAL 910	calcareous mudstone	3.5	FT	44		1/4	11.00
BAL 920	Mudstone	3.5	FT	50	33	1/8	6.25
BAL 925	Mudstone	4	FT	39		1/11	3.55
BAL 930	Mudstone	5	FT	48		1/8	6.00
BAL 935	Calcareous mudstone	3.5	FT	58	43	1/2	29.00
BAL 940	calcareous mudstone	2		43	24	1/4	10.75
BAL 950	calcareous mudstone	reddish brown	FT	50		1/4	12.50
BAL 960	calcareous mudstone	5	FT	63	46	1/4	15.75
BAL 970	mudstone	greenish grey	FT	17	13	1/4	4.25
BAL 980	mudstone	reddish brown	FT	22		1/4	5.50

Ballinlea-1 fossils and minerals data

Super-abundant (S): >150	Common (C): 41-80	Rare (R): 1-9
Abundant (A): 81-150	Present (P): 10-40	

Sample/depth (m)	Foraminifera	Ostracods	micro-gastropod	micro-bivalve	echinoderm fragment	ophiuroid fragment	shell fragment	trace fossil	quartz	calcite	muscovite	biotite	pyrite	carbonaceous material	glauconite
BAL345	A	P					P				S			P	P
BAL355	C	P			P		C		P		S	P	C	P	
BAL365	C	C													
BAL370	C	P			P		P				S	A			
BAL380	A	A													
BAL385	C	C			P		P				S	A	C		
BAL395	A	C	P				R								
BAL400	A	C	C		P		C				S	C	C	R	
BAL410	A	C	P		P	P	C				S	P	C	R	
BAL415	R	C	C												
BAL425	A	P	P		P	P	C				A	C	C	R	
BAL430	A	P	P												
BAL440	C	P	P		P	C	P				A	A	C	P	
BAL450	P	R	R		R	R	R	R			S	C	R	R	
BAL465	C	P	R		C	P	P				C		R		
BAL475	S	P	P		C	R	P	R	P		C		C	P	
BAL480	S	C													
BAL490	S	C	P		P	R	P		P		C		C	C	
BAL500	A	P	P		P		P	P			A		C	C	
BAL510	S	C			P	P	P		P		C	P	C	P	
BAL520	S	C	P		P	R		R	P		A	C	P	P	P
BAL530	S	C	R		P		P		C		C	P	P	P	
BAL540	A	C	R	R	P	R			P		S	P		P	
BAL545	P	P	R	R	R	R	R				A			P	
BAL550	A	C	R	R	P	P	P		P		C	C	P	P	
BAL560	S	C	R		R		R	R	P	R	A	C	P	R	

Ballinlea-1 fossils and minerals data

Super-abundant (S): >150	Common (C): 41-80	Rare (R): 1-9
Abundant (A): 81-150	Present (P): 10-40	

Sample/depth (m)	Foraminifera	Ostracods	micro-gastropod	micro-bivalve	echinoderm fragment	ophiuroid fragment	shell fragment	trace fossil	quartz	calcite	muscovite	biotite	pyrite	carbonaceous material	glauconite
BAL570	S	C	R	R	P	R	R	P	P	P	A	C	P	R	
BAL580	A	P	R	R	P	R	R	R		P	A	C	P	P	
BAL595	S	P	R	R	P	R	R	R			C		P	P	
BAL610	R	R		R	P		R	R	P		A	P	P		
BAL615															
BAL630															
BAL670															
BAL675									R		A	C	R		
BAL685	A	C	C	P	P	P	R				C		C	P	
BAL700	R	R	P	R	R		P	R			C		P	R	
BAL710	R	R	P	R	R	R	P	R		P	A	C	P	R	
BAL715	R	P	A	P		R	R	R	R	P	C	C	P	R	
BAL720	A	R	C	R	P			R							
BAL730	S	P	R	R	P	P	P	P			C		P	P	
BAL740	A	P	R	R	C	P	R	R			C	C	R	R	
BAL745	A	P	R	R	R	R	R	R		P	P		P	R	
BAL760	C	C	R	P	C	P	P	R			C		P		
BAL770	R	S		R				R			P			R	
BAL780	R	A			C	R	P	R			C	C		C	R
BAL785	P	S	R								R				
BAL790	P	S	P	P	P	P		R			A	A	R	R	
BAL800	A	A	R	R	P	R	P	R			P	C		C	P

Ballinlea-1 fossils and minerals data

Super-abundant (S): >150	Common (C): 41-80	Rare (R): 1-9
Abundant (A): 81-150	Present (P): 10-40	

Sample/depth (m)	Foraminifera	Ostracods	micro-gastropod	micro-bivalve	echinoderm fragment	ophiuroid fragment	shell fragment	trace fossil	quartz	calcite	muscovite	biotite	pyrite	carbonaceous material	glauconite
BAL810	A	A	P	R	C	P		R		R	A	C	R	R	
BAL815	R	S	R	R											
BAL820	R	A	R	R	P	P	R	R	S	R	C		P	P	
BAL830	R	C		R	R		R	R	A	P	C		P	R	
BAL835	R	P	R		P		R			L	C	C	R	R	
BAL845	R	C	R	R	R		R	R	S	C	C		P	P	
BAL855	C	A	R	R	P	R	P	R							
BAL860	R	R	R	R											
BAL865	P	P	R	R	P	R	R	R	P	L	C		P	P	
BAL875	R	R	R	R	R	R	R			L	C		P	R	
BAL885	C	C	P	P	R	P		R	P	R	C	C	R	R	
BAL890	P	P	P	P	P	P		R	P	L	C		P	R	
BAL900	R	S	R	R	P	R			R	R	C		P	R	
BAL910	P	S	C	P		P			R	R	C		P	R	
BAL920	S	A						R	P	L	A	C	R	R	
BAL 925	R	P	R	R	P	R	R				P	P	R	R	
BAL930	P	P	P	C	R	P	R				P	P			
BAL935	P	S	C	P	P	P	R	R	P	R	C		P	R	
BAL940	R	R	R												
BAL950		R	R	R						R	P	P	R	R	
BAL960	P	P		R	R	R	P	R	P	R	C		P	R	
BAL970		R													
BAL980	R	R													

Carnduff-1 Borehole processed samples

colour index:									
1 = white		4 = blueish grey							
2 = light grey		5 = dark grey	processed for microfossils						
3 = olive grey		6 = black	FT: freeze-thaw						

Depth (m)	Colour	Lithology	Description	Processed	Weight undergo freeze-thaw (g)	Weight after washed and dried (g)	Fraction picked	weight picked (g) (initial weight x fraction)
CRN170.7	3	calcareous mudstone		FT	32	4	1/16	2.00
CRN176	4.5	calcareous mudstone		FT	33	2	1/2	16.50
CRN182.9	4	limestone		FT	38	7	1/8	4.75
CRN186	2	calcareous mudstone	contains bivalve fossils	FT	24	4	1/2	12.00
CRN189.85	4.5	calcareous mudstone	present bivalve fossils	FT	9	1	1	9.00
CRN191.3	3	calcareous mudstone		FT	23	10	1/8	2.88
CRN198.6	3	calcareous mudstone	few bivalve fossils	FT	16	2	1/2	8.00
CRN202.9	5	calcareous mudstone		FT	19	6	1/2	9.50
CRN211	3	calcareous mudstone		FT	23	4	1	23.00
CRN216.75	4	calcareous mudstone		FT	18	1	1	18.00
CRN221.75	3	calcareous mudstone		FT	22	2	1/2	11.00
CRN232	3	calcareous mudstone		FT	18	1	1	18.00
CRN238.8	4.5	calcareous mudstone		FT	20	1	1	20.00
CRN241.5	3	calcareous mudstone		FT	20	1	1	20.00
CRN248.3	3	calcareous mudstone		FT	19	3	1/2	9.50
CRN252.5	4	calcareous mudstone	present bivalve fossils	FT	45	1	1	45.00
CRN259	4	calcareous mudstone		FT	35	1	1	35.00
CRN264.2	4	calcareous mudstone		FT	46	2	1	46.00
CRN273.2	4.5	calcareous mudstone		FT	40	1	1	40.00
CRN284.6	4.5	calcareous mudstone		FT	19	1	1	19.00
CRN290.85	4	calcareous mudstone		FT	40	2	3/4	30.00
CRN296.2	3	calcareous mudstone		FT	18	2	1	18.00
CRN301.6	3	calcareous mudstone		FT	20	2	1	20.00
CRN306.6	4	mudstone		FT	24	6	1/2	12.00
CRN314.9	4.5	calcareous mudstone		FT	23	4	1/2	11.50
CRN319.5	5	siltstone	few shell fragments	FT	18	10	1/8	2.25
CRN324.35	3	mudstone		FT	20	<1	0	0.00
CRN326	2	mudstone		FT	48	6	1/2	24.00

Carnduff-1 fossils and minerals data

| | Super-abundant (S): >150 | Common (C): 41-80 | Rare (R): 1-9 |
| | Abundant (A): 81-150 | Present (P): 10-40 | None (x): 0 |

Depth (m)	Foraminifera	Ostracods	echinoderm fragment	ophiuroid fragment	crinoid stem fragment	micro-gastropod	micro-bivalve	fish tooth	holothurians fragment	shell fragments	trace fossils	quartz	calcite	muscovite	biotite	pyrite	carbonaceous material	fragment of sandstone	glauconite	Remarks
CRN170.7	S	P	R	R	x	R	x	x	x	P	R	x	R	P	P	R	R	x	R	
CRN176	S	P	R	A	x	x	x	x	R	R	R	x	R	R	x	P	R	x	x	
CRN182.9	S	S	P	P	x	x	P	x	R	R	R	x	P	R	x	R	R	x	x	
CRN186	S	P	S	P	x	R	P	R	x	P	R	x	P	P	R	R	R	x	x	
CRN189.85	S	A	R	P	x	x	x	R	P	R	R	x	x	R	x	R	R	x	x	
CRN191.3	A	C	P	R	x	R	x	x	x	R	R	R	x	R	R	R	R	x	x	
CRN198.6	A	A	A	S	x	R	R	x	P	R	R	x	P	R	x	R	R	x	x	
CRN202.9	R	R	C	R	x	x	R	x	x	R	R	x	C	R	x	R	R	x	x	
CRN211	C	A	A	S	x	P	R	R	R	R	R	x	P	R	x	R	R	x	x	
CRN216.75	A	S	A	S	x	R	R	x	P	R	R	R	R	R	x	R	R	x	x	
CRN221.75	S	S	P	S	x	x	R	x	R	R	R	x	R	R	x	R	R	x	x	
CRN232	R	A	R	S	x	x	R	x	C	R	P	x	x	R	x	P	P	R	x	
CRN238.8	C	R	x	x	x	R	R	R	x	R	R	x	x	R	x	P	P	x	x	
CRN241.5	C	P	x	P	x	R	R	x	x	R	R	x	R	A	P	P	P	x	x	
CRN248.3	P	S	R	S	x	x	x	x	C	P	R	x	R	P	x	P	R	x	x	
CRN252.5	A	A	P	C	x	R	R	x	S	R	R	x	R	R	x	P	R	x	x	
CRN259	S	P	S	R	R	R	R	R	x	R	P	x	R	C	R	P	P	x	x	
CRN264.2	S	S	P	S	x	R	R	R	R	P	P	x	R	P	x	P	R	x	x	
CRN273.2	P	A	x	R	x	R	P	x	S	R	R	x	P	P	R	P	R	x	x	
CRN284.6	C	C	R	x	x	x	C	R	x	P	R	x	P	A	A	P	R	x	x	
CRN290.85	P	S	P	C	x	S	A	x	x	P	P	x	P	P	x	P	R	x	x	
CRN296.2	A	A	P	A	x	A	S	x	R	C	R	x	x	P	x	P	R	x	x	
CRN301.6	A	P	P	P	x	A	P	x	R	R	R	x	P	P	x	P	R	x	x	
CRN306.6	P	R	C	x	x	R	S	R	x	P	x	x	x	P	R	R	R	x	x	
CRN314.9	P	C	x	R	x	R	x	x	x	x	x	x	x	C	P	R	R	x	x	
CRN319.5	C	x	C	R	x	x	x	x	x	R	x	x	x	C	C	x	x	x	x	
CRN324.35	x	x	x	x	x	x	x	x	x	x	x	x	x	S	S	R	P	x	x	95% of residue is mica
CRN326	x	x	x	x	x	x	x	x	x	x	x	x	P	C	C	x	x	x	x	

APPENDIX H

Magilligan provided and processed samples

Colour Index:	processed for microfossils
1 = white	FT: freeze thaw method
2 = light grey	HP: hydrogen peroxide method
3 = olive grey	
4 = blueish grey	
5 = dark grey	
6 = black	

Depth (m)	Lithology	Colour index	Remark	Process 1st	Process 2nd	Weight undergo processed (g)	Weight after washed and dried (g)	Fraction picked	weight picked (g) (initial weight x fraction)
MAG19	Calcareous mudstone	2		FT		17	4	1/4	4.25
MAG42	Calcareous mudstone	1.5							
MAG45.7	Calcareous mudstone	2		FT		9	3	1/4	2.25
MAG50.85	Calcareous mudstone	2		FT		15	6	1/2	7.50
MAG55.75	Calcareous mudstone	1.5	trace of iron nodules	FT		11	3	1/4	2.75
MAG60.7	Limestone	1.5	trace of iron nodules						
MAG65.35	Calcareous mudstone	3		FT		12	3	1/4	3.00
MAG70.22	Calcareous mudstone	2	trace of iron nodules	FT		11	3	1/4	2.75
MAG76.69	Calcareous mudstone	2	trace of iron nodules	FT		15	4	1/4	3.75
MAG77.5	Limestone	3	trace of iron nodules						
MAG79	Calcareous mudstone	1.5	trace of iron nodules	FT	HP	7	3.5	1/2	3.50
MAG80.77	Calcareous mudstone	3							
MAG84.6	Calcareous mudstone	4	trace of iron nodues						

APPENDIX H

Magilligan provided and processed samples

	Colour Index:	processed for microfossils
	1 = white	FT: freeze thaw method
	2 = light grey	HP: hydrogen peroxide method
	3 = olive grey	
	4 = blueish grey	
	5 = dark grey	
	6 = black	

Depth (m)	Lithology	Colour index	Remark	Process 1st	2nd	Weight undergo processed (g)	Weight after washed and dried (g)	Fraction picked	weight picked (g) (initial weight x fraction)
MAG85.63	Calcareous mudstone	3		FT		2	2	1	2.00
MAG92.72	Calcareous mudstone	2		FT		4	2	1	4.00
MAG101.8	Calcareous mudstone	3		FT		8	4	1	8.00
MAG106.95	Calcareous mudstone	3		FT		23	10	1	23.00
MAG112	Calcareous mudstone	3		FT		8	2	1	8.00
MAG117	Calcareous mudstone	1.5		FT		22	8	1	22.00
MAG122	Calcareous mudstone	3		FT		6	3	1	6.00
MAG126.12	Calcareous mudstone	3		FT		17	11	1/4	4.25
MAG131.8	Calcareous mudstone	4		FT	HP	8	4	1/2	4.00
MAG141	Calcareous shale?	3		FT		23	10	1/4	5.75
MAG146	Calcareous mudstone	3		FT		8	2	1/4	2.00
MAG151	Calcareous mudstone	2		FT		7	3.5	1/2	3.50

Magilligan provided and processed samples

Colour Index:	processed for microfossils
1 = white	FT: freeze thaw method
2 = light grey	HP: hydrogen peroxide method
3 = olive grey	
4 = blueish grey	
5 = dark grey	
6 = black	

Depth (m)	Lithology	Colour index	Remark	Process 1st	2nd	Weight undergo processed (g)	Weight after washed and dried (g)	Fraction picked	weight picked (g) (initial weight x fraction)
MAG156.15	Calcareous siltstone	3	lamination of siltstone with fine sandstone						
MAG158	Calcareous mudstone	5		FT		8	2	1/4	2.00
MAG161.7	Calcareous mudstone	3		FT		19	10	1/2	9.50
MAG163.22	Mudstone	4	lamination of light grey siltstone and blueish grey mudstone	FT		6	6	1/2	3.00
MAG163.9	Mudstone	4		FT		4	4	1	4.00
MAG163.95	no samples provided								
MAG172	no sample provided								
MAG173.54	Calcareous mudstone	3	bivalve mould	FT		9	8	1/4	2.25
MAG175.1	Calcareous shale	5.5	abundant of bivalve fossils	FT		9	4.5	1/2	4.50
MAG175.58	Shale	5.5							
MAG177.9	Shale	5.5	clearly seen ribs of bivalve (Chlamys mayeri/Chlamys sp.)	FT		19	15	1/4	4.75
MAG179.43	Calcareous mudstone	5.5	has bivalve fossils, lamination	FT		6	3	1/2	3.00

Magilligan fossils and minerals data

Magilligan borehole

Super-abundant (S): >150	Common (C): 41-80	Rare (R): 1-9
Abundant (A): 81-150	Present (P): 10-40	None (x): 0

Sample/Depth (m)	foraminifera	ostracods	echinoderm fragment	ophiuroid fragment	crinoid stem fragment	holothurians fragment	micro-gastropod	micro-bivalve	fish tooth	shell fragments	trace fossils	calcite	muscovite	biotite	pyrite	carbonaceous material	quartz	fragment of sandstone	Remarks
MAG19	x	R	x	x	x	x	R	x	x	R	R	x	C	x	R	R	C	P	sandstone mostly in >500micro and 250-500micro fractions, quartz common in 63-250micro fraction
MAG45.7	x	R	x	x	x	x	x	x	x	x	x	x	A	C	P	R	C	C	white sandstone (matrix: silt; grain: quartz)
MAG50.85	R	R	R	x	x	x	x	R	x	R	x	x	P	R	R	x	x	x	
MAG55.75	x	x	x	x	x	x	R	x	x	x	x	C	x	P	x	C	x		
MAG65.35	C	P	P	P	P		P	R	x	P	x	x	R	x	R	R	A	A	Fragment of sandstones are dominant(95%) in >500micro & 250-500 micro fractions
MAG70.22	R	R	R	C	x	R	x	x	x	R	R	R	P	x	R	R	R	R	
MAG76.69	R	P	x	A	x	R	x	R	x	R	R	x	C	x	R	R	R	x	
MAG79	x	R	R	R	x	R	x	x	x	R	x	x	P	x	P	R	x	x	
MAG85.63	C	R	x	R	x	x	x	x	x	R	R	R	P	7		1	R	x	
MAG92.72	x	x	x	x	x	x	x	x	x	x	x	x	P	R	R	R	R	P	>500micro fraction consists of 100% fragment of quartz (sandstone contains quartz, biotite and muscovite)
MAG101.8	P	R	R	P	x	C	x	x	x	R	x	R	P	R	R	R	P	P	
MAG106.95	S	x	x	x	x	C	R	C	R	R	R	R	P	P	A	R	x	x	
MAG112	P	C	R	P	x	A	P	P	R	R	x	R	P	x	P	R	x	x	most of microbivalve and microgastropod covered by pyrite
MAG117	R	x	x	x	x	P	x	x	x	x	x	x	C	C	R	R	x	C	

Magilligan fossils and minerals data

Magilligan borehole

Super-abundant (S): >150   Common (C): 41-80   Rare (R): 1-9
Abundant (A): 81-150   Present (P): 10-40   None (x): 0

Sample/Depth (m)	foraminifera	ostracods	echinoderm fragment	ophiuroid fragment	crinoid stem fragment	holothurians fragment	micro-gastropod	micro-bivalve	fish tooth	shell fragments	trace fossils	calcite	muscovite	biotite	pyrite	carbonaceous material	quartz	fragment of sandstone	Remarks
MAG122	R	R	x	R	x	x	R	R	x	x	x	R	P	x	R	R	x	x	
MAG126.12	P	R	x	x	x	R	x	R	x	x	x	P	P	P	R	R	x	x	
MAG131.1	P	P	x	R	x	R	x	C	x	R	x	P	P	x	C	R	x	x	
MAG141	R	R	x	x	x	x	R	P	x	x	x	R	P	P	R	R	x	R	
MAG146	P	C	R	C	R	P	R	P	x	R	x	R	P	x	R	R	x	x	
MAG151	R	P	R	P	x	R	R	R	x	x	x	R	P	x	P	R	x	x	
MAG158	C	A	C	A	x	x	A	C	R	R	R	R	C	x	R	R	x	x	
MAG161.7	x	P	R	x	x	x	x	x	x	x	x	P	x	R	R	R	x	x	
MAG163.22	x	x	x	x	x	x	x	x	x	x	x	R	x	x	x	x	x	x	
MAG163.9	x	x	P	R	x	x	x	x	R	R	R	x	x	x	C	R	x	x	
MAG173.54	x	x	x	x	x	x	x	x	R	x	x	x	A	C	R	P	A	x	
MAG175.1	x	x	x	x	x	x	x	x	P	x	x	x	R	x	x	x	C	x	
MAG177.9	x	x	x	x	x	x	x	x	P	C	x	x	C	C	P	R	C	x	
MAG179.43	R	x	x	x	x	x	x	x	x	x	R	x	x	x	x	x	x	x	

Tircrevan Burn processed samples, fossils and minerals data

	Colour Index:							
	1 = white		Processed for micrfossils					
	2 = light grey		HP: hydrogen peroxide					
	3 = olive grey							
	4 = blueish grey							
	5 = dark grey							
	6 = black							
Sample	Lithology	Colour	Processed (method)	Initial weight	Final weight	Fraction	Weight picked
TB 05	Calcareous mudstone	4	HP	55	9	1/64	0.86
TB 04	Calcareous mudstone	4	HP	44	28	1/16	2.75
TB 03	Calcareous mudstone + sandstone	4+1	HP	46	7	1/8	5.75
TB 02	Fine sandstone (with black mud-drape)	1	HP	39	25	1/16	2.44
TB 01	Fine sandstone	1	HP	29	16	1/8	3.63

S (super-abundant): >150   C (common): 41-80   R (rare): 1-9
A (abundant): 81-150   P (present): 10-40   x (none): 0

Sample ID	Foraminifera	Ostracods	Echinoderm fragment	Ophiuroid fragment	Crinoid stem fragment	Micro-gastropod	Micro-bivalve	Fish tooth	Holothurian	Shell fragments	Trace fossil	Quartz	Calcite	Muscovite	Biotite	Pyrite	Carbonaceous material	sandstone
TB 05	A	A	x	x	x	R	C	x	P	x	R	x	R	C	P	P	R	x
TB 04	P	C	R	A	x	P	R	x	P	R	R	x	x	C	P	R	R	x
TB 03	x	x	x	x	x	x	x	x	x	x	x	C	x	P	P	x	C	P
TB 02	x	x	x	x	x	x	x	x	x	x	x	S	x	P	P	x	R	x
TB 01	x	x	x	x	x	x	x	x	x	x	x	S	x	P	P	x	x	x

APPENDIX K

White Park Bay processed samples

	Colour Index:		Processed for micrfossils				
	1 = white		HP: hydrogen peroxide				
	2 = light grey						
	3 = olive grey						
	4 = blueish grey						
	5 = dark grey						
	6 = black						
Sample	Lithology	Colour	Processed (method)	Initial weight (g)	Final weight (g)	Fraction	Weight picked (g)
WPB 07	Calcareous mudstone	4	HP	104	42	1/16	6.50
WPB 06	Calcareous mudstone	4	HP	99	38	1/16	6.19
WPB 05	Calcareous mudstone	4	HP	60	14	1/8	7.50
WPB 04	Mudstone	4	HP	55	18	1/8	6.88
WPB 03	Calcareous mudstone	4	HP	70	16	1/8	8.75
WPB 02	Calcareous mudstone	4	HP	29	5	1/4	7.25
WPB 01	Calcareous mudstone	4	HP	74	30	1/16	4.63

White Park Bay fossils and minerals data

S (super-abundant): >150			C (common): 41-80			R (rare): 1-9
A (abundant): 81-150			P (present): 10-40			x (none): 0

Sample ID	Foraminifera	Ostracods	Echinoderm fragment	Ophiuroid fragment	Crinoid stem fragment	Micro-gastropod	Micro-bivalve	Fish tooth	Holothurian	Shell fragments	Trace fossil	Quartz	Calcite	Muscovite	Biotite	Pyrite	Carbonaceous material	glauconite	sandstone
WPB 07	C	x	R	x	x	x	x	x	x	R	R	x	R	A	C	R	R	x	x
WPB 06	C	P	x	x	x	R	x	x	x	C	R	P	R	P	R	R	x	R	x
WPB 05	A	C	R	x	x	x	R	x	x	R	R	R	P	A	C	R	R	x	x
WPB 04	A	P	R	R	x	R	R	x	R	R	R	R	R	P	P	P	R	x	x
WPB 03	A	P	x	x	x	R	x	x	R	R	R	x	R	C	P	R	P	x	x
WPB 02	C	P	x	R	x	x	x	x	P	R	R	R	R	C	P	x	R	x	x
WPB 01	S	C	R	R	x	R	x	x	C	x	x	x	R	C	P	x	R	x	x