

# Uppermost Triassic to Lower Jurassic sediments of the island of Ireland and its surrounding basins

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1 Uppermost Triassic to Lower Jurassic sediments of the island of Ireland and its surrounding basins.

2

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4

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10

## 11 **Abstract**

12 The uppermost Triassic to Lower Jurassic interval has not been extensively studied across the island  
13 of Ireland. This paper seeks to redress that situation and presents a synthesis of records of the  
14 uppermost Triassic and Lower Jurassic from both onshore and offshore basins as well as describing  
15 the sedimentological characteristics of the main lithostratigraphical units encountered. Existing data  
16 have been supplemented with a re-examination and logging of some outcrops and the integration of  
17 data from recent hydrocarbon exploration wells and boreholes. The Late Triassic Penarth Group and  
18 Early Jurassic Lias Group can be recognised across the Republic of Ireland and Northern Ireland. In  
19 some onshore basins, almost 600 m of strata are recorded, however in offshore basins thicknesses in  
20 excess of two kilometres for the Lower Jurassic have now been recognised, although little detailed  
21 information is currently available. The transition from the Triassic to the Jurassic was a period of  
22 marked global sea-level rise and climatic change (warming) and this is reflected in the  
23 lithostratigraphical record of these sediments in the basins of Northern Ireland and offshore basins  
24 of the Republic of Ireland. In general, the sediments of this interval are thicker than those in Great  
25 Britain and have potential for detailed study of climatic and sea-level fluctuation.

26

27 **KEYWORDS:** *Stratigraphy, Basins, Ireland, Triassic, Jurassic, Penarth Group, Lias Group.*

28

## 29 **1. Introduction and geological setting**

30 Onshore records of uppermost Triassic and Lower Jurassic rocks on the island of Ireland are  
31 restricted to narrow outcrops around the coasts of counties Antrim and Londonderry in  
32 Northern Ireland that have been much affected by Holocene and Recent landslip. Inland

33 from the coastal sections the Triassic–Jurassic rocks are usually concealed beneath  
34 Cretaceous chalk, Paleogene lavas and locally Oligocene clays and lignites. The thickest and  
35 most complete onshore records of uppermost Triassic and Lower Jurassic sediments are  
36 from deep boreholes that have penetrated the younger cover rocks. Large parts of the  
37 concealed basins remain unexplored and so our understanding of the nature, extent and  
38 palaeogeography of the Late Triassic and Early Jurassic in this region is somewhat  
39 constrained. This lack of knowledge is compounded by the absence of detailed studies in  
40 recent years, an important exception being the study of the Larne foreshore (Simms &  
41 Jeram, 2007). However, a growing number of cores have become available (Boomer *et al.*  
42 202Xa, 202Xb, Raine *et al.* 202X) and further outcrops described (Raine *et al.* 202X) the  
43 results of these are included in the current volume. Uppermost Triassic and Lower Jurassic  
44 sediments are both widespread and thickly developed in a number of the offshore basins  
45 around the island of Ireland, particularly in the Republic of Ireland and these are also  
46 detailed below. The principal focus of this study is to outline the lithostratigraphic  
47 framework and sedimentological characteristics of onshore strata (principally occurring in  
48 Northern Ireland) in light of new records and to set this in the context of the individual  
49 basins and their wider relationship with offshore basins. The interval suffers from an  
50 absence of continuous faunal records and integration of ammonite biostratigraphy,  
51 calcareous microfossils, palynology and geochemistry with the sedimentology and  
52 lithostratigraphy will be required to unpick events within this interval.

53 The basin configuration during the Late Triassic and Early Jurassic across the north of the  
54 island of Ireland largely follows the configuration of pre-existing Permo-Triassic rift basins,  
55 located onshore and offshore around the island (Figure 1). Comparing Jurassic sediment  
56 thicknesses between different areas suggests that it was a time without major differential  
57 fault movement between the basins. It is not known to what extent the gravity highs  
58 between the Larne and Lough Neagh basins and the Lough Foyle and Rathlin basins (Figure  
59 2), or the basement rocks along the Highland Border influenced sedimentation at this time.  
60 Sediment thickness and facies variation between the Magilligan Borehole (Bazley *et al.*  
61 1997) (central Lough Foyle Basin) and onto the gravity high do not appear to vary much but,  
62 towards the south, the unconformity with Upper Cretaceous rocks (Chalk Group)  
63 progressively cuts out the Lias Group, Penarth Group, Mercia Mudstone Group and much of

64 the underlying Sherwood Sandstone Group, suggesting that there was pronounced uplift  
65 and tilting of this area during the Early Cretaceous. Cretaceous strata have been shown to  
66 progressively onlap the Highland Border Ridge (HBR) (Fletcher, 1977) and the only other  
67 Mesozoic aged rocks found across the border ridge are small outcrops of the Triassic  
68 Sherwood Sandstone Group. Jurassic sediments may be preserved within several small  
69 NNE–SSW graben (identified by gravity data) that cross the HBR, but they have not yet been  
70 explored by drilling. The only boreholes drilled over the HBR have recorded either Ulster  
71 White Limestone Formation of the Chalk Group or Sherwood Sandstone Group (GSNI  
72 unpublished records). If the Rhaetian and Hettangian/Sinemurian seas did not extend over  
73 the HBR, then a connection may have been established via what is now the offshore part of  
74 the Larne Basin.

75 Sedimentation during this interval was constrained by the marine inundation of a number of  
76 pre-existing basins as a result of continued sea-level rise and / or thermal subsidence on the  
77 edge of what is known as the Irish Massif. The extent of the sea in this area during the Late  
78 Triassic and Early Jurassic is somewhat speculative, with Naylor and Shannon (1982) and  
79 Ziegler (1990) having proposed that the whole of the island of Ireland was emergent during  
80 this time, and Naylor (1992) having shown a series of emergent areas on his  
81 paleogeographic reconstruction.

82

83 In Northern Ireland, uppermost Triassic and Lower Jurassic rocks are restricted to the  
84 Permo-Triassic rift basins (Rathlin, Lough Foyle, Larne and Lough Neagh). Of these, the  
85 Rathlin, Lough Foyle and Larne basins extend offshore, whilst the Lough Neagh Basin is  
86 located entirely onshore. The Larne and Lough Neagh basins are separated by a NW–SE  
87 trending interbasinal high (Figure 1) and these two basins are separated from the Rathlin  
88 and Lough Foyle basins to the north by a more pronounced basement high, dominated by  
89 Dalradian metasediments, representing a continuation of the HBR from Scotland.

90

91 As in other parts of the UK, the uppermost Triassic and Lower Jurassic succession in  
92 Northern Ireland can be divided into the Penarth Group and the Lias Group (Warrington,  
93 1997). The Penarth Group is a Triassic aged unit of fine-grained siliciclastic sediments, with

94 some carbonate-rich intervals deposited in a range of restricted marine and marginal  
95 marine to brackish environments. The Lias Group is represented by Jurassic open marine,  
96 blue-grey claystones and siltstones, with fossils abundant locally.

97

98 Beyond the confines of these basins, Jurassic rocks are encountered onshore in Ireland at  
99 only two locations. At Cloyne, near the city of Cork, clays infilling a karstic depression in the  
100 Carboniferous limestone yielded a palynoflora that indicates a late Early Jurassic to Mid-  
101 Jurassic age (Higgs and Beese, 1986). At Piltown, County Kilkenny, clastic sediments  
102 intercepted by exploratory boreholes into karstified Carboniferous limestones yielded a  
103 palynoflora indicating a Late Jurassic to Early Cretaceous (Kimmeridgian to Berriasian) age  
104 (Higgs and Jones, 2000).

105

106 Lias Group and Penarth Group sediments are extensively developed in offshore basins to  
107 the east and south of Ireland, including the Kish Bank, North and South Celtic Sea basins and  
108 the Fastnet Basin (Dobson and Whittington, 1979; Shannon, 1995; Ewins and Shannon 1995;  
109 Kessler and Sachs, 1995; Murphy and Ainsworth, 1991) basins. Well-developed successions  
110 of the Lias Group span the Hettangian to Toarcian interval and are overlain, in the North  
111 Celtic Sea Basin, by marine Middle Jurassic sediments (Aalenian–Bathonian). Sedimentation  
112 in some of these depositional areas continue uninterrupted into the UK offshore area, for  
113 example the UK part of the South Celtic Sea Basin, the St George’s Channel Basin and the  
114 Bristol Channel Basin (Tappin *et al.*, 1994). Thick Lower Jurassic successions are also present  
115 in the western offshore Ireland areas, including the Goban Spur (Colin *et al.*, 1992),  
116 Porcupine (Croker and Klemperer, 1989), Slyne, Erris and Donegal basins (Trueblood, 1992;  
117 Dancer *et al.*, 1999, 2005; Stoker *et al.*, 2017; Tate and Dobson 1989). Penarth Group  
118 successions are also proven in many of these basins although they are not well documented.

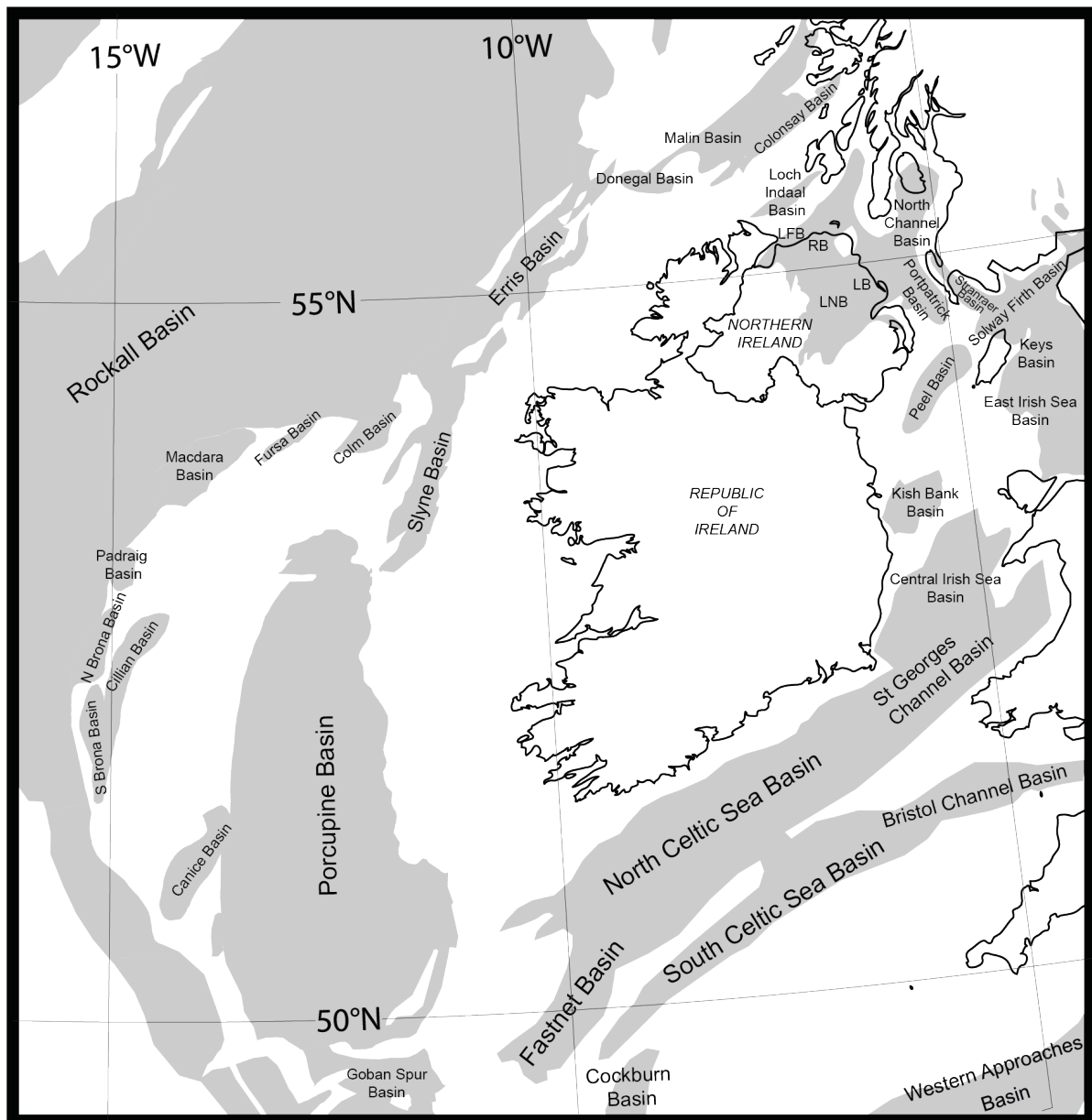
119

120 It should be noted that for the Republic of Ireland offshore area no formalised  
121 lithostratigraphic nomenclature exists. At the time of writing a new lithostratigraphic  
122 scheme is being developed by a consortium of companies led by Merlin Energy Resources

123 Ltd (hereafter referred to as Merlin, in prep) as part of a regional study commissioned by  
124 the Petroleum Affairs Division (PAD) and the Petroleum Infrastructure Programme ('PIP') of  
125 the Republic of Ireland government. The results will be published in 2020, but had not been  
126 released at the time of writing of the current publication. This new scheme will define a new  
127 lithostratigraphic (and biostratigraphic and sequence stratigraphic) scheme for the whole of  
128 offshore Ireland. For the Penarth and Lias groups new formations and members will be  
129 defined, but some existing UK onshore terms will also be retained in certain instances. In the  
130 current paper, therefore, recourse has to be made to the several informal lithostratigraphic  
131 schemes that exist for the area pending the publication of the new Merlin – PAD scheme.

132

133 On the UK Continental Shelf Triassic to Early Jurassic rocks are located within the Rathlin and  
134 Foyle basins that extend up the sound of Jura between Islay and the Mull of Kintyre. A small  
135 area of Triassic and Jurassic sediments also occurs within a NW-trending half graben called  
136 the Loch Indaal Basin (Figure 1), thickening toward the NW and bounded by the Leannan –  
137 Loch Gruinart fault system (Evans *et al.*, 1980).



138

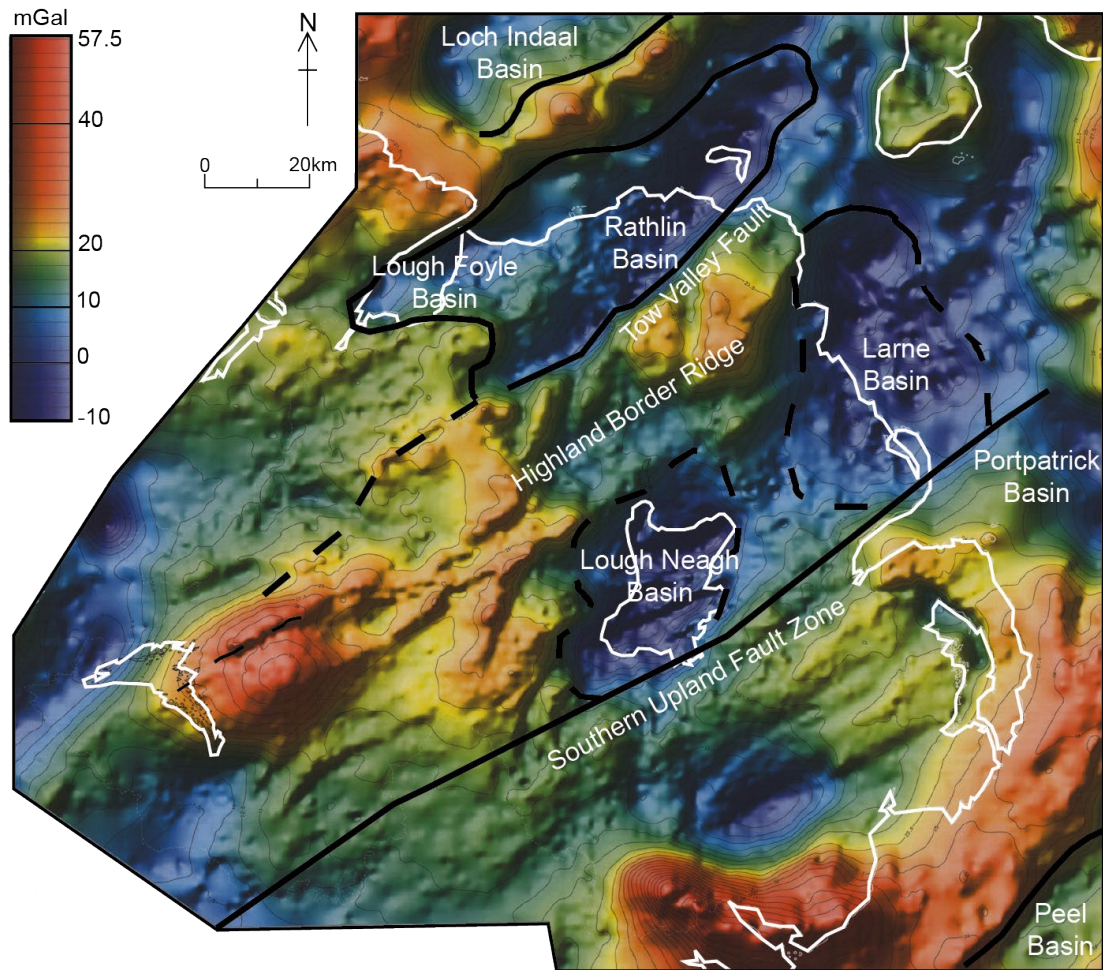
139 Figure 1. Location map showing the basins in and surrounding the island of Ireland. LB Larne

140 Basin, LNB Lough Neagh Basin, RB Rathlin Basin, LFB Lough Foyle Basin. Diagram is based on

141 offshore Republic of Ireland data from the Petroleum Affairs Division, while data on other

142 basins is based on McClean, 1978; Fyfe et al., 1993. For a more detailed representation of

143 the basin configuration in Northern Ireland see Figure 2.



144

145

146 Figure 2. Bouguer gravity anomaly data covering the NE of the island and with annotations  
147 showing the location of the sedimentary basins. Colour-filled/line contours of the observed  
148 values. Shaded-relief illumination from the north-west. Amended after Carruthers *et al.*,  
149 (1997).

150 In the offshore Republic of Ireland, a similar depositional style is apparent, with areas of  
151 thick Triassic sedimentation also being the locations of thick Lower (and Middle) Jurassic  
152 successions. The thickest known developments of the Lower Jurassic in offshore Ireland are  
153 in the most basinal part of the North Celtic Sea Basin area, in Quadrant 50, where more than  
154 2134 m [7000 ft] of Lower Jurassic section is proven by hydrocarbon exploration wells  
155 drilled in the area.

156



157 The preservation of Triassic and Lower–Middle Jurassic sediments in offshore Republic of  
158 Ireland basins is affected by two significant unconformities; one at the base of the Upper  
159 Jurassic (Tate and Dobson, 1989) and a further break, of large magnitude, at the base of the  
160 preserved Cretaceous. This may correlate with the ‘mid and late Cimmerian events’  
161 described from Northern Ireland (Naylor *et al.*, 2003; Green *et al.*, 2000).

162

163 In basins to the east and south east of Ireland a further major unconformity, at the base of  
164 the Gault Formation (Late Albian), also truncates Lower Jurassic strata. This latter  
165 unconformity also has expression in southern England. These unconformities are developed  
166 extensively across offshore Ireland and are responsible for the significant truncation of  
167 Lower Jurassic strata in all offshore basins in which rocks of this age were deposited (see  
168 below for details). Each of these breaks clearly corresponds to a major structural change in  
169 the tectonic evolution of the offshore Ireland area.

## 170 **2. Basin records**

### 171 *2.1. Onshore basins*

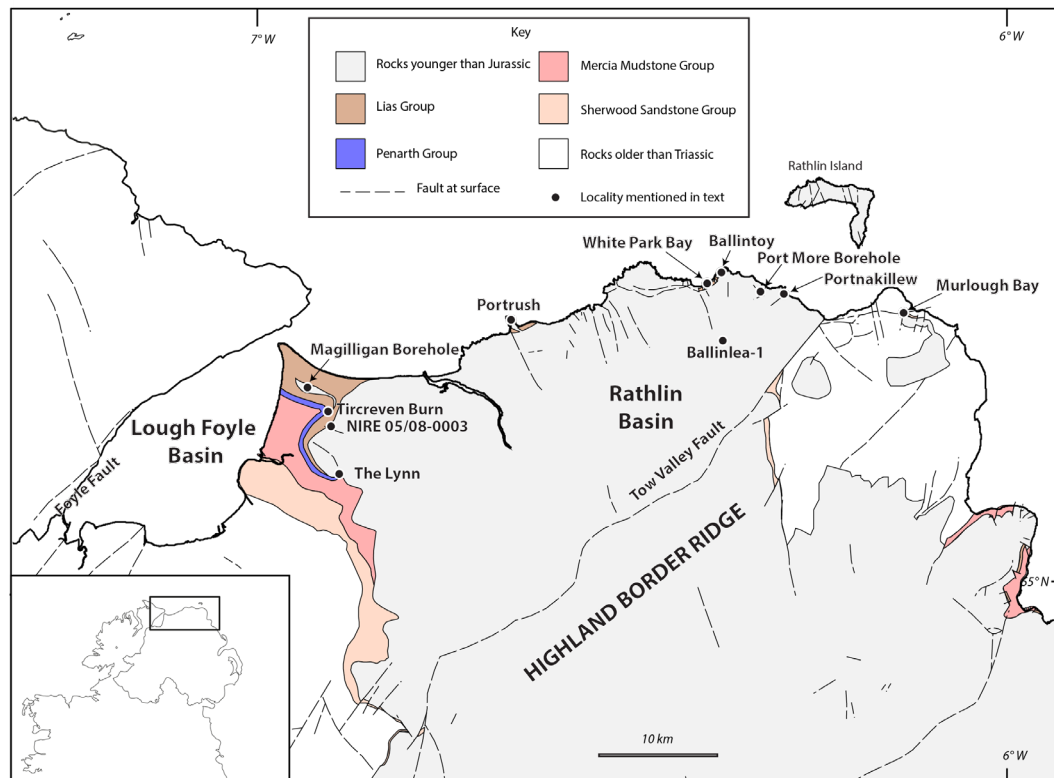
#### 172 *2.1.1. Rathlin and Lough Foyle basins*

173 The Rathlin and Lough Foyle basins form two opposing NE–SW trending half grabens. The  
174 Lough Foyle Basin is of more limited extent, but both basins extend offshore, and the Rathlin  
175 Basin extends beneath Rathlin Island and the Malin Shelf towards the Isle of Islay and the  
176 Sound of Jura (Figure 1). The Rathlin Basin formed through regional shear and stress during  
177 the late-Palaeozoic Variscan orogeny, which reactivated the Caledonian Tow Valley Fault  
178 (Figure 2), and the ensuing normal and dextral strike-slip faulting resulted in the formation  
179 of a rift basin later filled by a succession of sediments to form the Rathlin Basin. The  
180 opposing Lough Foyle rift basin is located to the NW and stretches into County Donegal in  
181 the Republic of Ireland and is defined by downfaulting on the Foyle Fault (Figure 2).  
182 Together the basins have, in previous literature, been termed the 'Rathlin Trough' (Dobson  
183 and Evans, 1974) or Rathlin Basin (Warrington, 1997). Onshore, the basin is partially covered  
184 by Paleogene basalts, which comprise the surface geology, whereas offshore the basalts are  
185 largely absent and rocks of Triassic to Cretaceous age lie at the sea bed.

186 Onshore exposures of uppermost Triassic and Lower Jurassic rocks in the Rathlin Basin are  
187 scarce and comprise a few small outcrops (Figure 3), such as at Portnakillew [55° 13' 31.0"  
188 N; 6° 17' 18.3" W], Ballintoy [55° 14' 32.7" N; 6° 22' 19.6" W], White Park Bay [55° 14' 5.5"  
189 N; 6° 23' 29.8" W] and Portrush [55° 12' 34.5" N; 6° 39' 17.5" W]. In the Lough Foyle Basin,  
190 only three principal outcrop localities (Tircreven Burn [55° 7' 49.6" N; 6° 53' 54.7" W],  
191 Tircorran stream section [55° 5' 31.1" N; 6° 55' 0.5" W] and The Lynn [55° 5' 36.0" N; 6° 53'  
192 20.0" W]) expose rocks of this age (Bazley *et al.*, 1997) (Figure 3). Subsurface records from  
193 the basins are better and include the Port More Borehole that was drilled in 1965–7 on a  
194 gravity low (Wilson and Manning, 1978) and the Ballinlea-1 well, drilled in 2008 in search of  
195 hydrocarbons in the Rathlin Basin (Boomer *et al.*, 202X). The Lough Foyle Basin has been  
196 examined by the Magilligan Borehole (spudded 1963) and by some recent mineral  
197 exploration boreholes (Raine *et al.*, 202X). In several locations across the basins significant  
198 dolerite and basalt sills (up to 223 m in thickness) have been encountered in the upper  
199 Triassic and Lower Jurassic strata, for example in the Port More (Wilson and Manning, 1978)  
200 and Magilligan (Bazley *et al.* 1997) boreholes and the Ballinlea-1 well. Bazley *et al.* (1997)  
201 estimated a maximum thickness of 180 m of Jurassic sediments in the Lough Foyle Basin by  
202 combining the thickness in the Magilligan Borehole of 74 m and 52 m in the Tircreven Burn  
203 section.

204

205



206  
207

208 Figure 3. Map showing the area of the Rathlin and Lough Foyle basins and the distribution of  
209 Triassic and Jurassic rocks at surface. The locations and boreholes mentioned in the text are  
210 shown. The outcrop width of the Penarth Group has been exaggerated slightly. Based on  
211 Geological Survey of Northern Ireland (1997).

212

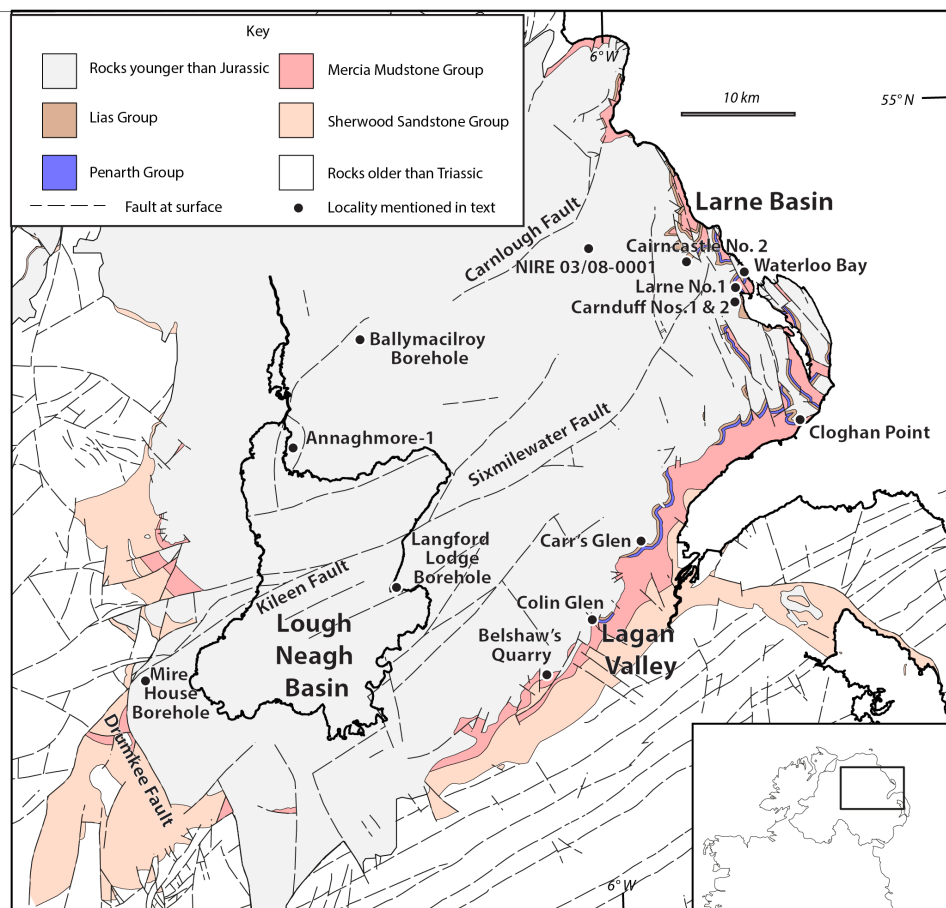
### 213 2.1.2. Larne Basin

214 The Larne Basin (Figures 1 and 2) lies in the Midland Valley terrane that stretches from SW  
215 Scotland across to Northern Ireland, with a large part of the basin located offshore in the  
216 North Channel between Northern Ireland and Scotland. The basin is oriented NE–SW and  
217 the thickness of Carboniferous to Cenozoic strata increases westward. Onshore, the basin is  
218 divided by the NE–SW-trending Sixmilewater Fault. Extension that was oriented ENE–WSW  
219 was followed in the Late Triassic and Early Jurassic with post-Early Jurassic to Late  
220 Cretaceous minor subsidence and uplift, resulting in a major erosional unconformity  
221 between the Lower Jurassic Waterloo Mudstone Formation and the Upper Cretaceous  
222 Hibernian Greensand Formation and Ulster White Limestone Formation (Shelton, 1997).

223

224 uppermost Triassic and Lower Jurassic strata are found throughout the basin and were  
 225 initially described by Tate (1867), who focused on the Waterloo Bay [54° 51' 37" N, 5° 48'  
 226 23" W] foreshore section at Larne (Figure 4). Later, that section together with a number of  
 227 smaller localities in the basin were described more fully by Ivimey-Cook (1975) and the  
 228 nearby 1962–3 Larne No.1 Borehole by Manning and Wilson (1975). There have  
 229 subsequently been a number of other deep boreholes in the basin, Larne No.2 (which  
 230 commenced in the Mercia Mudstone Group), Ballytober No. 1 (encountered the Lias Group  
 231 but recorded no Penarth Group), Cairncastle No. 2 (recorded both Lias Group and Penarth  
 232 Group and cored the upper part of the Lias Group), Carnduff No. 1 and Carnduff No. 2 cored  
 233 the Lias and Penarth groups in full. At outcrop at Waterloo Bay, Larne, the Upper Triassic  
 234 and Lower Jurassic rocks are well exposed (Simms and Jeram, 2007).

235



236

237 Figure 4. Map showing the distribution of Triassic and Jurassic rocks across the Lough Neagh  
 238 and Larne basins and into the present day Lagan Valley area. The outcrop localities and

239 borehole/well locations that are discussed in the text are shown. The thickness of the  
240 Penarth and Lias groups are exaggerated on the map to make them more visible. Based on  
241 Geological Survey of Northern Ireland (1997).

242

### 243 2.1.3. Present day Lagan Valley area

244 Between the Larne and Lough Neagh basins is the present-day Lagan Valley (Figure 4),  
245 bordered to the south by the Ordovician and Silurian low-grade metasediments of the  
246 Down–Longford Massif. The Upper Triassic and Lower Jurassic are intermittently preserved  
247 beneath the Cretaceous rocks along the Lagan Valley at the margins of the Antrim Plateau,  
248 for example at Colin Glen [54° 34' 46.4'' N, 6° 2' 10.9'' W] and Carr's Glen [54° 35' 38.0'' N,  
249 5° 57' 54.3'' W] (Figure 4). Only a few tens of metres are preserved at most but some stream  
250 sections expose both the uppermost Triassic and the Lower Jurassic. Early literature  
251 described the sections in and around the vicinity of Belfast at Colin Glen (the type section  
252 for the differently spelled Collin Glen Formation) and other small exposures (Tate, 1864;  
253 Lamplugh *et al.*, 1904). Other sections, such as at Belshaw's Quarry [54° 32' 14.9'' N, 6° 6'  
254 6.3'' W] show the Ulster White Limestone (Cretaceous) resting on the Mercia Mudstone  
255 Group.

256

### 257 2.1.4. Lough Neagh Basin

258 The Lough Neagh Basin is the deepest of the Permo-Triassic basins in Northern Ireland  
259 (Figure 2). The lough itself has restricted the collection of seismic profiles and drilling and  
260 hence most, of our knowledge on the structure of this basin has come from gravity data and  
261 a few deep boreholes around the margins of the lough (Figure 4). In the basin, Upper  
262 Triassic and Lower Jurassic sediments are largely concealed by Cretaceous limestones,  
263 Paleogene basalts, and Oligocene claystones and lignites. The asymmetric form of the basin  
264 is structurally controlled along its southern flank by northeast–southwest trending faults  
265 and resembles the southern part of the Rathlin Basin. Gravity modelling (Carruthers *et al.*,  
266 1997) predicted a total basin depth of almost 4 km. The stratigraphy of the basin has been  
267 tested in the Ballymacilroy and Langford Lodge boreholes, which both encountered Upper

268 Triassic and/or Lower Jurassic rocks. Much of the Upper Triassic and Lower Jurassic strata in  
269 this basin have been removed along the basin margin and so its thickness and distribution in  
270 the subsurface is poorly understood.

271

272 At the basin margin the Cretaceous strata rest directly on the Mercia Mudstone and  
273 Sherwood Sandstone groups and there is no outcrop of the Lias Group. In the subsurface,  
274 towards the south west margin of the basin, the Mire House Borehole penetrated 134.72 m  
275 of Upper Triassic and Lower Jurassic strata (Fowler *et al.*, 1961). Mire House was drilled in a  
276 gravity low, bounded to the west by the N–S trending Drumkee Fault and to the north by  
277 the ENE–WSW Kileen Fault, so it is conceivable that other thick successions may be  
278 preserved where there has not been Jurassic–Cretaceous uplift. The presence in the Mire  
279 House Borehole of a relatively thick Jurassic succession so close to the current basin margin  
280 suggests that Jurassic strata once extended beyond the main basin bounding faults. On the  
281 eastern margin of the basin the Langford Lodge Borehole, drilled on a fault-bounded  
282 interbasinal high, proved only 26.6 m of uppermost Triassic and Lower Jurassic. No other  
283 deep boreholes in the basin encountered Upper Triassic and Lower Jurassic rocks except for  
284 the Ballymacilroy Borehole, in the northern part of the basin, which proved 151 m of  
285 Jurassic (Thompson, 1979). Approximately 11 km to the south-west, on a structural high,  
286 Late Triassic to Early Jurassic sediments were absent in the Annaghmore No. 1 and  
287 Ballynamullan No. 1 wells due to erosion prior to the Late Cretaceous “late Cimmerian  
288 unconformity” (Naylor *et al.*, 2003).

289

## 290 *2.2. Offshore basins*

### 291 *2.2.1. Loch Indaal Basin*

292 The Loch Indaal Basin (Figure 2), a half graben, contains NW-dipping Permo-Triassic rocks  
293 capped by an unknown thickness of Jurassic rocks. In total there may be up to 2.5 km of  
294 sediment in the basin (Evans *et al.*, 1980; Fyfe *et al.*, 1993). Uppermost Triassic and Lower  
295 Jurassic sediments were proven in the Loch Indaal Basin by shallow boreholes 75/41, 75/44

296 (Evans *et al.*, 1980; Warrington 1997). The borehole 75/41 encountered 12.57 m of Penarth  
297 Group (Fyfe *et al.*, 1993). Borehole 75/44 penetrated 15.15 m of Lias Group sediments.

298

#### 299 2.2.2. Offshore Rathlin, Lough Foyle and Larne basins

300 There is little information on the offshore parts of these basins (Figure 2). There are some  
301 seismic lines that might allow the structure to be evaluated, but only a few shallow cores  
302 have been collected. The seabed across most of the offshore part the Larne basin is of  
303 Triassic strata but one of us [IB] has recovered an Early Jurassic (Pliensbachian) calcareous  
304 microfossil assemblage of ostracods and foraminifera from a BGS seabed sample just 5 km  
305 to the NW of Rathlin Island (Figure 3) demonstrating that Jurassic sediments outcrop in  
306 some of this offshore region.

307

#### 308 2.2.3. Kish Bank Basin

309 The Kish Bank Basin was primarily a Palaeozoic (Carboniferous) to Triassic (Sherwood  
310 Sandstone and Mercia Mudstone groups) depocentre (Naylor *et al.*, 1993; Dunford *et al.*,  
311 2001). Lias Group sediments are proven only in a sea-bed sample (Dobson and Whittington,  
312 1979); however, the precise age of these sediments is poorly constrained.

313

#### 314 2.2.4. Central Irish Sea Basin

315 At least 66 m of Lias Group siltstones and claystones, of Hettangian age, are present in the  
316 Central Irish Sea Basin above thick Palaeozoic and Triassic successions (Maddox *et al.*, 1995;  
317 Maingarm *et al.*, 1999). Studies of apatite fission track (AFTA) and vitrinite reflectance (VR)  
318 by Green *et al.*, (2001) have shown however, that the basin experienced a palaeo-thermal  
319 episode in the Late Jurassic – Early Cretaceous, suggesting burial under approximately three  
320 kilometres of additional section. These strata were then subsequently removed by uplift and  
321 erosion since the Early Cretaceous (Green *et al.*, 2001).

322

#### 323 2.2.5. Celtic Sea basins

324 The North Celtic Sea Basin is structurally linked to the Fastnet Basin to the west and to the  
325 St. George's Channel, Cardigan Bay, South Celtic Sea and Bristol Channel basins to the east.  
326 These form a series of linked rift basins that extend from the offshore Ireland waters east of  
327 Ireland into the western offshore UK area. The basins in the Celtic Sea are elongate  
328 Mesozoic extensional basins with a general ENE—WSW orientation that were subject to  
329 multiple phases of rifting (Early Triassic, Early Jurassic, Late Jurassic and Early Cretaceous)  
330 and inversion (Early Palaeogene and Neogene) (Hernon *et al.*, 2017). The North Celtic Sea  
331 Basin is separated from the South Celtic Sea Basin by the Labadie Bank — Pembrokeshire  
332 Ridge basement highs.

333

334 The tectonic and sedimentary history of the area through the Mesozoic is closely related to  
335 the staged opening of the North Atlantic. The Celtic Sea basins show gross similarities to  
336 other North Atlantic basins in orientation and timing of development. Three discrete phases  
337 of extension and fault-controlled subsidence can be recognized since the basin was formed  
338 in the Permian, although timings of these phases vary between authors (Rowell, 1995;  
339 Byrne, 2015; Hernon *et al.*, 2017).

340

341 More than 2000 m of Penarth Group and Lias Group strata are proven from the many  
342 hydrocarbon exploration wells that have been drilled in the Celtic Sea basins, with the  
343 thickest developments of the Lower Jurassic in offshore Ireland in the northern part of the  
344 basin, in Quadrant 50. Wells 50/3-1 and 50/3-3, drilled by Marathon in 1976 and 1991  
345 respectively, proved a total of more than 2134 m (7000 ft) of Lower Jurassic section.  
346 Furthermore, by extrapolating from these wells onto seismic data an even deeper and  
347 thicker, as yet undrilled, area of Lower Jurassic deposition can be inferred nearby in the  
348 deepest part of this basin (see Kessler and Sachs, 1995) to the west of the UK 103/1-1  
349 Dragon gas discovery well.

350

351 Copestake *et al.* (2017) illustrated a seismic line across this area and estimated a possible  
352 thickness of around 3000 m of Lower Jurassic in this basin on the basis of extrapolation from



353 wells such as 42/21-1 and UK 103/1-1. Kessler and Sachs (1995) described the Lower  
354 Jurassic succession in the northern part of the basin, focusing on the 50/3-1 and 50/3-3  
355 wells, and illustrated the development of two significant shallow marine sandstones, the  
356 Upper Sinemurian Sandstone and Lower Sinemurian Sandstone. These correlate with  
357 sandstones of the same age that are developed in the Fastnet Basin (see below). These  
358 sandstones are overlain by a thick development of Pliensbachian and Toarcian-Aalenian  
359 claystones and mudstones in this area. The Lower Jurassic section in these two wells was  
360 illustrated also by Copestake *et al.* (2017) and correlated with two wells from the Slyne  
361 Basin, 27/4-1 and 18/20-1, based on recognition of a succession of depositional sequences (J  
362 sequences of Partington *et al.*, 1993) across the Republic of Ireland offshore area. The  
363 Penarth Group was recognised in the Celtic Sea area by Shannon (1995) and was subdivided  
364 by him into a 'Lower Marl Member' and an overlying 'Upper Limestone Member'.

365

#### 366 2.2.6. Fastnet Basin

367 The Fastnet Basin, originally defined by Robinson *et al.* (1981) is a narrow elongate Mesozoic  
368 extensional basin that is genetically related and connected to the North Celtic Sea Basin. It  
369 contains considerable thicknesses of Triassic and Jurassic strata, although significantly  
370 affected by the erosional effects of the Berriasian (Base Cretaceous) unconformity.

371

372 Murphy and Ainsworth (1991) defined an informal lithostratigraphy for the Triassic and  
373 Lower to Middle Jurassic (Aalenian) of the Fastnet Basin. For the Lower Jurassic these are, in  
374 ascending order, the Basal Liassic Claystone, Liassic Limestone Unit and Liassic Marl Unit,  
375 which span the Hettangian to earliest Sinemurian. These are overlain by the Liassic  
376 Sandstone Unit, of Sinemurian age, which is succeeded by the Liassic Shale Unit that spans  
377 the Pliensbachian to Aalenian interval. Reference wells for these units included the 56/21-1,  
378 56/21-2 and 63/10-1 hydrocarbon exploration wells. The Liassic Limestone Unit represents  
379 alternating continental (freshwater to brackish water) to marine inner shelf environments  
380 (Murphy and Ainsworth, 1991). The development of marginal marine palaeoenvironments  
381 in the Fastnet Basin during the Hettangian represents a significant departure from the usual  
382 fully marine environments of the Early Jurassic in the region and shows depositional

383 similarities with the Hettangian – Lower Sinemurian succession in the Slyne Basin (see  
384 below).

385

386 The Liassic Limestone Unit generates a strong seismic reflector and can be used for mapping  
387 in the area (Robinson *et al.*, 1981). The Liassic Sandstone Unit correlates with the Upper and  
388 Lower Sinemurian Sandstones developed in the North Celtic Sea Basin, Quadrant 50 (see  
389 above) (Ewins and Shannon, 1995).

390

#### 391 2.2.7. Cockburn Basin

392 The Cockburn Basin is another in the series of sub-parallel basins in the Celtic Sea-Western  
393 Approaches area and lies to the southwest of the Fastnet Basin. No wells or boreholes have  
394 been drilled in the basin but, based on seismic correlation, a very similar stratigraphic  
395 succession to that of the Fastnet Basin is assumed to be present as well as a major base-  
396 Cretaceous (Berriasian) unconformity that truncates the Jurassic succession (Smith, 1995).

397

#### 398 2.2.8. Goban Spur Basin

399 A Lower Jurassic (Hettangian–Toarcian) succession totalling 1220 m in thickness was proved  
400 in the only well yet drilled in the basin, 62/7-1. The stratigraphic succession is very similar to  
401 that of the Fastnet Basin and is largely claystone dominated. It terminated in Hettangian  
402 strata and thus the Triassic section in the basin is unknown, although the basin is believed to  
403 have been initiated during the Triassic (Colin *et al.*, 1992).

404

#### 405 2.2.9. Porcupine Basin

406 The Porcupine Basin lies adjacent to the continental margin of north-west Europe and is the  
407 most westerly of a series of north-south rift basins that includes the Viking Graben in the  
408 North Sea (Croker and Klemperer, 1989). Major rifting took place during the Late Jurassic  
409 but Lower Jurassic and Triassic sediments are proven by wells drilled in the northern part of  
410 the basin, 26/21-1 and 26/22-1A, although the section here is severely truncated by an

411 unconformity beneath the Upper Jurassic (Croker and Klemperer, 1989). Lower Jurassic  
412 strata are probably present further south in the main part of the basin (Johnston *et al.*,  
413 2001) although this has not yet been proven by drilling.

414

#### 415 2.2.10. Slyne Basin

416 The Slyne Basin comprises a narrow, elongate, SW–NE orientated basin north east of the  
417 Porcupine Basin that was formed in Permian-Late Jurassic times and contains up to 600 m of  
418 Lower Jurassic strata (Stoker *et al.*, 2017). The stratigraphic succession is well known from  
419 hydrocarbon exploration and development wells, including those of the Corrib Gas Field,  
420 blocks 18/20 and 18/25 (see Dancer *et al.*, 1999, 2005). Several wells penetrated thick  
421 Triassic and Lower Jurassic successions (e.g. Trueblood, 1992, Dancer *et al.*, 1999, 2005 and  
422 Pritchard, 2016). Comparisons have been made between the Lower Jurassic successions in  
423 the Slyne Basin and the Hebrides Basin, on the isles of Skye and Raasay, western Scotland  
424 (discussed in Section 5).

425

#### 426 2.2.11. Erris and Donegal basins

427 The Erris Basin is a narrow elongate, Mesozoic basin that is connected to the largely  
428 Carboniferous Donegal Basin and lies adjacent to the eastern margin of the Rockall Basin  
429 northwest of Ireland. There has been limited drilling in these basins, but the 12/13-1A  
430 hydrocarbon exploration well at the edge of the Donegal Basin and 19/5-1 in the Erris Basin  
431 have proved Carboniferous, Permo-Triassic, Lower Jurassic and Cretaceous sediments  
432 beneath a Cenozoic cover (Tate and Dobson, 1989). The Lower Jurassic section is  
433 incomplete, representing only parts of the Sinemurian and Hettangian stages in argillaceous  
434 dominated lithofacies, with the section truncated by the base-Cretaceous unconformity  
435 (Chapman *et al.* 1999; Stoker *et al.*, 2017).

436

### 437 **3. Chronostratigraphy**

438 The chronostratigraphy of these basins is based largely upon ammonite stratigraphy,  
439 particularly in onshore outcrop sections, but chronostratigraphic and biostratigraphic age

440 interpretations are based on microfossil biostratigraphy in the extensive offshore basins and  
441 in some wells drilled onshore (such as Ballinlea-1, Boomer *et al.*, 202X). Ammonites are not  
442 recovered in non-cored hydrocarbon exploration wells due to destruction of large  
443 macrofossils by the drilling process but a refined biostratigraphic scheme has been  
444 developed (e.g. Ainsworth *et al.*, 1987, 1989), based on foraminifera, ostracods and  
445 occasional dinoflagellate cysts. A recent major review of the stratigraphy of offshore Ireland  
446 will incorporate newly defined microfossil based biozonation schemes for the Late Triassic  
447 to Early Jurassic interval (Merlin, *in prep.*).

448

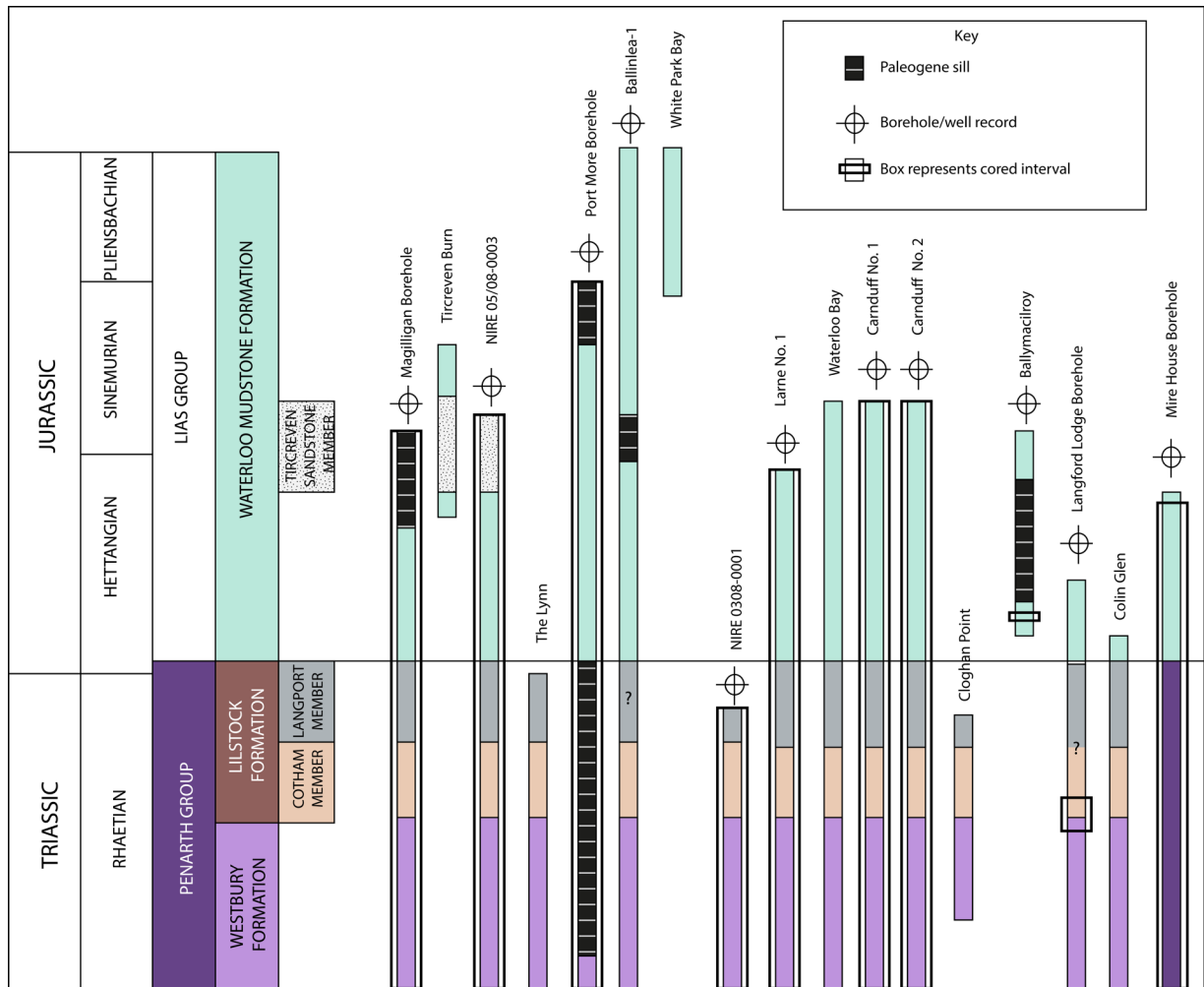
449 Ammonite stratigraphy has been published for some deep boreholes, with the most  
450 comprehensive from the Magilligan (Bazley *et al.*, 1997), Port More (Wilson and Manning,  
451 1978), Mire House (Fowler *et al.*, 1961) and Larne No. 1 boreholes (Manning and Wilson,  
452 1975). Discussion of outcrop ammonite records was presented by Warrington (1997).

453

454 The Rhaetian is present beneath most Jurassic sections. Jurassic strata in Northern Ireland  
455 range from Hettangian to Pliensbachian in age, although most sections preserve only the  
456 lower Hettangian and only on the north Antrim coast and in boreholes in the Rathlin Basin  
457 are strata as young as the Pliensbachian preserved (Figure 5). Younger strata are seemingly  
458 absent from Northern Ireland although derived fossils in a conglomerate at the base of the  
459 Cretaceous across the Highland Border Ridge indicate strata as young as Toarcian may once  
460 have been present.

461 Clasts with Upper Pliensbachian fossils have been historically reported in the glacial deposits  
462 near Ballycastle (Langtry, 1875; Gray, 1870) and Ballintoy (Tate, 1870). These reportedly  
463 resemble the Scalpay Sandstone Formation of Skye and Raasay (Inner Hebrides, Scotland)  
464 and from the block at Ballintoy a rich assemblage of fossils was obtained (Wilson and  
465 Robbie, 1966). Hartley (1933) and Savage (1963) recorded Toarcian ammonites from the  
466 basal Cretaceous conglomerate at Murlough Bay and Versey (1958) and Wilson and Robbie  
467 (1966) later recorded upper Pliensbachian ammonites from the same bed, suggesting that a  
468 more full succession of Jurassic was present in the vicinity prior to or during progradation of  
469 the Cretaceous shoreline sediments. More extensive successions are developed offshore,

470 spanning the entire Early Jurassic interval from the Hettangian to Toarcian and ranging  
 471 upwards into the Middle Jurassic.



472  
 473  
 474 Figure 5. The chronostratigraphy of outcrops, boreholes and exploration wells from onshore  
 475 basins in Northern Ireland showing the age of the sediments encountered.

476

477 **4. Lithostratigraphy of the Penarth Group**

478 The broad two-fold subdivision of the Penarth Group into the Westbury Formation and the  
 479 Lilstock Formation, as originally defined in southern England and South Wales (Warrington  
 480 *et al.*, 1980) is also applicable in Northern Ireland and to offshore areas around the island of  
 481 Ireland.

482

483 Historically, Portlock (1843) described some Late Triassic fossils from Northern Ireland,  
484 including the iconic Rhaetian bivalve *Rhaeticula contorta* (Portlock), referring to strata that  
485 are now included in the Penarth Group, but it was not until the work of Tate (1864) that  
486 these strata were placed in the 'Rhaetic', encompassing his '*Avicula contorta* shales' and  
487 overlying 'White Lias'. They continued to be termed 'Rhaetic' although it was alluded to by  
488 some authors that they could be correlated with the Westbury and the Lilstock formations  
489 elsewhere. Manning *et al.* (1970) used the divisions of 'Lower Rhaetic' and 'Upper Rhaetic'  
490 (terms that are now obsolete) for these sediments in the Belfast and Lagan Valley area.

491

492 The Penarth Group around Limavady, Co. Londonderry, was also divided into lower and  
493 upper 'Rhaetic' by Bazley *et al.* (1997) who identified a 'Lower Rhaetic' *contorta* Zone  
494 comprising dark grey mudstones thin limestones and siltstones, equivalent to the Westbury  
495 Formation, and an 'Upper Rhaetic' comprising reddish brown and pale grey calcareous  
496 mudstones attributed to the 'Cotham Beds' overlain by grey mudstones and limestones  
497 assigned to the 'Langport Beds'.

498

499 The Penarth Group is a thin but persistent unit, and remarkably constant in thickness. It  
500 ranges in thickness from 20.55 m in the Larne No. 1 Borehole (Larne Basin) to 21.64 m in the  
501 Magilligan Borehole (Lough Foyle Basin), 23.00 m (based on log response and cuttings  
502 description) in the Ballinlea-1 well (Rathlin Basin) and 20.31 m in the NIRE 05/08-0003  
503 Borehole. In the Lough Neagh Basin the Penarth Group is possibly represented by 9.75 m of  
504 marginal facies in the Mire House Borehole (Fowler *et al.*, 1961). Although a thin unit, these  
505 records from Northern Ireland are thicker than those from SW Britain, but comparable in  
506 thickness to parts of the East Midlands (Bridge *et al.*, 1998 p. 93; Old *et al.*, 1987 p.30).

507

508 In some borehole records it is not possible to differentiate individual units within the  
509 Penarth Group or assign them to the established lithostratigraphy. In the Mire House  
510 Borehole a unit between the Mercia Mudstone Group and the Lias Group may be an  
511 equivalent of part or all the Penarth Group, comprising 4.72 m of dark greenish grey soft

512 and clayey or hard fissile mudstones above 5.03 m of grey-green mudstones with quartz  
513 granules/pebbles and nodules of light grey-pink limestone (Fowler *et al.*, 1961). This rests on  
514 red and grey mottled calcareous claystones and red-brown marls attributed to the Mercia  
515 Mudstone Group. The grey-green rocks of the Penarth Group resemble the Collin Glen  
516 Formation, although it was noted that there may have been a disconformity at the top of  
517 the Mercia Mudstone Group. The presence of anhydrite in the Mercia Mudstone Group may  
518 suggest erosion down to a lower stratigraphical position and the erosion of the Collin Glen  
519 Formation, typically a green grey mudrock, might explain the resulting colour of the Penarth  
520 Group claystones. *Eotrapezium ewaldi* (Bornemann) at 746.76 m depth and *Gyrolepis* sp.  
521 from 777.01 m depth confirm a Rhaetian age and suggest correlation with the Penarth  
522 Group. No black shales are recognised in this succession but fossils within these facies  
523 suggest that the unit is a lateral equivalent of at least part of the Penarth Group.

524

525 The Langford Lodge Borehole (Manning *et al.*, 1970) was drilled in the east of the Lough  
526 Neagh Basin with very limited core recovery (just 1.0 m between 821.13–823.27 m).  
527 Perhaps 17.38 m of strata represent the Penarth Group but identifying individual units is  
528 difficult and there are discrepancies between the position of boundaries defined by wireline  
529 logs, which suggest the top is 4.5 m lower than indicated by cuttings, and gamma logs that  
530 suggest the base may be 3.05 m higher than indicated by cuttings (Manning *et al.*, 1970). In  
531 the Langford Lodge Borehole the base of the Cotham Member is possibly at 822.3 m and the  
532 boundary between the Westbury Formation and the overlying Cotham Member lies within  
533 the cored section suggesting a thickness of 6.05 m for the undifferentiated Langport and  
534 Cotham members, which includes grey to grey brown, sometimes micaceous, shales and  
535 shaley mudstone with *Eotrapezium ewaldi* and *Modiolus langportensis* (Richardson and  
536 Tutchter), and 11.33 m for the Westbury Formation, represented by black shales with  
537 *Eotrapezium concentricum?* *Protocardia rhaetica* (Merian) and *R. contorta*.

538

539 Strata assigned to the Penarth Group occur widely in offshore Irish basins but are poorly  
540 documented. The group was identified in the Celtic Sea area by Shannon (1995) and  
541 subdivided into a 'Lower Marl Member', which he correlated with the 'Rhaetian Marl Unit'

542 of Murphy and Ainsworth (1991) in the Fastnet Basin (see below), and an overlying 'Upper  
543 Limestone Member'. It is possible, however, that the 'Rhaetian Marl Unit' includes all or  
544 part of the Blue Anchor Formation of standard British Triassic nomenclature.

545

546 The Penarth Group is also present in several offshore basins that connect Ireland and the UK  
547 onshore areas, namely the Bristol Channel, St George's Channel and South Celtic Sea basins,  
548 suggesting contiguous deposition between these areas (see data in Tappin *et al.*, 1994). In  
549 the Corrib Field area (Block 18/20, Slyne Basin) Schmidt *et al.* (2006) included sediments  
550 that appear to be representative of the Penarth Group in the upper part of their Mercia  
551 Mudstone Group.

552

#### 553 *4.1. Westbury Formation*

554 The Westbury Formation is the lowest formation of the Penarth Group and, in many  
555 localities, overlies the green and red non-marine mudrocks of the Mercia Mudstone Group  
556 (Collin Glen Formation) with a sharp and erosive to somewhat gradational boundary. In  
557 some cores (Magilligan and Carnduff No. 2 boreholes) black mudstone has been injected  
558 along fractures in the underlying Collin Glen Formation. The unconformable break at the  
559 base of the Penarth Group (Westbury Formation) is comparable with that at the base of the  
560 group in south west Britain (Wilson *et al.*, 1990; Howard *et al.*, 2008; Gallois, 2009).

561

562 The top of the formation is marked by a change from black shales to light grey mudstones of  
563 the Lilstock Formation (Cotham Member). This boundary is commonly sharp, irregular and  
564 deformed, with clasts of Westbury Formation facies and fossils admixed with the Cotham  
565 Member facies.

566

567 In the Lough Neagh Basin the Westbury Formation was encountered only in the Langford  
568 Lodge Borehole. It may be 11.30 m thick here although this may be a less accurate figure  
569 than from other boreholes due to uncertainty in the cuttings and wireline picks.



570

571 One complete section has been recorded in the Lagan Valley area at Colin Glen, towards the  
572 margin of the Larne Basin, where there is probably 6.02 m of the Westbury Formation (Tate,  
573 1864). Further east and north in the Larne Basin there are many more records of the  
574 Westbury Formation, such as the Carnduff No. 2 Borehole (7.73 m), the NIRE 03/08-0001  
575 Borehole (7.17 m), the Waterloo Bay foreshore at Larne (7.29 m), and the Larne No. 1  
576 Borehole (8.28 m). In the Lough Foyle Basin 7.92 m is recorded in the Magilligan Borehole,  
577 6.38 m in the NIRE 05/08-0003 Borehole and at least 7.96 m at The Lynn. The only record  
578 from the Rathlin Basin is the Port More Borehole (660.70 to 664.77 m) but the upper part of  
579 the Westbury Formation here is obscured by a sill, below which only 4.07 m of the  
580 formation were cored with up to a further 1.22 m (the underlying uncored interval).  
581 Outcrop and borehole data from separate basins across Northern Ireland suggest that the  
582 Westbury Formation transgression was widespread across the area and sedimentation rates  
583 were relatively uniform.

584 Facies that comprise the Westbury Formation in Northern Ireland are similar to those across  
585 the rest of the UK, dominated by dark grey to black laminated claystones with subordinate  
586 siltstones, sandstones, sandy limestones and beds with low diversity shell accumulations.  
587 *Chlamys valoniensis* dominates in the sandstones, *Protocardia rhaetica* in the mudstones  
588 and *Rhaetavicula contorta* in the shales (Boomer *et al.*, 202Xb). Bioturbation is intense in  
589 the more silty and sandy intervals and at Waterloo Bay, Larne, comprises *Diplocraterion*,  
590 *Arenicolites*, *Rhizocorallium*, *Lockeia*, *Planolites*, *Cruziana* and *Teichichnus* (Boomer *et al.*,  
591 202Xb). Mudstones are generally well-laminated. Fish debris is common but no coarse bone  
592 beds containing reptile remains have been found comparable with those in the Westbury  
593 Formation of the Bristol Channel Basin.

594

#### 595 4.2. Lilstock Formation

596 Although generally richer in clastic material than elsewhere in the UK the Lilstock Formation  
597 in Northern Ireland can be similarly subdivided into two component members. Its position  
598 above the distinctive Westbury Formation and the presence of hiatus surfaces, soft  
599 sediment deformation and rare stromatolites allow correlation with the Cotham and

600 Langport members in Great Britain and hence the names are retained here. The division is  
601 primarily one where the boundary between the Cotham Member and the overlying  
602 Langport Member is gradational, but marked by a deepening of facies and an increase in  
603 bivalve diversity and carbonate content, reflecting a more open marine setting.

604

605 The Lilstock Formation is recognised across Northern Ireland but it varies in thickness and  
606 facies. In some recent papers the Cotham and Langport members in southwest Great Britain  
607 have been elevated to formation status (Gallois, 2008), but this has not been done here. In  
608 early research the strata above the black shales (Westbury Formation) and below the  
609 Waterloo Mudstone Formation, seen at Colin Glen in the Lagan Valley, was assigned by Tate  
610 (1864) to the 'White Lias'. Manning *et al.* (1970) termed it the 'Upper Rhaetic', as did  
611 Ivimey-Cook (1975), and only later were they equated with the 'Cotham Beds' by Thompson  
612 (1997) and by Bazley *et al.* (1997).

613

#### 614 4.2.1. Cotham Member

615 Although the lower boundary is sharp, the injection and mixing of Westbury Formation  
616 facies and their similar bivalve fauna suggests that there is little time gap and it is therefore  
617 largely conformable. In the lower part of the Cotham Member in NIRE 0308-0001 there are  
618 lower decimetre-scale alternations of very dark grey and light grey mudstone. Deformation  
619 of the boundary is not seen in core, but it is exceptionally well demonstrated at Cloghan  
620 Point [54° 44' 34.1", 5° 43' 6.2" W]. Identification of the Rhaetian bivalve *R. contorta* in the  
621 lowest beds of the Cotham Member (Bazley *et al.* 1997; Manning *et al.* 1970) seems to  
622 support that the lower Cotham Member is of similar age to the top of the Westbury  
623 Formation in Northern Ireland. The base of the member is readily correlated with sections in  
624 Great Britain, where dark shales are fairly abruptly succeeded by paler mudstones with soft-  
625 sediment deformation.

626

627 The upper boundary of the Cotham Member is gradational and taken at a change from  
628 rippled siltstone-claystone heteroliths, with or without carbonate, to a darker more clay

629 dominated succession, at least initially, that locally contains diagenetic carbonate beds  
630 (Simms and Jeram, 2007). Simms (2003) incorrectly assigned the upper part of the Cotham  
631 Member to the Lias Group but subsequently (Simms, 2007) revised the lithostratigraphy,  
632 extending the top of the Cotham Member upwards and distinguishing a lower and upper  
633 Cotham Member with the boundary at the mudcracked surface (4.80 m above the top of  
634 the Westbury Formation). The section was further described by Simms and Jeram (2007),  
635 who placed the top of the Cotham Member at the change from silt-dominated to darker-  
636 grey, mud-dominated sediments and at the top of a series of silty limestones (top of Bed 7  
637 of Simms and Jeram, 2007), 1.47 m above the mudcracked surface seen on the Waterloo  
638 Bay foreshore.

639

640 The Cotham Member in Northern Ireland comprises greenish grey and red-brown claystones  
641 and silty claystones, with variable amounts of coarse siltstone to fine sandstone, lenticular-  
642 bedded heterolith. The siltstone and sandstone beds comprise mm- to cm-scale wave  
643 reworked current ripples. Some beds of sandstone display mud drapes and flaser bedding.  
644 Beds of hummocky cross-stratified sandstone are noted at outcrop. In many sections and  
645 cores beds display a variety of soft sediment deformation features. These sedimentary  
646 features are widespread and enable the Cotham Member to be correlated between sections  
647 and across into Great Britain (Simms, 2003, 2007).

648

649 Fossils are noticeably less common compared to the underlying or overlying units but the  
650 Cotham Member locally contains bivalves, many of which are similar to those in the  
651 Westbury Formation. The upper parts are increasingly devoid of fossil remains, save for  
652 isolated *Euestheria* sp. and local plant fragments of *Naiadites* sp. (366.5 m in Carnduff No.  
653 2), but trace fossils on the underside of beds are indicative of interface trails and bivalve  
654 resting traces. Additionally, at one outcrop a thin stromatolite bed is seen toward the top of  
655 the member.

656

657 The Cotham Member is 6.20 m thick at Waterloo Bay and elsewhere in the Larne Basin the  
658 thickness varies from 9.51 m in the NIRE 03/08-0001 Borehole, 7.18 m in the Carnduff No. 2  
659 Borehole, approximately 7.80 m at Cloghan Point, about 7.62 m in Colin Glen (Tate, 1864)  
660 and perhaps 5.11 m in Larne No. 1 Borehole. The Cotham Member has not yet been  
661 identified in the Lough Neagh Basin while in the Rathlin Basin it is cut out by dolerite sills in  
662 the Port More Borehole and not differentiated in the Ballinlea-1 well. It is better known in  
663 the Lough Foyle Basin where it is 8.28 m thick in the Magilligan Borehole (Bazley *et al.* 1997),  
664 9.14 m in the NIRE 05/08-0003 Borehole (Raine *et al.*, 202X) and 6.28 m at The Lynn (Bazley  
665 *et al.*, 1997).

666

667 The most interesting features of the Cotham Member are a number of beds or structures  
668 that have either value in regional correlation or preserve important events in the geological  
669 history of the Late Triassic of the region. They include intervals of soft sediment  
670 deformation, a distinctive red-brown mudstone interval, a mud-cracked horizon and the  
671 presence of a microbialite.

672

673 Deformation has been recorded from sections of the Cotham Member across Northern  
674 Ireland (Tate, 1867; Ivimey-Cook, 1975; Bazley *et al.*, 1997; Simms, 2003, 2007). In the Larne  
675 Basin deformation is seen in distinct horizons and, although not recorded in the Larne No. 1  
676 Borehole by Ivimey-Cook (1975), it is clearly seen at the Waterloo Bay foreshore and in  
677 other nearby boreholes (Carnduff No. 1, Carnduff No. 2, NIRE 03/08-0001), so it presumably  
678 was missed in the description of the core. In the Rathlin Basin the same interval is deformed  
679 although the intervals appear to be less well defined, perhaps reflecting reduced contrast in  
680 the claystones, which lack silt laminae and ripples. Simms (2003) provided a comprehensive  
681 list of localities where the deformation was present.

682

683 The red-brown coloured interval in the middle of the Cotham Member was first noted by  
684 Tate (1864), at Colin Glen, and subsequently in the Larne No. 1 Borehole (Manning and  
685 Wilson 1975) and in the Lough Foyle Basin (Bazley *et al.*, 1997). The latter authors

686 commented on its superficial resemblance to the red mudstones of the Mercia Mudstone  
687 Group and also parts of the Cotham Member in Lincolnshire, eastern England. The unit is  
688 therefore widespread and can be recognised in all cores and at most outcrops, except in the  
689 Waterloo Bay foreshore section where thermal metamorphism has altered the colour  
690 making it difficult to identify.

691

692 A hiatus can be recognised in the upper part of the Cotham Member, with cracks extending  
693 down as much as 15 cm and filled with sand, capped by a 2 cm thick fine-grained wave  
694 rippled sandstone. Other sandstones below this level are swaley cross-stratified. It may  
695 correlate with other similar surfaces in South Wales and St Audrie's Bay, Somerset, England  
696 (Simms, 2003, 2007; Simms and Jeram, 2007).

697

698 The recorded presence of *R. contorta* within the red-brown mudstones from the Larne No. 1  
699 Borehole by Manning and Wilson (1975) led to them placing a large part of the Cotham  
700 Member in the Westbury Formation. Although Ivimey-Cook (1975) also examined the Larne  
701 No.1 Borehole and although he expressed doubts as to whether the borehole samples were  
702 in correct order, he did not change the placement of the boundary. This was corrected by  
703 Warrington (1997) who revised the base of the Cotham Member downward. Comparison of  
704 previous descriptions of the Waterloo Bay foreshore (Tate, 1867; Ivimey-Cook, 1975; Simms  
705 and Jeram, 2007) and Larne No. 1 Borehole (Manning and Wilson, 1975) with the boreholes  
706 at Carnduff (Boomer *et al.*, 202Xb) confirms the suggestion by Warrington (1997). With a  
707 reassignment of these brown beds to the Cotham Member it means that the Westbury is  
708 therefore 8.59 m thick (rather than 13.69 m), a similar thickness to Carnduff-2 (7.20 m),  
709 NIRE 03/08-0001 (7.19 m) and on the nearby Waterloo Bay foreshore (7.29 m).

710

#### 711 4.2.2. Langport Member

712 The lower boundary of the Langport Member is taken at the transition from ripple-  
713 laminated and banded siltstones and calcareous siltstones to darker claystones with more  
714 porcellanous and structureless limestone. The top of the member, and the top of the

715 Lilstock Formation, is marked by a change to dominantly claystone lithologies with  
716 increasing faunal diversity and is taken at a marked darkening of mudrocks and reduction in  
717 silt and mica. Simms and Jeram (2007) noted that the top of the Langport Member at  
718 Waterloo Bay was characterised by a distinctive series of thin micritic limestone beds and  
719 laminae, containing rounded and angular clasts of mudstone and abundant compacted  
720 bivalves, above which a one metre thick dark grey shaly mudstone was considered to mark  
721 the base of the Waterloo Mudstone Formation. This was revised down to below the  
722 limestones by Simms *et al.* 202X.

723

724 The Langport Member is up to 6.92 m at its thickest development, in the Larne Basin in the  
725 Carnduff No.2 Borehole and is 7.49 m thick at Waterloo Bay, Larne. In the Lough Foyle Basin  
726 it is 4.92 m thick, with the upper part possibly condensed, in the NIRE 08/05-0003 Borehole  
727 and just 2.7 km to the northwest of it in the Magilligan Borehole 5.44 m were recorded  
728 (Bazley, 1997).

729

730 Typical Langport Member lithologies in Northern Ireland include siltstone and claystone  
731 heterolith, porcellanous limestone, with common shell beds containing bivalves, largely  
732 dominated by *Protocardia rhaetica*. In the Lough Foyle Basin there is less silt and increased  
733 numbers of limestone beds throughout the member in the NIRE 05/08-0003 Borehole and  
734 were more abundant in the Magilligan Borehole core (Bazley *et al.* 1997). In NIRE 05/08-  
735 0003 these limestones are micritic in the lower part, but the top few beds (55 cm) are  
736 composed of grainstones, consisting of ooids and shell debris, with large-scale cross  
737 stratification and claystone clasts. A grainstone bed recorded from The Lynn by Bazley *et al.*  
738 (1997) when observed in thin section is a carbonate grainstone to wackestone, comprising  
739 ooids and peloids with recrystallised shell fragments. This bed may correlate with the  
740 grainstone beds in NIRE 05/08-0003 some 5.5 km to the north-northwest. In the Larne Basin  
741 however, other than the basal limestone and claystone beds, the member is siltier,  
742 comprising siltstones and silty claystones. The limestones at the base are present in the less  
743 silty part of the member and reflect a short-lived switching to facies that persisted until the  
744 base of the Waterloo Formation in the Lough Foyle Basin.

745

746 Some of the thickness variation in the Langport Member across Northern Ireland may be  
747 due either to difficulties in identifying the top of the member, erosion of its upper part, or  
748 varying accommodation space/sedimentation rates. Furthermore, since the base and top  
749 are locally gradational there may well be a degree of boundary diachroneity. Limestones  
750 that span the lower boundary complicate matters if used for correlation, as they are  
751 independent of silt content. Simms and Jeram (2007) included a series of five limestones  
752 immediately above the mud-cracked layer on the Waterloo Bay foreshore section in the  
753 upper part of the Cotham Member. In the Lough Foyle Basin, the Langport Member is  
754 carbonate-rich and the Cotham Member is carbonate-poor, but in the Larne Basin,  
755 carbonate beds straddle the boundary. There is a bed in the Waterloo Bay section at which  
756 there is a sharp change to darker grey mudrocks and structureless limestones. Ripple cross-  
757 laminated siltstone beds are absent above the boundary and only appear again higher up  
758 the section. This change can also be seen in the Carnduff No. 1 and No. 2 cores, but it is  
759 more subtle at Cloghan Point.

760

## 761 **5. Lithostratigraphy of the Lias Group**

762 The Lias Group in Northern Ireland is represented by a clay-dominated succession assigned  
763 to a single lithostratigraphic unit, the Waterloo Mudstone Formation. It ranges from the  
764 Hettangian to Early Pliensbachian in age and, wherever present, it conformably overlies the  
765 Penarth Group. Offshore the Lias Group is widespread around the island of Ireland.  
766 Variations in lithofacies, both laterally and vertically, through the Hettangian to Aalenian  
767 allow subdivision into a number of formations and members, several of which have been  
768 informally defined (e.g. Millson (1987) in the Celtic Sea area and Murphy and Ainsworth  
769 (1991) in the Fastnet Basin). Comparisons have been drawn between the Slyne Basin,  
770 offshore western Ireland, and the Hebrides Basin (e.g. Trueblood, 1992) with  
771 lithostratigraphic terms from the latter being applied to the former basin pending a new  
772 lithostratigraphic scheme for offshore Ireland (Copestake *et al.*, 2017; Merlin, *in prep*).  
773 Hebridean terms that have in the past been used in the Slyne Basin include the Broadford  
774 Beds (Hettangian—Sinemurian), Pabay Shale, Scalpay Sandstone (Pliensbachian) and

775 Portree Shale (Toarcian) formations, as illustrated by the 27/13-1A well (Trueblood, 1992;  
776 Trueblood and Morton, 1991).

777

778 In addition, an Upper Sinemurian sandstone unit, which was penetrated in the 27/4-1 well  
779 has been termed the 'Suisnish Sandstone' (Pritchard, 2016), after a sandstone of equivalent  
780 age on the Isle of Skye. However, it is unlikely that the two sandstone units are actually  
781 contiguous and a new name will soon be published for the Slyne Basin sandstone member  
782 (Merlin, in prep) as well as for some of these other formations that probably are not true  
783 correlatives of the Hebrides Basin units. The 'Suisnish Sandstone' in the Slyne Basin  
784 correlates approximately with the 'Upper Sinemurian Sandstone' of the North Celtic Sea  
785 Basin (Kessler and Sachs, 1995).

786

787 Strata assigned to the 'Broadford Beds' by some authors in the Slyne Basin (see above) were  
788 deposited in non-marine to marginal marine environments, as indicated in particular by the  
789 development of anhydrites. This is quite different from the fully marine 'Broadford Beds' of  
790 the Hebrides Basin (see Hesselbo *et al.*, 1998; later renamed as the Breakish and Ardnish  
791 formations, see Morton, 2004). For this reason, this unit, as developed in the Slyne Basin,  
792 will be given a new name in the Merlin (in prep.) scheme.

793

794 The Lower Jurassic succession in two wells from the Slyne Basin, 27/4-1 and 18/20-1, was  
795 illustrated by Copestake *et al.* (2017), together with seismic lines through these wells. The  
796 latter well will become a type well in the new lithostratigraphic scheme to be published for  
797 offshore Ireland (Merlin, in prep.). This scheme will fully discuss the comparisons between  
798 the Hebridean Basin Jurassic stratigraphy and that of offshore Ireland, as well as with other  
799 areas of Jurassic development in the UK region, such as the western UK offshore areas (as  
800 described by Tappin *et al.*, 1994) and UK onshore basins. In the new scheme, some  
801 established UK terms will be utilised where appropriate, whereas in some cases new  
802 nomenclature will be introduced.

803



## 804 **5.1. Waterloo Mudstone Formation**

805 The Waterloo Mudstone Formation ranges in age from Early Hettangian to Early  
806 Pliensbachian. The stratigraphic top of the Waterloo Mudstone Formation (Mitchell, 2004)  
807 in Northern Ireland has not yet been encountered, probably removed by erosion across the  
808 island. Only Pliensbachian or older strata are preserved (Figure 5) here, whereas younger  
809 strata are preserved in basins across the Hebrides (Fyfe *et al.*, 1993). At some localities the  
810 Lias Group is entirely absent where Cretaceous rocks rest unconformably on Triassic or older  
811 strata.

812

813 With the exception of the limestones occurring in the lower part of the formation in the  
814 Larne Basin, the base of the Waterloo Mudstone Formation represents a change to a more  
815 clay-dominated, more bioturbated and generally darker grey facies than the underlying  
816 Lilstock Formation. The formation is also marked by a more diverse fauna than that of the  
817 underlying Penarth Group, reflecting more open marine deposition. At the Waterloo Bay  
818 foreshore section a one metre thick shaly mudstone may correlate with the 'paper shale' at  
819 the base of the Lias Group (Blue Lias Formation) in the Bristol Channel Basin (Simms and  
820 Jeram, 2007). The boundary with the underlying Penarth Group in the Rathlin and Lough  
821 Foyle basins is taken at the base of claystones that are less micaceous than those of the  
822 upper Penarth Group with an increasing abundance of marine indicators, including crinoids,  
823 bivalves and *Thalassinoides* and *Teichichnus* burrows.

824 What remains of the Waterloo Mudstone Formation is up to 605 m thick (seen at Ballinlea-  
825 1, Boomer *et al.*, 202X), although most boreholes and outcrops record much less. In the  
826 Lough Foyle Basin Bazley *et al.* (1997) estimated a maximum thickness of 180 m, deduced  
827 from thicknesses in the Magilligan Borehole (74 m) and Tircreven Burn (52 m). Additional  
828 borehole data, that includes the whole Tircreven Sandstone Member as a reference point,  
829 confirms this estimate, with 167.2 m of Lias Group strata recorded from the NIRE 0508/0003  
830 Borehole and Tircreven Burn.

831

832 In the north of the Lough Neagh Basin, the Ballymacilroy Borehole penetrated 151 m of  
833 Waterloo Mudstone Formation above a Paleogene sill (Thompson, 1979). No ammonites  
834 were recovered but bivalves, crinoids and echinoid spines suggest a Hettangian age while  
835 foraminifera and ostracods indicate that the succession is Hettangian to Early Sinemurian in  
836 age, and most typical of the Bucklandi Zone (Thompson, 1979). To the southwest of this  
837 borehole, at the SW margins of the Lough Neagh Basin, the Mire House Borehole  
838 penetrated 124.97 m of Waterloo Mudstone Formation. Records from elsewhere in the  
839 basin are sparse and in the east of the Lough Neagh Basin only the Langford Lodge Borehole  
840 encountered Waterloo Mudstone Formation, with around 9 m estimated from wireline logs  
841 and cuttings). The formation is absent through much of the Lagan Valley but, where present  
842 such as in Colin Glen and Carr's Glen, does not exceed a few tens of metres. It is only in the  
843 Larne Basin, at the Waterloo Bay foreshore section and in the nearby Larne No. 1 and  
844 Carnduff boreholes is there any appreciable thickness of Waterloo Mudstone Formation  
845 preserved (170.78 m in the Carnduff No. 2 Borehole).

846

847 The formation is dominated by claystones and silty claystones with minor intervals of  
848 siltstone, sandstone and limestone, particularly in the lower parts. Limestones are not  
849 abundant, a feature that distinguishes the Waterloo Mudstone Formation from the Blue Lias  
850 Formation in Britain. Siderite cemented limestones and siltstones are present at White Park  
851 Bay.

852

853 In Northern Ireland prior to drilling the Ballinlea-1 well (605 m Waterloo Mudstone  
854 Formation) its maximum-recorded thickness of 492 m was in the Port More Borehole,  
855 however, dolerite sills accounted for a significant proportion of this total. Dolerite intrusions  
856 were also encountered in the Ballinlea-1 well, reducing the net thickness of Waterloo  
857 Mudstone to 561 m, but other factors also complicated attempts to estimate the total  
858 thickness of the formation here. A shallower interval of Waterloo Mudstone Formation (45  
859 m thick) lay above an 11 m-thick hard cryptocrystalline limestone and beneath a 95 m thick  
860 dolerite intrusion and overlying Ulster White Limestone Formation. The drillers interpreted

861 this as a reverse fault repetition based on the presence of glauconite at the base of the  
862 limestone.

863

864 Currently the Waterloo Mudstone Formation is not sufficiently well known to warrant  
865 further subdivision other than the Tircreven Sandstone Member (Bazley *et al.* 1997), is  
866 recognised south of the Magilligan peninsula. The Tircreven Sandstone Member is best  
867 exposed in Tircreven Burn, this unit is approximately 14 m thick at outcrop but is partly  
868 obscured by faults and superficial deposits and it was not until drilling of the NIRE 05/08-  
869 0003 borehole that the full thickness (21.64 m) was cored (Raine *et al.*, 202X).

870

871 In general, the Tircreven Sandstone Member comprises a succession of siltstone/sandstone  
872 heteroliths and fine sandstones that become more coarse-grained, cleaner and thicker  
873 bedded, with cross stratification and bioturbation by *Diplocraterion*, towards the top. Black  
874 carbonaceous claystones in the upper part contain abundant woody material at Tircreven  
875 Burn above which are calcareous sandstones with *Gryphaea arcuata* Lamarck and rare  
876 ammonites. In the NIRE 05/08-0003 Borehole the Tircreven Sandstone Member lacks the  
877 abundant carbonaceous material and there is an upwards gradational change from an  
878 upper, 4 m-thick, fossiliferous sandy limestone to dark grey calcareous mudstone.

879

880 The youngest parts of the Waterloo Mudstone Formation, of Early Pliensbachian age, were  
881 encountered in the Port More Borehole and Ballinlea-1 well. At outcrop the Waterloo  
882 Mudstone Formation of Early Pliensbachian age (*Ibex* zone) is exposed at Portnakillew near  
883 Kinbane Head (Wilson and Robbie, 1966) and also at Oweynamuck at the east end of White  
884 Park Bay (Wilson and Manning, 1978; Simms and Edmunds, 202X).

885

## 886 **6. Summary**

887 Relatively thin exposures of the uppermost Triassic to Lower Jurassic interval are recognised  
888 onshore in Northern Ireland, while much thicker sequences are now known from both

889 onshore and offshore basins on the island of Ireland. Only the uppermost Triassic Penarth  
890 Group and lowermost parts of the Lower Jurassic sequence have been studied in detail and,  
891 where present, they often provide largely continuous records through this important period  
892 in earth history. However, minor differences in the completeness of the records between  
893 basins reflect the unique structural setting and independent syn-sedimentary processes that  
894 are unique to each basin. Facies variability and the succession of individual units shows  
895 strong similarities with contemporaneous units in southern Britain suggesting widespread  
896 development of the distinct facies in the Penarth Group in particular, though there remains  
897 the possibility that some of the more marginal marine units may be diachronous.

898 The youngest sediments encountered onshore are of Early Pliensbachian age, while some of  
899 the offshore basins may well demonstrate continuing sedimentation through into the  
900 Middle and Late Jurassic.

901

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907

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909

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