# UNIVERSITY OF LEEDS

This is a repository copy of *The Hettangian–Sinemurian (Lower Jurassic)* strata of *Redcar, Cleveland Basin, NE England: facies and palaeoecology.* 

White Rose Research Online URL for this paper: <u>https://eprints.whiterose.ac.uk/228140/</u>

Version: Accepted Version

# Article:

Atkinson, J.W., Wignall, P.B. orcid.org/0000-0003-0074-9129 and Page, K.N. (2020) The Hettangian–Sinemurian (Lower Jurassic) strata of Redcar, Cleveland Basin, NE England: facies and palaeoecology. Proceedings of the Yorkshire Geological Society, 63 (2). pp. 77-87. ISSN 0044-0604

https://doi.org/10.1144/pygs2019-011

© 2020 The Author(s). This is an author produced version of an article published in Proceedings of the Yorkshire Geological Society (PYGS). Uploaded in accordance with the publisher's self-archiving policy.

#### Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

#### Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk https://eprints.whiterose.ac.uk/

## 1 The Hettangian-Sinemurian (Lower Jurassic) strata of Redcar, Cleveland Basin,

- 2 **NE England: facies and palaeoecology**
- 3 J.W. Atkinson<sup>1\*</sup>, P.B. Wignall<sup>1</sup> & K.N. Page<sup>2</sup>

<sup>4</sup> <sup>1</sup>School of Earth and Environment, University of Leeds, Leeds. LS2 9JT, UK

5 <u>\*gy12jwa@leeds.ac.uk</u>

<sup>2</sup>Camborne School of Mines, University of Exeter, Penryn Campus, Penryn, Cornwall
7 TR10 9FE, UK

8

# 9 Abstract

The foreshore at Redcar hosts the oldest Jurassic succession exposed on the 10 Yorkshire-Cleveland Coast but has received little attention since the late 19<sup>th</sup> century. 11 Temporary removal of beach sands by winter storms early in 2018 allowed for a 12 13 sedimentological and palaeontological study of a nearly 60 m-thick foreshore section. 14 The rocks are latest Hettangian to early Sinemurian in age (Early Jurassic) and comprise five coarsening-upward cycles (parasequences) that grade from mudstones 15 through siltstones into *Gryphaea*-rich shell beds. Ammonites are reasonably common 16 along with a diverse benthos that includes abundant bivalves (e.g. Gryphaea, 17 Cardinia, Luciniola, Plagiostoma and Oxytoma) and rarer serpulids, gastropods, 18 foraminifera and solitary corals. In the upper part of the section thicker-shelled taxa 19 are commonly bored by cirripedes and bryozoans. Despite relatively high benthic 20 diversity and intense bioturbation, pyrite framboids are common with size distributions 21 suggesting deposition under a moderately oxygen-restricted water column. The 22 Redcar succession postdates the end-Triassic mass extinction by as much as 4 million 23

years and the diverse marine assemblages indicate recovery was substantiallycomplete by this time.

26 Keywords: pyrite framboid, marine recovery, dysoxia, Gryphaea

27

# 28 Introduction

The Cleveland Basin, North Yorkshire and Cleveland, preserves one of the 29 classic Lower Jurassic successions that has provided important evidence on 30 numerous aspects of the Early Jurassic world, such as the Toarcian Oceanic Anoxic 31 Event (e.g. Little & Benton 1995; McArthur et al. 2000; Cohen et al. 2004; Kemp et al. 32 2005; Wignall et al. 2005; Danise et al. 2013) and the Global Stratotype Section and 33 Point (GSSP) for the Sinemurian-Pliensbachian stage boundary (Meister et al. 2004). 34 Earlier stratigraphic intervals in the Lower Jurassic have been relatively neglected 35 because of poor coastal exposures and scarcity of inland records, which mostly 36 comprise temporary exposures recorded in the 19th century (Tate & Blake 1876), or 37 borehole studies (Ivimey-Cook & Powell 1991; Powell et al. 1992). Redcar Rocks is 38 the only locality in the Cleveland Basin where rocks of the Hettangian and lowermost 39 Sinemurian are currently exposed. The intertidal platforms were meticulously sampled 40 by Tate and Blake and their results were published in 1876. Their bed descriptions are 41 somewhat difficult to interpret but they provided a useful sketch map of the foreshore 42 depicting the locations of key ammonite finds (expanded in Page 2004a). The 43 succession was subsequently reported in Gad's (1966) unpublished PhD thesis and 44 by van Buchem & McCave (1989) although neither provided a detailed section nor any 45 palaeontological study. Lord (1971) published a taxonomic study of the ostracods of 46 the Redcar section and remarked that 'it is hoped that a full revision of this fine section 47

will not be long delayed' (Lord, 1971, p.644). The problem with the Redcar succession 48 is its frequent cover beneath beach sand, as Tate & Blake (1876, p. 56) noted: - 'the 49 occasions, however, when so large an expanse of rock is in view, as we have shown 50 on the plan, are few'. Fortunately, the storms in February-March 2018 removed great 51 quantities of the sand cover exposing a section almost as good as seen by Tate & 52 Blake more than 140 years before. Our study provides a detailed log of the 53 54 sedimentary succession alongside a record of fossil occurrences. We assess the palaeoenvironments through analysis of fossil communities, sedimentary facies and 55 56 reconstruction of palaeo-redox conditions using framboidal pyrite size distributions (cf. Atkinson & Wignall 2019). Redcar Rocks provide a new perspective on the Hettangian 57 and Sinemurian interval that allows comparison with the East Midlands Shelf and the 58 well-documented Blue Lias Formation of southwest Britain and contributes new data 59 on the changing environmental conditions and biotic recovery following the end-60 Triassic mass extinction event. 61

62

#### 63 Geological setting

The Cleveland Basin formed as part of a series of small extensional basins 64 within a shallow epicontinental seaway (Powell 2010). During the Early Jurassic the 65 basin was bordered by the Pennine High landmass to the west and the Market 66 Weighton High to the south (e.g. Powell 2010, Fig. 2). The oldest Jurassic-aged rocks 67 within the Cleveland Basin are assigned to the Redcar Mudstone Formation, a 68 mudstone- and siltstone-rich succession that is divided into the following members: a 69 70 lowermost Calcareous Shale Member defined by the presence of carbonate nodules; the Siliceous Shale Member, bearing sandy horizons; the Pyritous Shale Member, a 71 dark shale rich in pyrite, and the Ironstone Shale Member, characterized by beds of 72

siderite nodules (Fig. 1). The Redcar Mudstone Formation is between 250 and 283 m 73 thick near Redcar, thinning southwards (Powell 1984). The Redcar Rocks outcrop 74 exposes much of the Calcareous Shale Member, while the nearby Coatham Rocks 75 reveal higher strata in the Redcar Mudstone Formation and the overlying 76 Pliensbachian-aged Staithes Sandstone Formation, albeit only at very low tide (Figs. 77 1 & 2). Exposure is discontinuous, and some intervals remain obscured even when 78 79 much of the beach sand has been removed. In the cliffs and foreshore exposures of Robin Hood's Bay some 40 km to the southeast, only the upper c. 20 m of the 80 81 Calcareous Shale are exposed, meaning that these lower beds can be studied only at Redcar (Fig. 1). 82

83

#### 84 Materials and methods

Logging of the Calcareous Shale Member was undertaken along the foreshore 85 at Redcar Rocks using a high-precision Jacob's staff with laser sight (Patacci 2016), 86 and sampled beds were allocated numbers, Red 1 - 31 (non-sequentially, omitting 87 Red 25). Benthic diversity was assessed by species counts at semi-regular intervals. 88 Fossils within rock masses were identified on freshly split surfaces of approximately 89 equal volume of mudstone (~0.5 x 0.5 x 0.3 m). In exposed shell beds, fossils were 90 identified in situ on bedding surfaces. Species range extensions are inferred from 91 occurrences higher in the succession at Robin Hood's Bay, Staithes and Hawsker 92 Bottoms based on data presented in Atkinson and Wignall (2020). To reduce the 93 effects of sampling intensity and smooth the resulting diversity curve, Range Through 94 95 (RT) species richness was calculated – this is the sum of observed, raw species counts and ghost ranges per sample horizon. Sediments were also studied in thin sections 96

97 which allowed occurrences of microfossils (especially foraminifera) and shell
98 fragments to be noted.

A subset of the sampled horizons was analysed for changes in oxygenation 99 regime using pyrite framboids. Framboids are spheres of aggregated pyrite 100 microcrysts that form at the boundary between oxic and sulphidic waters (Wilkin et al. 101 102 1996). Under euxinic conditions (free H<sub>2</sub>S) the redox boundary occurs in the water column and framboids grow to around 5 µm in diameter before they sink down from 103 the chemocline and cease to grow. Pyrite framboid populations from such settings 104 have a small mean diameter and show a narrow size range (Wilkin et al. 1996). In 105 oxic-dysoxic settings the redox boundary is within the uppermost sediments allowing 106 framboids to grow to larger and more varied sizes as they can remain at the 107 chemocline for longer (Wilkin et al. 1996). Although Wilkin et al. (1996) suggested it 108 was not possible to distinguish framboids that formed in the sediment under a dysoxic 109 water column from those that formed in the sediment under an oxic water column, the 110 former conditions are generally characterised by much greater numbers of framboids 111 (Wignall & Newton 1998). Employing the method from Wignall & Newton (1998), pyrite 112 framboid diameters were measured from carbon-coated polished stone chips 113 approximately 2 x 1 cm in size set into resin blocks, and viewed using a Tescan 114 VEGA3 XM Scanning Electron Microscope (SEM) with a backscatter electron detector. 115 Ideally 100 framboids were measured from each sample within a designated one-hour 116 analysis time. Mean framboid diameter and standard deviation were calculated for 117 each sample and plotted on what is referred to herein as a Wilkin diagram (cf. Wilkin 118 et al. 1996). 119

120 **Results** 

121 Sedimentology

The measured section spans a thickness of some 50 metres predominantly of 122 mudstone and silty mudstone with thin, calcareous, shell-rich beds (Fig. 3). Spacing 123 of shell beds occurs with some degree of cyclicity. This can be seen on a foreshore 124 map, where closely spaced shell beds form resistant scars, or intertidal headlands, 125 with less resistant mudstones containing fewer shell beds forming the embayments in-126 between (Fig. 2). Between 16-22 m from the base of the measured section (beds 66-127 128 98 of Tate & Blake 1876) there are 16 closely spaced shell beds forming the intertidal headland known as Jenny Leigh's Scar (Fig. 2). Shell beds between 36-38 m form 129 130 another intertidal headland, Stokesley Scar (beds 35-53 of Tate & Blake). Above 42 m, shell beds and sandy intercalations become proportionally more dominant, forming 131 East Scar (beds 32-11 of Tate & Blake). 132

The mudstones are medium to light grey in colour with little of the primary fabric 133 retained owing to pervasive bioturbation, resulting in silt-grade quartz and detrital 134 carbonate grains being scattered throughout and shell fragments often rotated to high 135 angles (Fig. 4A). Sporadic horizons of carbonate concretions occur within the 136 mudstone intervals usually in close association with shell beds. Between around 24-137 32 m (beds 55-64 of Tate & Blake) siderite nodules are found either scattered or 138 forming distinct horizons, with this part of the succession having the lowest 139 concentration of shell beds (Fig. 3). 140

Individual shell beds are up to 0.3 m thick and include large numbers of disarticulated *Gryphaea* and *Cardinia* shells (Figs. 4B & 5) with abundant thinner shelled debris, including recognisable bivalve and echinoderm fragments. The lower parts of the shell beds consist of mudstone with a high proportion of thin shell fragments, grading up into siltier and sandier strata with larger and more numerous bioclasts, mostly *Gryphaea*, culminating in shelly limestones cemented by sparite (i.e. biosparite, Fig. 4C). Small lenses of mudstone can persist between larger shells in
these biosparites. Shell beds sampled at horizons Red 8, 9, 15 and 17 all contain
glauconite-replaced echinoderm fragments.

Above 40 m the succession becomes increasingly silty, until at 42-47 m where fine sandstones form East Scar (Figs. 2 & 3). Each bed is composed of homogeneous siltstone with quartz and detrital carbonate grains, grading up into carbonatecemented fine-grained sandstone rich in shell debris and *Gryphaea*. This part of the succession also features elongate, cigar-shaped phosphatic nodules, approximately 5 cm long, which preserve burrow mottling (Fig. 4D).

Viewed under a SEM, many of the Redcar beds feature diagenetic ankerite grains, ovoid in shape and typically <10  $\mu$ m in length, often at high abundances within some samples (Fig. 6A). Thin sections show that iron oxide is common in Red 27 and 29, both as discrete grains and infills of foraminifera tests, which may originally have been siderite or pyrite grains and pyrite infills respectively, prior to oxidation.

161

#### 162 *Fauna*

Ammonite faunas collected from the lower 9 m of the section are dominated by *Schlotheimia* of the Angulata Chronozone, of latest Hettangian age (Fig. 7A). These are replaced by Arietitidae in the basal Sinemurian, Conybeari Subchronozone (Bucklandi Chronozone), including *Metophioceras* spp.. Unfortunately, no ammonites were found from Jenny Leigh's Scar during this survey, although previously reported finds include *Coroniceras* ex grp *rotiforme* (J. de C. Sowerby) indicating the Rotiforme Subchronozone is present on the scar (Page 2004a).

Placement of the Rotiforme-Bucklandi Subchronozone boundary is still 170 unclear, although *Coroniceras* ex grp *multicostatum* (J. Sowerby) was collected from 171 Red 14 suggesting the late Bucklandi Subchronozone is present (multicostatum 172 Biohorizon Sn14 of Page 1992, 2010). The lowest part of the succeeding 173 Semicostatum Chronozone is recognisable by occurrences of *Paracoroniceras* sp. in 174 the upper beds of Stokesley Scar, with well-preserved and, occasionally, encrusted 175 examples of Arnioceras collected from the mudstones above (Fig. 7B). The 176 Scipionanum Subchronozone is recognised by Agassiceras with Arnioceras 177 178 acuticarinatum (Simpson) collected from Red 29 and Red 30.

Based upon range through (RT) species richness, total benthic diversity was 179 modest during the Angulata Chronozone with fewer than 10 species present, but then 180 rises markedly to 15 species in the first shell bed of Jenny Leigh's Scar. Above this 181 level benthic diversity increases further to around 22 species and remains stable for 182 the remainder of the succession (Fig. 8). The assemblages are dominated by bivalves 183 with a broad range of ecologies present. Of the suspension feeding guilds of bivalve 184 there is one epifaunal reclining species, three cementing, one epifaunal facultative 185 motile, eight epibyssate and three endobyssate, four shallow infaunal, including one 186 abundant species that likely hosted sulphur-oxidising chemosymbiotic bacteria, and 187 also two deep infaunal taxa (Table 1). Deposit-feeding bivalves were also common 188 with six species recorded. After bivalves, gastropods form the next significant 189 190 component with large forms present (up to 66 mm height and width) such as Pleurotomaria cognata Chapuis & Dewalque (Fig. 7C), although most are small (~1-2 191 mm) high-spired forms seen only in thin section (Fig. 7D). Echinoderms, especially 192 193 echinoid spines and ophiuroid plates, are a common component of the shell beds. Red 12 also contains articulated specimens of *Isocrinus psilonoti* (Quenstedt) including cirri 194

(Fig, 7E). Serpulids are locally common and several species are present, with dense,
 intergrown nests of small diameter specimens found in Red 8 (Fig. 4E).

Gryphaea arcuata Lamarck occurs throughout the entire succession and is the 197 most conspicuous fossil, especially in the shell beds where their thick shells dominate 198 (Fig. 5). In the upper shell beds of Jenny Leigh's Scar, the thick-shelled Cardinia listeri 199 200 (J. Sowerby) is also found in high numbers alongside *G. arcuata*. Shell beds also contain subordinate faunas including Luciniola limbata (Terquem & Piette) and the 201 solitary coral Trocharea guettardi (Blaniville) (c. 35 m, bed 55 of Tate & Blake). 202 Cardinia and Gryphaea specimens in the shell beds of Stokesley and East Scar 203 frequently display a range of borings, which are infilled by matrix testifying they are of 204 Jurassic origin (Fig. 7F-L). Most are slit-like in form and pinched at one end, typical of 205 barnacle borings (Häntzschel 1975) such as Zapfella, Rogerella and Simonizapfes; 206 207 the last has a distinctive sock-shaped cross section, seen in a broken Cardinia from Red 15 (Fig. 7J). A fine network-like boring was seen on *Cardinia* shells. These do not 208 penetrate the shell to any significant depth however, and may have been formed by 209 boring bryozoans (Fig. 7K). Other borings include simple rounded holes and elongate 210 gashes (Fig. 7H). Evidence for constrained growth in a specimen of *Cardinia* was also 211 found. This specimen shows that normal growth was impeded partway through the 212 individual's life resulting in irregular growth lines and a miss-shaped outline, and may 213 indicate overcrowding (Fig. 7L). 214

Borings are very rare in the shell beds of Jenny Leigh's Scar and shells are generally in a better state of preservation, with articulated *Cardinia* notably more common.

Although fossils are most conspicuous in the shell beds many species occur within the mudstones, including thin-shelled protobranch species, *Luciniola limbata*, Oxytoma inequivalvis (J. Sowerby) and Pseudolimea pectinoides (J. Sowerby) (Fig.
8). Large logs of fossilised wood were also noted.

Tate & Blake (1876) reported four coral-hosting beds at Redcar, but only their second uppermost coral bed (Red 16 = bed 55 of Tate & Blake) was seen during this study, which hosts solitary coral *Trocharea guettardi* (Blainville) and scallop *Chlamys textoria* (Schlotheim). Solitary corals like *Trocharea* are widespread in the Angulata and Bucklandi chronozones of the British Isles (Negus 1983), being recorded from Lincolnshire (Brandon *et al.* 1990), Larne in Northern Ireland (Negus 1983) and Glamorgan, South Wales (Trueman 1930).

Foraminifera were identified from thin sections and are predominately elongate, uniserial taxa (*Pseudonodosaria*, *Paralingula*, *Dentalina*), that occupy a shallow infaunal niche (Rita *et al.* 2016). *Glomospirella*, an epifaunal form with discoidal coiled morphology (Rita *et al.* 2016) was found in Red 2. Red 27 hosted the greatest abundance of foraminifera with numerous examples of *Lenticulina*, an opportunistic taxon. Ostracods were also encountered in several beds (Red 2, 3, 15, 20, 24).

235

## 236 Framboidal pyrite analysis

Pyrite was found in all samples, both as euhedral crystals and framboidal pyrite, and locally forming a pyrite cement (Red 28). Framboids often occur in clusters or streamers surrounded by clouds of dissociated pyrite microcrysts (Fig. 6B). During the one-hour per sample analysis time over 100 framboids were counted from each polished chip, save for two samples which contained >70 framboids each. All samples show framboid populations that plot in the middle to upper oxic-dysoxic field of the Wilkin diagram (Figs. 3 & 9). There is no distinction between framboid populations measured from shell beds and mudstones, and equally no systematic change in
average framboid diameters or standard deviation up-section. Overall, the measured
succession contains framboids with average diameter of 8.35 µm and standard
deviation of 4.31 µm.

248

#### 249 **Discussion**

Redcar presents a mudstone-dominated succession encompassing the 250 Hettangian-Sinemurian (Angulata-Bucklandi chronozones) boundary, with a 251 reasonably diverse benthic fauna. Five distinct parasequences (shallowing-up cycles) 252 are recognised, each passing upwards from mudstone-dominated to shell bed-253 dominated facies. The associated grain size increase suggests the shelly horizons 254 represent shallower/more proximal environments. The first parasequence forms the 255 base of the exposed section to the top of Jenny Leigh's Scar, the second culminates 256 in the top of Stokesley Scar, the third and fourth occur in East Scar and the lower part 257 of the fifth forms the uppermost part of the section at Redcar Rocks (Fig. 8). 258 Superimposed on this overall succession there is a long-term, weakly expressed, 259 coarsening upwards trend that is associated with a reduction in parasequence 260 thickness, suggesting that accommodation space was declining. The long-term 261 increase in boring intensity, culminating in the shells found in Stokesley and East Scar, 262 indicates diminishing sedimentation rates and more prolonged exposure on the sea 263 floor compared to shells from the stratigraphically older, and more expanded, Jenny 264 Leigh's Scar shell beds. Brandon et al. (1990) also reported a comparable increase in 265 boring intensity in strata of the Lyra Subchronozone in Lincolnshire. 266

Similar mud/siltstone-shell bed cycles occur in the Felixkirk borehole, 40km 267 south-west of Redcar (lvimey-Cook & Powell 1991), and in Lincolnshire, 200 km to the 268 south (Brandon et al. 1990). There, similar cycles continue into higher levels of the 269 Semicostatum Chronozone, as with similar beds reported from the younger 270 succession at Robin Hood's Bay, 40 km south-east of Redcar (Page 2004b). 271 Correlation of individual beds, cycles or parasequences between basins is, however, 272 inconsistent, for example the shell beds of Jenny Leigh's Scar correspond to a 273 mudstone-dominated interval in Lincolnshire, the Lvra-Scipionianum 274 but 275 Subchronozone is characterised by shell beds and siltstones in both regions. Correlation is confounded further by non-sequences in the Bucklandi chronozone in 276 both the Felixkirk Borehole and in Lincolnshire (Brandon et al. 1990; Howard et al. 277 2009; Ivimey-Cook & Powell 1991) 278

The mud/siltstone-shell bed cycles represent generally guiet water mudstone 279 deposition interspersed with storm events and subsequent periods of prolonged 280 winnowing, which generated shell beds dominated by the thick-shelled Cardinia listeri 281 and Gryphaea arcuata. G. arcuata is especially common, which led Tate & Blake 282 (1876) to describe these shell beds as 'gryphites'. Shell beds seen at Redcar lack the 283 sharp erosive bases typical of tempestites, and equivalent similar beds in the Felixkirk 284 Borehole show a mixture of sharp and gradational bases. Powell (2010) suggested 285 this was due to mixing of the sediment during post-storm bioturbation. The prolific 286 abundance of *Gryphaea* in the Angulata to Semicostatum chronozones of the British 287 288 Lower Jurassic may reflect the preservability of their robust shells (Simms 2004; Radley 2008; Pugh et al. 2014), especially so in condensed and winnowed settings. 289

Interpreted eustatic sea-level curves for UK onshore Lower Jurassic 291 successions are currently based on the Hebrides Basin for the Angulata-Turneri 292 Chronozone interval, combined at higher stratigraphic levels with interpretations from 293 the Cleveland Basin and eventually the Wessex Basin (Hesselbo & Jenkyns 1998; 294 Hesselbo 2008). Relative sea-level change indicated by the Redcar succession is only 295 partially consistent with the Hebridean curve. Thus, a relative sea-level fall indicated 296 297 during the Rotiforme Subchronozone is coincident with the formation of the Jenny Leigh's Scar shell beds, but relative sea-level rise then purportedly occurs through the 298 299 Bucklandi Subchronozone to peak in a Lyra Subchronozone highstand (Hesselbo 2008). At Redcar this initial sea-level rise is coincident with the deposition of 300 mudstones (24-32 m, beds 55-64 of Tate & Blake), but other intervals of shallowing 301 within the Bucklandi Subchronozone, not indicated in the Hebrides Basin, saw the 302 formation of the Stokesley Scar shell beds. The Lyra Subchronozone at Redcar 303 records relatively shallow-water deposition in parasequences of diminished thickness 304 compared with the underlying examples. If the relative sea-level rise interpreted in the 305 Hebrides Basin Lyra Subchronozone succession also occurred in the Cleveland Basin, 306 then equivalent parasequences at Redcar would be expected to thicken upwards due 307 to increased accommodation space; quite the opposite is reported in this study. The 308 Redcar succession could instead record a transition from early, aggradation-309 310 dominated parasequences to late, progradation-dominated, highstand deposition expressed in a relatively nearshore setting. 311

312

The Redcar succession provides insights into the recovery from the end-Triassic mass extinction event. The exact timing of this recovery is contentious as a range of durations for the Hettangian have in recent years been proposed, from earlier

estimates of 1.7-2 million years (Schaltegger et al. 2008; Ruhl et al. 2010; 2016; Guex 316 et al. 2012; Hüsing et al. 2014) to the most recent cyclostratigraphic estimations of 317 >4.1 million years (Weedon et al. 2019). As the Redcar section records the Hettangian-318 Sinemurian boundary, the age model used has clear implications on the duration of 319 the recovery. Sections elsewhere in the UK have shown that recovery was rapid, with 320 sea floor community structure re-established prior to the Planorbis Chronozone and 321 322 bivalve diversity essentially stabilising in the mid-Hettangian (Atkinson & Wignall 2019). The Redcar section does not expose the lowermost Hettangian, however, it 323 exhibits a faunal assemblage that is diverse and features a wide range of ecological 324 groups seen elsewhere in correlative British Lower Jurassic successions (Brandon et 325 al. 1990; Atkinson & Wignall 2019). It differs slightly from some other successions in 326 the paucity of large *Plagiostoma giganteum* J. Sowerby and *Pinna similis* Chapuis & 327 Dewalque which abound elsewhere, most notably in the limestone-dominated 328 successions of Glamorgan (Hallam 1960; Atkinson & Wignall 2019; Atkinson et al. 329 2019). 330

Bivalve diversity per ammonite zone in the Calcareous Shale Member at 331 Redcar can be compared with recovery trends in the contemporary Scunthorpe 332 Mudstone and Blue Lias formations of the Midlands and southern UK respectively 333 (Table 2). For the Angulata Chronozone the Redcar section appears less diverse than 334 that of the East Midlands Shelf; this may be an effect of more shell beds having been 335 sampled from this zone in the Scunthorpe Mudstone Formation. However, the Redcar 336 succession does host an equivalent bivalve species richness to the contemporaneous 337 Blue Lias of the Dorset Basin. 338

Bucklandi Chronozone bivalve diversity for the Redcar Mudstone Formation exceeds that reported by Brandon *et al.* (1990) for the Scunthorpe Mudstone

Formation and far exceeds the diversity of the Blue Lias in Dorset at this time, but is 341 comparable to the Bristol Channel Basin if additional records from museum collections 342 are included (Atkinson & Wignall 2019). The elevated Redcar diversity may reflect the 343 more habitable conditions of the shallower water Cleveland Basin site, although the 344 prevalence of framboidal pyrite and common occurrences of Luciniola suggest the 345 presence of H<sub>2</sub>S within the sediment. The entire Redcar succession contains a 346 347 framboid size distribution suggestive of an oxic-dysoxic water column, again resembling the Bristol Channel Basin of South Wales (Fig.10), and contrasting with 348 349 evidence of anoxia reported from Central Somerset and Dorset during the Bucklandi Chronozone (Atkinson & Wignall 2019). There are no comparable pyrite framboid 350 studies from the Scunthorpe Mudstone Formation. 351

352

## 353 Conclusions

Redcar Rocks provide a valuable record of Hettangian/Sinemurian deposition 354 in the Cleveland Basin and allow comparison with the well-documented sections of the 355 Scunthorpe Mudstone Formation of the East Midlands Shelf and the classic Blue Lias 356 of southwest Britain. The Redcar record also allows the current interpretations of sea-357 level changes during the Hettangian-Sinemurian to be referenced in detail against the 358 Cleveland Basin succession for the first time. The lowest strata belong to the 359 Calcareous Shale Member and are comparable to time-equivalent members of the 360 Scunthorpe Mudstone Formation of the Midlands. Both lack the cyclical development 361 of limestone-marl-shale seen in the Blue Lias Formation. Instead the Calcareous 362 363 Shale Member features coarsening-upward cycles that grade from mudstones to mass accumulations of Gryphaea arcuata and Cardinia listeri in sandy shell beds or 364 limestones. Benthic diversity is comparably high through much of the section with a 365

wide range of ecologies represented, suggesting advanced levels of recovery from the
end-Triassic mass extinction event some 1.7-4 Myr earlier. Reconstruction of marine
oxygenation levels from pyrite framboid populations suggests persistent, though weak,
oxygen restriction in the Cleveland Basin and complements the recent findings of
Atkinson and Wignall (2019) that showed the majority of the Early Jurassic
epicontinental sea in Britain experienced some degree of oxygen restriction.

372

## 373 Acknowledgements

We wish to thank the YGS for providing funding for this project via the Yorkshire Geological Society Research Fund in its inaugural year, Tom Charman of Natural England for permissions to sample the Redcar Rocks, Harri Wyn Williams for his excellent thin-section making and Dave Bond for the use of his slide scanner. We also wish to thank John Powell, Mike Simms and Andy Howard (handling editor) for their comments which much improved this work.



Fig. 1 Lithostratigraphical subdivisions and stratigraphical ranges of relevant Lower
 Jurassic localities in the Cleveland Basin, from Simms (2004). Age model from Ruhl
 *et al.* (2016) and Weedon *et al.* (2019).



Fig. 2 A. UK location map showing Lower Jurassic outcrop and key sedimentary
basins modified from Gründel et al. (2011). Basin codes as follows: DB – Dorset Basin;
CSB – Central Somerset Basin; BCB – Bristol Channel Basin; SB – Severn Basin;
EMS – East Midlands Shelf; MWH – Market Weighton High; CB – Cleveland Basin. B.
Foreshore map of Redcar and Coatham rocks with geological units and scar names
(Page 2004a).



Fig. 3 Graphic log of Redcar Rocks including box and whisker plots of pyrite framboid
analyses. Each box depicts 25<sup>th</sup> and 75<sup>th</sup> percentiles, central line is median, whiskers
illustrate minimum and maximum framboid diameters. Solid circles show raw species
richness per sampled horizon.



Fig. 4 Photomicrographs of thin sections. A. Red 23, Mudstone with shell fragment
rotated by burrowing. B. Red 28, example shell bed including *Gryphaea* shell with
simple boring on the right. C. Red 6, example of biosparite D. Red 24, phosphatic
nodule featuring burrow mottling. E. Red 8, two nests of serpulid tubes.



404

**Fig. 5** *Gryphaea*-rich shell bed (Red 19) at outcrop. Hammer 30 cm long.



406

Fig. 6 SEM images. A. Red 11, silty mudstone with abundant ankerite grains,
appearing as pale grey, rice-shaped grains in cross section. B. Red 15, shell bed
limestone with pyrite framboids surrounded by a cloud of dissociated pyrite
microcrysts.



Fig. 7 Examples of fossils collected from Redcar; specimens housed in Whitby
Museum. A. Red 1, *Schlothemia* sp. (WHITM: 2020/1.1); B. Red 21, *Arnioceras* sp.
encrusted by *Liostrea irregularis* (Münster) (WHITM 2020/1.2); C. Red 17, *Pleurotomaria cognata* Chapuis & Dewalque (WHITM: 2020/1.3); D. Red 2
photomicrograph of microgastropod in thin section; E. Red 12 *Isocrinus psilonoti*

(Quenstedt), partially articulated specimen with cirri, photographed *in situ;* F – I. Red
15, *Cardinia listeri* (J. Sowerby) featuring a range of cirripede borings (WHITM:
2020/1.4-8). J. cross-section through part of *C. listeri* shell (I) showing potential *Simonizapfes*; K. detail of *C. listeri* shell (I) with possible bryozoan borings; L. *C. listeri*with growth defect, dashed line projects normal shell outline. A-C whitened using
ammonium chloride, scale bars 1 cm unless otherwise stated.



Fig. 8 Species range chart and Range Through (RT) species richness for Redcar
Rocks. For range chart, dark circles show horizons that species were encountered

during field collections, shaded squares for species encountered only in thin sections.
Connecting line indicates range of species, extensions to ranges based on personal
observations and species occurrence data presented in Atkinson and Wignall (2020).
Inverted black triangles on the left indicate the stratigraphic range of the five
parasequences.



Fig. 9 Mean framboid diameter (μm) against standard deviation of framboid diameters
(Wilkin diagram) for Redcar. Dashed line indicates anoxic/oxic-dysoxic threshold
(Wilkin *et al.* 1996). Samples plotted as being either from shell beds or from the
intervening mudstones and siltstones, with shaded regions illustrating the spread of
results.



Fig. 10 Average framboid diameter and standard deviation for the Blue Lias in three
basins in southwest Britain. D – Dorset Basin; B – Bristol Channel Basin; S – Central
Somerset Basin (from Atkinson & Wignall 2019); C – Cleveland Basin (this study).

SPECIES	ECOLOGY	
Gryphaea arcuate Lamarck	surficial, non-motile, reclining suspension feeder	
Atreta intusstriata (Emmrich)	surficial, cemented, suspension feeder	
Terquemia difformis (Schlotheim)	surficial, cemented, suspension feeder	
Liostrea irregularis (Münster)	surficial, cemented, suspension feeder	
Plagiostoma giganteum J. Sowerby	epibyssate, suspension feeder	
Plagiostoma punctatum J. Sowerby	epibyssate, suspension feeder	
Pseudolimea pectinoides (J. Sowerby)	epibyssate, suspension feeder	
Antiquilima succincta (Schlotheim)	epibyssate, suspension feeder	
Grammatodon (Cosmetodon) sp.	epibyssate, suspension feeder	
Oxytoma inequivalvis (J. Sowerby)	epibyssate, suspension feeder	
Camptonectes cf.auritus (Schlotheim)	epibyssate, suspension feeder	
Chlamys textoria (Schlotheim)	epibyssate, suspension feeder	
Entolium lunare (Roemer)	surficial, facultative motile, suspension feeder	
Modiolus sp.	endobyssate, suspension feeder	
Pinna sp.	endobyssate, suspension feeder	
Cuneigervillia hagenowi (Dunker)	endobyssate, suspension feeder	
Neocrassina sp.	shallow infaunal, suspension feeder	
Cardinia listeria (J. Sowerby)	shallow infaunal, suspension feeder	
Protocardia philippianum (Dunker)	shallow infaunal, suspension feeder	
Luciniola limbata (Terquem & Piette)	shallow infaunal, suspension feeder with chemosymbionts	
Dacryomya heberti (Martin)	shallow infaunal, deposit feeder	
Palaeonucula navis (Piette)	shallow infaunal, deposit feeder	
Ryderia doris (d'Orbigny)	shallow infaunal, deposit feeder	
<i>Rollieria bronni</i> (Andler)	shallow infaunal, deposit feeder	
Palaeoneilo elliptica (Goldfuss)	shallow infaunal, deposit feeder	
indeterminate protobranch	shallow infaunal, deposit feeder	
Gresslya sp.	deep infaunal, suspension feeder	
Pleuromya striatula Agassiz	deep infaunal, suspension feeder	

Table 1 Bivalve ecologies encountered within the Redcar sequence, assigned from
published literature (Johnson 1984; Hodges 1991, 2018; Wignall 1990; Damborenea
& Manceñido 2005; Ros-Franch *et al.* 2014)

BASIN	ANGULATA	BUCKLANDI	SEMICOSTATUM
Cleveland	7	23 (24)	16 (20)
East Midlands Shelf	14	8 (13)	29 (30)
Dorset	8	Under sampled	6
Central Somerset	11	12	Nd.
Bristol Channel	17 (28)	13 (26)	29
Severn	Nd.	13	Nd.

446

Table 2 Bivalve species richness per chronozone for four basins of the classic Blue Lias Formation and the Scunthorpe Mudstone Formation from the East Midlands Shelf compared with the correlative succession in the Cleveland Basin. Bracketed values show Range Through bivalve species richness, for Bristol Channel Basin this value includes specimens housed in the National Museum of Wales. Bivalve species richness data from Atkinson and Wignall (2019; 2020) and Brandon et al. (1990).

453

454 References

Atkinson, J.W. & Wignall, P.B. 2019. How quick was marine recovery after the endTriassic mass extinction and what role did anoxia play? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **528**, 99–119,
https://doi.org/10.1016/j.palaeo.2019.05.011.

Atkinson, J.W & Wignall, P.B. 2020. Body size trends and recovery amongst bivalves
following the end-Triassic mass extinction. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **538**, https://doi.org/10.1016/j.palaeo.2019.109453

Atkinson, J.W., Wignall, P.B., Morton, J.D. & Aze, T. 2019. Body size changes in
bivalves of the family Limidae in the aftermath of the end-Triassic mass extinction:
the Brobdingnag effect. *Palaeontology*, **62**, 561-582,
https://doi.org/10.1111/pala.12415.

Brandon, A., Slumber, M.G. & Ivimey-Cook, H.C. 1990. A revised lithostratigraphy for
the Lower and Middle Lias (Lower Jurassic) east of Nottingham, England. *Proceedings of the Yorkshire Geolocial Society*, **48**, 121-141,
https://doi.org/10.1144/pygs.48.2.121

Cohen, A.S., Coe, A.L., Harding, S.M. & Schwark, L. 2004. Osmium isotope evidence
for the regulation of atmospheric CO<sub>2</sub> by continental weathering. *Geology*, 32,
157-160, https://doi.org/10.1130/G20158:1

Damborenea, S. & Manceñido, M.O. 2005. Biofacies analysis of HettangianSinemurian bivalve/brachiopod associations from the Neuquén Basin (Argentina). *Geologica Acta*, 3, 163–178, https://doi.org/10.1344/105.000001405.

Danise, S., Twitchett, R.J., Little, C.T.S. & Clémence, M.-E. 2013. The impact of global
warming and anoxia on marine benthic community dynamics : an example from
the Toarcian (Early Jurassic). *PLoS ONE*, **8**, e56255,
https://doi.org/10.1371/journal.pone.0056255.

Gad, M.A.M.A. 1966. A Geochemical Study of the Liassic Rocks of the Yorkshire *Coast.* University of London.

482 Gründel, J., Kaim, A., Nützel, A. & Little, C.T.S. 2011. Early Jurassic gastropods from

483 England. *Palaeontology*, **54**, 481–510, https://doi.org/10.1111/j.1475484 4983.2011.01043.x.

Guex, J., Schoene, B. *et al.* 2012. Geochronological constraints on post-extinction
recovery of the ammonoids and carbon cycle perturbations during the Early
Jurassic. *Palaeogeography Palaeoclimatology Palaeoecology*, **346–347**, 1–11.
https://doi.org/10.1016/j.palaeo.2012.04.030.

- Hallam, A. 1960. A sedimentary and faunal study of the Blue Lias of Dorset and
  Glamorgan. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 243, 1–44, https://doi.org/10.1098/rstb.1960.0003.
- Häntzschel, W. 1975. *Treatise on Invertebrate Paleontology Part W Miscellanea Supliment 1. Trace Fossils and Problematica*, 2nd ed. Teichert, C. (ed.). Boulder,
- The Geological Society of America, Inc. and The University of Kansas.
- 495 Hesselbo, S.P. 2008. Sequence stratigraphy and inferred relative sea-level change
- 496 from the onshore British Jurassic. *Proceedings of the Geologists' Association*,

497 **119**, 19–34, https://doi.org/10.1016/S0016-7878(59)80069-9.

- Hesselbo, S.P. & Jenkyns, H.C. 1998. British Lower Jurassic sequence stratigraphy. *In: Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*. SEPM
  Special Publications No. 60.
- Hodges, P. 1991. The relationship of the Mesozoic bivalve *Atreta* to the Dimyidae. *Palaeontology*, **34**, 963–970.
- Hodges, P. 2018. *The Early Jurassic Bivalvia from the Hettangian and Lower Sinemurian of South-West Britain Part 2.* London, Monograph of the
  Palaeontographical Society, https://doi.org/10.1080/02693445.2017.11963960.
- Howard, A.S., Warrington, G. et al. 2009. Geology of the Nottingham district. *Memoir*

507 *of the British Geological Survey*, Sheet 126 (England and Wales)

Hüsing, S.K., Beniest, A. et al. 2014. Astronomically-calibrated magnetostratigraphy 508 of the LowerJurassic marine successions at St. Audrie's Bay and East 509 (Hettangian-Sinemurian; UK). 510 Quantoxhead Somerset. Palaeogeography, Palaeoclimatology, Palaeoecology, 403. 43–56. 511 https://doi.org/10.1016/j.palaeo.2014.03.022 512

- Ivimey-Cook, H.C. & Powell, J.H. 1991. Late Triassic and early Jurassic
  biostratigraphy of the Felixkirk Borehole, North Yorkshire. *Proceedings of the Yorkshire Geological Society*, **48**, 367–374.
- Johnson, A. 1984. *The Palaeobiology of the Bivalve Families Pectinidae and Propeamussiidae in the Jurassic of Europe*. München, Zitteliana.
- Kemp, D.B, Coe, A.L., Cohen, A.S. & Schwark, L. 2005. Astronomical pacing of
  methane release in the Early Jurassic period. *Nature*, **437**, 396-399,
  https://doi.org/10.1038/nature03983
- Little, C.T.S. & Benton, M.J. 1995. Early Jurassic mass extinction : A global long-term
   event. *Geology*, 23, 495–498, https://doi.org/10.1130/0091 7613(1995)023<0495.</li>
- Lord, A. 1971. Revision of some Lower Lias ostracoda from Yorkshire. *Palaeontology*,
  14, 642-665.

McArthur, J.M., Donovan, D.T., Thirlwall, M.F., Fouke, B.W & Mattey, D. 2000.
Strontium isotope profile of the early Toarcian (Jurassic) ocean anoxic event, the
duration of ammonite biozones, and belemnite palaeotemperatures. *Earth and Planetary Science Letters*, **179**, 269-285, https://doi.org/10.1016/S0012821X(00)00111-4

531 Meister, C., Aberhan, M., et al. 2004. The Global Boundary Stratotype Section and 532 Point (GSSP) for the base of the Pliensbachian Stage (ower Jurassic), Wine 533 Haven, Yorkshire, UK. *Episodes*, **29**, 93–106.

Negus, P.E. 1983. Distribution of the British Jurassic corals. *Proceedings of the Geologists' Association*, 94, 251–257, https://doi.org/10.1016/S00167878(83)80043-1.

537 Page, K.N. 1992. The sequence of ammonite correlated horizons in the British
538 Sinemurian (Lower Jurassic). *Newsletters in Stratigraphy* 27, 129-156.

Page, K.N. 2010b. Stratigraphical Framework. In: Lord, A.R. and Davis, P.G. Fossils
from the Lower Lias of the Dorset Coast, Palaeontological Association Field Guide
to Fossils 13: 33-53.

- Page, K.N. 2004a. Redcar Rocks. *In*: Simms, M. J., Chidlaw, N., Morton, N. & Page,
  K. N. (eds) *British Lower Jurassic Stratigraphy*. Peterborough, Geological
  Conservation Review Series, No. 30, Joint Nature Conservation committee, 245–
  250.
- Page, K.N. 2004b. Normanby Stye Batts-Miller's Nab (Robin Hood's Bay). *In*: Simms,
  M. J., Chidlaw, N., Morton, N. & Page, K. N. (eds) *British Lower Jurassic Stratigraphy*. Peterborough, Geological Conservation Review Series, No. 30,
  Joint Nature Conservation committee, 250–262.

Patacci, M. 2016. A high-precision Jacob's staff with improved spatial accuracy and
laser sighting capability. *Sedimentary Geology*, **335**, 66–69, https://doi.org/DOI:
10.1016/j.sedgeo.2016.02.001.

Powell, J.H. 1984. Lithostratigraphical nomenclature of the Lias Group in the Yorkshire
Basin. *Proceedings of the Yorkshire Geological Society*, **45**, 51–57.

Powell, J.H. 2010. Jurassic sedimentation in the Cleveland Basin: a review.
 *Proceedings of the Yorkshire Geological Society*, **58**, 21–72,
 https://doi.org/10.1144/pygs.58.1.278.

Powell, J.H., Cooper, A.C. & Benfield, A.C. 1992. *Geology of the County around Thirsk*. British Geological Survey Memoir, England and Wales, Sheet 52.

Pugh, A.C., Danise, S., Brown, J.R. & Twitchett, R.J. 2014. Benthic ecosystem
dynamics following the Late Triassic mass extinction event : Palaeoecology of the
Blue Lias Formation, Lyme Regis, UK. *Proceedings of the Ussher Society*, **13**,
255–266.

Radley, J.D. 2008. Gryphaea beds (upper Scunthorpe Mudstone Formation; Lower
Jurassic) at Scunthorpe, North Lincolnshire, north-east England. *Proceedings of the Yorkshire Geological Society*, **57**, 107–111.

Rita, P., Reolid, M. & Duarte, L. V. 2016. Benthic foraminiferal assemblages record
major environmental perturbations during the Late Pliensbachian – Early Toarcian
interval in the Peniche GSSP, Portugal. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **454**, 267–281, https://doi.org/10.1016/j.palaeo.2016.04.039.

Ros-Franch, S., Márquez-aliaga, A. & Damborenea, S.E. 2014. Comprehensive
database on Induan (Lower Triassic) to Sinemurian (Lower Jurassic) marine
bivalve genera and their paleobiogeographic record. *Paleontological Contributions*, 8, 1–219, https://doi.org/10.17161/PC.1808.13433.

Ruhl, M., Deenen, M.H.L., Abels, H.A., Bonis, N.R., Krijgsman, W. & Kürschner, W.M.
2010. Astronomical constraints on the duration of the early Jurassic Hettangian
stage and recovery rates following the end-Triassic mass extinction (St Audrie's
Bay / East Quantoxhead, UK). *Earth and Planetary Science Letters*. 295, 262–

- 579 276. https://doi.org/10.1016/j.epsl.2010.04.008.
- Ruhl, M., Hesselbo, S.P. *et al.* 2016. Astronomical constraints on the duration of the
  Early Jurassic Pliensbachian Stage and global climate fluctuations. *Earth and Planetary* Science Letters, **455**, 149-165,
- 583 https//doi.org/10.1016/j.epsl.2016.08.038
- 584 Schaltegger, U., Guex, J., Bartolini, A., Schoene, B. & Ovtcharova, M. 2008. Precise
- 585 U–Pb age constraints for end-Triassic mass extinction, its correlation to volcanism
- and Hettangian post-extinction recovery. *Earth and Planetary Science Letters,*

587 **267**, 266–275. https://doi.org/10.1016/j.epsl.2007.11.031.

- Simms, M.J. 2004. Hock Cliff. In: Simms, M. J., Chidlaw, N., Morton, N. & Page, K. N.
- (eds) *British Lower Jurassic Stratigraphy*. Peterborough, Geological Conservation
   Review Series, No. 30, Joint Nature Conservation committee, 164–170.
- 591 Simms, M.J. 2004. The Cleveland Basin, Introduction. In: Simms, M. J., Chidlaw, N.,
- 592 Morton, N. & Page, K. N. (eds) *British Lower Jurassic Stratigraphy*. Peterborough,
- 593 Geological Conservation Review Series, No. 30, Joint Nature Conservation 594 committee, 239–245.
- 595 Tate, R. & Blake, J.F. 1876. *The Yorkshire Lias*. London.
- Trueman, A.E. 1930. The lower Lias (bucklandi Zone) of Nash Point, Glamorgan.
   *Proceedings of the Geologists' Association*, **41**, 148–159.
- van Buchem, F.S.P. & McCave, I.N. 1989. Cyclic sedimentation patterns in Lower Lias
   mudstones of Yorkshire (GB). *Terra Nova*, 1, 461–467.
- Weedon, G.P., Page, K.N. & Jenkyns, H.C. 2019. Cyclostratigraphy, stratigraphic
  gaps and the duration of the Hettangian Stage (Jurassic): insights from the Blue
  Lias Formation of southern Britain. *Geological Magazine*, **156**, 1469–1509,

603 https://doi.org/10.1017/S0016756818000808.

- Wignall, P.B. 1990. Benthic palaeocology of the Late Jurassic Kimmeridge Clay of
   England. Special papers in palaeontology, 43.
- Wignall, P.B. & Newton, R.J. 1998. Pyrite framboid diameter as a measure of oxygen
- deficiency in ancient mudrocks. *Americna Journal of Science*, **298**, 537–552,
  https://doi.org/10.2475/ajs.298.7.537.
- Wignall, P.B., Newton, R.J. & Little, C.T.S. 2005. The timing of paleoenvironmental
   change and cause-and-effect relationships during the Early Jurassic mass
   extinction in Europe. *American Midland Naturalist*, **305**, 1014–1032.
- Wilkin, R.T., Barnes, H.L. & Brantley, S.L. 1996. The size distribution of framboidal
  pyrite in modern sediments: An indicator of redox conditions. *Geochimica et Cosmochimica Acta*, **60**, 3897–3912, https://doi.org/10.1016/00167037(96)00209-8.
- 616