THE ECOLOGY AND BIOSTRATIGRAPHY OF LOWER CRETACEOUS FORAMINIFERA IN THE NORTH SEA BASIN

By

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Abstract

The Early Cretaceous witnessed a progressive rise in global sea level (following the marked global low stand at the end of the Jurassic). Global temperature also rose, and species richness increased for some calcifying marine organisms – gastropods, bivalves, ostracods, calcareous nannoplankton, and foraminifera among them. This project investigates Early Cretaceous foraminiferal assemblages from a range of depositional settings and palaeodepths in the North Sea Basin and the surrounding region to study the impact of global and local environmental changes on foraminiferal communities from both shallow and deep-water. This study will aim at understanding key ecological shifts that ultimately provided the opportunity for diversification within the foraminifera. The fossil material studied was obtained from the following sites: 1. Filey Bay outcrop section, and 2. North Fordon G1 borehole from the Cleveland Basin in Yorkshire, which represent the shelfal environment. 3. 16/26-B3, and 4. 15/30-7 ST2 boreholes from the Britannia Field in the Witch Ground Graben. 5. North Jens-1 borehole from the Danish Central Graben. The last three sites represent the upper bathyal environment. The results of this project provided information regarding three initial hypotheses involving increasing species richness and ecological niches expansion for planktic, benthic calcareous and agglutinated foraminifera as each of these foraminiferal groups was found to increase in species richness and abundance in specific stages of the Lower Cretaceous. However, for agglutinated foraminifera, their initial hypothesis could not be confirmed entirely because the palaeodepths of the upper bathyal environment were not significant enough to develop a proper deep-water agglutinated foraminiferal assemblage.

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Abbreviations

DCA	Detrended Correspondence Analysis
DWAF	Deep-Water Agglutinated Foraminifera
FB	Filey Bay
FCN	Foraminifera Cretaceous North
FCS	Foraminifera Cretaceous South
FDO	First Downhole Occurrence
GEUS	Geological Survey of Denmark and Greenland
LDO	Last Downhole Occurrence
NFG1	North Fordon G1
NJ1	North Jens-1
OAE	Oceanic Anoxic Event
RC	Red Chalk
SC	Speeton Clay

1 INTRODUCTION

The study of foraminiferal evolution in the world's oceans throughout geological time provides one of the most complete and insightful evolutionary records on the planet. Their wide dispersal and high sensitivity to environmental changes make them one of the most advantageous fossil groups for understanding the dynamics of earth systems in the past.

Foraminiferal species richness and abundance were affected by some of the major extinction events in the geological record, such as the Permo-Triassic and Cretaceous-Paleogene extinctions (Haynes, 1981; Jones, 2006; PBDB; https://paleobiodb.org). Nevertheless, the foraminiferal speciation rate recovered after extinctions, frequently increasing, and the fossil group expanded into new ecological niches (Haynes, 1981; Jones, 2006; Kaminski et al., 2010). Extinction events mark both the onset and end of the Mesozoic Era. Nevertheless, this Era displayed the highest diversification rate for agglutinated foraminifera outside the Holocene epoch (see Figure 1, Figure 2) (Haynes, 1981; Jones, 2006, 2013; Kaminski et al., 2010). Calcareous benthic and planktic foraminifera’s diversity also increased substantially during the Mesozoic (BouDagher-Fadel, 2012; Haynes, 1981; Jones, 2006, 2013; Kaminski et al., 2010).

Midway through the Mesozoic Era, the Early Cretaceous witnessed a progressive rise in global temperature (Landwehrs et al., 2021), sea level (following the marked global low stand at the end of the Jurassic) (Snedden and Liu, 2010), and species richness for some calcifying marine organisms – e.g., gastropods, bivalves, ostracods, calcareous nannoplankton, and foraminifera, among others (House and Kerr, 1989; Armstrong and Brasier, 2005; Bown, 2005; Alroy, 2010; PBDB, https://paleobiodb.org).

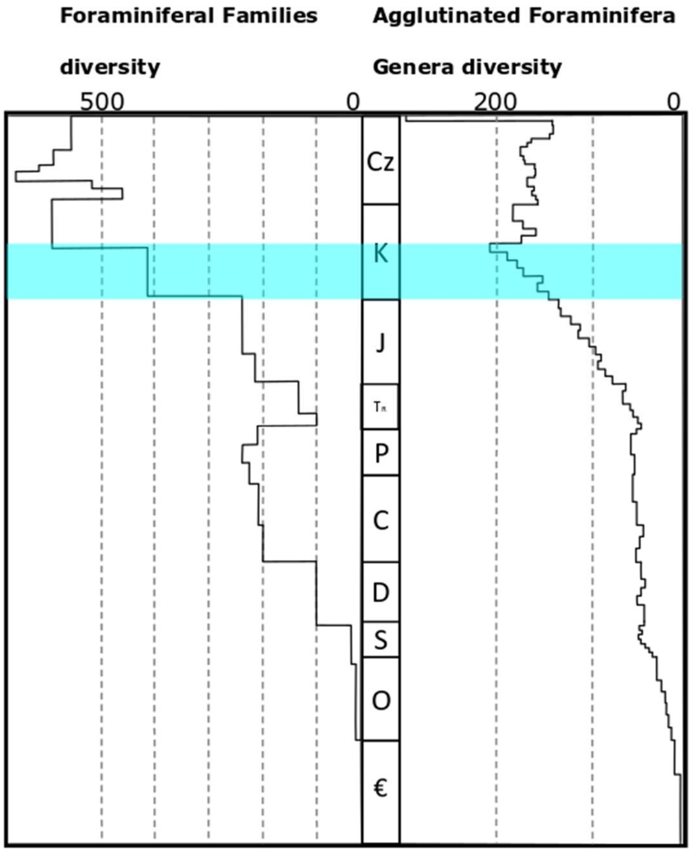


Figure 1. Foraminiferal diversity trends through time. Modified from Jones, (2011); Kaminski et al., (2010).

This project investigates Lower Cretaceous foraminiferal assemblages of the North Sea Basin and the surrounding region. Its main objective is to study the impact of environmental changes (both global and local scale events) on the evolution of benthic and planktic foraminifera in various marine habitats (shallow shelves and deeper-water basins). This study will report some of the palaeoecological and palaeoenvironmental evidence for diversification within the foraminiferal group in this interval, ultimately resulting in high diversification rates compared to other geologic epochs such as the Late Cretaceous.

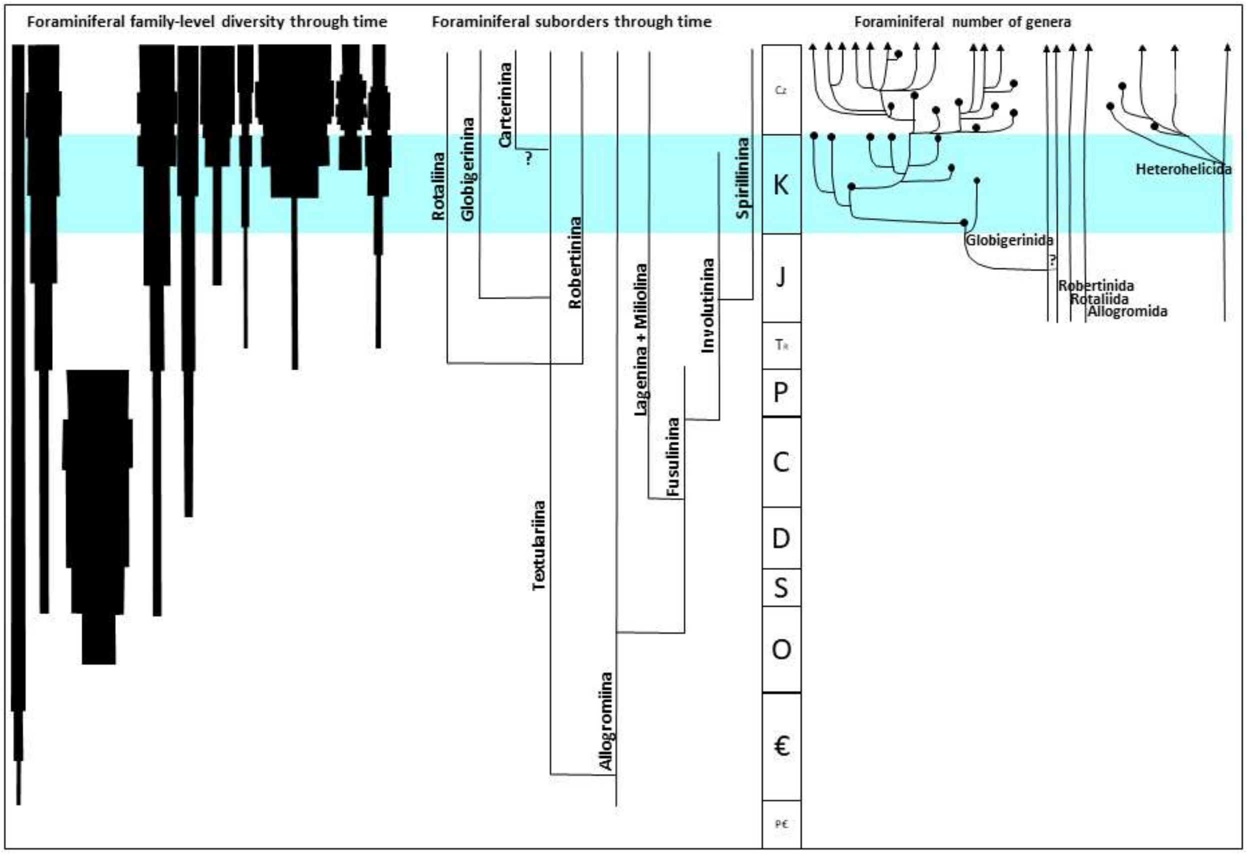


Figure 2. Foraminiferal diversity trends through time at family, suborders, and genera level. Modified from BouDagher-Fadel, (2012); Haynes, (1981); Jones, (2013); Loeblich and Tappan, (1988).

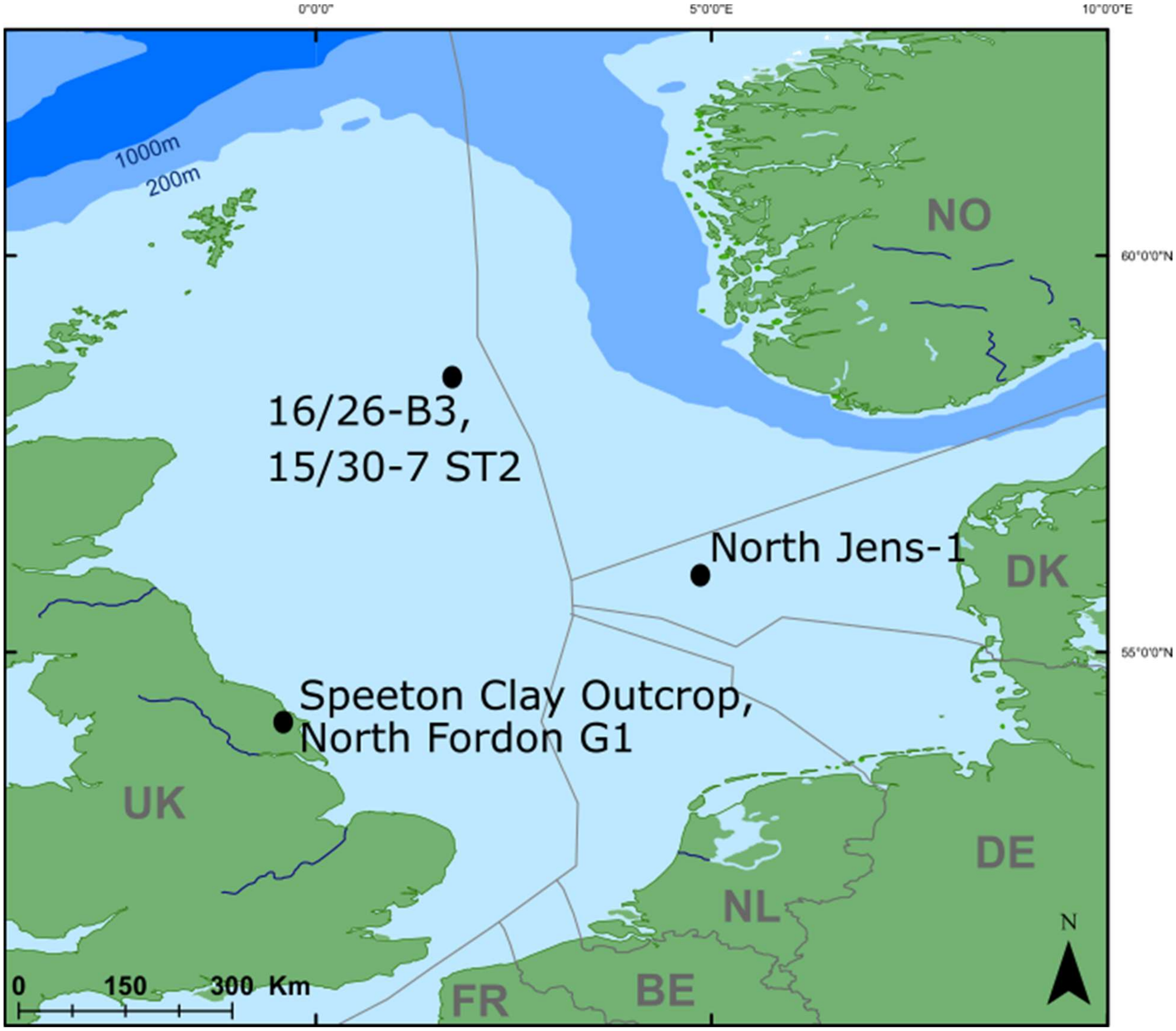


Figure 3. Location map of the sampling sites in the Danish North Sea for North Jens-1; British North Sea for the Britannia Field boreholes 16/26-B3, 15/30-7 ST2; Yorkshire for Speeton Clay outcrop and North Fordon-G1 borehole. Modified from Zanella and Coward, (2003).

This project will evaluate a range of palaeo-depths. The only shallow-water palaeoenvironment studied in this project is the Lower Cretaceous (and Upper Jurassic) Kimmeridge Clay, Speeton Clay and Hunstanton formations. They were sampled in a coastal exposure in North Yorkshire, and a nearby borehole (North Fordon G1) held at the British Geological Survey Core Repository (BGS) in Keyworth, Nottinghamshire (see Figure 3).

Deeper water palaeoenvironments were investigated at two sites in the Central North Sea and the Danish Central Graben. The former is located at the junction of the Witch Ground, Central and Viking grabens in British waters of the North Sea, in the Britannia Field. There, through the boreholes, 16/26-B3 and 15/30-7 ST2, a composite section encompassing the Lower Hauterivian to the Middle Albian was assembled to investigate the Valhall, Carrack, Britannia Sandstone and Rødby formations (see Figure 3).

The second deep-water site is an offshore well in the Central Graben of the Danish North Sea named North Jens-1. Cored intervals are held by the Geological Survey of Denmark and Greenland (GEUS) in Copenhagen, Denmark. The cored intervals comprise the Valhall, Tuxen, Sola and Rødby formations that broadly correspond to the latest Valanginian, Barremian, and Aptian (see Figure 3) (Ineson, 1993; Mütterlose and Bottini, 2013; Copestake et al., 2003; Ineson et al., 2022).

Additional data sources and reference material are found in unpublished doctoral theses and publications relating to Early and 'mid'-Cretaceous microfossils with valuable datasets that bring a different perspective. For example, Fletcher's (1966) slides housed at the Natural History Museum in London (NHM) and Crittenden's (1988) material, previously housed at the University of Plymouth, has now been transferred to the NHM. The former British Petroleum microfossil collection is also housed at the NHM (NHM, 2014). Foraminiferal specimens from these resources were examined, creating opportunities to conduct analyses at the assemblage level to investigate the palaeoenvironments and evolution of Lower Cretaceous foraminifera.

1.1 Objectives

The objectives for this project can be summarised as follows,

1. To investigate the biostratigraphical distribution of foraminiferal groups throughout the Lower Cretaceous of the North Sea Basin and its margins.
2. To characterise the foraminiferal assemblages across space (shallow versus deep-water basinal settings) and time (Lower Cretaceous stages) regarding relevant palaeoecological indicators such as species richness and abundance.

The first objective will be achieved through the micropalaeontological characterisation of individual stratigraphic sections from Lower Cretaceous formations. The second objective involves comparing microfossil assemblages from different settings (e.g., from shallow and deep-water areas) among themselves. Achieving these objectives should help the reader increase their understanding of the evolution of Lower Cretaceous Foraminifera in topics such as:

Benthic Agglutinated taxa: that were succeeding in deep-water environments.

Benthic Calcareous taxa: that were flourishing in marine shelves.

Planktic taxa: which appeared in high abundance for the first time in the fossil record.

Before addressing these specific topics, we will first examine the changing Lower Cretaceous environments of the North Sea Basin.

1.2 Evolution of the North Sea basin landscape through the Lower Cretaceous

Oakman and Partington (1998), Coward *et al.* (2003), Zanella and Coward (2003) described the tectonic evolution processes and the resulting structural framework of the North Sea. The reader is advised to review the previous authors to understand the global and local processes operating before, during and after the Lower Cretaceous times and shaped the landscape where sediments and the foraminiferal fauna were transported and deposited. Since this project is not focused on the tectonic evolution of the North Sea, we will not offer a discourse and literature review on the matter beyond what we considered strictly necessary in each chapter. However, it is helpful to have a brief look at the geological architecture of the North Sea in general is today and highlight some of the relevant structures of the basin nearby the areas of study.

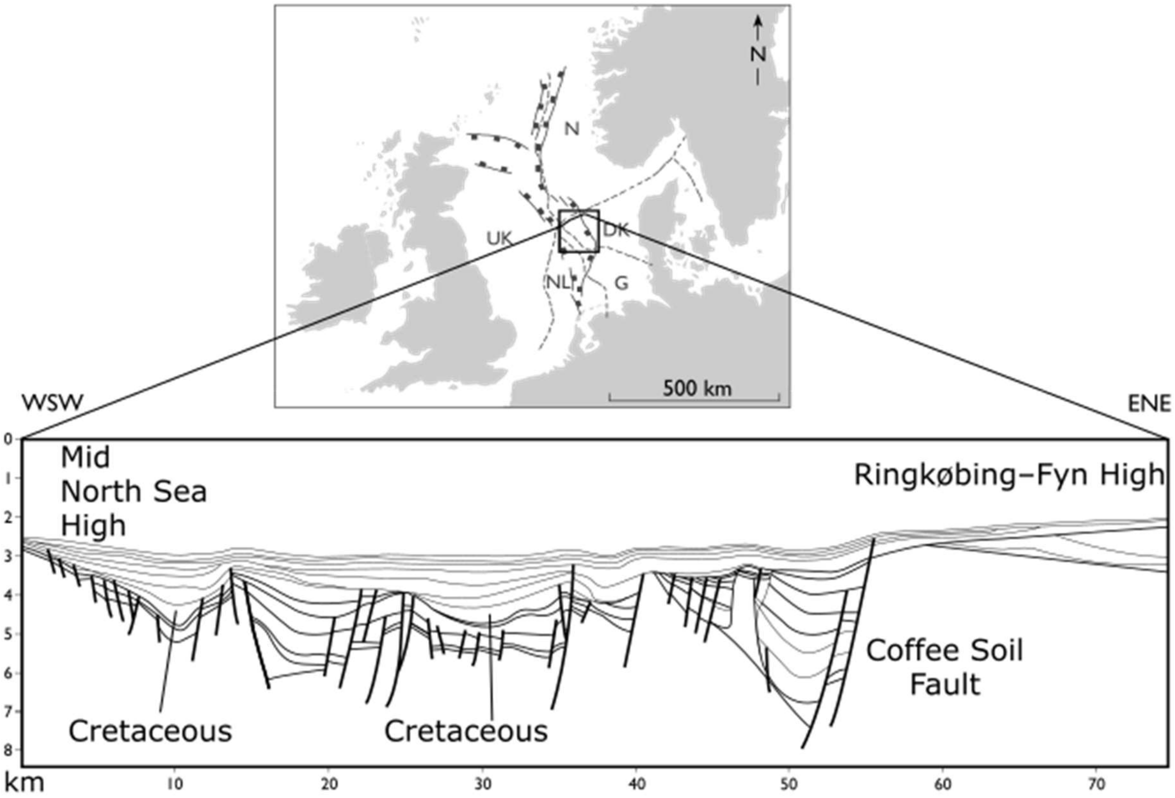


Figure 4. Diagrammatic structural cross-section of the northern part of the Danish Central Graben. Modified from Møller and Rasmussen (2003).

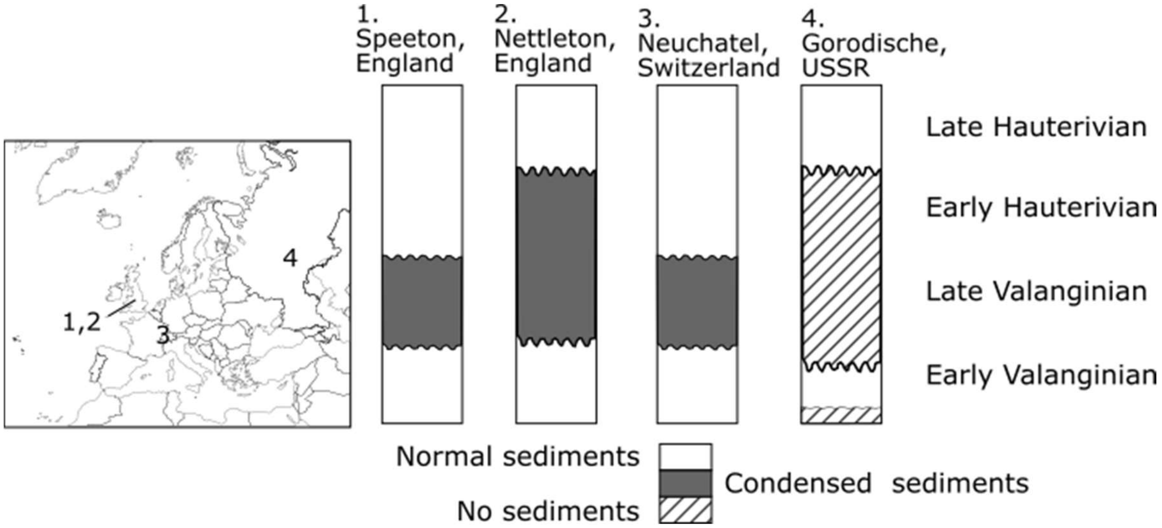


Figure 5. Erosion/Condensation in selected European Lower Cretaceous sections. Modified from Rawson and Riley (1982).

Figure 4 and Figure 6 highlight some of the defining features of the North Sea, a collection of normal and reverse faults that affected rock piles under an extensive and later passive and dormant tectonic state, which is discussed in detail in the chapters of this thesis. The result is a collection of failed graben arms and horsts located towards the middle of the North Sea surrounded by a shoaling marine floor on the European continental shelf.

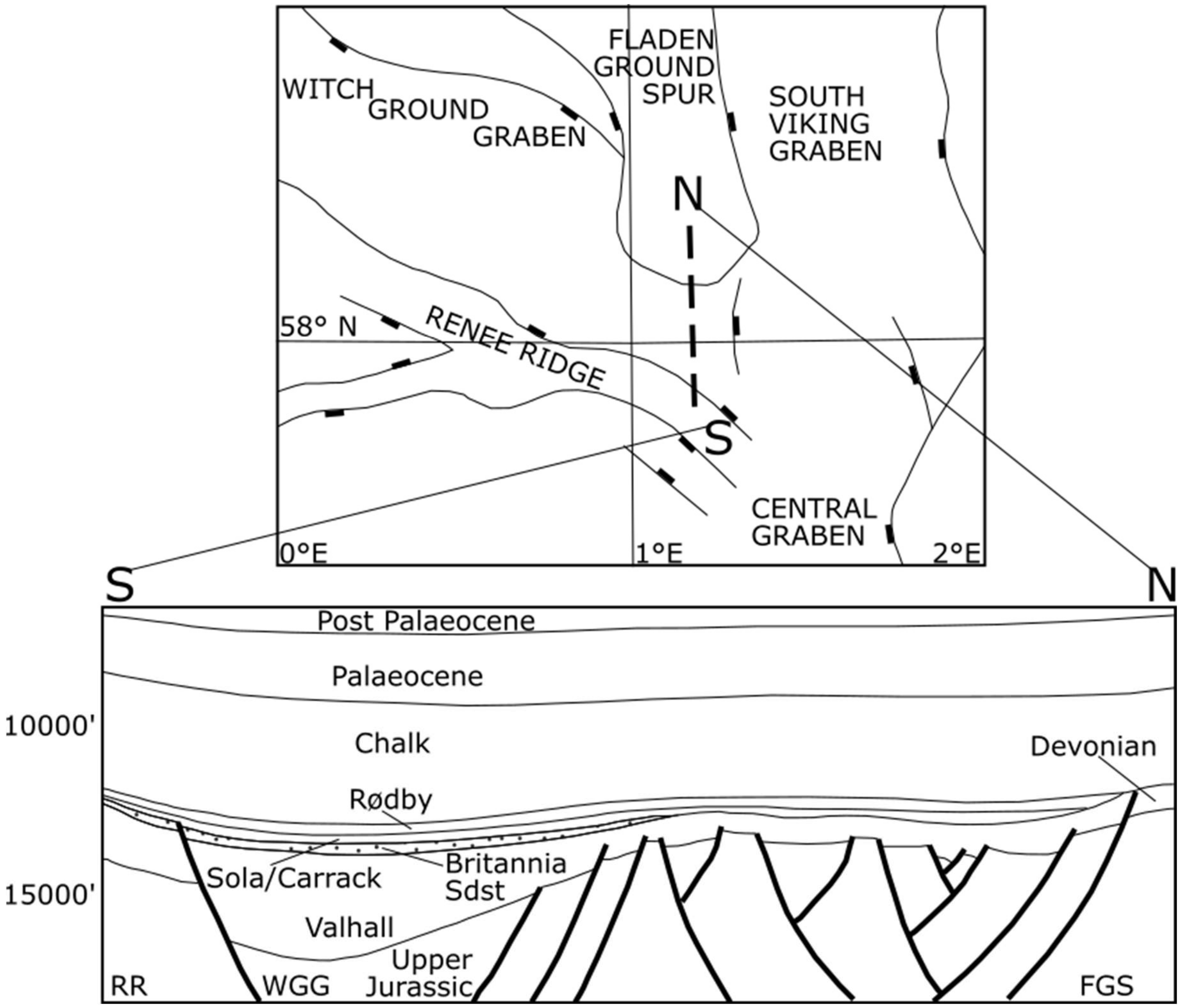


Figure 6. Diagrammatic structural cross-section across the Witch Ground Graben. Modified from Guy (1992).

When looking at the North Sea deposits, it is beneficial to consider the presence of condensed sections and the lack of sediments due to erosive processes. The tectonic activity helped develop several unconformities in the Lower Cretaceous sections of the North Sea and surrounding regions (see Figure 5) (Rawson and Riley, 1982). Hiatuses and unconformities show up in the geological and biostratigraphic records of the sections studied in this project, and they are explained in chapters 2 and 3.

1.3 Patterns of evolution in Lower Cretaceous Foraminifera

In addition to the biostratigraphic review for the Lower Cretaceous in the North Sea in chapters 2 and 3, we should be looking for keys regarding Lower Cretaceous foraminiferal development.

Tappan and Loeblich (1988) stated several ideas around foraminiferal evolution and diversification in the Cretaceous. For example, they suggested that early Mesozoic marine eutrophication was caused by interconnected continents restricting seaways and affected smaller foraminifera's expansion and development. For instance, dark clay sediments of Jurassic and Cretaceous age propitiated the development of flattened and elongated Lagenina tests, likely as an evolutionary adaptation to burrowing in the shallower few centimetres of organic-rich sediments in search of detritus to scavenge.

Tappan and Loeblich (1988) also suggested that vertical stratification of the water column was encouraged by the Cretaceous climate and vast epicontinental seas. However, there was not a significant latitudinal temperature zonation. They suggest that nutrient influx was reduced, oceanic circulation slow, upwelling, and nutrient recycling were minor. These conditions favoured the evolution of large and complex genera of Textulariina and Miliolina in warm, oligotrophic, shallow-water carbonate shelves (Tappan and Loeblich, 1988). The conditions mentioned above also favoured the diversification of planktic foraminifera. Tappan and Loeblich (1988) stated warm, vertically stratified seas had minor clastic input resulting in euxinic bottom waters and organic-rich pelagic sediments. Phytoplankton (dinoflagellates, calcareous nannoplankton, silicoflagellates, chrysomanads, and diatoms) diversified in the photic zone, as did the planktic foraminifera. Cretaceous Heterohelicidae, Guembelitriidae, Globuligerinidae, Globigerinelloididae, Favusellidae, and Rugoglobigerinidae have tests that are nearly globular or constructed of loosely attached spherical chambers, hence a low surface area relative to volume and low specific gravity (Tappan and Loeblich, 1988). Tappan and Loeblich (1988) suggest that planktic foraminifera inhabited the more oxygenated oceanic surface layer of areas with black anoxic sediments. Tappan and Loeblich (1988) wrote that as the seas retreated in the Late Cretaceous, continental runoff increased, the carbonate shelf environment disappeared, and oceanic circulation was enhanced. Hallock (1982) remarked that eutrophication results in the slow-growing, long-lived, symbiont-bearing individuals being quickly outcompeted by smaller, faster-growing autotrophs and heterotrophs.

Tappan and Loeblich (1988) suggest that scarcity of nutrients led to the evolution of many symbiont-bearing taxa. However, eutrophication is not necessarily the only cause of extinction. Corals lose their symbionts (also known as bleaching) on modern reefs results sometimes from more significant than normal temperature fluctuations, salinity fluctuations or increased turbidity from out-of-the-norm runoff. Regardless of which causes were dominant, by the end of the Cretaceous, 93 per cent of the planktic genera, most larger agglutinated foraminiferal genera, 90 per cent of the larger porcelaneous genera, and 80 per cent of the larger Rotaliina faced extinction (Tappan and Loeblich, 1988).

Kiessling et al. (2003) discussed benthic foraminifera as vital components of bioclastic limestones and reef constructions in carbonate platforms such as the subtropical northern Tethys margin and tropical carbonate platforms of the Early Cretaceous. These carbonate platforms continued expanding towards high latitudes in the Late Cretaceous, providing ecological space for the development of foraminifera (Kiessling et al., 2003).

Hart (1999) discussed that for benthic foraminiferal taxa, the selection of an evolutionary type will have to follow a diverse set of rules. Instead, for planktic foraminifera, the selection of evolutionary type may be left to available water depth and/or trophic resources (Hallock, 1982).

Hart (1999) continued his argument by pointing out that the Cretaceous planktic foraminiferal evolution and diversification processes can be seen following sea-level curves for the same time. Sea-level was at the same time controlled by oceanic spread and crust formation rates. However, the evolutionary storyline is interrupted by bioevents, such as faunal turnovers, that may, in principle, related to anoxic water masses' growth and oxygen-depleted stratification of water columns as a result of change in world's oceans. Hart (1999) added that foraminiferal diversity in the earliest Cretaceous is a continuation of low-diversity trends in the Jurassic, with little change happening until the Barremian, when species richness increased slightly. By the mid-Aptian, rapid diversification coincided with the initial stages of the South Atlantic and Eastern Indian openings. Data from (Larson, 1991; Larson and Erba, 1999) may suggest that sea-level rose quickly, as did ocean crust and spreading rates in this geological interval.

(Hart, 1999) quoted Hart and Bailey (1979) in their usage of planktic/benthic ratios through the Cretaceous chalk of England to suggest that faunal changes were directly affected by available water column depth, despite being, in principle, free to move towards deeper water oceanic environments instead of staying in the shelves. Adventurous taxa that moved into deep water will face extinction in the Late Cretaceous as they were unable to re-turn to shallow-water niches, whereas more conservative taxa that stayed in shallow-water environments survived the negative changes and some of them went even to survive the Cretaceous-Palaeogene extinction event (Hart, 1999; Hart and Bailey, 1979).

Leckie et al. (2002) use the accelerated evolutionary activity recorded in the Aptian, Albian, and Cenomanian planktic foraminifera and nannofossils to argue that a series of significant perturbations in the ocean-climate system may have occurred during that period; the Oceanic Anoxic Events (OAEs) being a testimony to some of those changes.

Rückheim, Bornemann and Mutterlose (2006) analysed planktic foraminifera from the Barremian to Albian interval of the Central North Sea and suggested that the overall dominance of trochospiral smooth-walled hedbergellids indicates aerobic and mesotrophic to eutrophic surface water conditions that would have been disrupted from time to time (i.e., becoming more dysaerobic or deeper) judging by the occasional presence of planispiral globigerinellids and trochospiral-flattened ticinellids, respectively. Rückheim et al. (2006) also studied the benthic foraminifera and discovered that, based on the predominant specimens (epifaunal calcareous, predominantly trochospiral morphogroups), the bottom-water conditions of the Barremian to the earliest Aptian were suboxic. Both aerobic and dysaerobic species were present, suggesting seasonal particulate organic matter fluxes from the surface waters. The agglutinated species are abundant towards the Aptian – Albian boundary, reaching almost fifty per cent of the assemblage. However, agglutinated benthic foraminifera remain subordinate to benthic calcareous ones.

In summary, Rückheim et al. (2006) defined the Barremian to earliest Aptian of the Central North Sea as a marine, temporarily restricted environment. This environmental generalisation is broadly confirmed by intermittent appearances of planktic foraminifera with the atypical planispiral tests — they may indicate occasional linking of Boreal and Tethyan faunas.

For the Late Aptian to Early Albian stages, Rückheim et al. (2006) suggested an open-oceanic environment with temperate and aerobic surface water conditions due to the diverse planktic foraminiferal assemblages. These included rare occurrences of planispiral, clavate and trochospiral-flattened morphotypes, suggesting a connection of the North Sea with the Tethys. However, the benthic foraminifera assemblages indicate aerobic to dysaerobic bottom-water conditions.

In addition, it is worth mentioning the impact of Oceanic Anoxic Events and their impact on Cretaceous microfossil assemblages. For instance, Leckie et al. (2002) listed the possible causes of the negative $\delta^{13}C$ excursion recorded in marine carbonates of the Early Aptian age, thought to be one of the distinctive features of the OAE1a. The hypotheses listed included: first, increased upwelling rates of nutrient- and ^{12}C-rich intermediate waters. Second, accelerated hydrologic cycle and higher weathering rates induced by CO_2-driven global warming. Third, isotopically light, mantle-derived CO_2 associated with the eruption of Ontong Java-Manihiki before an interval of enhanced productivity and organic carbon burial. Finally, dissociation of isotopically light methane hydrates in continental margin sediments. Iron fertilisation associated with the superplume eruption triggered increased productivity during the OAE1a (Larson and Erba, 1999).

Bärbel et al. (2012) explained that the Mesozoic oceanic anoxic events, including the OAE1a in the Aptian, saw a remarkable enlargement of the ocean's oxygen minimum and deep anoxic zones. According to evidence put forward by the authors (Bärbel et al., 2012), these OAEs were triggered by the emplacement of large igneous provinces, degassing of immense volumes of CO_2 and associated environmental consequences of warming, lower oxygen solubility, and possibly ocean acidification. Bärbel et al. (2012) suggested that a few Cretaceous OAEs were associated with turnover in planktic communities. Deformities and minor size reduction in coccoliths, as well as a massive increase in the abundance of heavily calcified nannoconids, were observed.

Hart (1999) cited Kauffman and Hart (1996) to suggest that several Early Cretaceous bioevents were related to developing oxygen-depleted and black shale sedimentation in deep-water environments. For instance, the mid-Aptian planktic foraminiferal expansion was derailed by the Paquier anoxic event (French Albian) (Bréhéret et al., 1986). In addition, in the Late Cenomanian there is a major faunal turnover closely associated with the Bonarelli Event (OAE2) (Hart, 1999).

It is thought that OAEs affected the microfossil assemblages of the North Sea in the Aptian and Albian stages. Some of them, such as OAE1a, represented by the Fischschiefer Member in two of the studied areas of the North Sea (Mütterlose et al., 2014; Riley et al., 1992), were of global magnitude (Larson and Erba, 1999; Leckie et al., 2002). Others, like the Munk Marl/Hauptblätterton event of the latest Early Barremian, were regional-scale events (Ainsworth et al., 2000; Crittenden et al., 1991; Garrett et al., 2000). It is worth framing some of the characteristics of these events in a general way. More details about the specifics of each event are in the individual chapters.

1.4 The Lower Cretaceous beyond the North Sea Basin

Holbourn and Kaminski (1997) studied deep-sea benthic foraminifera of the Lower Cretaceous of the Indian Ocean from over ten wells spudded during DSDP and ODP research expeditions. Biostratigraphic analyses on almost five hundred samples were summarised as a collection of microfossil assemblages for each drilling site, which resulted in the proposal of a benthic foraminiferal zonation for the Lower Cretaceous of the Indian Ocean. Interestingly, the results are similar in some ways to the Lower Cretaceous of the North Sea. First, the palaeobathymetric conditions of the Indian Ocean resemble a similar trend of deepening throughout the Lower Cretaceous, as manifested in the faunal succession discovered in their study. The deepening is associated with the Australian margin's subsidence post-breakup from the Indian subcontinent (Holbourn and Kaminski, 1997). Foraminiferal assemblages composed of agglutinated foraminifera suggest slightly restricted conditions in the Late Valanginian and Hauterivian. In contrast, oceanic-affinity foraminiferal assemblages point to increased ventilation in pelagic settings from the Barremian to the Albian.

Changes in oceanic circulation and the depth of the CCD may have also influenced faunal assemblages. Holbourn and Kaminski (1997) cited Barron and Peterson (1990), Hay (1988), Kaiho and Saito (1994), Larson (1991), Roth (1989), Spicer and Corfield (1992), Brass et al. (1982), Schlanger et al. (1981), Vogt (1989) to suggest that the interconnected nature of the marine setting meant that events such as intraplate volcanism, periodic intensification of atmospheric circulation, enhanced coastal upwelling, magnified terrigenous runoff, and the increased production of warm, saline bottom water with low-oxygen content (due to high evaporation in shallow seas), led to amplified fertility in surface waters and oxygen deficiency in bottom waters, impoverishing the foraminiferal assemblages of the mid-Cretaceous. However, conditions may have changed for the better around the mid-Albian when significant improvements to deep-water ventilation and the CCD deepening allowed diverse foraminiferal assemblages to thrive and manifest themselves. For a detailed explanation, refer to Holbourn and Kaminski (1997).

Holbourn and Moullade (1998) discussed the Aptian to Cenomanian benthic foraminifera from the African Equatorial margin. The foraminiferal assemblages indicate a combination of Tethyan, South Atlantic and local, endemic microfossil faunal influences, suggesting that connections to open ocean, the Tethys probably remained occasionally restricted during the Albian - Early Cenomanian. However, there is no evidence for widespread bottom-water anoxia. Foraminiferal assemblages show variable numbers of miliolids, patellinids, and trocholinids, characteristic of mid- or inner-shelf settings and some gavelinellids and nodosariids typical of the outer shelf to upper bathyal environments. The absence of deep-water agglutinated benthic foraminifera (DWAF) precludes a deep bathyal environment of deposition.

Bartenstein and Bettenstaedt (1962) and Bartenstein (1978) studied the Lower Cretaceous of north-west Germany and provided foraminiferal, and ostracod biozonations comparing them with ammonoid zonation charts developed for the area (Kemper, 1976). Bartenstein (1976b, 1977, 1979) showed a biostratigraphic scheme for the Berriasian to Albian of temperate and Tethyan facies in basins worldwide, mainly in the northern hemisphere. Over eighty benthic foraminiferal species were used in the zonation schemes.

Bartenstein (1976) continued his studies of the Boreal Lower Cretaceous by comparing East Canada's Lower Cretaceous with the equivalent units of north-west Germany and Europe. He stated that the stratigraphic coincidence between East Canada and north-west Germany is, surprisingly, exact. These similarities make biostratigraphic schemes of both benthic foraminifera and ostracods work well. Bartenstein (1976) noted that it is possible to compare the Lower Cretaceous temperate facies of the southern tips of Africa and South America. A similar type of stratigraphic comparison of the Barremian to Albian between the tethyan realm of Central America and the boreal realm of north-west Europe is possible (Bartenstein, 1976b, 1985). Bartenstein (1985) presented a stratigraphic chart for the Barremian to Albian in Trinidad and Tobago, including important index foraminifera. In the foraminiferal assemblages of these Caribbean islands, planktic foraminifera dominate the Upper Albian (and Cenomanian). For the Lower Albian and Aptian, the planktic and benthic foraminifera display similar abundance percentages. However, for the Barremian assemblages, benthic foraminifera index specimens predominate. Bartenstein (1985) stated that a similar pattern is true for several Lower Cretaceous depositional areas worldwide.

Bralower *et al.* (1995) developed integrated biostratigraphy for the Cretaceous period based on planktic foraminifera, calcareous nannofossils and calpionellids. The integrated scheme works best for mid- and low-latitude stratigraphic sequences. The planktic foraminiferal zonation schemes used are from the original work of Caron (1985) and Sliter (1992). Bralower *et al.* (1995) highlighted three significant challenges for implementing a worldwide planktic foraminifera zonation scheme: first, the correlation between high- and low-latitude zonations is not well established. Second, a few bioevents are known to be diachronous. Third, the Hauterivian through Aptian biostratigraphy of planktic foraminifera is in a state of constant change.

In Romania, Neagu (1997, 2000) studied the agglutinated foraminifera from the southern Dobrogea area and published a comprehensive taxonomy of selected families. This study provides a window to the exchange between Lower Cretaceous faunas from tethyan and boreal affinities. He linked morphology and test characteristics of agglutinated foraminifera with limiting environmental factors, as species from a determined genus living in cold, boreal water basins with coarse clastic sediment agglutinate tests with the coarse available material. In contrast, species from the Tethys' inner carbonate platform sedimentary facies made a fine, smooth test due to the reduced amount of clastic sediment.

Kaminski and Geroch (1992) compared Lower Cretaceous DWAF biostratigraphic schemes from the Flysch deposits of the Carpathians in Poland and Romania with those from the pelagic deep-sea Argo Abyssal Plain of the Indian Ocean. The researchers stated that almost all stratigraphic ranges of species on both sites partially coincide, with a few exceptions, such as *Trochammina abrupta*. A few challenges to the success of these correlations are the lack of calibrated standard magnetic polarity time scales with standard planktic microfossil zonations. Kaminski and Geroch (1992) suggested that intra-basinal changes to palaeoceanographic factors such as the CCD and the location of upwelling areas are possible. Litho- and bio-facies changes due to surface-water productivity can be diachronous, complicating biostratigraphic interpretations and correlations (Kaminski and Geroch, 1992). One important conclusion is that the assumption for a unique global DWAF zonation scheme for the Lower Cretaceous is not valid. Barriers to migration, among other factors, can preclude species from ever arriving at ocean basins. A statistical approach is necessary to discriminate between global microfossil signals and local variations (Kaminski and Geroch, 1992).

Riegraf and Luterbacher (1989) studied DSDP Legs 1 to 80 and provided an overview of the Lower Cretaceous foraminiferal biostratigraphy for drilled areas in the Pacific, North and South Atlantic, and Indian Oceans. In the latter ocean, microfossil faunas described as "primitive agglutinated foraminifera" from temperate waters did not indicate a stratigraphic range more accurate than Berriasian to Hauterivian. Dissolution or redeposition are said to have affected most benthic calcareous foraminiferal tests. Poor microfossil assemblages characterise the Berriasian to Aptian interval in the Pacific Ocean, and these provide limited biostratigraphic and palaeoecological value. Albian foraminiferal assemblages provide better worldwide correlation opportunities. The North Atlantic assemblages are not well represented in the interval between the uppermost Jurassic and the Valanginian because low sea levels caused breaks in the stratigraphic record. The Valanginian to Barremian interval shows moderately rich to poor microfaunas. *Praedorothia ouachensis* is a relevant fossil marker for this period (Riegraf and Luterbacher, 1989). Recovery is less successful in this interval because of areas with black shale lithologies. The Hauterivian to Aptian interval is characterised by biozones of

Gavelinella barremiana, *Gaudryina dividens*, and *Conorotalites aptiensis* (Riegraf and Luterbacher, 1989). In the Albian stage, a genuinely global fauna of agglutinated and calcareous foraminifera (the *Pseudoclavulina gaultina*) is found in black-shale free areas of oceanic environments(Riegraf and Luterbacher, 1989). A few ornamented nodosariid species (*Citharina*, *Lenticulina*), as well as species of *Gavelinella*, *Conorotalites*, *Pleurostomella*, *Valvulineria* and *Osangularia* play an important biostratigraphic role in the Berriasian to Albian interval (Riegraf and Luterbacher, 1989).

Gradstein et al. (1999) studied microfossils of increasingly oceanic areas dating back to the North Atlantic opening in the Cretaceous. They characterised the Hauterivian to Early Barremian deposits as thin, varicoloured, marly lithologies that gained a darker character upwards through the sedimentary pile, a testimony of maritime ventilation changes from oxic to dysaerobic. These deposits displayed abundant foraminifera of the *Falsogaudryina* genus, nodosariids and Ostracoda, implying a predominantly shallow (neritic) environment. In contrast, the mid-Cretaceous interval, from Aptian to Early Cenomanian, was characterised by dark mudstones and minor sandy lithologies. Deep-water agglutinated foraminifera and planktic floods of the *Hedbergella* genus are found in this interval, perhaps suggesting an upper bathyal environment and a poorly aerated marine environment.

1.5 General Considerations

All figured specimens from North Jens-1 will be housed at the Geological Survey of Denmark and Greenland (GEUS) in Copenhagen, Denmark. All other specimens will be housed in the Lapworth Museum of Geology, the University of Birmingham, accession numbers will be given in publications.

This thesis is the result of the author's research work. However, there are contributions in specific sections.

For section 2.1 of this document, as explained in subsection 2.1.6, the initial micropalaeontological picking for the Filey Bay dataset was carried out by two students from the School of Geography, Earth and Environmental Sciences at the University of Birmingham, Aimee Milenkovic and Luke Price. Further micropalaeontological work related to sorting, taxonomy, etc., was carried out by the author. As explained, this sample set was collected in the Field by Network Stratigraphic's Dr Haydon Bailey and Dr Liam Gallagher with invaluable support from Professor Peter Rawson. The author also visited the site with Prof. Rawson and sampled additional beds under his guidance in a field trip organised by the Geologists' Association.

The foraminiferal taxonomy used in this project received input from Dr Haydon Bailey. Dr Kirsty Edgar advised on planktic foraminiferal taxonomy suggesting authoritative sources. Dr Ian Boomer reviewed preliminary manuscript versions of the chapters in this thesis, and his help was instrumental with project planning, laboratory work, and results in general.

Dr Emma Sheldon from GEUS provided the calcareous nannofossil biozonation used for the North Jens-1 analysis in section 3.2. In subsection 3.2.4.1, most of the ideas in the paragraph are from Dr Sheldon. Figure 23 displays the nannoplankton zones produced by Dr Sheldon and colleagues at GEUS. Section 3.2.6 contains ideas from the nannopalaeontological work from Dr Sheldon, which are appropriately referenced in the text whenever necessary. Section 3.2.8 includes one paragraph regarding palaeoenvironmental interpretation insights from the calcareous nannofossils written mainly by Dr Sheldon and slightly modified by the thesis' author.

2 SHALLOW-WATER PALAEOENVIRONMENT

2.1 The Lower Cretaceous foraminifera of the Speeton Clay and Hunstanton formations of the Flamborough Head Heritage Coast and the North Fordon G1 well in the Cleveland Basin, Yorkshire, U.K.

2.1.1 Abstract

The foraminiferal assemblages of two sites in the Cleveland Basin in Yorkshire, the historic Filey Bay section of the Speeton Clay and the North Fordon G1 borehole, were examined under micropalaeontological protocols. A hundred and fifteen samples were analysed. The data were analysed using different techniques such as hierarchical clustering and detrended correspondence analysis. The results suggest that the foraminiferal assemblages of the Speeton and Hunstanton formations can be subdivided into sub-assemblages based on wall-type and life-mode criteria. This may indicate pulses of restricted versus more connected marine conditions throughout the Lower Cretaceous stages of Yorkshire's North Sea basinal shelf. The results provide opportunities to be compared with deeper-water environments within the North Sea Basin.

2.1.2 Introduction

The Yorkshire coastline deposits provide an outstanding window into the marine Lower Cretaceous environments of the North Sea Basin. The coastal section between Filey Bay and Flamborough Head, near Speeton, Yorkshire, is a reference point for all offshore deposits of the same age in the boreal realm (Mitchell and Underwood, 1999; Rawson et al., 1978). The two benthic microfossil sample sets used in this project detail changing foraminiferal assemblages in response to several processes. The first dataset comes from the Filey Bay section; the second is from the North Fordon G1 borehole, a few kilometres to the north-west of Scarborough, Yorkshire (see Figure 7). The Lower Cretaceous foraminifera recovered from these two sample sets provide a unique opportunity to understand foraminiferal environments when they were likely to expand into new ecological niches following the early Mesozoic extinction events. In addition, these two sample sets provide a unique view into increasing speciation rates, which are reported in the literature after the early Mesozoic crises (Jones, 2011; Kaminski et al., 2010). Similar processes are observed in Lower Cretaceous deposits elsewhere (Bartenstein and Bettenstaedt, 1962; Holbourn and Kaminski, 1997; Rückheim et al., 2006), as benthic calcareous foraminifera flourished in marine shelves of the Lower Cretaceous and agglutinated foraminifera flourished in deep-water ecological niches. At the same time, planktic foraminifera became abundant in the fossil record for the first time in the Lower Cretaceous.

2.1.3 The Geological Background of the Cleveland Basin and the British Shelf of the North Sea

During the Early Cretaceous, sedimentation of the Cromer Knoll Group in the British North Sea was concentrated in three depocenters: the offshore Sole Pit Basin and related shelves, the mixed onshore/offshore East Midlands Shelf and Cleveland Basin. The latter experienced rapid subsidence, was partially structurally controlled and provided a unique record of the Lower Cretaceous stage (Rawson, 2006). Industry-recovered offshore stratigraphic sequences may not present a complete picture of the Lower Cretaceous of the North Sea Basin because of their nature; most of them would have targeted structural highs, where the stratigraphic sequences may be incomplete (Pegrum and Spencer, 1990; Copestake et al., 2003; Spencer et al., 1996).

The Cleveland Basin

Although relatively small, the Cleveland Basin formed part of a series of extensional basins and epeiric seas through the mid-Mesozoic (Powell, 2010; Imber et al., 2014). The Cleveland Basin was connected to the offshore North Sea Basin via the Sole Pit Basin and the Central Fault Zone. It also shared a border in the north with the Mid North Sea High, west with the Pennine High and south with the Market Weighton High's downfaulted northern margin (Rawson, 2006). The latter was connected to the East Midlands Shelf and kept subsidence and sedimentation rates in the south lower than those in the Cleveland Basin. Powell (2010) explained that the Middle Jurassic sediments were deposited following transgressive pulses from the south. The pattern subsequently switched to substantial regression during the Jurassic–Cretaceous boundary interval. However, a transgressive pattern resumed during the Late Berriasian (and endured for most of the Lower Cretaceous) (Rawson and Riley, 1982), possibly, with similar sediment sources to those of Jurassic.

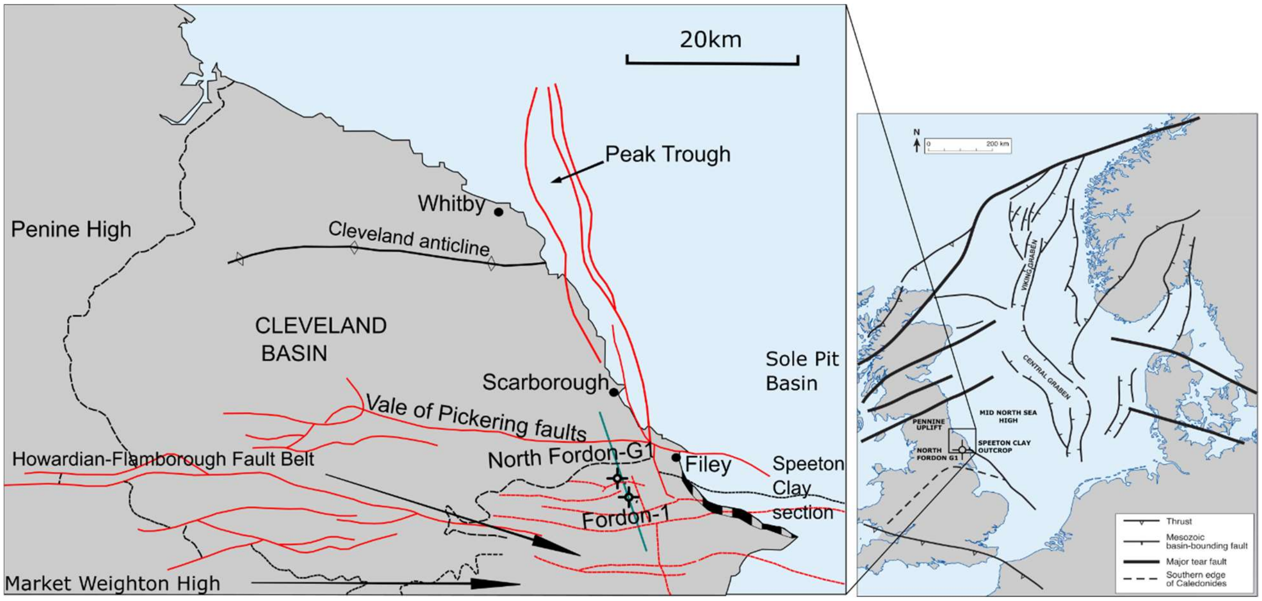


Figure 7. Location of the North Fordon G1 borehole and the Speeton Clay section in the Cleveland Basin; modified from Powell, (2010); Coward et al. (2003).

The Cleveland Basin was tectonically active throughout much of the Mesozoic, exemplified by a disconformity between the Kimmeridge Clay and the Speeton Clay formations, overlain by a 10 cm thick phosphatic nodule band, also known as the E bed of the Speeton Clay Formation (Fm subsequently) (Rawson, 2006). The disconformity suggests non-deposition or erosion in the approximately 10 Ma break between the two units. Features such as the Peak Trough, a north-south striking structure bounded by normal faults, were active in this area during the Jurassic and Early Cretaceous times (Imber et al., 2014). Seismic reflection profiles provide evidence for syn-tectonic sedimentation, evidenced by thickness changes in Jurassic and Lower Cretaceous units (Kirby and Swallow, 1987; Imber et al., 2014) notably, near the Bempton and Speeton faults. The former, a southward dipping listric fault anchored in evaporitic layers overlying

Permian deposits. The regular roll-over of strata formed a thick Lower Cretaceous sedimentary wedge, seen in the North Fordon G1 record. This sedimentary wedge is thicker than the sediment pile in the footwall and north of the Bempton fault (Kirby and Swallow, 1987; Imber et al., 2014). From this point onward, the sedimentary deposition was continuous but thin, as evidenced by the coastal sediments south of Filey Bay. The end of the Early Cretaceous witnessed uplift and erosion in the area, resulting in angular relationships with the overlying Upper Cretaceous Chalk deposits (Kirby and Swallow, 1987). Subsidence in the Cleveland Basin continued steadily throughout the Jurassic and Cretaceous. However, the basin later experienced tectonic inversion resulting in an east-west trending Cleveland anticline and associated structures (Imber et al., 2014).

2.1.4 Geology and stratigraphy of the Filey Bay section

The Yorkshire coast provides an essential reference for Jurassic and Cretaceous offshore sections in the North Sea (Rawson and Mütterlose, 1983; Lott et al., 1986), and it was beneficial for the energy industry in the last century. In the context of this study, it provides a unique point of comparison for microfossil assemblages across the North Sea Basin. The cliffs and shoreline facing the Filey Bay between Scarborough and Flamborough Head provide the most continuous exposure of the boreal Lower Cretaceous in north-west Europe (Fletcher, 1973). Early geological mapping of the area by William Smith and later efforts by the British Geological Survey laid the palaeontological and stratigraphical foundation laid the framework for many subsequent studies on this coastline (Fletcher, 1966; Hill, 1888; Judd, 1868; Khan, 1962; Lamplugh, 1889, 1923; Mitchell, 1995; Mitchell and Underwood, 1999; Neale, 1960a, 1962b, 1960b; Neale and Sarjeant, 1962; Rawson, 2018; Rawson and Mütterlose, 1983; Hart et al., 2008).

The shoreline at the southern end of Filey Bay can be accessed via a public footpath from the Reighton Sands holiday village, near Speeton. A walk on the beach towards the southeast provides access to an outcrop of over a kilometre long, including the exposure in cliffs and patches in the intertidal zone on the coast stripped off to reveal intervals of geological formations. A detailed field guide for this area can be found in Rawson (2018). The state of the outcrop is not the best for sedimentology and stratigraphy studies. Prone-to erosion lithologies built a soft geomorphologic expression covered by vegetation and debris. Small landslips of small magnitude are common, often related to faults and other structures. A geologist on a short field trip visit without an expert guide, like geology Professor Peter Rawson, might struggle to make any sense of the stratigraphy at all. Stratigraphic studies must rely on beach exposures, which are not always accessible, depending on tides and storms to clear the shoreface.

From the north-west to the south-east, the outcrop presents the Jurassic Kimmeridge Clay Fm (older rocks can be found to the north-west, but the area of study for the current project starts to the east of the public footpath). The Lower Cretaceous Speeton Clay Fm beds, followed by the Hunstanton Fm (formerly known as 'Red Chalk'). Finally, the lower part of the Upper Cretaceous White Chalk Group. Detailed descriptions of the outcrop can be found in Fletcher (1969); Judd (1868); Kaye (1964); Lamplugh (1889); Mitchell and Underwood (1999); Neale (1960b, 1974); Rawson (1983, 2018); Hart et al. (2008). Figure 9 and Figure 11 show a stratigraphic log of the Speeton Clay Fm and its subdivisions for the study locations used in this project.

Speeton Clay Fm (Berriasian-Albian)

The Lower Cretaceous, Speeton Clay Fm, is part of the Cromer Knoll Group. It is a lateral equivalent of the Valhall Fm of the Central North Sea and the Vlieland Shale Member, Lower Holland Marl Member and Middle Holland Shale Member of the Dutch southern North Sea (Crittenden, 1982). Its thickness at the Filey Bay section is over 91.4 m (300 feet) and almost 213 m (700 feet) at the North Fordon G1 location. In addition to the Cleveland Basin, the Speeton Clay Fm is seen at outcrop in other parts of eastern England, particularly Lincolnshire and Norfolk, where it occurs as sandstones, clays, limestones, and ferruginous sediments. These are considered inner-shelf deposits, shallower water, sedimentary facies compared to the Yorkshire deposits, which represent the outer shelf, relatively deep but shallower than the deep-water facies of the North Sea Central Graben (Cameron et al., 1992; Kent et al., 1980). The Speeton Clay Fm on the Yorkshire Coast comprises calcareous mudstones and shales exhibiting various colours, including brown, grey, green, and grey-black; there are horizons with sandstones, siltstones and phosphatic-nodules (Cameron et al., 1992). The fossil content of both macro and microorganisms is abundant in some layers.

The Speeton Clay Fm rests unconformably upon fine-grained Late Jurassic sediments of the Kimmeridge Clay Fm. Seismic profiles across the Cleveland Basin show a low angle unconformity between the Jurassic and the Cretaceous deposits (Cameron et al., 1992). Basal Late Berriasian beds display low-fossil content, non-calcareous and organic-rich facies, not unlike the Kimmeridge Clay. Upwards through the section, the calcareous content increases, organic matter content decreases, and fossil abundance increases (Cameron et al., 1992; Lott et al., 1986). Rawson and Riley (1982) suggested that these lithological changes are widespread throughout the North Sea Basin. They may be associated with the Late Ryazanian (Berriasian) transgression, bringing well-oxygenated waters to replace the oxygen-depleted waters at the bottom of the basin. This episode is possibly related to tectonic subsidence in the North Sea grabens, which Knox and Fletcher (1978) attributed to outside-of-the-basin volcanism.

Hunstanton ('Red Chalk') Fm (Albian-Cenomanian)

Crittenden (1982) quotes Rhys (1974) defining the Red Chalk Fm as a mudstone, calcareous to slightly calcareous, red-brown with consistent small amounts of white to light grey mottling and lesser dark grey mottling. Electric logs show that the carbonate content increases gradually toward the top of the formation, as evidenced by decreasing radioactivity (gamma-ray) and increasing density (sonic velocity). The Red Chalk Fm, first mentioned by Smith (1816) and used for several decades in the sense of Hill (1888);

Jukes-Browne and Hill (1903, 1904), was deemed not worthy of formal lithostratigraphic status by Wood and Smith (1978). The latter suggested that the name Hunstanton Chalk Member of the Ferriby Chalk Fm should be used instead, which was adopted by later authors (Gaunt et al., 1992). However, the Red Chalk raised interest among the geological community so that authors like Mitchell (1995) restudied the Red Chalk unit and suggested the Hunstanton Fm as a formal name. Mitchell and Underwood (1999), Rawson (2006) and other recent authors comply with this suggestion. The unit's geographic distribution is most of the southern North Sea Basin and selected sectors of the northern and central North Sea basins. Inland, Rawson (2006) confirmed the presence of the Hunstanton Fm in the Cleveland Basin and over the East Midlands area. However, its lithological character is a pink to brownish-red impure limestone, with abundant quartz particles and fossils, slightly different from its offshore equivalents (Cameron et al., 1992; Kent et al., 1980). The unit is thinner onshore (5 – 13 m) than offshore (20 – 30 m). Kent et al. (1980) suggested that the red colour of the Hunstanton Fm may be due to red mud washed from a low-lying lateritised contemporary land area. He also indicated that the ferruginous material could have been derived from Triassic sediments exposed by salt tectonics (Kent, 1967). Crittenden (1982) correlated the Hunstanton Fm to the Upper Holland Marl Member of the Dutch southern North Sea and the Rødby Fm of the Central North Sea. Figure 9 and Figure 11 show the position of the Hunstanton Fm in the stratigraphic sections studied in this project.

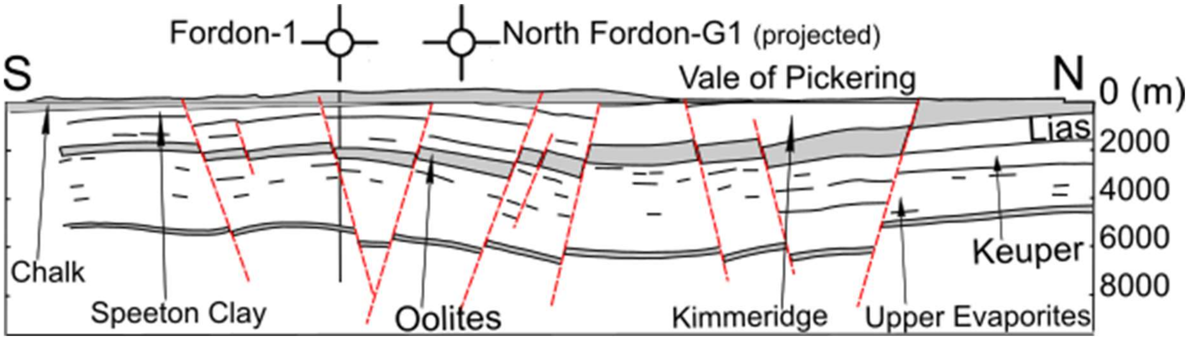


Figure 8. Geological section across the Cleveland Basin. The location of the North Fordon-G1 and Fordon G1 boreholes is shown. The Speeton Clay and the Hunstanton formations are thin layers at the top of the geological section. Adapted from Falcon and Kent (1960). The location of the section can be seen in Figure 7 as a green line.

2.1.5 The Lower Cretaceous biostratigraphy of the Cleveland Basin

Extensive biostratigraphic work has been carried out on the Lower Cretaceous of Yorkshire. Starting with Judd (1868), who studied the Speeton Clay Fm based on belemnites, ammonites and other fossils that subdivided the unit on upper, middle and lower Neocomian. Lamplugh (1889) amended Judd's work based on belemnites by suggesting that the Filey Bay section comprising the Speeton Clay and the Kimmeridge Clay Fm be divided into six zones based on five belemnite biozones and one coprolitic bed of black phosphatised nodules. These zones are named A to F, starting at the top and proceeding downwards in the stratigraphic column, and they remain until today, having been studied in detail by recent workers. The first micropalaeontological study, on the foraminifera of the Speeton Clay Fm, was carried out by Sherlock (1914), who systematically described over thirty species and attempted comparison with specimens from Germany and England. Khan (1962) studied over 120 foraminiferal species and determined the stratigraphic range for thirty index species from the Speeton Clay Fm and equivalent units in north-western Germany. However, his samples are not labelled according to specific beds in Yorkshire but according to large bed intervals (A-E); therefore, the biozones are not precise. In his unpublished thesis, Fletcher (1966) provided a detailed taxonomical description for the most relevant foraminifera in the Lower B, C and D beds of the Speeton Clay Fm outcrop, south of Filey Bay. Fletcher also identified the most abundant specimens in some of the cored intervals at the North Fordon G1 borehole. Bartenstein and Bettenstaedt (1962) presented foraminifera and ostracod occurrence data from the Lower Cretaceous of north-western Europe, many familiar to the Lower Cretaceous in Yorkshire. Bartenstein (1956) had previously studied the Hauterivian of Lincolnshire. Neale (1960a, 1962b) presented a detailed taxonomic study of the ostracod assemblages from the North Fordon G1 borehole and the D beds of the Speeton Clay Fm outcrop at Filey Bay, as well as a complete stratigraphic and biostratigraphic scheme for the Speeton Clay Fm (Neale, 1974). Fletcher (1973) produced a detailed biostratigraphic analysis of the foraminiferal faunas of the D, C and Lower B beds of the Speeton Clay Fm at Filey Bay. Hart et al. (2008) later studied the same interval to establish a sequence-stratigraphy framework for the Lower Cretaceous of Yorkshire and possibly the entire North Sea Basin, based on foraminiferal events. Mitchell and Underwood (1999) investigated the microfossil content (foraminifera and ostracods) of the upper part of the Speeton Clay Fm (the upper B and the A beds). Banner and Desai (1988) and Banner et al. (1993) studied planktic foraminifera (Globigerinina) from the Speeton

Clay Fm section at Filey Bay and other offshore locations in the Central North Sea, all within the Cromer Knoll Group of Lower Cretaceous age. King et al. (1989) established a foraminiferal biostratigraphic framework for the Cretaceous of the North Sea divided into two geographical areas, north and south. Taylor (1978) and Bown et al. (1998) published details of the calcareous nannofossil biostratigraphy of the Lower Cretaceous of the Yorkshire Coast and the North Sea Basin.

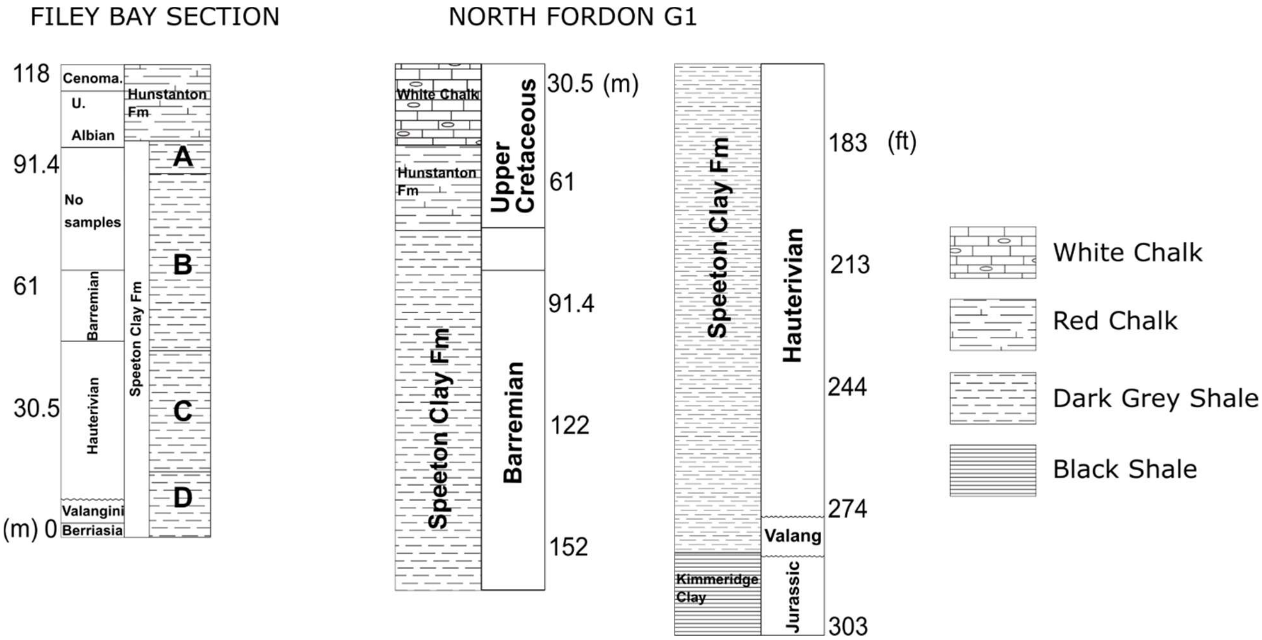


Figure 9. Filey Bay and North Fordon G1 borehole stratigraphic sections sampled for this project. Chronostratigraphy and lithostratigraphy based on Neale (1974); – Filey Bay, Geological Division (1960); Fletcher (1966); Mitchell and Underwood (1999); Neale (1962a); Rawson and Mütterlose (1983); Hart et al. (2008) – North Fordon G1. Note the differences in thickness between the two sites. The location for both sites can be seen in Figure 7.

2.1.6 Methods

A hundred and fifteen samples, 58 from outcrop, 25 from core and 32 from ditch-cuttings, have been examined. The Filey Bay section provided outcrop material, whereas the North Fordon G1 borehole provided both core and ditch-cuttings samples. The outcrop material is a composite study from two separate datasets collected by Liam Gallagher and Haydon Bailey with the helpful guidance of Peter Rawson from Hull University. One set of samples is housed at the NHM, London; additional samples are housed at the School of Geography, Earth and Environmental Sciences, University of Birmingham. On the other hand, the North Fordon G1 borehole was drilled by the British Petroleum Corporation in 1955. Its core and ditch cutting samples are housed at the British Geological Survey Core store in Keyworth, Nottinghamshire. Most of the selected samples are from the Speeton Clay Fm, with some additional material from the Kimmeridge Clay and Hunstanton formations and the Chalk Group. Samples were processed and analysed following the methods described by Castañeda et al. (2021). The results of the microscopic analyses were summarised into range charts that are available in the appendix section. The range charts for the Filey Bay and North Fordon G1 sections were arranged according to First Downhole Occurrences (FDO). This allowed for comparisons between each sample set and with biostratigraphic schemes widely used for the micropalaeontological studies of the Lower Cretaceous of the North Sea, such as King et al. (1989). It is worth noting that the biostratigraphic data from the North Fordon G1 borehole comes with intrinsic uncertainty associated with caving; however, the interspersed cored intervals allowed to cross-check the assemblages. In addition, the degree of caving within individual ditch cuttings samples was assessed. The occurrence of distinct, upper section lithologies, such as the ‘red chalk’ and ‘white chalk’ at stratigraphically lower levels, where the predominant lithology is dark marl or claystone, suggested that these minor percentages of red and white fragments were indeed cavings.

2.1.7 Foraminiferal biostratigraphic framework

Figure 10 presents the biostratigraphic interpretation for the Filey Bay section resulting from the micropalaeontological work in the current project. The biostratigraphy is based on a number of zonal index foraminiferal species suggested by King et al. (1989) for the “shelf” facies (FCS), primarily found in the southern North Sea, as well as on many literature references such as those presented in the section above. Most previous biostratigraphic work agrees with Neale (1974) for the Speeton Clay Fm. The results of this project (seen in Figure 10) suggest a slightly different biostratigraphic (and chronostratigraphic) interpretation than Neale’s, which will be presented below.

Lingula ovalis zone.

This zone is only found in the North Fordon G1 borehole, at the bottom of the section, in what, possibly, is the Lower D Beds and perhaps, the Kimmeridge Clay Fm. It is marked by millimetric fragments of the brachiopod *L. ovalis,* found in Upper Jurassic Kimmeridge Clay Fm deposits elsewhere in north-west Europe (Fletcher, 1966; Peyton, 1873; Phillips, 1873). The age for this zone based on the fossil content must be Late Jurassic to

Berriasian. The biozone is shown in the range chart for the North Fordon borehole in the appendix at measured depths (MD) between 301 to 302 m (988 to 992’).

No agglutinated foraminifera zone.

This is the only biozone suggested in this project which radically departs from King et al. (1989)’s FCS model for the Lower Cretaceous of the southern North Sea. It is found in both sampling locations in Speeton Clay Fm beds between 280 to 301 m (920 to 988’) MD at North Fordon and 2 to 5 m (6 to 16’) high above the base of the E bed for the Filey Bay section (equivalent to beds D5C to D6J). As the name suggests, this biozone is marked by benthic calcareous foraminifera and the total absence of agglutinated foraminifera. The age for this biozone is undetermined, although it may be Early Valanginian or Berriasian.

Protomarssonella kummi and benthic calcareous foraminifera zone.

This biozone is based on King et al. (1989)’s FCS zone 3b, which, according to them, represents the Early Hauterivian and, in some areas, the Late Valanginian too. It is found between 230 to 280 m (755 to 920’) MD at North Fordon and between 5 to 16.5 m (16 to 54’) high at Filey Bay (equivalent to beds C11A to D3B). *P. kummi* is present in low numbers; therefore, it is used in addition to the predominant benthic calcareous fauna in this interval to characterise the biozone.

Haplophragmium aequale zone.

This biozone is based on King et al. (1989)'s FCS zone 4b, representing a section of the Late Hauterivian. *H. aequale* appears continuously although in low abundance over its biostratigraphic range, found between 16.5 to 47 m (54 to 154') high (equivalent to beds C9D to LB6) at Filey Bay and 230 to 127 m (755 to 416') MD at North Fordon.

Hoeglundina caracolla zone.

This biozone is based on King et al. (1989)'s FCS zone 5, representing the Early Barremian. *H. caracolla* and other members of the Epistominidae, such as *Epistomina hechti*, appear in abundance in underlying biozones and have their FDO at the top of this zone. The biozone is found between 127 to 82.3 m (416 to 270') MD at North Fordon and 47 to 96 m (154 to 315') MD at Filey Bay (equivalent to beds LB5D to A4).

Gavelinella spp. zone.

This biozone is based on King et al. (1989)'s FCS 6a biozone, after the *Gavelinella barremiana*, representing the Late Barremian. At the study sites, the presence of the genus *Gavelinella* is remarkable. A few species are present and are helpful for the characterisation of the biozone, including *G. baltica*, *G. brielensis*, *G. stelligera*, *G. intermedia*, *G. sigmoicosta*, *G.* species 1. which leads the authors to suggest a *Gavelinella* genus biozone instead of a single species. This biozone is found between heights 96 to

116 m (315 to 380’) (equivalent to beds A3 to 3RC) at the Filey Bay section and 82.3 to 67.1 m (270 to 220’) MD at North Fordon.

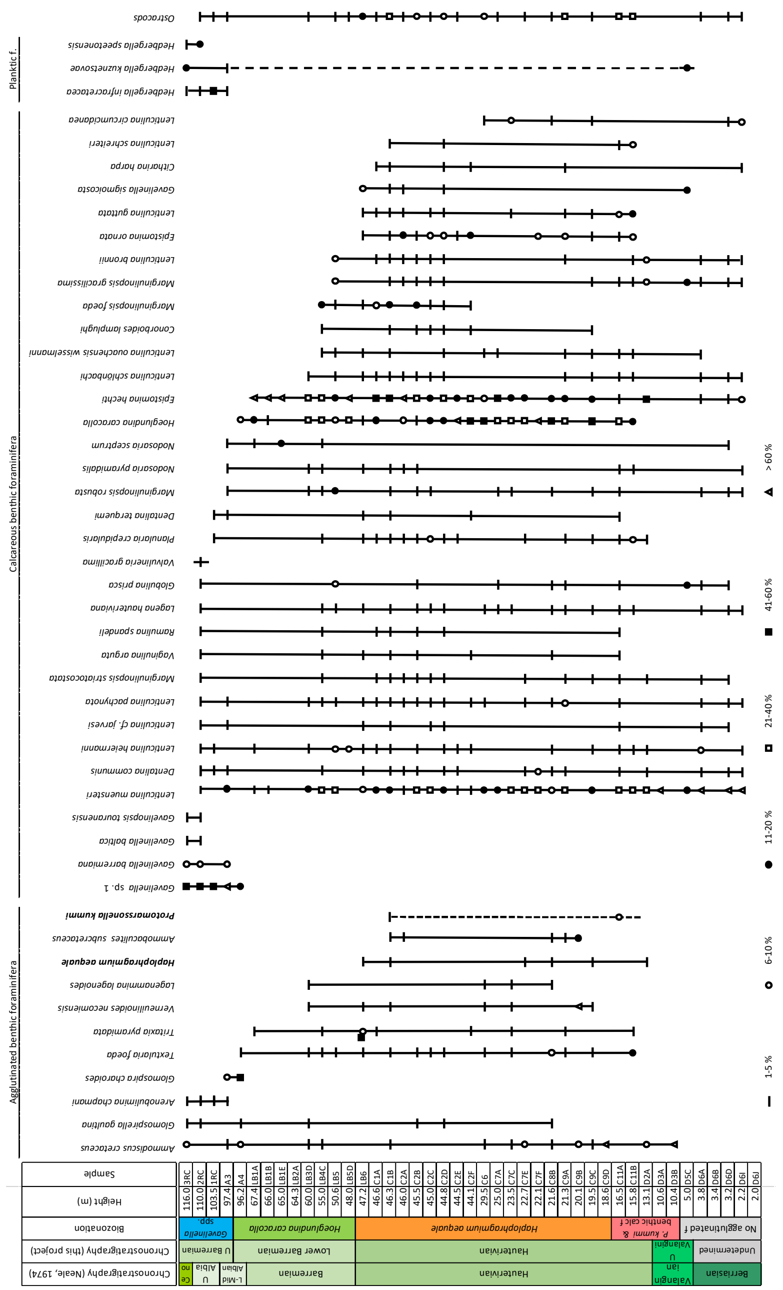


Figure 10. Range chart for the Filey Bay section displaying Speeton Clay and Hunstanton formations intervals.

Hedbergella infracretacea zone.

This biozone is based on King et al. (1989)'s FCS biozone 7, representing the Early Aptian. This biozone is found only at the North Fordon site, between 67.1 and 48.8 m (220 and 160') MD. The recovery in the overlying beds is poor. Therefore, it cannot be ruled out that this biozone could have a more extended biostratigraphic range. *H. infracretacea* is abundant, as well as *H. speetonensis* and *H. kuznetsovae*.

Correlation between both sites

Figure 11 displays a biostratigraphic correlation between the two sampling sites, Filey Bay and North Fordon. Both sampling sites show similar taxa, leading to a biozonation scheme that correlates satisfactorily between the two areas. Several species in the range chart from Figure 10 (and the range charts in the appendix) display similar stratigraphic ranges in both sampling locations. Note that the uppermost and lowermost biozones, *L. ovalis* and *H. infracretacea,* are only present on the North Fordon, which was possible to sample almost entirely. In contrast, the Filey Bay section did not provide access to every layer of the Speeton Clay and Hunstanton formations; therefore, significant sampling gaps exist. However, the available samples are enough to develop a biostratigraphic model for each site, as presented in the section above (see Figure 10, Figure 11) and correlate both sites (Figure 11).

In addition, the micropalaeontological results allow for comparing the sites on a species-by-species basis. For instance, benthic foraminifera like *Glomospirella gaultina*, *Arenobulimina chapmani*, *Glomospira charoides*, *Tritaxia pyramidata*, and many others have similar patterns and order for FDO and biostratigraphic ranges on both sampling locations. However, there are differences; for example, stratigraphic thicknesses tend to be more extensive at the North Fordon site. The reason is that structurally controlled subsidence in the Cleveland Basin affected the Lower Cretaceous sedimentary pile. It provided larger accommodation space for sediment accumulation in the west of the Hunmanby Fault (Neale, 1960a). In contrast, other sites such as the seafront where the Filey Bay section is found display a thinner section.

Despite structurally controlled thickness differences between the two sampling locations, the species-by-species correlation works remarkably well for some species from the Epistominidae. The last appearance of *E. hechti* at the Filey Bay section is at the Lower B1A bed, 73.6 meters above the base of the E bed. The last appearance of *H. caracolla* is at Bed A4, 96 m high. According to Neale (1974), this bed lies between the Barremian and the Lower and Middle Albian. Notice that in the chronostratigraphic model developed in this project, the A4 bed is situated in the Lower Barremian. There is a 22 m sampling gap covering the Cement Beds and the Upper B beds. It is possible that the proper last stratigraphic appearance of *E. hechti* may be found in the bypassed section.

At North Fordon, the last appearances of *E. hechti* at 125 m (410') MD and *H. caracolla* at 67.1 – 68.6 m (220 – 225') MD occur in the same order as at the Filey Bay section. The FDO of the Epistominidae is followed by the Last Downhole Occurrence (LDO) (also known as first appearance datum) of planktic foraminifera in both datasets (119 – 120 m (390 – 395') MD at North Fordon, 96.2 m (Bed A3) for the Filey Bay section), which increases the confidence on the biostratigraphic correlation in this stratigraphic interval. As stated in the previous section, the FDO of *H. caracolla* is a noted Lower Barremian biostratigraphic event in the southern North Sea basin shelf facies (King et al., 1989). The occurrence of planktic foraminifera in North Fordon below the sample at 133 – 134 m (435 – 440') MD may be attributed to caving for two reasons: first, the samples immediately above (125, 127 m (410', 416') MD) and the ones further up (82.3 – 86.6 m (270' – 284') MD), which are side-wall core samples, do not show more than one or two specimens of planktic foraminifera from the genus *Hedbergella*. Second, the sediment colour in these planktic foraminifera recorded below 133 m (435') MD has a red character, like the samples typical of the Hunstanton Fm. For the beds immediately above the Epistominidae FDO, a flood of planktic taxa assigned to the *Hedbergella* genus marks another correlatable event in both sampling locations. According to King et al. (1989), the FDO of *H. infracretacea* is of Early Aptian age for the southern North Sea Basin's southern FCS (shelfal) facies.

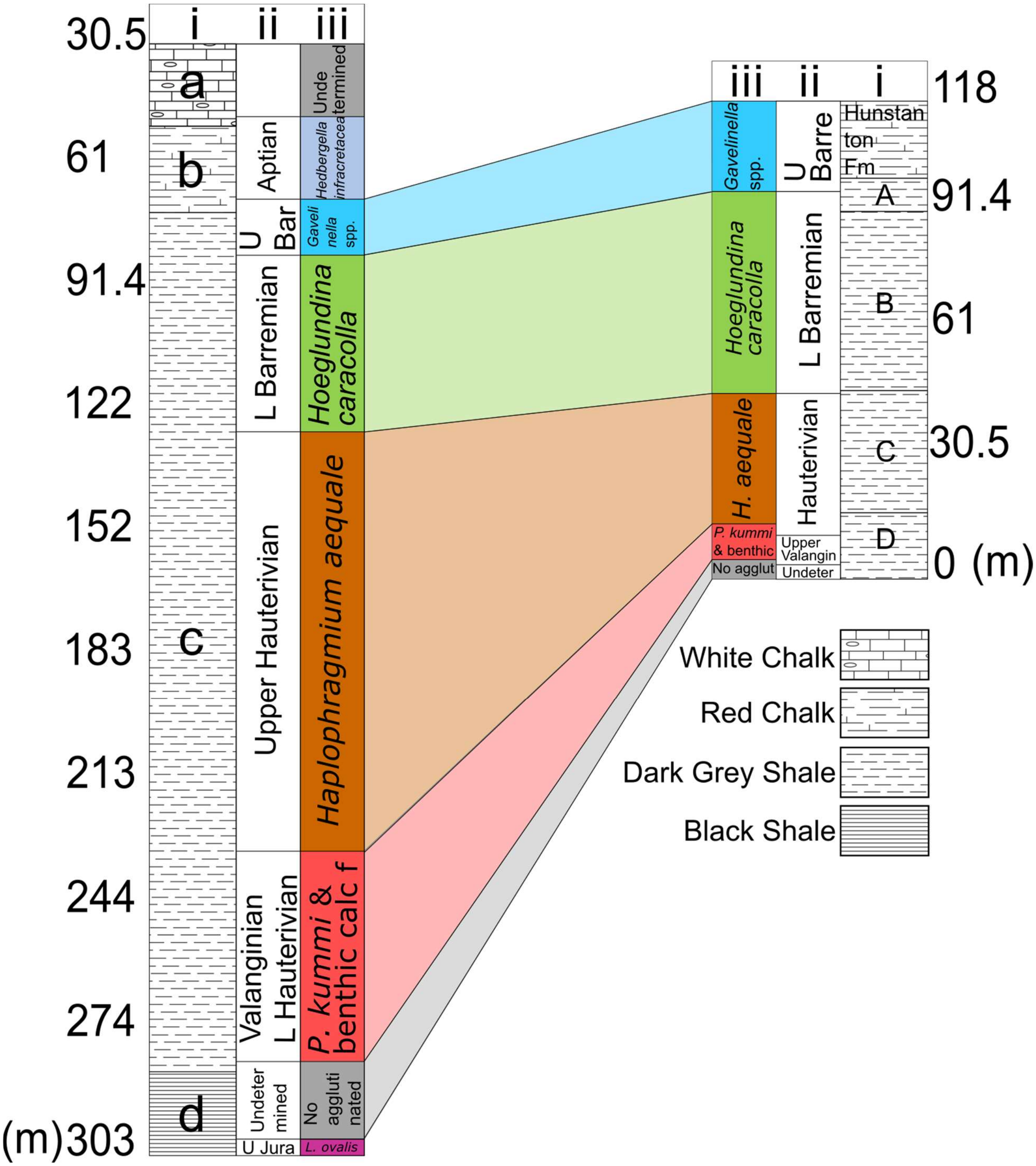


Figure 11. LEFT: North Fordon G1 borehole; **i.** Lithostratigraphy from Geological Division, (1960). **ii.** Chronostratigraphy (this project). **iii.** Biostratigraphic zones proposed in this project. **a.** Upper Cretaceous White Chalk. **b.** Hunstanton Fm. **c.** Speeton Clay Fm. **d.** Kimmeridge Clay Fm. RIGHT: **iii.** Biostratigraphic zones proposed in this project. **ii.** Chronostratigraphy (this project) **iii.**

Lithostratigraphy from Fletcher, (1969); Mitchell and Underwood, (1999); Neale, (1962b); Rawson and Mütterlose, (1983); Hart et al., (2008), **A-D** are Speeton Clay Fm. divisions.

The North Fordon G1 lithology information shown in Figure 11 suggests that the borehole's uppermost section (samples between 30.5 – 50.3 m (100' – 165') MD) corresponds to the Upper Cretaceous 'Lower Chalk' (Neale, 1960a). The beds underlying the Epistominidae's FDO are grouped under the biozone defined by the *Haplophragmium aequale*'s FDO, which has a similar biostratigraphic range and abundance in both sampling locations and dates back to the Hauterivian (King et al., 1989). The underlying stratigraphic section is marked by the *P. kummi* first downhole occurrence at the bottom of both sampling sections. King et al. (1989) suggested that this species occurs in the Lower Hauterivian of the southern North Sea's southern (shelfal) facies. These beds are underlain by an interval with no agglutinated benthic foraminifera, marking the bottom of both sampling sections, which does not feature on the basin-wide biostratigraphic charts. Although, only in North Fordon, the bottom section displays brachiopods from the genus *Lingulina*, dated Late Jurassic and Berriasian (Fletcher, 1966). It is worth noticing that this study's sample sets do not cover every Speeton Clay Fm bed. Therefore, the biostratigraphic results will present gaps in the stratigraphic record; some gaps are missing samples rather than geological factors.

2.1.8 Microfossil Assemblages and their relevant characteristics

In addition to the biostratigraphic scheme produced for the Speeton Clay and Hunstanton formations, a more simplistic division of the microfossil assemblage is obtained by considering presence/absence data of agglutinated versus calcareous wall types and benthic versus planktic life modes, as described below. The robustness of this simplistic view's assumptions of the microfossil population is tested below through multivariate analysis techniques. Figure 12 and Figure 13 illustrate these assemblages; additional information and complete range charts can be found in the appendix.

In brief, the microfossil assemblages explained below differ from each other based on predominant wall type, species diversity and abundance, which, along with additional micropalaeontological information, may suggest drastic changes in specific palaeoenvironmental conditions.

These assemblages can be reduced to three types of fossil faunas: first, benthic foraminifera-dominated (agglutinated and calcareous); second, calcareous benthic foraminifera-dominated; and third, calcareous planktic foraminifera-dominated. The benthic foraminifera fossil faunas alternate with the only calcareous benthic ones, except for the top of the section fauna at the Filey Bay section, where planktic taxa dominate.

2.1.8.1 Filey Bay section

Four foraminiferal Assemblages are recognised, FB1 – FB4, based on presence/absence data of wall-types and life modes described above, significant biostratigraphic events, abundance and diversity data, and minor input from the hierarchical clustering approach. Although, a further discussion of the quantitative methods is presented below. Note that the assemblages in Figure 12 roughly correspond to geological stages of the Lower Cretaceous (see Figure 11).

Foraminiferal Assemblage FB1 (D6 – D5)

Foraminiferal assemblages from the base of the section (beds D5 to D6) are dominated by calcareous benthic foraminifera agglutinating taxa are absent. The assemblage is dominated by the Lenticulininae and a minor component of the Epistominidae. These beds are catalogued as Valanginian due to their foraminiferal content of zonal index species (discussed in section 2.1.7). The lower section (almost all the D6 beds) is catalogued as "undetermined" age because of the lack of indicative micropalaeontological content.

Foraminiferal Assemblage FB2 (LB3D – D3B)

The following assemblage occupies the middle part of the Filey section, from the Lower B Beds (Spath, 1924) level three to the upper part of the D Beds (D3 in this sample set) and encompasses all C Beds. This interval is dated as Early Barremian, Hauterivian and Late Valanginian.

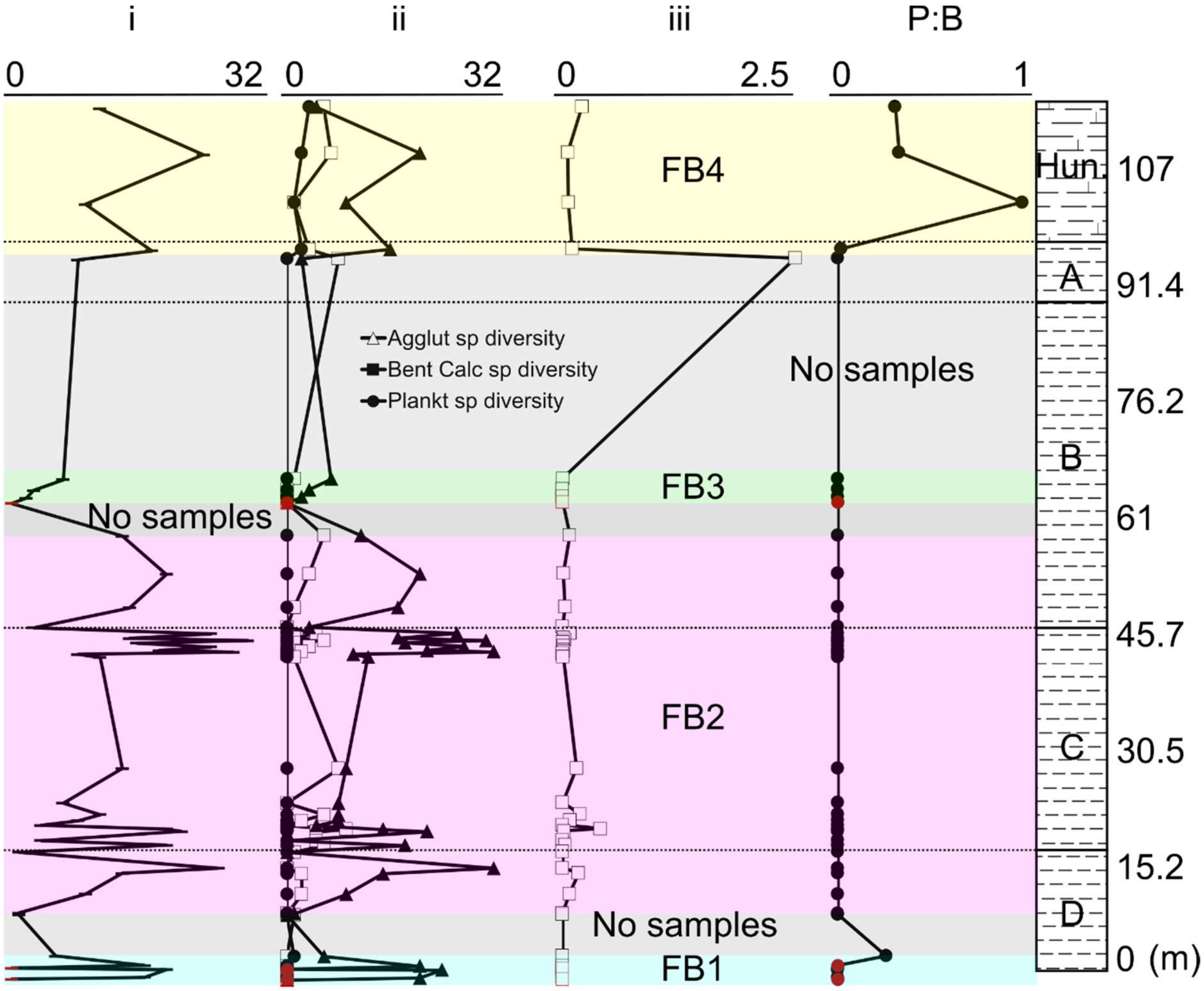


Figure 12. Results from the microfossil analysis for the samples of the Speeton Clay Fm at the Filey Bay section. i. Foraminiferal species richness. ii. Foraminiferal species richness of agglutinated, calcareous benthic and planktic species. iii. Agglutinated:Calcareous benthic foraminifera ratio. P:B. Planktic:Benthic foraminifera ratio. On the right-hand side of the figure, see a general lithological log and height markers in metres for the Filey Bay section. The lithological key is found in Figure 11. Red dots, triangles, rectangles, and dashes represent barren samples.

Around 50 of the 60 calcareous benthic foraminifera species and 17 of the 23 agglutinated foraminifera species are present in this interval, making it the most diverse and profuse assemblage from the Filey Bay section. There is also a significant presence of ostracods, gastropods and ichnofossil traces, which are helpful indicators of palaeoenvironmental conditions. Some beds, including C11, Lower B6 and Lower B4, witness important speciation and extinction events in the section. The most abundant taxa in this assemblage belong to the Epistominidae.

Foraminiferal Assemblage FB3 (LB1A – LB1E)

Assemblage FB3 shares similarities with Assemblage FB1, agglutinated foraminifera absent and calcareous benthic foraminifera rare to common, with usually one or two species dominating. The Epistominidae occur in flood abundance in bed LB1A with Lenticulininae a subordinate component. This assemblage is found in the upper part of the 'Lower Beds' (LB1 and LB2), containing Barremian invertebrate fossils (Fletcher, 1973; Neale, 1974; Rawson and Mütterlose, 1983; Lott et al., 1986). In this project, these beds are dated as Early Barremian. All taxa in this assemblage are also found in assemblages FB1 and FB2. The upper limit of this assemblage broadly coincides with the last occurrence of the Epistominidae in this section. The assemblage has the lowest species richness of the four recognised in the Filey section.

Foraminiferal Assemblage FB4 (Top Red Chalk – A4)

The youngest assemblage is the only one to feature planktic foraminifera.

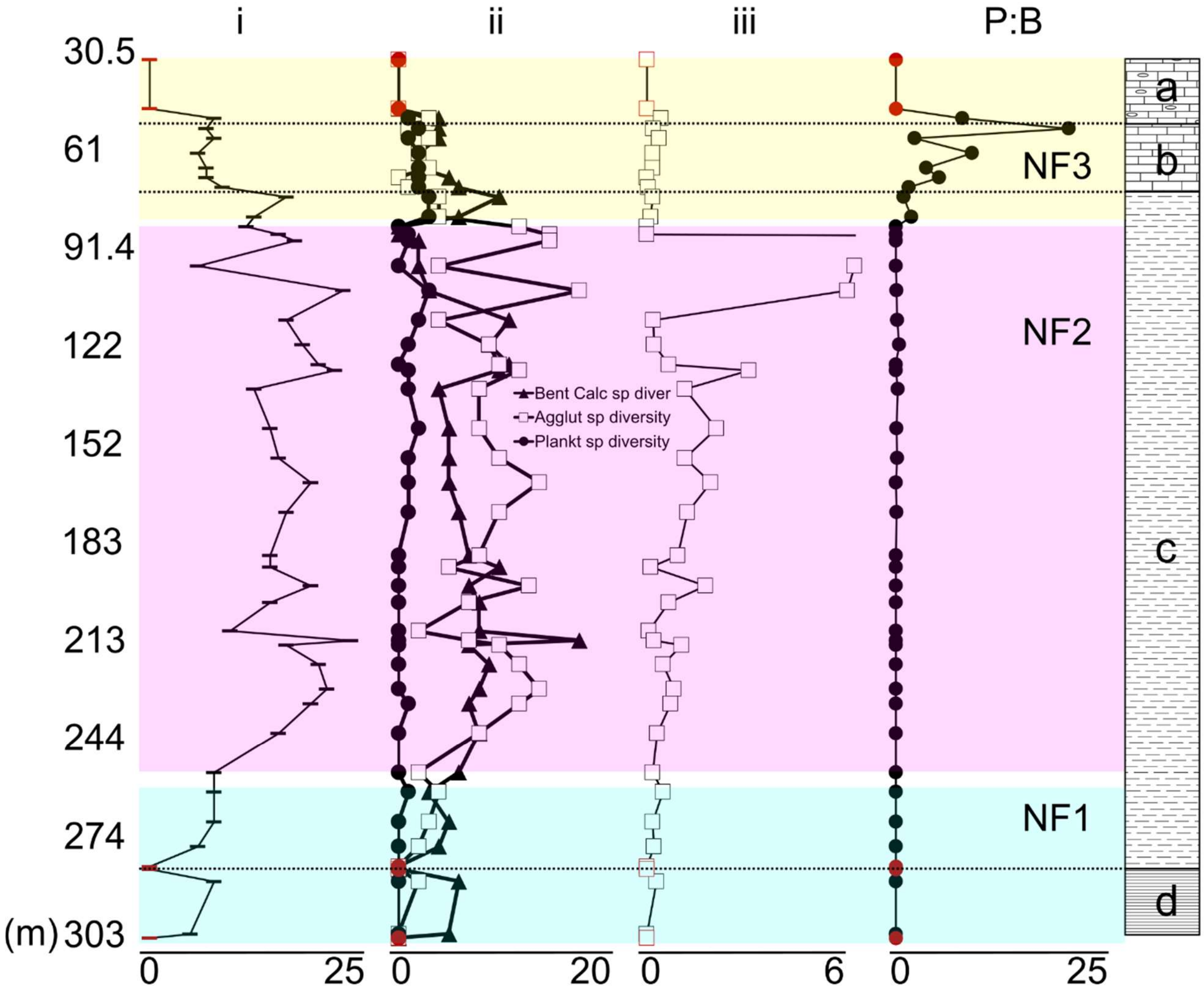


Figure 13. Results from the microfossil analysis for the samples of the North Fordon G1 borehole. i. Foraminiferal species richness. ii. Foraminiferal species richness of agglutinated, calcareous benthic and planktic species. iii. Agglutinated:Calcareous benthic foraminifera ratio. P:B. Planktic:Benthic foraminifera ratio. Borehole depth markers in metres are found on the left-hand side of the figure. A general lithological log is found on the right-hand side of the figure, whose lithological key is found in Figure 11. Red dots, triangles, rectangles, and dashes represent barren samples.

However, the interval is dominated by profuse calcareous benthic foraminifera of the genus *Gavelinella*, followed by abundant planktic foraminifera of the *Hedbergella* genus.

The assemblage shows at least thirteen species of agglutinated foraminifera and around thirty species of calcareous benthic foraminifera. Assemblage 4 also marks the FDO of several agglutinated and calcareous benthic foraminifera species. The assemblage is recorded in beds A3, A4 of the Speeton Clay Fm and several red beds of the Hunstanton Fm. These beds are assigned to the Upper Barremian (Figure 10).

2.1.8.2 North Fordon G1 Borehole

The changing composition of the foraminiferal assemblages in the North Fordon G1 Borehole is shown in Figure 13. Three assemblages (NF1 – NF3) were recognised based on the same criteria used for the Filey Bay section: presence/absence data of wall-types and life modes, significant biostratigraphic events, abundance and diversity data, and minor input from the hierarchical clustering approach. The oldest assemblage, from the base of the borehole, at 301 m (988') MD, up to the sample at 239–241 m (785-790') MD. The second assemblage ranges from (230-232 m (755-760') to 82.3 (270') MD. The third and youngest assemblage spans the interval between the samples 79.2-80.8 m (260-265') and 48.8-50.3 m (160-165') MD (samples representing an interval, such as 239-241 m (785-790'), are ditch cuttings, while samples with only one depth number, such as 82.3 m (270’), are core samples).

Foraminiferal Assemblage NF1 (Samples 301 to 258-259 m (988' to 845-850') MD)

The assemblage at the base of the North Fordon borehole resembles Assemblage FB1 from Filey Bay in its predominant benthic calcareous foraminifera in a monotonous, low-diversity assemblage characterised by poor abundance. Agglutinated foraminifera are extremely rare, and those that were recorded may be the result of cavings. The most abundant taxa belong to the Epistominidae, Conorboididae and the Lenticulininae. Neale (1960) assessed the age of the lowest beds in the borehole (containing Assemblage NF1) as Kimmeridgian, Valanginian and Hauterivian. Nannofossil data (Shrouder, unpublished data) suggests a similar age range except that the base of the sequence is more likely to be Berriasian. Unfortunately, the foraminiferal assemblage does not contain relevant biostratigraphic markers at this level, so the correlation is made based on similarities in assemblage composition. Fragment of the brachiopod *L. ovalis*, found in this interval, support an age range of Late Jurassic to earliest Cretaceous, which is the age put forward in this project.

Foraminiferal Assemblage NF2 (Samples 251-253 to 82.3 m (825-830' to 270') MD)

Assemblage NF2 has a higher species richness than Assemblage NF1. All the species recorded, except two, are common to both assemblages. Assemblage NF2 is similar to Assemblage FB2. It also includes several FDOs for benthic foraminifera in the North Fordon borehole, mostly of agglutinated foraminifera and a few benthic calcareous foraminifera, which are helpful to characterise the upper boundary of this assemblage. The Epistominidae remain abundant throughout the bottom and middle section of this assemblage (251-253 m (825-830’) to 125 m (410’) MD) but almost absent from the upper section (119-120 m (390-395’) to 82.3 m (270’) MD). The microfossil population is enriched by Conorboididae, Cancrisidae and Gavellinellidae foraminifera displaying moderate but steady abundance values. The agglutinating Haplophragmoididae and the Ammodiscidae are common throughout the assemblage. The planktic foraminiferal genus *Heterohelix* occurs in the core within this assemblage, albeit in low numbers. The assemblage age is believed to be Valanginian to Barremian (Neale, 1960a) and Aptian (Shrouder, unpublished nannofossil data). For this project, this long section is dated as Valanginian, Hauterivian and Early Barremian (see appendix).

Foraminiferal Assemblage NF3 (Samples 79.2-80.8 m (260-265') to 48.8-50.3 m (160-165') MD)

The assemblage at the top of the borehole is characterised by calcareous benthic foraminifera with intermittent floods of planktic foraminifera, whereas agglutinating foraminifera are rare. Several FDO for benthic taxa belonging to the Gavellinellidae, Vaginulinidae and Nodosariidae occur in this interval, which are helpful in the characterisation of this assemblage and the main influx of the *Hedbergella* genus is the most distinctive feature. The FDO of microfossils, such as *Reophax minuta* and *H. infracretacea*, may indicate support Aptian and Albian age ages (King et al., 1989). For the interpretation put forward in this project these beds are regarded as Upper Barremian and Aptian (see appendix).

2.1.9 Multivariate Analysis of Assemblages

The first (simple) approach to assemblage analysis suggested four assemblages for the Filey Bay dataset (FB1 to FB4) and three in the North Fordon borehole (NF1 to NF3) (see Figure 12, Figure 13). In this section, hierarchical clustering analysis will be applied to test the robustness of the “simplistic” (simplistic because it divides the microfossil population mainly based on wall-type) methodologies used in previous sections. The objective of running cluster analysis on the microfossil data of the Lower Cretaceous sites from Yorkshire is to assemble observations into relatively homogeneous groups or "clusters", the members of which are alike and simultaneously, unlike members of other groups. Hierarchical clustering joins the most similar observations, then successively connects the most similar observations to these (Aldenderfer and Blashfield, 1984). The hierarchical clustering analysis of the microfossil assemblages was carried out on the software PAST (Hammer et al., 2001). The assemblages were analysed with the input data arranged according to the Q-mode under stratigraphic constraints using the unweighted paired-group arithmetic clustering algorithm (UPGMA) and the cosine theta (θ) similarity coefficient, according to Aldenderfer and Blashfield (1984); Davis (2002); Parker and Arnold (2003); Sneath and Sokal (1962); Buck et al. (1999); Lagoe et al. (1997). The results are displayed as dendrograms according to the similarity index in Figure 14. The results indicate more clusters than the number of assemblages produced by the “simplistic” approach discussed previously.

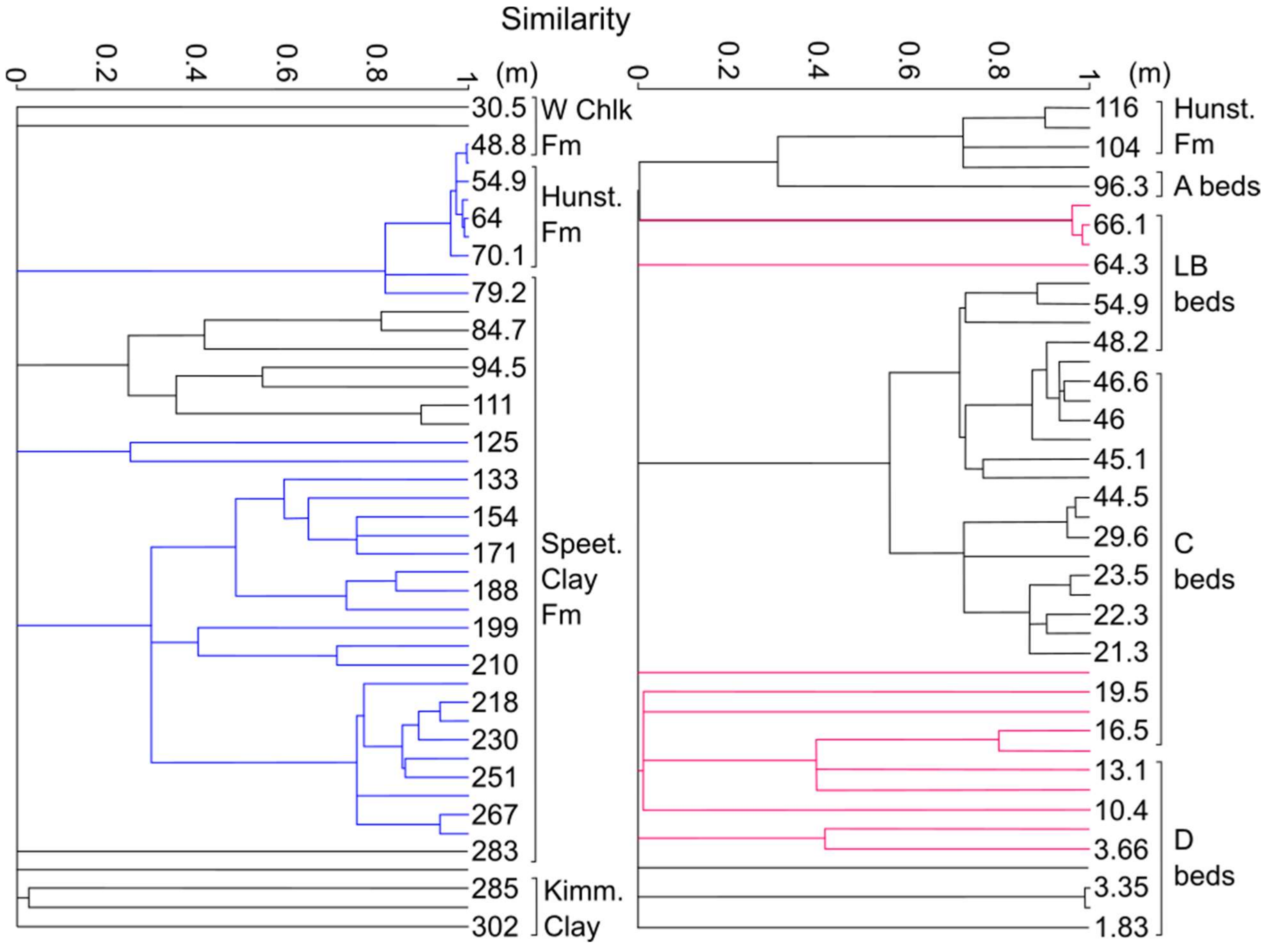


Figure 14. Hierarchical clustering of microfossil data from this project. The dendrogram on the left corresponds to the North Fordon G1 borehole samples; the dendrogram on the right represents the Filey Bay Section samples. The different colours highlight the authors' cluster interpretation for each dataset.

The clusters are shown in black, blue, and red in Figure 14. However, to the authors, the hierarchical clustering results do not appear to be conclusive enough; they do not satisfactorily explain some samples, and several branches have disappointingly low similarity values (Figure 14). Therefore, continuing with a quantitative inquiry into the micropalaeontological results, we calculated a Preference Index (PI) based on formula one (shown below).

PI values greater than 1 indicate a preferential abundance in that same group greater than its mean abundance in the entire data set. In contrast, a value less than 1 shows a tendency to be less abundant than average. Taxa with PI values significantly greater than one are designated as the most relevant species in any given assemblage in terms of presence/absence (Lagoe et al., 1997). It can be used for palaeoenvironmental interpretations if one considers the dominant species a worthy representative of a microfossil assemblage. This simplification is helpful if the environment of the predominant fossil species is known or can be inferred from other known conditions. The preference index (PI_{Aij}) for the group of foraminiferal species in the microfossil assemblages was calculated according to the following formula (1):

$$PI_{Aij} = 1/n \sum_{j=1}^{n} a_{Aij} \ / \ 1/m \sum_{j=1}^{m} a_{tj}$$

Where PI_{Aij} is the preference index of the *jth* taxon in the data set for the *ith* assemblage (*Ai*)

$1/n \sum_{j=1}^{n} a_{Aij}$ is the mean abundance of the *jth* taxon in the *ith* assemblage

$1/m \sum_{j=1}^{m} a_{tj}$ is the mean abundance of the *jth* taxon in the total (*t*) data set

The PI results help identify foraminiferal species relevant to each foraminiferal assemblage and the detrended correspondence analysis process (DCA). DCA, also known as Detrended Reciprocal Averaging, is a technique used in ecological studies for biological gaussian distributions along environmental gradients (Davis, 2002; Gauch, 1982; Greenacre, 2010; Hill, 1973; Hill and Gauch, 1980; Oksanen and Minchin, 1997; Pielou, 1984; Lagoe et al., 1997). The DCA's results enable displaying fossil species along environmental gradients, which support ecological inferences from analysis techniques such as hierarchical clustering or the “simplistic” wall-type analysis. The results are beneficial for interpreting palaeoenvironments and fossil assemblages without sufficient palaeoenvironmental information (Lagoe et al., 1997).

The DCA was computed with the PAST software program (Hammer et al., 2001). Plots showing only two of the three axes generated on each subgroup (list of samples and list of fossil species) can be seen in Figure 15 and Figure 16. In Figure 15 A to D, sample points plotting close together contain similar faunas. Specimen points (Figure 16) tend to co-occur. It is worth mentioning that the shape of the ordination looks similar in samples and species points in the two plots (Figure 15 and Figure 16). This feature is related to DCA's maximisation of correlation between sample and specimen scores (Lagoe et al., 1997). We looked at this correlation in our search for the relevant species that define faunal gradients shown in the plots.

To further inquire into the microfossil assemblages' analyses laid out in Figure 12 and Figure 13, we plotted the four assemblages from Figure 12 in the sample DCA plot in Figure 15 A. This plot shows that the microfossil assemblages' analysis from Figure 12 is robust because each assemblage occupies a discrete area of the graph. The first three assemblages cluster on the left and the fourth assemblage clusters on the right of the plot, along axis one, respectively. Assemblage two is intermediate in faunal similarity values between assemblages one and three. These remarks agree with the micropalaeontological observations in the Filey Bay section, on which assemblages one and three are fundamentally different from the other assemblages by displaying an absence of benthic agglutinated foraminifera and the assemblage four is different by showing planktic foraminifera. In contrast, assemblage two is a mixture or intermediate of the main micropalaeontological features of the other assemblages.

Figure 15 B highlights that most of the ordination displays a low planktic to benthic foraminifera ratio. Only on the right side of axis one in the plot, values for the ratio are significant, which correlates with assemblage four (FB4). The P:B ratios may lead the observer to think that the right-hand side of the plot agglomerates deeper water samples than on the left side.

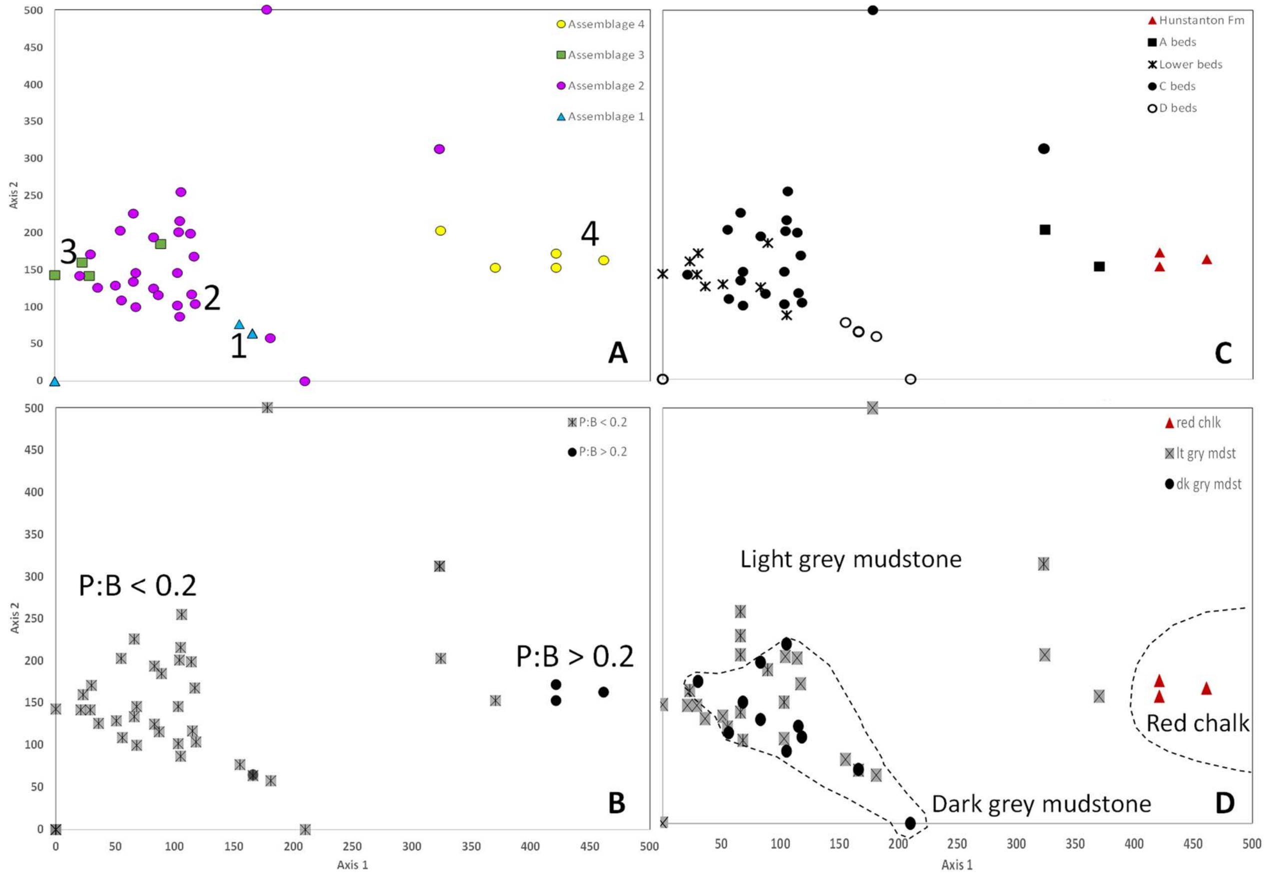


Figure 15. DCA plot of samples for axes 1 and 2 for the Speeton Clay Fm. section at Filey Bay. Samples are located within the ordination plot because of their faunal similarity to each other. A. The distribution of microfossil assemblages is shown in colours over the samples DCA plot: yellow-assemblage 4; green-assemblage 3; magenta-assemblage 2; blue-assemblage 1. B. Planktic to benthic foraminifera ratio plotted with a threshold value of 0,2. C, D. Sample DCA plots on which lithology type and lithological unit have been plotted, respectively.

Our analysis can be continued by looking at the different geological units and the sedimentary description of the rocks from which samples were extracted in Figure 15 C, D. It is worth noting that the Hunstanton Fm and the A and D bed members of the Speeton Clay Fm plot on separate areas of the graph. With a few exceptions, the same places are occupied by the microfossil assemblages from above. This may indicate that the primary control on the foraminiferal assemblages is lithology.

Evidently, environmental factors contribute to changing sedimentary environments of deposition, which in turn produces changing lithologies. Figure 15 D summarises the lithological variety of the Speeton Clay and Hunstanton formations. The lithological complexity is higher than it is sensible to plot in a single graph. For this reason, considerable simplifications to the lithological characteristic of the samples were made. However, red-coloured chalks and dark grey mudstones occupy discrete zones of the DCA ordination, whereas the light grey mudstones spread across the left side of the plot and are rarely found on the right side of the plot. Significant lithological features like organic matter content (present on the dark grey mudstones) occupy a discrete zone in the left of the plot, indicating that sedimentary environments conducive to organic matter preservation may display fossil assemblages like those plotting on the same location in the graph; an assumption that needs to be tested.

Figure 16 A shows the species' DCA ordination on which the wall type distribution was plotted. Benthic foraminifera are spread throughout most of the plot but concentrated on the left and centre of the plot. In contrast, planktic foraminifera are shown on a separate area on the right-hand side of the primary axis. Agglutinated benthic foraminifera are restricted to the upper half of the plot, and calcareous walled foraminifera occupy the bottom half of the plot area. Notice that earlier, in the assemblage discussion, some of the micropalaeontological assemblages of Filey Bay (assemblages one and three) and North Fordon (assemblage one) lacked agglutinated foraminifera, displaying an impoverished calcareous fauna instead.

In contrast, the remaining assemblages had a wide variety of benthic and calcareous taxa, suggesting favourable conditions for developing diverse ecological niches for foraminiferal population development. The calcareous benthic foraminifera-dominated monotonous assemblages may represent shallow water, low diversity, restricted environments, like assemblage one on both sampling sites (FB1 and NF1). However, the intervals where diversity increased rapidly, like on assemblage two of both sites, were most likely linked to sea-level rise (Rawson and Riley, 1982). The assemblages at the top of both sampling sections (Figure 12 and Figure 13) represent a flooding event in the basin, marked by the sudden increase in planktic foraminifera. Figure 16 A validates the “simplistic” analysis from previous sections. Wall-type and life-mode are among the most notable features for the characterisation of the Speeton Clay and Hunstanton formations.

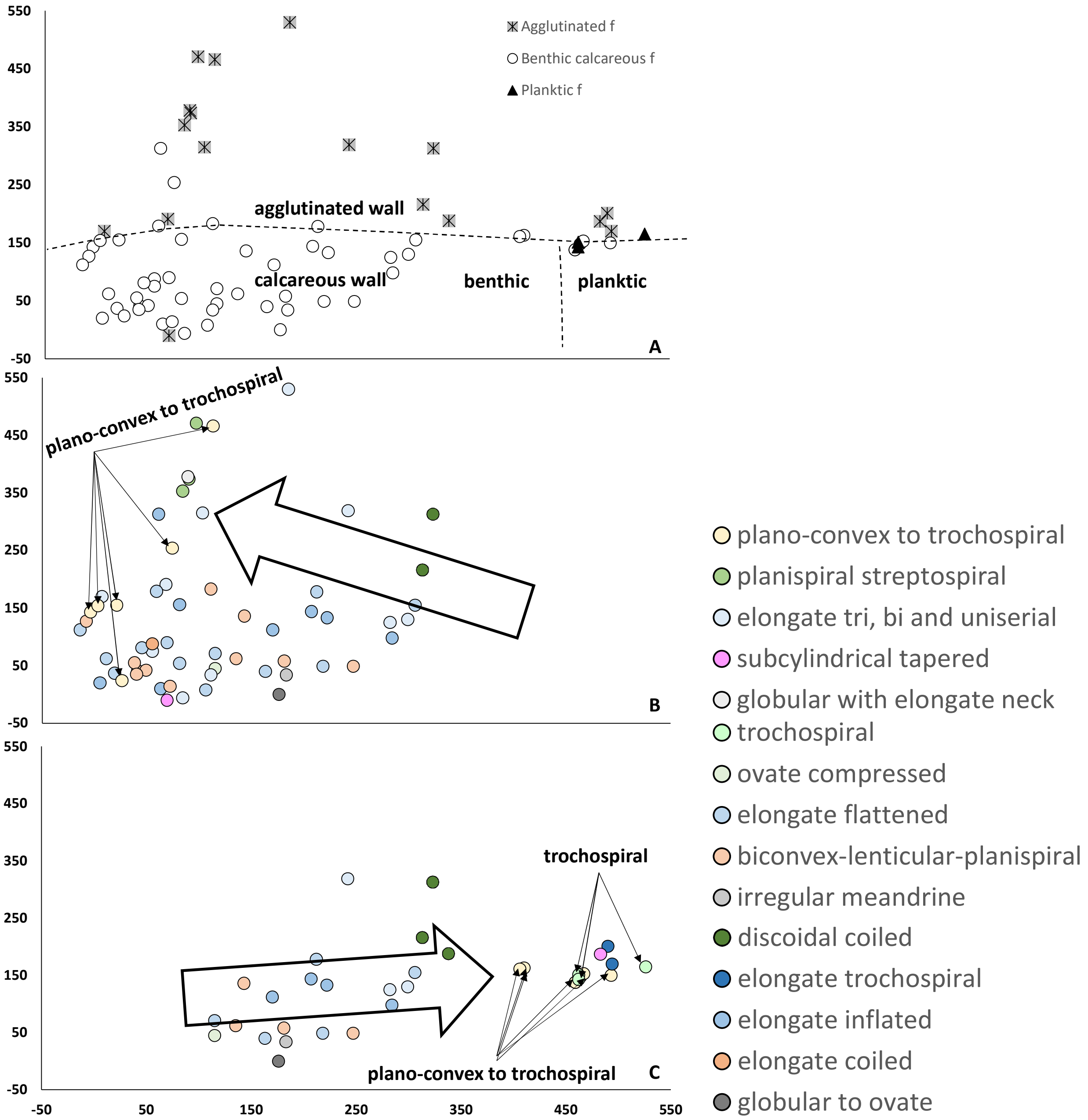


Figure 16. DCA plot of fossil species for axes 1 and 2 for the Speeton Clay Fm section at Filey Bay. Species are located within the ordination plot based on their co-occurrence pattern within the samples examined. A. distribution of wall-type and life-mode. B, C. Foraminiferal species grouped by test form for species whose FDO is in different geological stage: the Barremian, Hauterivian, Valanginian or Berriasian (B); the Aptian or Albian (C) of the Speeton Clay Fm section at Filey Bay's sample set. The arrows point in the direction of the test form types whose species are known, from the literature, to inhabit deeper marine environments (upper bathyal to shelf-slope) than those reported to live in shallower marine environments (shelf environments).

Figure 16 B and C show foraminiferal test forms plotted onto the DCA ordination of fossil foraminifera species. Palaeoenvironmental inferences can be made based on features such as test form. The arrows in Figure 16 B and C point in the direction of the test form types whose species are known, from the literature, to inhabit deeper marine environments (upper bathyal to shelf-slope) than those reported to live in shallower marine environments (shelf environments). A hypothesis arising from the P:B ratio (Figure 15 B) suggested the deep-water taxa plot on the right-hand side of the primary axis. This hypothesis turns out to be true for the Aptian to Albian assemblages (Figure 16 C).

It is highlighted by the presence of planktic foraminifera and benthic calcareous gavelinellids, which suggest a connection to open marine waters. However, for earlier geological periods such as Hauterivian and Barremian, the primary axis shows (Figure 16 B) that species located to the extreme left of the ordination and towards the middle of the secondary axis were, in fact, in open marine conditions. This is in complete agreement with the micropalaeontological observations; in Hauterivian and Barremian, the fossil genera that indicate a sort of open marine conditions are *Hoeglundina* sp. and *Epistomina* sp., which plot in the suggested area to the left (see Figure 16 B).

The features of the DCA method suggest that the “simplistic” microfossil assemblage analysis is correct and helps explain lithological and environmental pressures on the microfossil population. However, it is time-restricted, meaning that geological time should be considered in plots including samples ranging over long geological periods, hence Figure 16 B and C.

2.1.10 Summary

The Filey Bay section and North Fordon G1 borehole microfossil data shown in the figures above suggest a Lower Cretaceous (Kimmeridgian to Aptian) foraminiferal assemblage dominated by benthic calcareous taxa with agglutinated and planktic taxa becoming relevant (even predominant for the latter) at intervals. Our interpretation of the microfossil assemblages FB1 to FB4 (for Filey Bay) and NF1 to NF3 (for North Fordon) have captured the microfossil population's dynamics. The efficacy of our micropalaeontological understanding of the study areas was tested by hierarchical clustering and detrended correspondence analyses. The bottom line of the results of these analyses is that the "simplistic" wall-type assemblage analysis is correct. These analyses also indicated a palaeoenvironment of deposition that was deepening over time, becoming deeper towards the mid-Cretaceous from an Early Cretaceous state that was relatively shallow. The micropalaeontological results also provided an opportunity to correlate the sampling locations with the rest of the North Sea by identifying zonal index species used by King et al. (1989) in their Cretaceous biostratigraphic schemes for the North and South areas of the North Sea. This is important as this is the first complete record published from the North Fordon G1 borehole since the sixties when John Neale and others published preliminary studies referenced in this text.

2.1.11 Conclusions

The foraminiferal assemblages of the Lower Cretaceous Speeton Clay and Hunstanton formations in the Yorkshire coast are of low to medium diversity from mainly shelfal and shallow marine palaeoenvironments. Fine-grained clastic lithologies with significant organic matter content and various degrees of bioturbation and low diversity fossil assemblages may indicate restricted environments. The fossil assemblages seem to be characterised by a different array of wall types and living modes, which may support the initial hypothesis for this project regarding the evolution of benthic calcareous and agglutinated foraminifera in the shelf and graben of the North Sea in the Early Cretaceous.

Data availability

Foraminiferal abundance data sets are available online at https://edata.bham.ac.uk/

3 DEEP-WATER PALAEOENVIRONMENT

3.1 Palaeoenvironmental interpretation of the Lower Cretaceous Britannia Field, North Sea, U.K.

3.1.1 Abstract

The foraminiferal assemblages of the boreholes 16/26-B3 and 15/30-7 ST2 from the Britannia Field were analysed. They provide opportunities for understanding the landscape in hemipelagic to pelagic environments that predominated during the Lower Cretaceous stages at the triple junction between the Witch Ground, Viking, and Central grabens in the North Sea. The results provide support to a continued marine transgression palaeoenvironmental hypothesis, marked at the lower stages of the Cretaceous by terrigenous sediments displaying a poor microfossil assemblage suggesting restricted conditions, to a secondary stage, towards the mid-Cretaceous, to a carbonate-rich pelagic sedimentary environment with an influx of planktic foraminifera indicating an increase in open oceanic conditions. The poor preservation and low abundance of the foraminiferal assemblages hinder further palaeoenvironmental characterisation of the study area.

3.1.2 Introduction

According to Copestake et al. (2003), the Britannia hydrocarbons field is a gas-condensate field drawing large hydrocarbon volumes from Lower Cretaceous sediments of the North Sea. It was discovered in 1975 and extended across the blocks 15/29a, 15/30a, 16/26a, 16/27a and 16/27b (Hill and Palfrey, 2003; Ainsworth et al., 2000). A dipclosure and stratigraphic pinch-out entrap the Britannia Field accumulation in a series of stacked, mass flow sandstone packages of the Britannia Sandstone Formation (Ainsworth et al., 2000; Copestake et al., 2003). Its gross reservoir interval averages between 350 to 600 ft thick (Jones et al., 1999). The onlap of reservoir sandstones onto the Fladen Ground Spur provides the closure to the north. The closure to the south is structural (Copestake et al., 2003). To the east, the accumulation is trapped against a system of north-south faults and associated folding of the Eocene age. Not much detail has been published on the hydrocarbon-water contact on the closing in on the west. The gas-condensate reserves are primarily contained in either clean, high-density turbidite sandstones or more-muddy slurry-flow deposits; porosity is constant at around 15%, and permeabilities average 30 mD in the east and 60 mD in the west (Lowe and Guy, 2000; Copestake et al., 2003; Jones et al., 1999). Blackbourn and Thomson (2000); Copestake et al. (2003) suggest that the hydrocarbons in the Britannia Field are derived from mature Kimmeridge Clay Formation source rocks below and east of the accumulation. The development of the Britannia Field shows a constant-pressure gas column with a discontinuous thin (40 ft) oil rim (Hill and Palfrey, 2003; Copestake et al., 2003; Garrett et al., 2000; Jones et al., 1999).

3.1.3 Regional geological landscape

The North Sea basin is located on the north-west European continental shelf, an area with a complex geological history, beginning with Pangea's rifting process, which started in the Early Jurassic. This event led to the opening of the North Atlantic Ocean. The opening up of the North Sea is related to these global tectonic events (Glennie and Underhill, 1998;

Ziegler, 1975, 1981). The Late Jurassic marked the end of an east-west tensional regime for the North Sea as the major axis of extension moved west, where the North Atlantic started to open, at the onset of a north-bound compression regime. The results of this compressional regime are felt more profoundly in the mid and Late Cretaceous (Oakman and Partington, 1998).

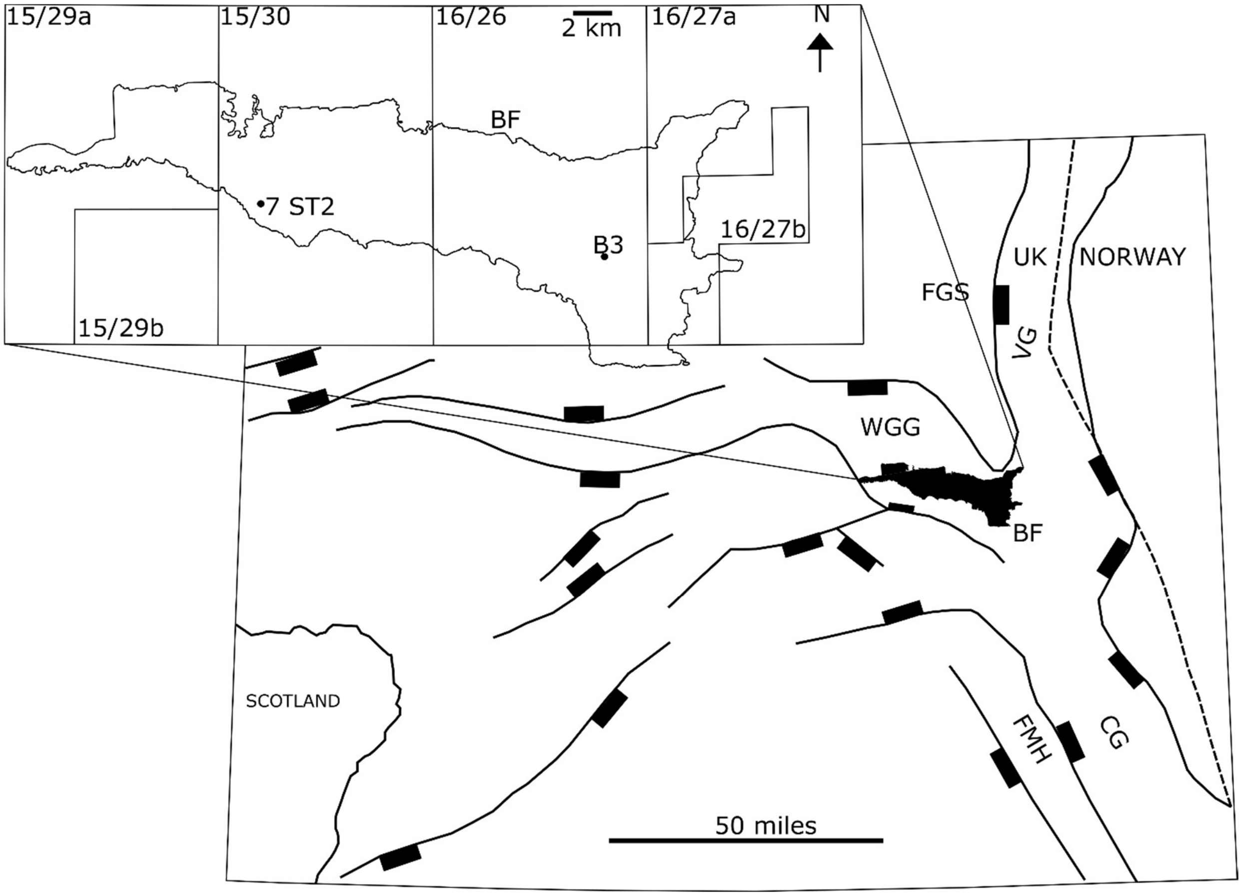


Figure 17. Significant Tectonic features of the Outer Moray Firth, North Sea, in the surrounding area of the Britannia field. BF: Britannia Field. VG: Viking Graben. FGS: Fladen Ground Spur. WGG: Witch Ground Graben. CG: Central Graben. FMH: Forties – Montrose High. The UK/Norway Median line is shown in a dashed line. The numbers 15/29a to 16/27b are the leased Exploration and Production blocks. The boreholes 15/30 7 ST2 and 16/26 B3 are in the black dots. Modified from Hill and Palfrey (2003); Ainsworth et al. (2000).

The North Sea's main rifting phase may have taken place just before the Early Cretaceous, allowing for the development of the Viking Graben, Central Graben and Moray Firth basins triple-rift system (Johnson et al., 1993; Zanella and Coward, 2003). The central pulse of faulting dates to the mid-Oxfordian to early Kimmeridgian. However, it did not stop there. The rifting continued until the Early Cretaceous (Glennie and Underhill, 1998; Ziegler, 1981). The main rifting pulse was accompanied by a significant eustatic sea-level drop expressed in north-west Europe by a regional regression (Ziegler, 1981). Rawson and Riley (1982) demonstrated that a highly condensed sedimentary section had been referred to as the 'Base Cretaceous Unconformity' or the 'late Cimmerian unconformity' in seismic interpretations. They counted at least seventeen stratigraphic breaks (and their related facies/faunal changes), mostly eustatic association, between the Upper Jurassic and the mid-Cretaceous of the North Sea and surrounding areas. Rawson and Riley (1982) point out that there is no significant regional hiatus at the base of the Valhall Formation or the Jurassic-Cretaceous boundary. The bottom of the Valhall is isochronous, representing a facies change marking the Late Berriasian transgression. Over structural highs, there may be a significant hiatus at the base of the Valhall Formation. Still, off-structure, this will pass into several seismically undetectable breaks within the Kimmeridge Clay and Valhall Formations (Rawson and Riley, 1982). The Late Berriasian lowering of sea level caused the emergence of large areas and temporary disruption of sedimentation to the deeper parts of the North Sea Rift, which makes the earliest Cretaceous appear represented in condensed facies, and the presence of significant unconformities is erroneously deduced (Rawson and Riley, 1982). During Valanginian to Early Aptian times, sea levels rose again, although temporarily reversed during the middle Aptian (Ziegler, 1981). Throughout the Early Cretaceous, there were emerged land areas that persisted despite the rising sea levels. These regions were close to the graben basin, where the Britannia Field is found. They are related to the old rifting stage. These areas contributed as local clastic sources to Early Cretaceous sub-basins (Tyson and Funnell, 1987; Copestake et al., 2003). Mid-Jurassic volcanic structures are covered by Upper Jurassic and Lower Cretaceous sediments such as those from the Cromer Knoll Group (Stewart, 1999).

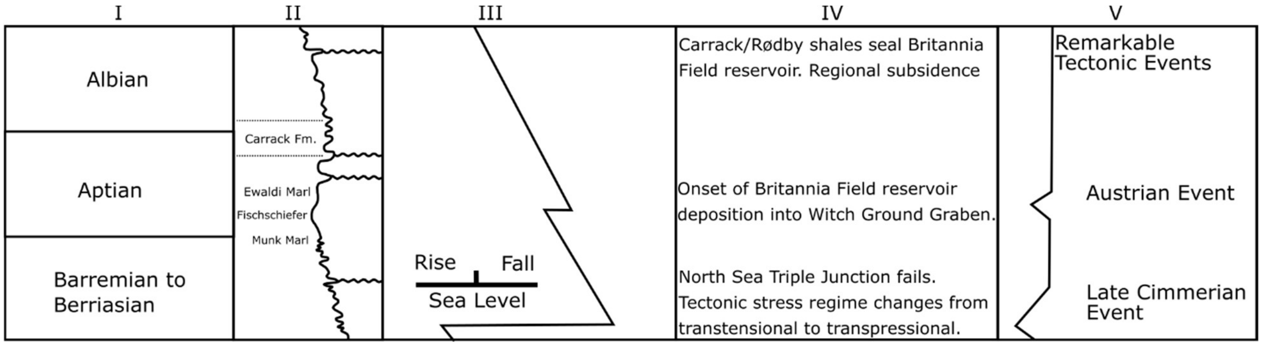


Figure 18. Tectonic history of the Britannia Field. I: Chronostratigraphy. II: North Sea detailed Relative Sea Level Curve; landwards to the left. III: North Sea simplified Sea Level Curve. IV: Relevant local events in the geological history of the Britannia Field area. V: Major plate-wide tectonic events curve influencing the Britannia Field area. Modified from Hill and Palfrey (2003); Jeremiah (2000).

3.1.4 Geology and stratigraphy of the Lower Cretaceous of the Britannia Field

Figure 19 displays a summary chart of the lithostratigraphy of the Cromer Knoll group for some areas of the North Sea, including the surrounding areas of the tectonic triple point between the Viking, Central and Witch Grabens, where the Britannia Field lies.

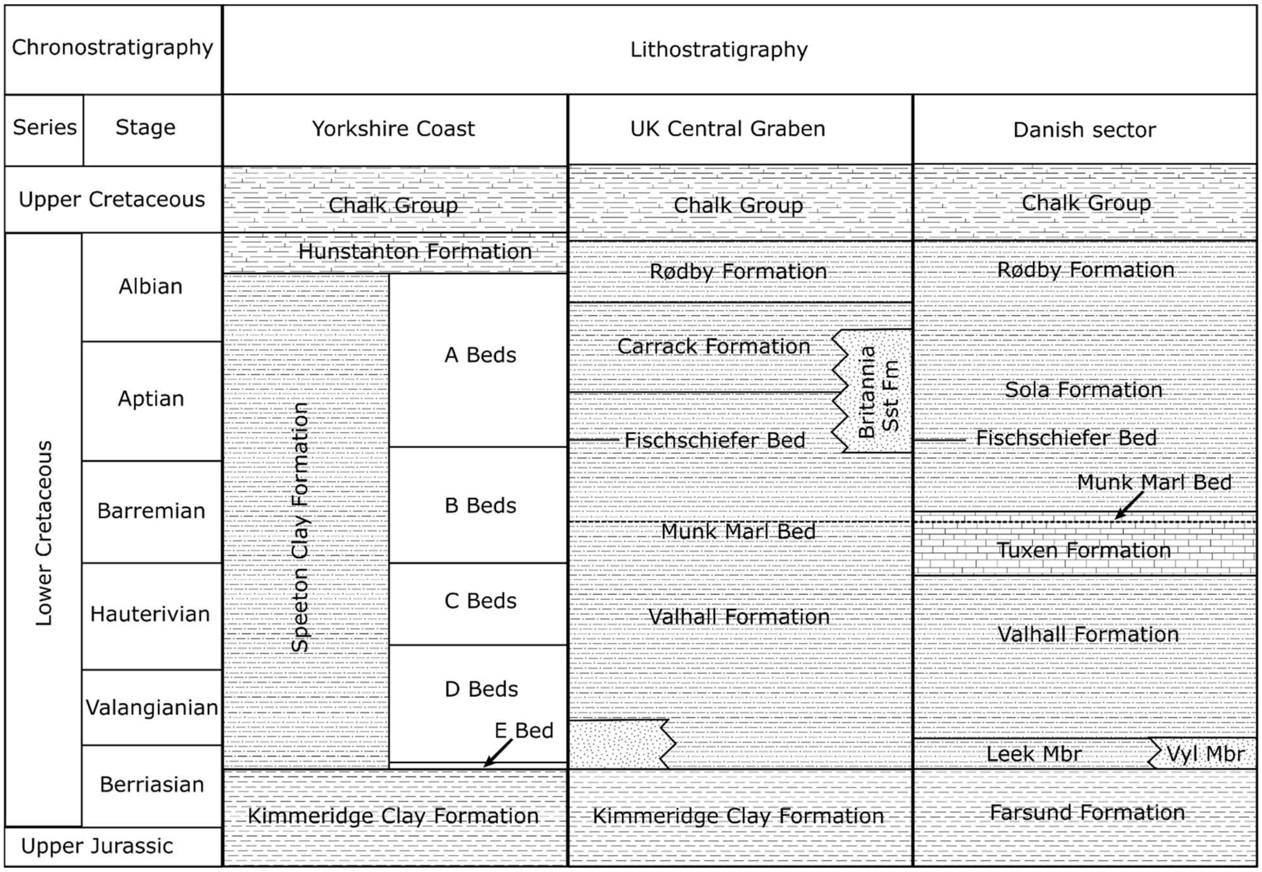


Figure 19. Lower Cretaceous lithostratigraphy of the Cromer Knoll Group. Modified from Copestake et al. (2003); Rawson et al. (1978).

The stratigraphic framework used in this work is based on basin-wide studies such as Johnson and Lott (1993), Oakman and Partington (1998), Copestake et al. (2003), Crittenden et al. (1991) and local-scale studies such as Ainsworth et al. (2000). At first glance, some of the lithostratigraphic proposals differ from each other. These differences may be due to recommendations published in the literature that do not necessarily resonate within the industry community; therefore, informal names are maintained (Copestake et al., 2003). We will adhere to the Copestake et al. (2003) nomenclature framework to keep things clear.

Valhall Formation

Deegan and Scull (1977) originally defined this formation as a soft grey, light grey and reddish grey calcareous mudstone or shale grading into marl. Those two lithologies exist in roughly equal proportions. However, Johnson and Lott (1993) reviewed its lithology as calcareous mudstones, chalky mudstones, limestones and sandstones situated between the Kimmeridge Clay Formation and their novel "Carrack Formation" (also referred to as Sola Formation in the industry). Inside the Moray Firth and UK Central Graben areas, the Valhall unit transitions laterally into the Britannia Sandstone and other coarse lithology formations (Johnson and Lott, 1993). Oakman and Partington (1998) suggest that because of sea-level high stands in northern latitudes, extensive anoxic (in basinal contexts) or dysaerobic (in continental shelves) episodes can be found all over the North Sea's sub-basins. Among these episodes, three major ones are the Early Barremian Munk Marl (known as Blätterton in Germany), the Early Aptian Fischschiefer and the

Cenomanian/Turonian boundary Plenus Marl. The first two are found in the Valhall Formation; therefore, it is worth describing them.

Munk Marl Bed

Jensen et al. (1986) defined a 0.3 to 1 m thick black, laminated, pyritic shaly bed of claystone with algal rich organic matter content as the Munk Marl bed, a new key bed in the Danish North Sea. Crittenden et al. (1991) equate the Munk Marl with the Blätterton facies of the Early to mid-Barremian of north-west Germany. Garrett et al. (2000) suggest that the Munk Marl/Hauptblätterton represents a period of maximum regional flooding identifiable on seismic data across north-west Europe. Ainsworth et al. (2000) indicated that the Munk Marl/Hauptblätterton was deposited during the Latest Early Barremian, contemporaneous to a major transgressive pulse that led to anoxic, locally dysaerobic, bottom waters.

Fischschiefer Member

Riley et al. (1992) elevated the Fischschiefer marker in the area surrounding the Scapa Field in the British North Sea to member status, taking the name from the contemporaneous, thinly laminated "Fisch-Schiefer" from the Lower Saxony basin of middle Lower Aptian time (Kemper, 1973). An absence of benthic fossils characterises the Fish Shales (literal translation for the German Fisch Schiefer), perhaps due to anaerobic processes of the near-bottom waters; fish remains and planktic foraminifera are plentiful (Kemper, 1973). Lithologically, the Fischschiefer marker comprises dark grey or black mudstones, exceptionally rich in organic matter, displays paper-thin lamination and a thin internal limestone horizon (Riley et al., 1992). Ainsworth et al. (2000) suggested that the deposition of the Fischschiefer occurred during the Early Aptian and noted that sandstone is found within the Fischschiefer Member in several wells within the Britannia Field. Mütterlose et al. (2014) explained that the Fischschiefer level is a "Selli Level equivalent", which is a lithological expression of the Oceanic Anoxic Event 1a of Early Aptian age, which is an event linked to increasing marine productivity (Erbacher et al., 1996).

Ewaldi Marl Member

Ainsworth et al. (2000) described sediments in the Britannia Field that are laterally equivalent to the Ewaldi Marls of north-west Germany as medium grey and red marls/calcareous claystones, associated with indurated, microcrystalline limestones. Jeremiah (2000) suggested that the Ewaldi Marl was contemporaneous with a brief episode of Austrian tectonism whose effects are felt in the Moray Firth area. He indicated that the Ewaldi Marl registered a high sea-level span representing an early highstand deposit widespread throughout the North Sea basin (Jeremiah, 2000). Crittenden et al. (1991) refer to the light to dark-grey marls and limestones, usually with a red colouration as a correlatable unit with the *ewaldi* Marls of north-west Germany ranging in age from the latest Early Aptian to the earliest late Aptian, which was first described by Ernst (1927).

Abundant red-stained *Hedbergella* spp. foraminifera are found in horizons within the unit, which occur alongside numerous benthic calcareous foraminifera such as *Valvulineria gracilima* (Crittenden et al., 1991).

Britannia Sandstone Formation

Johnson and Lott (1993) suggested a lithological signature of sandstones with interbedded mudstones for the Britannia Sandstone Formation. Further, they described the sandstones as pale grey, mainly fine to medium grain, with local pockets of coarse grain. Induration varies from hard to friable with sparse calcareous cement. The interbedded mudstones are, apparently, typical of the Valhall and Carrack formations, and they may be the key to subdividing the Britannia Sandstone Formation into two members. 'Valhall affinity' for the bottom part, whereas dark grey fissile mudstones with thin ash bands for the upper, 'Carrack like' member (Johnson and Lott, 1993). Bisewski (1990) suggests that the two "members" of the Britannia Sandstone Formation would be separated by a '*Hedbergella* marker' whose top may be characterised by a flood of red-stained *H. infracretacea* (Johnson and Lott, 1993). Guy (1992) recognised six main sand facies resulting from high- and low-density fluidal flow, plastic flow, and the pre-existing topography. His descriptive work suggests numerous sediment gravity flow processes carrying sandy sediments onto the slope foot (Guy, 1992). According to Zwaan (2018) and Jeremiah (2000), the Kopervik Fairway supplied sands from the East Orkney High in the west to the Britannia field reservoirs. Oakman (2005) suggested that the deep marine sands of the Britannia Field represent a fundamentally different depositional system for the Aptian to Albian interval. In principle, the system is like the Cenozoic configuration, which involved sediment transport over long distances sourced from the exposed North Atlantic [the North Sea, in this case] rift shoulders, contrasting to the preceding confined Upper Jurassic turbidite fans. The age of the Britannia Sandstone Formation is mid-Barremian to Late Aptian (Johnson and Lott, 1993). Ainsworth et al. (2000) divide the Britannia Sandstone Formation in the Britannia Field into the Lapworth (and its three sub-members), Kilda and Bosun members. Bisewski (1990) credited the Austrian tectonism as the driving force behind the regression in the Central North Sea and increased clastic input in the upper part of the Lower Cretaceous.

Carrack Formation

Johnson and Lott (1993) described a lithology of dark grey, carbonaceous, pyritic, non-calcareous marine mudstones, siltstones, and associated mass-flow sandstones between the Valhall and the Rødby formations. The mudstones' dark grey, carbonaceous, non-calcareous marine facies contain a microfossil fauna dominated by agglutinated foraminifera. It may suggest a phase of basin restriction with bottom-water oxygen depletion (Johnson and Lott, 1993). The dominant lithology is stiff and blocky to fissile in hand sample. The thickness of the unit ranges between forty and a hundred metres. The age of the Carrack Formation is Late Aptian to the latest Early Albian (Johnson and Lott, 1993). The Carrack formation is coeval with what has been described for the southern

North Sea as the Sola Formation by Hesjedal and Hamar (1982), to the upper part of the same unit in the Danish Central Graben as described by Jensen et al. (1986). Ainsworth et al. (2000) suggested a lithostratigraphic model on which the Carrack Formation is informally denominated 'Lower Sola Formation' and parts of the Rødby Formation are named 'Upper' Sola Formation. This lithostratigraphic framework will not be used in this research project because it confuses the name of the Sola Formation that was adequately defined in the Danish North Sea (Jensen et al., 1986).

Rødby Formation

Larsen (1966) named the grey to reddish-brown sandy marl deposits of Albian and Upper Aptian age found in the well Rødby-1 near the Danish seaside town of the same name. Deegan and Scull (1977) indicated that the unit could display pink to red in colour and claystone to calcareous shale and marls with scattered limestone breaks, in addition to the traditional description from the Rødby-1 borehole. Ainsworth et al. (2000) described a lithology dominated by light to medium grey, greyish red marls and calcareous claystones that are much darker and less calcareous towards the base. Although, light coloured limestones are found throughout the Rødby Formation. Crittenden et al. (1991) observed a gradual increase upwards in the overall calcareous content of the Formation. Johnson and Lott (1993) recognised the presence of the Rødby Formation in the basinal areas of the Central North Sea and South Viking Graben, where it lies between the Carrack and the Hidra formations. However, it may be absent through non-deposition and erosion over basin highs. Its thickness ranges between eighty to one hundred and eighty metres in basinal settings and less than thirty metres over basin highs and margins (Johnson and Lott, 1993). The Rødby Formation probably correlates with the Upper Holland Marl Member of the Holland Formation in the Dutch North Sea and the Hunstanton (Red Chalk) Formation in the British side of the southern North Sea (Deegan and Scull, 1977; Johnson and Lott, 1993). The Rødby Formation displays a diverse planktic foraminiferal assemblage, suggesting well-oxygenated, relatively high sea levels with a path for open oceanic circulation into the North Sea region (Johnson and Lott, 1993). The red colouration in the marl deposits can be derived from the carrying into suspension of material from the weathered surface that probably covered considerable parts of the land areas that the sea invaded in the Albian transgression (Larsen, 1966).

3.1.5 The biostratigraphical background of the Britannia Field

The following references are relevant for understanding the biostratigraphy of the Britannia Field and surrounding areas. Copestake et al. (2003) show several significant biostratigraphic marker species that support their proposed sequence stratigraphic scheme of the Lower Cretaceous of the North Sea.

Jeremiah (2001) presented thirty-one nannoplankton zones for the Lower Cretaceous of the North Sea Basin, focusing on the Upper Barremian to Lower Albian interval based on core and outcrop samples.

Ainsworth et al. (2000) suggested a biostratigraphic framework for the Britannia Field reservoir (the Early Barremian to earliest Albian) based on the study of almost three thousand samples from over fifty wells, most of which comprised cored sections. The biostratigraphic study comprehended the analysis of fossil calcareous nannoplankton, foraminifera and palynomorph assemblages which yielded forty-nine zones and thirty-eight subzones. The calcareous nannoplankton zonation scheme contained fourteen zones and fifteen subzones. On the micropalaeontological side, the zonation scheme has twelve zones and four subzones. The interspersed fine-grained lithologies underwent microfossil analysis favouring the sandstone and siltstone beds of the reservoir levels.

Rutledge (1994) developed a nannoplankton biostratigraphic framework based on outcrop and borehole material from north-west Europe, intending to establish a model for the Boreal Lower Cretaceous.

King et al. (1989) introduced a two-fold foraminiferal zonation scheme for the deep-water and shelfal facies found in a significant part of the North Sea Basin.

Crittenden (1987) suggested a biostratigraphical framework for the Aptian of the southern North Sea. Later he expanded his work in Crittenden (1988) to include the Early Cretaceous interval using material from ten boreholes from the southern North Sea.

Furthermore, he compared Albian and Aptian sections from north-west Europe with his southern North Sea boreholes.

Burnhill (1982); Burnhill and Ramsay (1981); developed a biostratigraphic scheme based on planktic foraminifera for the Mid-Cretaceous, part of which is helpful in this study, namely for the Albian stage.

3.1.6 Biostratigraphic work in this study: material, methods, and results—analysis of the microfossil assemblages of the Britannia field.

Numerous wells have been drilled in the Britannia Field (the current number is unknown for the author, although fifteen years ago, the tally was way over sixty boreholes (Sumner et al., 2005)). Samples from some Britannia cored sections are stored at the Earth Sciences Department of the University of Birmingham. The principal author searched on the National Data Repository (NDR) (Oil&Gas_Authority, 2021) for boreholes that entirely covered the Lower Cretaceous section. However, this was impossible to find; most wells cover the reservoir beds (mainly the sandstones of the Britannia Sandstone Formation) plus a few hundred feet; therefore, two boreholes were selected, trying to maximise the stratigraphic section to be studied. A second constraint on the borehole selection process was the sandy and silty nature of the reservoir beds because it is well known that the best microfossil recovery was obtained from argillaceous or limestone beds in the Britannia Field (Ainsworth et al., 2000).

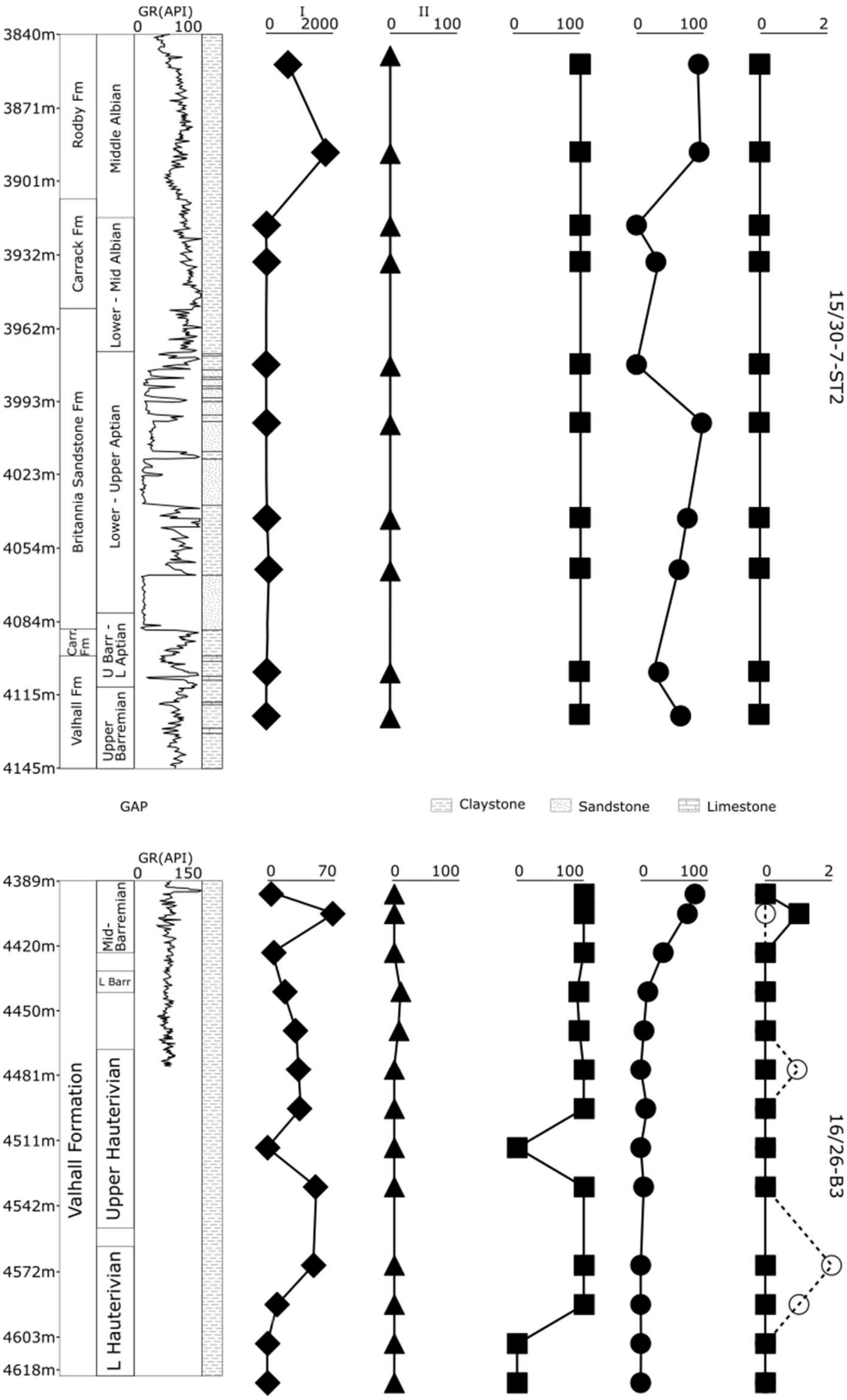


Figure 20. Microfossil results for the boreholes 16-26-B3 and 15-30-7-ST2. Lithostratigraphic symbols are from U.S.G.S. (2006). I, VI: number of foraminifera per gram in the 500 to 63 µm,

notice the change in scale between the two boreholes. II, VII: benthic agglutinated foraminifera as a percentage of all benthic foraminifera. III, VIII: benthic calcareous foraminifera as a percentage of all benthic foraminifera. IV, IX: planktic foraminifera as a percentage of all foraminifera. V, X: number of bivalves (squares) and ostracods (circles). Lithostratigraphy, Chronostratigraphy and Electric logs are modified from Britannia Operator Limited (1990, 1995).

Therefore, the search at the NDR's archives included a review of the composite well logs of drilled boreholes paying particular attention to the composite lithology log or gamma-ray log, when available. In this way, the author discriminated between those boreholes that drilled through a thicker sandstone section with few or no argillaceous sections based on the lithological patterns inferred from the logs. As a result, two boreholes were chosen that presented the best opportunity for sampling the fine-grained lithologies of the Lower Cretaceous succession of the Britannia Field. The first borehole, 16/26–B3, was drilled by the Britannia Operator Limited (a joint venture between Chevron UK Ltd and Conoco UK Ltd) in 1995 to a total measured depth of 4624 m (15171'); it aimed to recover fossiliferous sequence from Hauterivian and Barremian age. The author selected twenty-six samples between 4395 and 4623 m (14420 and 15170 feet) of measured depth for laboratory processing, of which twelve ended up being analysed under the microscope. The second borehole, 15/30-7 ST2 drilled by Conoco UK Limited on behalf of the joint venture with Chevron in 1990 to a total depth of 4180.3 m (13715') after a troubled drilling operation that incurred two side-tracks. Nineteen samples from the Barremian, Aptian and Albian between 3582.7 and 4123.9 m (12640' and 13530') were processed in the laboratory. Ten were analysed under the microscope by the author. A summary of the results of the microscope analysis for both wells can be seen in Figure 20.

These results show poor microfossil assemblages in both boreholes. In this context, microfossil abundance is low, with most samples providing a few dozens of specimens per gram of sediment in the 500 to 63 µm grain size fraction. The calcareous benthic taxa dominate the foraminiferal community at the borehole 16/26-B3, i.e., in the Hauterivian and Barremian of the Britannia Field. Around ten genera of benthic foraminifera were identified in the samples, including *Ammodiscus*, *Lenticulina*, *Dentalina*, *Glomospirella*, *Valvulineria*, *Gavelinella*, *Falsogaudryinella*. Agglutinated foraminifera are rare; however, their presence is vital for the biostratigraphic correlation of the bottom part of the section. Ostracods and bivalves are found in the bottom part of the section. Planktic foraminifera dominate the upper part of the section. They dominate the upper section of the 16/26-B3 borehole and are seen dominating the assemblages found in the 15/30-7 ST2 borehole, i.e., the Upper Barremian, Aptian and Albian of the Britannia Field; among the identified species are abundant the *Blefuscuiana aptiana orientalis* and the *B. rudis*.

The first downhole occurrence (FDO) of the agglutinated foraminifera *Falsogaudryinella* genus is found at 4440.9 m (14570') in the well 16/26-B3. Although preservation does not allow the identification of specimens down to species level, there is good reason for the author to believe that the *F. xenogena* species is present. The FDO of this species marks the Mid to Lower Barremian, according to King et al. (1989). This would confirm that the proto-age model agrees with industry reported ages for the Barremian from the 16/26-B3 borehole (Britannia Operator Limited, 1995), as seen in Figure 20. The planktic foraminifera flood at the top of the 15/30-7 ST2, in the samples found at 3852.7 and 3889.2 m (12640' and 12760'), is consistent with the mid-Cretaceous elsewhere in the basin (Burnhill, 1982; Crittenden, 1987; Mitchell and Underwood, 1999; King et al., 1989).

3.1.7 Palaeoenvironmental interpretation

There is limited information to assess the palaeoenvironments of the Britannia Field reservoir from the sample material recuperated from the boreholes 16/26-B3 and 15/30-7 ST2. As mentioned above, low abundance of specimens, low diversity, and poor preservation quality hinder palaeoenvironmental solid hypotheses based solely on microfossil material.

However, lithology provides a good palaeoenvironmental framework to work in. The storyline told by the rocks throughout the Lower Cretaceous is one of a continued marine transgression – with occasional regressive events. It represents a transition from primarily terrigenous, probably hemipelagic, sediments to carbonate-rich, pelagic sediments in the Upper Cretaceous. These lithologies testify to the increase in open-oceanic influences that north-west Europe experienced after the mid-Cretaceous (Johnson and Lott, 1993; Ainsworth et al., 2000; Crittenden et al., 1991).

Starting with the Kimmeridge Clay Formation at the Berriasian stage, sedimentary conditions at the seafloor were favourable for preserving organic matter and mudstone deposition, reflecting, likely, a marine hemipelagic environment (Johnson and Lott, 1993).

The sedimentary environment changed for most of the Valhall Formation deposition during the Berriasian trough Aptian stages. A bioturbated, lighter coloured, calcareous claystones and marls lithology indicates a predominantly aerobic, outer sublittoral marine environment. Although recurring anoxic or dysoxic sea-floor conditions were present at times during the deposition of the Hauptblätterton / Munk Marl Bed and the Fischschiefer Member as evidenced by dark grey claystones and organic-rich shales. Reddened sediments at the top of the Valhall Fm indicates well-oxygenated, iron-enriched waters (Johnson and Lott, 1993; Ainsworth et al., 2000).

The Britannia Sandstone Formation is evidence of sediment gravity flow pulses within an otherwise oxygenated, open marine basin that later became restricted. Proof of it is shown by the transition from calcareous to dysaerobic interspersed muddy lithologies, referred to as either Valhall (for the bottom section) or Carrack (for the upper half) affinity lithologies. The basin topography played a role in defining the environment for the sandstone facies, which are sourced from then-contemporaneous, high-energy, shallow shelf sands. This fact is confirmed by the presence of skeletal debris, glauconite grains and uniform grain size (upper-fine to lower-medium in the sand fraction). The best candidates for the source area are the south flank of the Fladen Ground Spur, the Renee Ridge, the Jaeren High, the Halibut Horst, and the Kopervik Fairway (some can be seen in Figure 17). Sandy material was transported down the slope into the basinal floor by liquified debris flows or high and low-density turbidites (Downie and Stedman, 1993; Guy, 1992; Jeremiah, 2000; Johnson and Lott, 1993; Oakman, 2005; Ainsworth et al., 2000; Jones et al., 1999; Zwaan, 2018).

The overlying Carrack Formation marked a phase of basin restriction, low energy sublittoral environment with bottom-water oxygen depletion as evidenced by dark grey, carbonaceous, non-calcareous marine mudstones, likely due to tectonically controlled basin enclosure. Towards the top of the unit, the sediment deposition was due to an increased supply of terrigenous materials, in conjunction with a short-lived regressive phase when the erosion base was lower while suspended materials within the water column soared (Johnson and Lott, 1993; Ainsworth et al., 2000).

At the top of the study section, the Rødby Formation was deposited in a well-oxygenated, outer sublittoral marine environment. The increasingly calcareous sediments of the Rødby Formation mark an inflexion point in the North Sea basin lithological history, from hemipelagic, clay-dominated lithologies typical of the Lower Cretaceous to the pelagic chalky limestone sediments of the Upper Cretaceous, suggesting more open oceanic influence and higher sea levels.

Unconformities disrupt the stratigraphic sequences of the Britannia Field, several of them, mostly of eustatic origin (Rawson and Riley, 1982), which makes correlation of biostratigraphic events between wells impossible in occasions in the Britannia Field (Ainsworth et al., 2000). However, it is vital to acknowledge the role that condensed sections, due to continued Lower Cretaceous transgression and episodic sedimentary starvation, may play in the makeup of condensed sections that may be mistaken for unconformities (Rawson and Riley, 1982).

The microfossil assemblages support a deepening palaeobathymetry with intermittent shallowing pulses in the North Sea basin throughout the Lower Cretaceous, resulting in a more connected and open marine setting by the mid-Cretaceous. Agglutinated benthic foraminifera seem to suggest phases of more restricted water circulation (indicated by their association with hemipelagic, mostly terrigenous, fine-grained sediments). However, for most of the sampled sections in boreholes, 16/26-B3 and 15/30-7 ST2, the percentage of agglutinated foraminifera is not dominant in the assemblage. Benthic calcareous and planktic foraminifera indicate well-oxygenated marine environments by displaying moderate diversity and associating with pelagic and carbonate-rich lithologies. This fact is valid throughout the sampled sections in boreholes 16/26-B3 and 15/30-7 ST2. The calcareous benthic foraminifera are present in low to moderate quantities displaying low diversity, which suggests neither a completely open nor an entirely restricted environment, rather a transitional one, as the lithology suggests, from restricted basins to more connected and ventilated marine bodies. The presence of a few ostracod specimens and bivalve shell fragments in the bottom part of the section (borehole 16/26-B3) suggests a decent oxygen supply in those intervals.

High-quality sedimentological data and interpretations of the Britannia Sandstone Formation available in the literature suggest that the material was sourced from a shallow shelf and transported down the slope into deeper basinal areas to be deposited. This project did not sample the coarse-grained sand bodies, as mentioned above. Instead, it sampled the finer-grained lithologies interspersed between the high energy clastic deposits. The micropalaeontological data recovered in this survey does not suggest that the microfossil assemblages of the interspersing fine-grained beds showed any other environment than the hemipelagic/pelagic characteristics that featured in the underlying (Valhall Formation) or overlying (Carrack Formation) beds. The gravity-dominated processes' transitory nature did not completely disturb or alter the predominant environment of deposition in the basin and its associated faunal assemblages.

3.1.8 Conclusions

The lithological successions and associated microfossil faunas of benthic calcareous, agglutinated, and planktic foraminifera of the Lower Hauterivian to Middle Albian deposits of the Britannia Field area suggest a transition from clay-dominated sediments deposited under restricted basinal conditions towards a calcareous-affinity type of sediments deposited in more connected and open oceanic conditions. The microfossil material recovered from the boreholes 16/26-B3 and 15/30-7 ST2 shows predominantly low to moderate abundance and diversity, suggesting low productivity. A more detailed study with core material may improve the view and understanding of the microfossil landscape for these sections of the Lower Cretaceous of the North Sea.

Data Availability

Complete data sets will be available at the University of Birmingham's online repository.

3.2 Lower Cretaceous foraminifera of the North Jens-1 well, Danish Central Graben

3.2.1 Abstract

This study investigates Hauterivian to Aptian foraminiferal assemblages from the North Jens-1 exploration well of the Valdemar Field, Danish sector of the North Sea. This interval witnessed progressive global sea-level and temperature rise, reflected in the fluctuating diversity and abundance of several calcifying marine organisms, including the foraminifera. Fifty-six core samples were examined for benthic and planktic foraminifera from the North Jens-1 well. The foraminifera provide biostratigraphic control and reflect changes in the depositional environments of the Valdemar Field. The foraminiferal ranges are considered with existing biostratigraphic schemes for the early Cretaceous of the North Sea. In addition to the foraminiferal biostratigraphy, a comparative chronostratigraphic framework is supported by calcareous nannofossil data provided by external collaborators. During this period, marked evolutionary changes in the foraminifera include the diversification and increasing dominance of planktic taxa and the proliferation of benthic calcareous and agglutinated foraminifera in the lower stages of the Lower Cretaceous. The relatively low-abundance benthic assemblages indicate a relatively deep-water (outer neritic to bathyal), pelagic depositional setting. Changing foraminiferal species richness and abundance patterns can be correlated to Mesozoic local changes in water depth and regional geological events.

3.2.2 Introduction

The Central Graben of the North Sea is dissected by N-S and NW-SE trending structures of Mesozoic origin, comprising faulted blocks and half-grabens (Surlyk and Ineson, 2003). Some of these structures are aulacogen branches oriented approximately N-S, N-NW, and W-E (Figure 21). They are interpreted as lingering features of a failed rift while other structural features surround the failed rift with primary lineations of NE-SW, NW-SE, and N-S. The tectonic regime in the area changed from extensional in the Jurassic to compressional by the Late Cretaceous. Evidence of tectonic activity can be observed in Lower Cretaceous sedimentary deposits that display high siliciclastic content whereas, by contrast, Upper Cretaceous sections show a predominantly calcareous character (Ineson, 1993; Møller and Rasmussen, 2003; Coward et al., 2003; Zanella and Coward, 2003).

Continued normal faulting characterised the tectonic setting in the earliest Cretaceous of the North Sea. The sedimentary deposition of clastic wedges against fault scarps was typical; subsequent sediments were deposited during early post-rift thermal subsidence. At this time, significant tectonic activity was happening, demonstrated in seismic profiles that show sedimentary wedges thinning out and draping a chaotic post-rift seafloor (Møller and Rasmussen, 2003; Zanella and Coward, 2003). Extension ceased during the Early Cretaceous as the rift system transitioned into a passive thermal subsidence state. Transgressive sediments covered the syn-rift topography forming the so-called Base Cretaceous Unconformity (Coward et al., 2003).

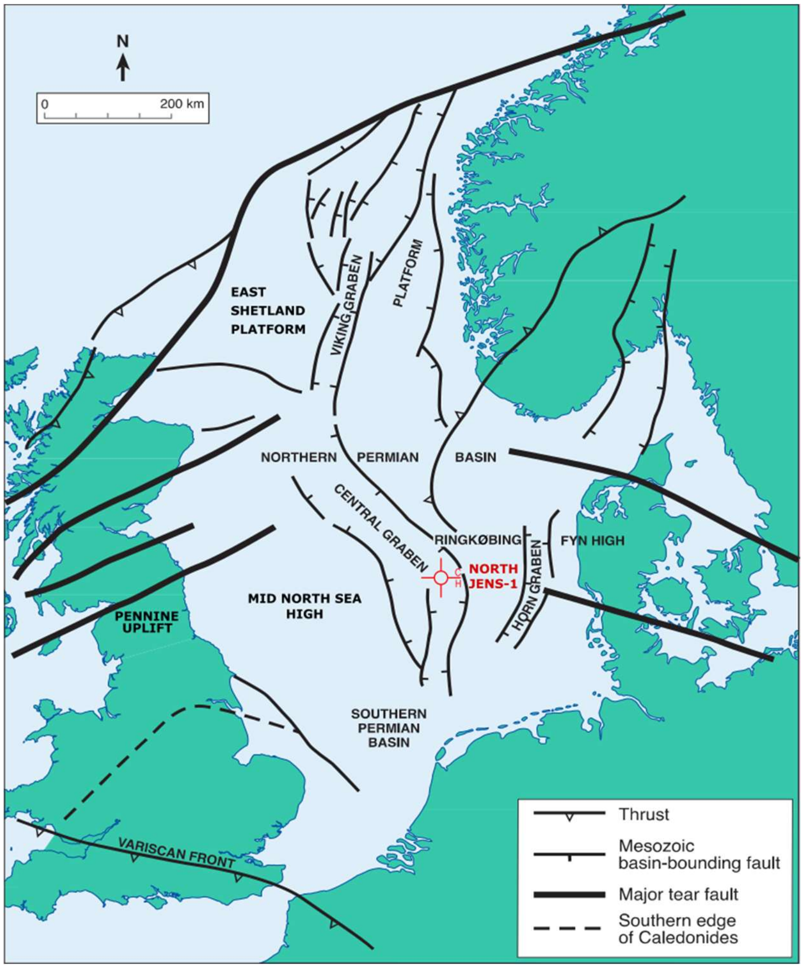


Figure 21. Tectonic map of the North Sea Basin and surrounding regions highlighting the major structural features near the North Jens-1 well, modified from Coward et al. (2003).

The North Jens-1 well is located on the Valdemar hydrocarbon field of the Danish Central Graben (Figure 21), on the crest of a positive structure (Copestake et al., 2003) which is related to a fault which was likely a reactivated extensional-fault initially associated with early Mesozoic rifting (Vejbæk, 1986b). This exploration well was partly cored, and it is one of those intervals (early to mid-Cretaceous) that is the focus of this work. Microfossil evidence indicates that the area was marine throughout the Early Cretaceous (Jensen and Buchardt, 1987). Sea-levels rose progressively across the North Sea Basin during the Early Cretaceous, reaching a maximum during the Late Cretaceous Turonian Stage. Minor unconformities, or ravinement surfaces, were likely caused by sub-surface erosion during episodes of subsequent sea-level fall (Haq, 1991).

Jensen et al. (1986), Jensen and Buchardt (1987), Ineson (1993) and others have previously examined the sedimentology, stratigraphy, geochemistry, and micropalaeontology of the North Jens-1 area. Jensen et al. (1986) provided lithological descriptions of the Mesozoic formations in the Danish Central Graben, including those comprising the Lower Cretaceous cored section in North Jens-1, i.e., the Valhall, Tuxen, Sola and Rødby formations (see also Jensen et al. (1986); Michelsen et al. (1987)). Jensen and Buchardt (1987) suggested that late Hauterivian, Barremian and Aptian deposition in the Danish Central Graben occurred at or near the base of slope and basin plain. Therefore, the material from North Jens-1 provides unique access to an almost complete Lower Cretaceous cored section from what would have been a relatively deep-water environment at that time.

Lower Cretaceous sedimentary units of the Danish Central Graben are generally carbonate-rich throughout (Figure 22); many are dominated by planktic microfossils representing largely pelagic environments with only a minor hemipelagic component. Variation in the supply of siliciclastic detritus content contributes to the alternation between relatively pure and impure carbonates (Jensen and Buchardt, 1987). Differential subsidence affected basins and blocks on a local level, and consequently, the thickness of the Lower Cretaceous units varies widely. Dominantly calcareous units are interspersed with clastic and organic-rich units, the latter represented by the Munk Marl Bed and the Fischschiefer Member. Jensen and Buchardt (1987) suggest that oxic to restricted-oxygen conditions prevailed during the sedimentation of the chalk-like Tuxen Formation (Fm subsequently), except for the Munk Marl Bed, which was deposited under more dysoxic conditions. They also proposed dysoxic conditions for the deposition of the Sola Fm. These authors put several hypotheses for the establishment of anoxic conditions in the North Sea, but the precise reasons remain unclear (Jensen and Buchardt, 1987). Therefore, the foraminiferal assemblages reported below represent a relatively deep-water, basinal setting and a range of bottom-water oxygenation conditions.

Ineson (1993) divided the Lower Cretaceous section of North Jens-1 into eight stratigraphic units, based mainly on the lithology and electric-log characteristics. He suggested a stratigraphic framework marked by three depositional sequences, the Valhall, Tuxen and Sola formations. In this framework, unconformable surfaces mark sequence boundaries. In contrast, organic-rich marker beds at the top of glauconitic intervals indicate transgressive surfaces. Ineson (1993) described the carbonates of the Tuxen and Sola formations as nannofossil chalks with minor proportions of skeletal material such as foraminifera and *Inoceramus* prisms. The clay fraction was characterised by kaolinite with subordinate illite and other clays (Ineson, 1993). A simplified representation of the lithological composition, thickness, and age of the units relevant to North Jens-1 is shown in Figure 22, together with a summary of the changing foraminiferal assemblage composition.

The North Jens-1 well provides an almost complete Lower Cretaceous cored section from a relatively deep-water palaeoenvironment for the North Sea, particularly when compared to the palaeoshelves recorded along the Yorkshire Coast and North Germany (Bartenstein and Bettenstaedt, 1962; Fletcher, 1966). This stratigraphic interval also witnesses significant evolutionary changes within the foraminifera, including the marked increase in abundance of the planktonic foraminifera (Banner and Desai, 1988; Banner et al., 1993) and the downslope migration of many agglutinated benthic taxa into relatively under-explored ecological niches of deeper waters (Kaminski et al., 2010).

3.2.3 Biostratigraphic background

Cretaceous sediments from both the onshore and offshore of the North Sea Basin have been studied for more than a century, often associated with the search for hydrocarbon resources. The pioneering studies of Bartenstein (1978, 1979); Bartenstein and Bettenstaedt (1962) reported the foraminifera and ostracods of the marine Lower Cretaceous of Germany. They provided the basis for a biostratigraphic subdivision for the onshore Lower Cretaceous of north-west Europe. Stratigraphic and palaeontological studies on outcrops and boreholes of the Speeton Clay, Yorkshire Coast of eastern

England (Figure 21), confirm that the stratigraphic distribution of foraminifera, and other groups, from shelves on the western margin of the North Sea Basin is similar to those from onshore Germany (Fletcher, 1966; Neale, 1962b; Neale and Sarjeant, 1962).

A broad perspective on Lower and mid-Cretaceous stratigraphy and foraminiferal micropalaeontology of the central North Sea Basin can be found in Burnhill (1982), while Sandman (1986) focussed on the foraminifera and depositional palaeoenvironments of the Middle and Upper Albian Gault Clay Fm in East Anglia. Crittenden (1988) examined the Early Cretaceous foraminiferal biostratigraphy of the southern North Sea Basin and attributed changes in the foraminiferal assemblages through time to palaeoenvironmental changes, faunal interchange with open oceanic areas of the Tethys and a developing North Atlantic. Banner et al. (1993) discussed Barremian to Aptian planktic foraminifera and established biozones for the Danish Central Graben.

Rutledge (1994), Bown et al. (1998) and Jeremiah (2001) developed calcareous nannofossil zonation schemes applicable to the North Sea Basin, while Duxbury (2001) provided a palynological biostratigraphic framework. The biozonation schemes of Jeremiah (2001) and Duxbury (2001) were calibrated for the North Sea by Copestake et al. (2003) via magnetostratigraphy and the sequence-stratigraphic framework. The primary foraminiferal biostratigraphic reference for the present work is that of King et al. (1989). They noted the marked faunal difference between shallow and deep-water palaeoenvironments in the Cretaceous of the North Sea Basin. These depth-related biofacies changes prohibited using a single zonal scheme across the basin. Consequently, two biozonation schemes were established: FCS (Foraminifera Cretaceous South) for the 'shelf' facies, predominant in the southern North Sea and the basin margins; in contrast, FCN (Foraminifera Cretaceous North) applied to deep-water, outer neritic and bathyal facies prevalent in the Central and northern North Sea.

3.2.4 Material and methods

The North Jens-1 hydrocarbon exploration well was drilled in 1985 and proved the commercial viability of the Valdemar Field. A total of 77 metres (254 feet) of core was recovered from 2240 to 2259 m (7350' to 7410') and from 2269 to 2328 m (7445' to 7639') (there is a coring gap from 2259 to 2269 m (7410' to 7445')) spanning the Hauterivian, Barremian and Aptian stages of the Valhall, Tuxen and Sola Formations (note that depths are shown in metres as well as in feet, as is standard for the exploration industry).

The cored interval in this study can be subdivided into four primary lithologies: chalk, claystone, calcareous shale (or marlstone) and argillaceous limestone (or marly chalk). These cover the uppermost Valhall Fm and most Tuxen and Sola formations. Nonetheless, the lithologies are heterogeneous and complex. That complexity is highlighted by varying degrees of bioturbation and lamination, horizons with enhanced mineralisation, e.g., glauconite and pyrite, and the occurrence of thin, high-energy beds (coarse and pebble grain size). The present study is supported by geochemical and petrophysical data from Mütterlose and Bottini (2013), including bulk-rock Total Organic Carbon (TOC), calcium carbonate content and stable carbon isotope ($\delta^{13}C$) data from the Upper Barremian and Lower Aptian successions. Jensen and Buchardt (1987) reported the geochemistry of the organic carbon-rich rocks of the Sola and Tuxen formations in the areas surrounding the Valdemar Field. Copestake et al. (2003) presented wireline logs and a lithological description for North Jens-1 (Figure 22).

3.2.4.1 Nannofossil biostratigraphic framework

One hundred thirty-three nannofossil samples were prepared using Bown and Young's (1998) simple smear slide technique to provide a comparative plankton-based biostratigraphic scheme throughout the study interval. Simple relative abundance counting was employed, with a minimum of 300 specimens counted from each slide. The slides were examined using a Leica DM 2500P light microscope under x1000 magnification. All slides are stored at GEUS. A detailed description of the nannofossil breakdown and assemblages will be published elsewhere, but the stratigraphic framework arising from those data is shown in Figure 23.

The Lower Cretaceous 'BC' boreal nannofossil zonation scheme of Bown et al. (1998) and the 'LK' North Sea Basin and Saxony Basin zonation of Jeremiah (2001) are applied to this study (Figure 23). Previous nannofossil biostratigraphic studies on parts of the North Jens-1 core have focused on the Late Barremian to Early Aptian section, e.g., Jeremiah

(2001) and Mütterlose & Bottini (2013). The nannofossil data presented here covers the whole of the cored section. The oldest sample from the cored section (2328 m (7638.7')) is dated as Early Hauterivian BC9 (LK24A-23), and the youngest sample (2240 m (7350.50')) as Upper Aptian BC19-21 (LK12). All BC and LK zones/subzones are present, indicating a complete section. However, zones BC12 (LK20d) and BC13 (part of LK20c) are thin, suggesting a possible hiatus at this level or stratigraphic condensation in this well.

3.2.5 Foraminiferal biostratigraphy

A total of fifty-six sediment samples (each *c*. 50 g) were taken from the core for calcareous micropalaeontology at an approximate spacing of 2 m (6 feet), with increased resolution around abrupt lithological changes. Sub-samples of *c*.20 g were oven-dried and weighed before soaking in water and subjected to several freeze-thaw cycles until the residue was disaggregated. Further soaking in a decahydrate sodium sulphate solution and additional freeze-thaw cycles was required in some cases, and petroleum ether/white spirit techniques were applied to the most recalcitrant samples. Ultimately, only 31 samples could be successfully disaggregated for micropalaeontological analysis; of these, three were barren. The remainder were quantitatively split to provide at least 300 specimens thoroughly picked above the 125 μm size with additional observations of the 63 μm split in selected samples. Samples are arranged in faunal slides and lodged in the Lapworth Museum of Geology collections, University of Birmingham.

Microfossil preservation is generally good throughout the core. Foraminiferal tests coated with pyrite were occasionally observed in parts of the Sola Fm. In the upper Sola Fm, an impure, chalky matrix surrounds planktic foraminifera fragments, obscuring the aperture and first chambers in many specimens, making identifying species level difficult. Many representatives of *Dentalina* and *Lenticulina* were broken, possibly due to processing. Jensen and Buchardt (1987) suggested that strong diagenetic effects in the Tuxen and Sola formations were unlikely since the values of $\delta^{18}O$ and $\delta^{13}C$ in their carbonate fraction are typical of marine carbonates exposed to little or no diagenesis when compared with nearby Danish Central Graben fields.

At least 37 species of foraminifera belonging to 24 genera were identified in North Jens-1. The microfossil assemblages include ten species of agglutinated benthic foraminifera and 23 species of calcareous-walled benthic foraminifera. Three species of the planktic genus *Hedbergella* are recorded in the section, and this genus becomes significantly more abundant towards the top of the section. Changing species abundance and species richness are illustrated in Figure 23. Agglutinated and calcareous benthic taxa dominate the Hauterivian to Barremian assemblages, while predominantly planktic foraminiferal assemblages characterise the Aptian. The age model follows Jeremiah (2001), Ogg et al. (2012), Gale et al. (2020).

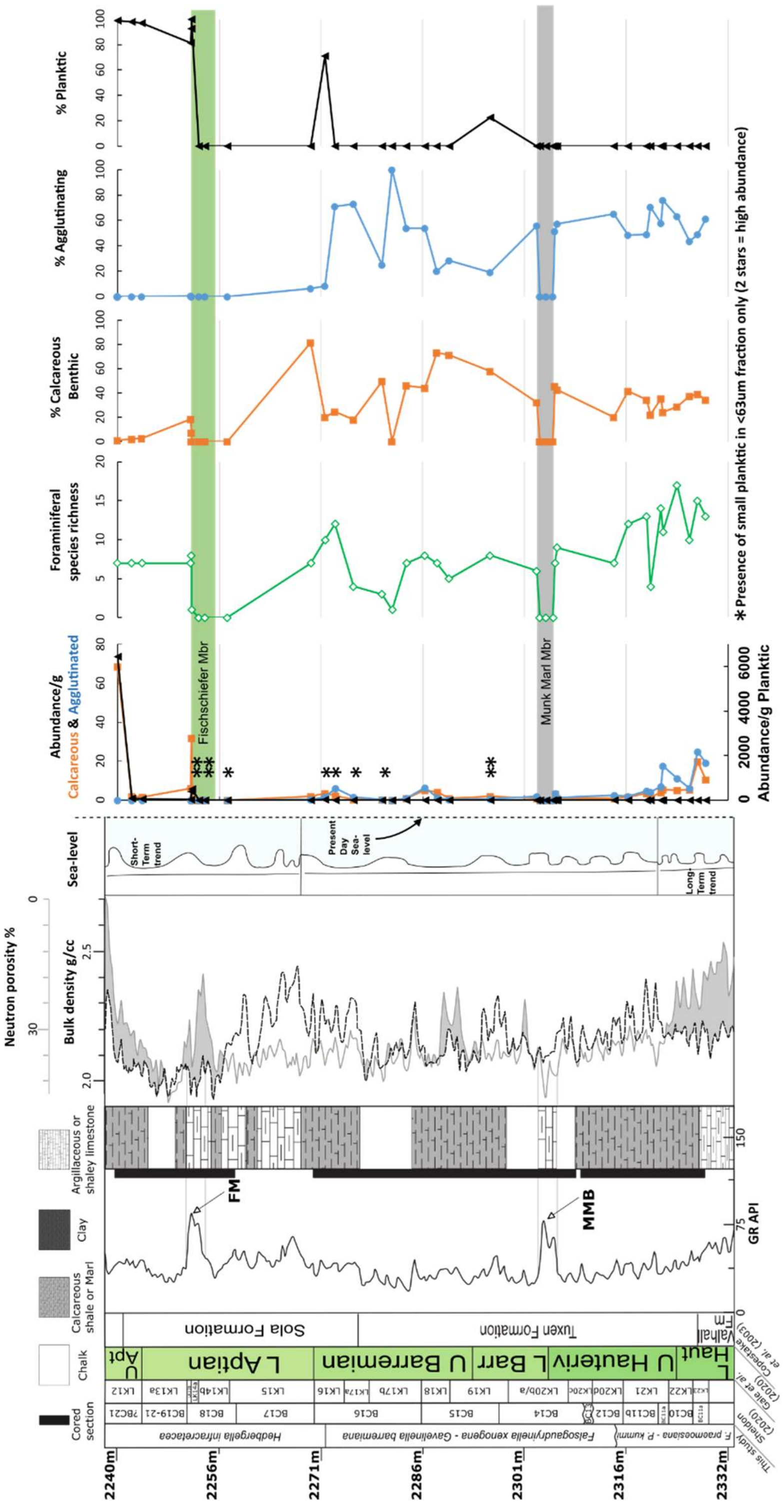


Figure 22. Key microfossil changes through the North Jens-1 well plotted against chronostratigraphy, lithostratigraphy and biostratigraphic schemes. Electric logs and lithology from

Copestake et al. (2003) and sea-level curve from Snedden and Liu (2010). FM: Fischschiefer Member; MMB: Munk Marl Bed.

3.2.5.1 Hauterivian (2311 – 2328 m (7582' – 7639'))

The assemblages in this interval display low foraminiferal abundance and high species-richness dominated by benthic foraminifera; ostracods are also present at many levels. The most abundant taxa are the agglutinated species *Ammodiscus cretaceus* and *Glomospira charoides*, which could suggest slightly restricted conditions at the time of deposition (Olson and Leckie, 2003). The agglutinated foraminifera *Falsogaudryinella praemoesiana*, a zonal index species for the deep-water North Sea (King et al., 1989; Kaminski et al., 1995), is particularly abundant in a thin bed of calcareous mudstone/claystone at 2324 m (7625') depth. The abundance of benthic foraminifera reaches its lowest at c. 2320 m (7612').

King et al. (1989) suggested two notable, basin-wide Hauterivian zonal index species, *Protomarssonella kummi* and *F. praemoesiana.* The Late Hauterivian of the North Sea basin, biozone FCN 4 of King et al. (1989), is marked by an interval with a high abundance of *F. praemoesiana* (Bailey, *pers. comm.,* 2019). A slightly moderate scenario supporting the former statement is found in the North Jens-1 foraminiferal assemblage. A moderate abundance of *F. praemoesiana* specimens is recorded between 2320 m (7610’) and 2328 m (7639’), in the BC9 to BC11b Nannofossil Zones that characterise the Hauterivian (see nannofossils’ discussion above). However, the abundances are not as relevant as expected (according to testimonial evidence from other areas in the basin). This may suggest that the late Hauterivian event is not recorded in North Jens-1. A related piece of information is the evidence for minor tectonic inversion in the Central Graben starting around the mid-Hauterivian (Vejbæk, 1986a; Vejbæk and Andersen, 1987) which may account for the absence of abundant *F. praemoesiana* at Upper Hauterivian beds. Subsidence and the shifting of sediment depocentres are seen in the area surrounding the North Jens-1 well, resulting in an incomplete record for Lower and mid-Cretaceous sediments in wells such as Adda-2 and E-1, east of the Valdemar Field (Ineson, 1993; Vejbæk, 1986a; Vejbæk and Andersen, 1987).

The case for stratigraphic condensation or a hiatus is further supported by nannostratigraphy. A mid-Cretaceous hiatus has been recognised from nannofossil data to the east of the North Jens-1 well (Bown et al., 1998). Starting within BC12 (the lowest part of zone BC12 is preserved) in Adda-2 and SE Adda-1 (east of North Jens-1 on the Adda Field). In SE Adda-1, part of zones BC12, all BC13 & 14, and probably part of BC 15 are missing. In Adda-2, part of zone BC12, part of BC13, and all BC14 & BC15 are missing (Sheldon, *pers. comm.,* 2020). This seems to confirm our observations for the *F. praemoesiana* biozone FCN 4 in North Jens-1.

3.2.5.2 Lower Barremian (2311 – 2297 m (7582' - 7536.75'))

Species richness decreases at the top of the Upper Hauterivian (~2316 m (7600')). As a result, the Lower Barremian interval is characterised by consistently low abundance and low diversity foraminifera and ostracod assemblages. The first appearance of planktic foraminifera in this core (*Hedbergella infracretacea*) is at 2303 m (7556') (Lower Barremian) in the 63 µm fraction. The same species first appears in the 125 µm fraction a little higher in the borehole at 2296 m (7533') in a one metre-thick, burrowed, massive argillaceous limestone. The most abundant species in this interval are *Lenticulina muensteri*, *F. xenogena, G. charoides* and *G. gordialis.* Species richness remains relatively low until the mid-Barremian when both abundance and species richness increase sharply, although not reaching the same level as the previous intervals.

3.2.5.3 Upper Barremian and transition to Aptian (2297 – 2240 m (7536.75' - 7350'))

High variability in abundance and species richness of benthic foraminifera characterise the Upper Barremian. Benthic foraminifera dominate the microfossil assemblage, except for the Barremian to Aptian transition, where planktic foraminifera become markedly abundant. Upper Barremian assemblages remain relatively low abundance with variable species richness. Benthic foraminifera display a bi-modal pattern in the Upper Barremian, reaching outstanding species richness and abundance values in calcareous claystone lithologies (Figure 22, samples 2273 m (7457'), 2286 m (7501')), whereas species richness and abundance minima are recorded in the massive, impure chalk units (Figure

22, 2281 m (7485')). Zonal index species for this interval are the benthics *F. xenogena* and *Gavelinella barremiana,* both of which are considered among the most valuable markers for the northern and deep-water settings of the Barremian of the North Sea (King et al., 1989).

Recovery is limited across the Barremian – Aptian transition in the North Jens-1 core. However, the few samples available (2253, 2257 m (7393', 7404')) reveal an interval almost devoid of foraminifera. This may be associated with poor environmental conditions that culminated in the deposition of the organic-rich Fischschiefer Member (Figure 22) a few feet above. This marker bed is barren at the base but displays a high abundance of dwarf planktic foraminifera at the top (2251 m (7386' 7")) in the smallest fraction (63-125 µm). An impoverished benthic fauna at 2253 m (7393'), highlighted by the lack of ostracods, may suggest decreasing oxygen levels at the seafloor during sedimentation preceding the onset of the basin-wide low oxygen levels that resulted in the deposition of the Fischschiefer Member.

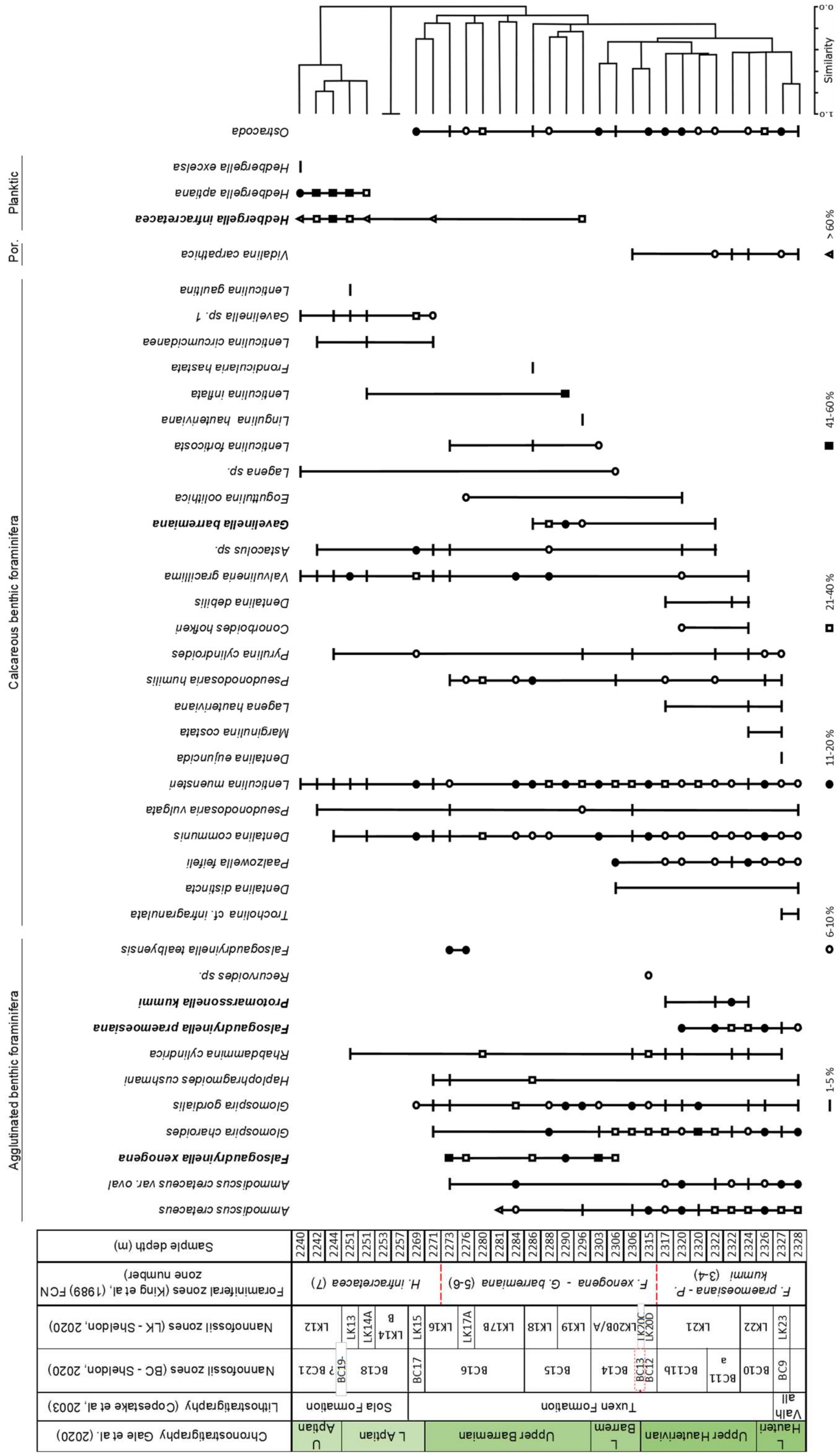


Figure 23. Foraminiferal distribution chart for the Hauterivian to Aptian interval of the North Jens-1 well. The taxa in bold are zonal index species for the deep-water Lower Cretaceous succession

in the Central and southern North Sea (King et al., 1989). The dashed red lines represent likely stratigraphic condensed sections/hiatuses. The chronostratigraphy is based on Gale et al. (2020) and unpublished GEUS data. The lithostratigraphy is taken from Copestake et al. (2003). Right: stratigraphically constrained, hierarchical cluster analysis of the foraminifera assemblages from North Jens-1, using PAST (Hammer et al., 2001). Settings: 'Paired group (UPGMA)' algorithm, 'Bray-Curtis' similarity index.

Earliest Aptian and latest Barremian samples (e.g., 2257 m (7404')) are barren, but the overlying samples reveal a rapid increase in foraminiferal abundance and modest diversity increase, particularly in planktic foraminifera (Figure 22, sample 2251 m (7386')). The most abundant benthic foraminifera are *Valvulineria gracillima, L. muensteri* and *Gavelinella* sp.1. The planktic foraminifera *H. infracretacea* is the most abundant species, with hundreds of specimens per gram of sediment.

3.2.6 Foraminiferal Biozonation

The deep-water FCN biozones of King et al. (1989) are followed in this study. Note that many, but not all, of the key Valanginian, Hauterivian, Barremian and Aptian, deep-water foraminifera species of that scheme are recorded in the North Jens-1 well (Figure 23). King et al. (1989) noted that the lowest Cretaceous (Ryazanian) deep-water, outer sublittoral and bathyal facies of the North Sea is characterised by a low-diversity, agglutinant-foraminiferal species dominated assemblage that has *Haplophragmoides* spp. as the biostratigraphic zonal index taxonomic group for the FCN 1 Zone. In the present study, the oldest samples studied are presumed to be of Early Hauterivian age (Zone FCN 3), with *Haplophragmoides cushmani* constituting less than 5% of the total assemblage in the lowest part of the core. This microfossil evidence rules out the presence of Zone FCN 1. *Marssonella kummi* gives name to the Upper Valanginian to Lower Hauterivian biozone (FCN 3) of King et al*.* (1989). However, *M. kummi*, reassigned by Desai and Banner (1987) to *Protomarssonella*, is recorded in North Jens-1 between 2324 m (7625') and 2317 m (7601'), indicating an Early Hauterivian (possibly Late Valanginian) age for the base of the core, equivalent to Zone FCN 3. The recovery of very few *Trocholina* cf. *infragranulata* could also suggest that the bottom of the Tuxen Fm is, potentially, of Valanginian age, according to King et al. (1989). They indicated that *T. infragranulata* marks, without a doubt, the Lower Valanginian and possibly, the Upper Valanginian. However, the specimens of *T.* cf. *infragranulata* found in the core at 2327 m (7635') and 2328 m (7639') do not have the preservation quality necessary to identify them as *T. infragranulata*, hence the 'cf.'. Therefore, the bottom of the North Jens-1 section is, according to the authors, Lower Hauterivian. However, it could be dated as Late Valanginian if superior processing techniques than those used in this project, were applied to North Jens-1. As to the occurrences of *T.* cf. *infragranulata* and associated *Paalzowella feifeli*, it is known that their presence is likely to be facies-controlled, representing a shelfal association (Bailey, *pers. comm.,* 2019).

The agglutinating species *Falsogaudryinella moesiana* gives its name to the Upper Hauterivian biozone (Zone FCN 4) in the King et al. (1989) scheme. Kaminski et al*.* (1995) suggested that all Upper Hauterivian to Barremian specimens from the North Sea basin previously regarded as *F. moesiana* should be assigned to *F. praemoesiana* (Kaminski et al., 1995), with which we concur. This zonal index species is present in low to moderate abundance from 2324 m (7625') to 2276 m (7466') in North Jens-1. The informal name "*Falsogaudryinella* sp. X" was used by King et al. (1989) to define the Lower Barremian Biozone FCN 5. However, Kaminski et al. (1995) later assigned that taxon to a new species, *F. xenogena*, present in North Jens-1 between 2306 m (7564') and 2273 m (7457'). The presence of *G. barremiana* (2296 to 2286 m (7533' to 7501')) confirms an interval equivalent to the mid-Upper Barremian biozone (Zone FCN 6) of King et al. (1989).

Occurrences of *H. infracretacea* at 2271 m (7452') mark the onset of an Upper Barremian - Lower Aptian biozone (Zone FCN 7). The presence of *H. aptiana* and *H. excelsa* also support an Aptian age (Young et al., 2017). The Upper Aptian – Lower Albian (Zone FCN 8) marker species *Verneuilinoides chapmani* was not recorded in the present study, nor was *Globigerinelloides gyroidinaeformis*, an informal marker for the Lower Albian (Zone FCN 9) (Moullade, 1966; King et al., 1989). According to Ineson (1993) and Copestake et al. (2003), parts of the Upper Aptian are absent in the North Jens-1 well. The nannofossil biostratigraphy suggests that only the Lower part of the Upper Aptian is present (Sheldon, *pers. comm.,* 2020).

3.2.7 Foraminiferal biozonation of the North Jens-1 Well

The microfossil biostratigraphic data outlined above permits the recognition of three workable foraminiferal biozones in the North Jens-1 well. Two of these biozones align with four of King et al.'s (1989) original FCN zones, while the third corresponds to a single FCN zone (Figure 23). The biostratigraphic interpretations are based on first downhole occurrences to make the data comparable with the King et al. model, despite the samples coming from the core material. In addition to microfossil ranges, the proposed biozonation scheme considers the results of the hierarchical clustering of the abundance data shown in Figure 23, incorporating quantitative analysis of assemblage composition through the section as well as biostratigraphic range. The three biozones recognised in the present study are outlined below.

3.2.7.1 P. kummi – F. praemoesiana Biozone (equivalent to FCN Zones 3 & 4)

King et al.'s (1989) Zones FCN 3 and 4 defined the deep-water Hauterivian of the North Sea. The biostratigraphic data from North Jens-1 (Figure 23) does not allow the separation of the two individual biozones recognised by King et al. (1989). However, the two fossil marker species (*P. kummi* and *F. praemoesiana*) are present in the borehole. Therefore, they are incorporated into a single biozone ranging from 2328 to 2317 m (7639' to 7601'). This largely coincides with the entire stratigraphic range for *P. kummi* and *F. praemoesiana* in North Jens-1. The biostratigraphic range of both species co-occurs, which should not be the case, according to the literature. It is worth remembering that the King et al. (1989) scheme is, of necessity, a generalised basin-wide scheme and some local ranges will extend above or below their summarised biostratigraphic ranges.

Furthermore, the likely presence of a condensed sequence or stratigraphic hiatus at the top of the *F. praemoesiana* biozone is discussed below.

3.2.7.2 F. xenogena – G. barremiana Biozone (equivalent to FCN Zones 5 & 6)

This biozone extends from the sample at 2315 m (7594') to the sample at 2273 m (7457'). A short acme zone of *G. barremiana* between 2286 and 2296 (7501' and 7533') indicates the presence of a mid- and Upper Barremian succession (King et al., 1989). The upper boundary of the biozones is defined by the first occurrence of *F. xenogena* at 2273 m (7457'). The benthic agglutinated taxon, *F. xenogena,* displays a long stratigraphic range characterised by changing relative abundances, which precludes a clear biozone boundary definition of Zones FCN 5 and 6. The bottom part of this combined biozone, which represents the Early Barremian, is the youngest stratigraphic level devoid of planktic foraminifera in the sediment fraction larger than 125 µm in North Jens-1.

3.2.7.3 H. infracretacea Biozone (equivalent to FCN Zone 7)

An Aptian biozone is recognised from 7452' to the top of the studied interval at 2240 m (7350'); the high abundances of planktic foraminifera characterise it. The acme zone for *H. infracretacea* and *H. aptiana* (2251 to 2240 m (7386' to 7350')) represents Lower and Upper Aptian intervals in the North Jens-1 well. The first downhole occurrence of these species of *Hedbergella* must occur in stratigraphic levels above the sampled section.

3.2.8 Palaeoenvironments

Boreal species of nannoconid nannofossils (e.g., *Nannoconus abundans* and *Nannoconus borealis*) occur from Zone BC13-16. They indicate that the North Sea Basin was a restricted basin. This particular group of calcareous nannofossils represent clear, surface waters, devoid of significant proportions of clay grade siliciclastic material in suspension (Müller, 1976; Mütterlose and Bottini, 2013). They constitute <13% of assemblages from the Upper Hauterivian, peaking in Zone BC16. These surface waters are interpreted to have been relatively warm during the deposition of the Munk Marl (Zone BC14), through Zone BC15 and over the Upper Barremian and Lower Aptian transition due to increases in warm water taxa such as *Rhagodiscus asper* (Mütterlose and Böckel, 1998). Periodic increases of freshwater input during deposition of the Tuxen Fm (Zones BC10-11, BC14, early BC16) are suggested by increased abundance of taxa assigned to *Micrantholithus* and *Braarudosphaera;* together, these taxa indicate more marginal conditions (Thierstein, 1976). Increased nutrient influx is suggested during nannofossil Zones BC11 & 12 and also before and after deposition of the Munk Marl due to increasing abundance of species assigned to *Zeugrhabdotus*, *Discorhabdus* and *Biscutum* (Bischoff and Mütterlose, 1998; Erba, 1992; Roth and Bowdler, 1981; Roth and Krumbach, 1986; Watkins, 1989).

The benthic foraminifera and ostracod assemblages in the North Jens-1 well display low abundance and moderate species richness, reflecting a relatively deep-water depositional environment and restricted bottom water circulation at times, as supported by ichnogenus such as *Chondrites, Teichichnus*, *Planolites* and *Zoophycos* throughout the sampled interval of North Jens-1, suggesting a sublittoral to bathyal palaeo-water depth setting (MacEachern et al., 2010).

. Benthic foraminifera dominate the North Jens-1 microfossil assemblages until the Aptian, which sees an influx of planktic foraminifera. The microfossil assemblage at the bottom half of the section, including part of the Hauterivian and Barremian, is characterised by agglutinated and calcareous benthic foraminifera along with ostracods, indicating intermittent pulses of well-oxygenated conditions. Despite this being a relatively deep-water environment, this interval may well represent the shallowest part of the sequence examined in this study.

The planktic to benthic (P:B) ratio shows a marked increase within the Aptian with the establishment of the influx of hedbergellid taxa. While caution should be exercised around the use of modern analogues of planktic to benthic ratio as a palaeo-water-depth proxy (Jorissen, 1988; van der Zwaan et al., 1990), the influx of planktic foraminifera is taken as an indicator of increasing water depth in this study. The sharp increase in abundance of taxa such as *H. infracretacea*, *H. aptiana* and *H. excelsa* in the Aptian reflects the gradual increase in water depth throughout the Lower Cretaceous (Figure 23).

The planktic genus *Hedbergella* is suggested to indicate intermediate water-depths (Caron and Homewood, 1983; Hart, 1980, 1999; Hart and Bailey, 1979), even reaching shallow water-depths, less than 100 m (Leckie, 1987). However, some have advised caution with palaeo-depth assumptions for fossil planktic foraminifera (Premoli Silva and Sliter, 1999; Ando et al., 2010; Birch et al., 2013), water depths would increase further to a maximum in the Late Cretaceous.

The presence of ostracods in most samples suggests that oxygen levels at the seafloor were never significantly dysoxic; ostracods require higher dissolved oxygen concentrations than foraminifera for healthy physiological development (Armstrong and Brasier, 2005). The Munk Marl Member and Fischschiefer Member are barren of microfossils on the sediment fractions larger than 125µm. Although, the latter shows abundant dwarf planktic foraminifera from the *Hedbergella* genus in the sediment fraction between 63µm and 125µm. These two Members are interpreted as basin-wide anoxic events; the Fischschiefer Member being the local expression of the global Oceanic Anoxic Event 1a of the Early Aptian (Mütterlose and Bottini, 2013; Jensen et al., 1986). The Fischschiefer Member is located at the top of a high stand system tract and is interpreted as representing a maximum flooding surface (Ineson et al., 1997). However, the Munk Marl Bed is likely to be the product of a low stand system tract. High levels of terrigenous material and low levels of deep-marine water indicators are found in the sedimentary record (Posamentier and James, 1993; Ineson et al., 1997). However, alternate views suggest a different interpretation, on which the Munk Marl Bed, equivalent to the Hauptblätterton, was deposited under a transgressive pulse (Ainsworth et al., 2000).

Figure 24 shows a schematic cross-section (modified from Copestake et al*.,* 2003) which summarises the distribution of palaeoenvironments along the western margin of the North Sea Basin during the Late Valanginian to Late Barremian interval. According to Copestake et al*.* (2003). Such environmental conditions remained relatively unchanged during the Aptian and Early Albian. The North Jens-1 well, seen on the right-hand side of Figure 24, represented a relatively deep-water location in the basin depocentre and along the lower part of the basin slope. In contrast, the North Fordon G1 and Speeton Clay sections, located at the west side of Figure 24 (left-hand side), represent a shelfal environment, with shallower water depth compared to the basin depocentre, as suggested by the lithology and fossil content. The complex interaction of tectonics and sea-level variation brought about facies changes throughout the Lower Cretaceous of the North Sea. The interpreted depositional environment of the Tuxen and Sola formations is represented towards the right of Figure 24, near the graben depocentre, where fine-grained clastic deposits accumulated (Copestake et al., 2003).

It is worth considering that exploration wells, such as North Jens-1, typically target positive structures that might favour the entrapment of hydrocarbons. So, the relatively lowest-lying areas of the basin may not be represented in the available cores. As a result, the deepest-water microfossil assemblages in the basin may not be necessarily present in the North Jens-1 study.

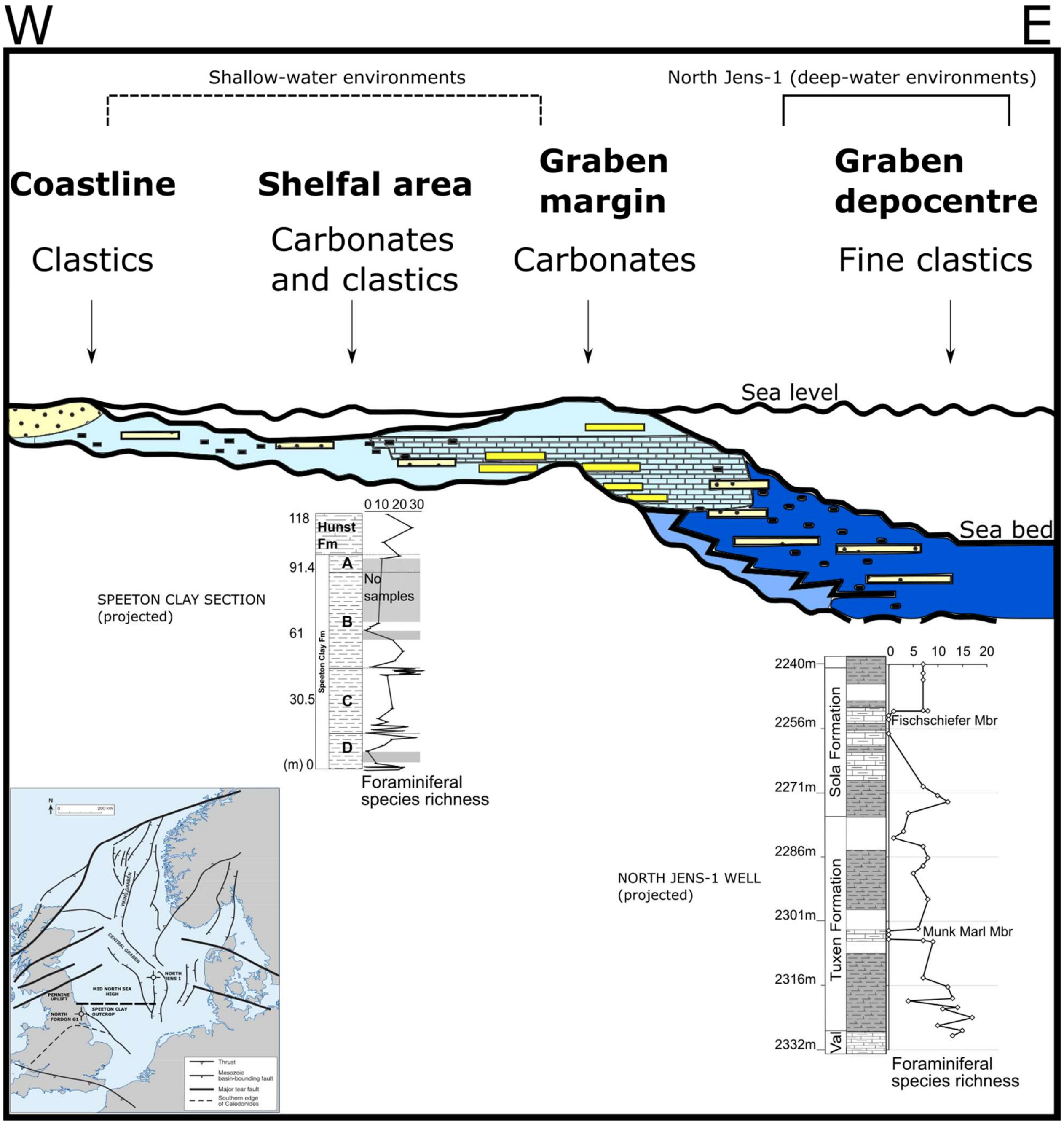


Figure 24. Schematic palaeoenvironmental cross-section across the western margin of the North Sea Basin. Modified from Copestake et al. (2003).

3.2.9 Systematic Palaeontology

This section organises species in taxonomic order according to various benthic and planktic foraminifera classifications. The supra-generic classification of agglutinated foraminifera follows Kaminski (2004, 2014). For calcareous walled foraminifera, the classification follows Mikhalevich (2013).

Class **Foraminifera** d'Orbigny, 1826

Subclass **Tubothalamana** Pawlowski, Holzmann and Tyszka, 2013

Order **Ammodiscida** Mikhalevich, 1980

Suborder **Ammodiscina** Mikhalevich, 1980

Superfamily **Ammodiscoidea** Reuss, 1862

Family **Ammodiscidae** Reuss, 1862

Subfamily **Ammodiscinae** Reuss, 1862

Genus *Ammodiscus* Reuss, 1862

Ammodiscus cretaceus (Reuss), 1845

1845 *Operculina cretacea* (Reuss) p. 35, pl. 13, figs. 64-65

1934 *Ammodiscus cretacea* (Reuss); Cushman p. 45-47

1989 *Ammodiscus cretaceus* (Reuss); King p. 452, pl. 9.1, fig. 3

2005 *Ammodiscus cretaceus* (Reuss); Kaminski & Gradstein p. 145, fig. 14

Description. Test planispiral, close coiled, circular or oval, coil increasing in size (thickness) gradually, coils coil around proloculus, followed by undivided planispirally enrolled tubular chamber, which may show transverse growth constrictions but no internal partitions; wall agglutinated; aperture at the open end of the tubular chamber (Cushman, 1934; Loeblich and Tappan, 1964; Reuss, 1845).

Remarks. The species *A. cretaceus* is used despite reports that constrain its stratigraphic range to Late Cretaceous and Cenozoic (Kaminski and Gradstein, 2005; King et al., 1989). *Ammodiscus* sp. 1 (oval) is used for a planispiral form that fulfils the taxonomic criteria reported in Kaminski and Gradstein (2005). Still, its shape is consistently oval, and the outer whorl is reinforced, like a thickened external rim. However, the change from elliptical to round profile is common in *A. cretaceus*. There are size variations between the specimens, ranging from 10's µm to 500 µm.

Chronostratigraphy. Cretaceous to Late Eocene (Kaminski and Gradstein, 2005).

Subfamily **Usbekistaniinae** Vialov, 1968

Genus *Glomospira* Rzehak, 1885.

Glomospira charoides (Jones and Parker), 1860

1860 *Trochammina squammata* Jones & Parker, var. *charoides* Jones & Parker p. 304

1982 *Glomospira charoides* (Jones and Parker); Burnhill p. 68, pl. 2, fig. 2, 4

1989 *Glomospira charoides* (Jones and Parker); King p. 455, pl. 9.1, fig. 17

2005 *Glomospira charoides* (Jones and Parker); Kaminski & Gradstein p. 22, fig. 22

2013 *Glomospira charoides* (Jones and Parker); Holbourn *et al.* p. 268-269

Description. Rounded, spherical test, test coils streptospirally or trochospirally along a vertical axis around the proloculus. The outer layer shows several whorls. Coiling varies in specimens from loose to tight. Commonly, earlier chambers are not visible. Chamber walls are finely agglutinated, sugary texture. Aperture is at the end of the tube (Burnhill, 1982; Jones and Parker, 1860; Loeblich and Tappan, 1964; Holbourn et al., 2013; King et al., 1989).

Remarks. Shapes vary widely, as the last chamber coils parallel or perpendicular to the primary vertical axis around the proloculus. Shape variation made some specimens mistaken by *G. gaultina,* but they fulfil more description criteria for *G. gordialis* and *G. charoides*. Although, the specimens were not sliced up in the axial section to reveal the first two chambers and allow differentiation between *Glomospira* and *Glomospirella*. Some specimens identified initially as *Glomospirella diffundens* were later reclassified into *Glomospira charoides* as they fulfil the most important taxonomic criteria. Several specimens classified as *Glomospirella irregularis* were later reclassified into *Glomospira gordialis.*

Chronostratigraphy. Mesozoic to Recent as Age range. *G. charoides* is reported as the most common species in the Cretaceous (Holbourn et al., 2013).

Subclass **Globothalamana** Pawlowski, Holzmann and Tyszka, 2013

Order **Lituolida** Lankester, 1885

Suborder **Lituolina** Lankester, 1885

Superfamily **Lituoloidea** de Blainville, 1827

Family **Haplophragmoididae** Maync, 1952

Genus *Haplophragmoides* Cushman, 1910

? *Haplophragmoides* cf. *cushmani* Loeblich and Tappan, 1946

1946 *Haplophragmoides* cf. *cushmani* Loeblich and Tappan p. 244, pl. 35, figs. 4a-b

1989 *Haplophragmoides* cf. *cushmani* Loeblich and Tappan; Morris and Coleman p. 208, pl. 6.3.1, fig. 1

Description. Test involute, planispiral coiling, coarse agglutinated wall, compressed, almost squashed. Aperture is meant to be in an equatorial interiomarginal slit, not visible in these specimens. (Loeblich and Tappan, 1946, 1964; Morris and Coleman, 1989).

Remarks. The specimens look badly squashed under the microscope. Still, it is possible to see simple and straight sutures as a single *Haplophragmoides* specimen. Unlike other species present in the sample set, the ? *Haplophragmoides.* cf. *cushmani* specimens found are not well preserved and not excellent for further analysis.

Chronostratigraphy. Ryazanian for *Haplophragmoides.* spp. in deep-water outer sublittoral and bathyal facies prevalent in the central and northern North Sea (King et al., 1989).

Superfamily **Recurvoidodea** Alekseychik-Mitskevich, 1973

Family **Ammosphaeroidinidae** Cushman, 1927

Subfamily **Recurvoidinae** Alekseychik-Mitskevich, 1973

Genus *Recurvoides* Earland, 1934.

? *Recurvoides* sp.

Description. Test free, subglobular coiling streptospiral, with few chambers in each whorl, later whorls in differing planes so that exterior somewhat resembles *Trochammina*, although only earlier periphery and not all earlier whorls are visible from the spiral side; wall agglutinated, thin; aperture small, areal, with distinct bordering lip (Loeblich and Tappan, 1964).

Remarks. Specimens with five or six round chambers; sutures obscured; wall irregular, finely agglutinated. Not the best examples. Not good preservation. Aperture is not clear, and some of the last chambers could have been knocked off the specimens either before lithification or during sample processing in the lab.

Chronostratigraphy. Middle Albian for *R.* sp. in deep-water outer sublittoral and bathyal facies prevalent in the central and northern North Sea (King et al., 1989).

Suborder **Verneuilinina** Mikhalevich and Kaminski, 2004

Superfamily **Verneuilinoidea** Cushman, 1911

Family **Reophacellidae** Mikhalevich and Kaminski, 2004

Genus *Falsogaudryinella* Bartenstein, 1977

Falsogaudryinella xenogena Kaminski, Neagu and Platon, 1995

1989 *Falsogaudryinella* sp. *X* King p. 410, pl. 8.1, fig. 11

1995 *Falsogaudryinella xenogena* Kaminski, Neagu and Platon p. 148, pl. 4, figs. 2-3, pl. 5, figs. 10, 13

Description. Test relatively short in comparison with other species of *Falsogaudryinella*. Trochospiral coiling, initially with three small chambers, although early sutures may not be visible due to preservation issues. Size (width) rapidly increases up to the last chambers; the last chambers themselves are small. Aperture is not always apparent. Wall finely agglutinated. Polygonal shape, like an inverted pyramid, with angular vertices. (King et al., 1989; Kaminski et al., 1995)

Remarks. *F. xenogena*'s wall seems affected by micro-crystallization in diagenetic stages. It looks crystalline at low magnification, but at high power, it is possible to see the agglutinated character of the wall. The shapes change drastically from early to later chambers. Specimens with a triangular shape, very angular. Some specimens are squashed, and other small ones might be juvenile specimens, which makes difficult taxonomical classification.

Chronostratigraphy. Late Hauterivian to Barremian for *F. praemoesiana*; Early and Middle Barremian for *F. xenogena*; Albian for *F. moesiana*; Late Albian for *F.* sp. 1 in deep-water outer sublittoral and bathyal facies prevalent in the central and northern North Sea (King et al., 1989).

Falsogaudryinella praemoesiana Kaminski, Neagu and Platon, 1995

1975 *Uvigerinammina hannoveriana tealbyensis*. (Bartenstein) p. 36, pl. 18 figs. 24-31

1995 *Falsogaudryinella praemoesiana* Kaminski, Neagu and Platon p. 148, pl. 1, figs. 12-17, 24-49 pl. 5, fig. 8

Description. Test relatively large; elongated, a high trochospire with three to four and a half chambers in the early stage, later becoming gradually biserial, and finally nearly uniserial. Cross-section rounded-trigonal; chambers globular, moderately inflated, increasing rapidly in size such that the final chamber occupies about half of the whole test. Sutures depressed, slightly curved, well visible at least in the later stage. Wall finely agglutinated consisting of calcareous cement. Aperture an elongated elliptical orifice or a slit bordered by a rim (King et al., 1989; Kaminski et al., 1995).

Remarks. *F. praemoesiana* differs from *F. moesiana* in its large size, and more globular chambers. The species rapidly becomes biserial. Some specimens display a very distinctive pseudo-uniserial arrangement of the final stage. *F. moesiana* is present in the Albian and Aptian of the shelf biofacies predominant in the southern North Sea (King et al., 1989; Kaminski et al., 1995).

Chronostratigraphy. Late Hauterivian (common) to Early Barremian (rare) in the central and northern North Sea deep-water outer sublittoral and bathyal facies (King et al., 1989).

Phylum **Foraminifera** d'Orbigny, 1826 nomen translat. Mikhalevich, 1980

Class **Nodosariata** Mikhalevich, 1992

Subclass **Nodosariana** Mikhalevich, 1992

Order **Nodosariida** Calkins, 1926

Suborder **Nodosariina** Calkins, 1926

Superfamily **Nodosarioidea** Ehrenberg, 1838

Family **Nodosariidae** Ehrenberg, 1838

Genus *Dentalina* Risso, 1826

Dentalina communis (D'Orbigny)

1826 *Nodosaria (Dentaline) communis* D'Orbigny p. 254

1966 *Dentalina communis* (D'Orbigny); Fletcher p. 210-211, pl. 16, figs. 16-21

1980 *Dentalina communis (*D'Orbigny); Sliter pl. 6, figs. 19, 20

Description. Test elongate, variable size, can reach several hundreds of micrometres in length. Uniserial, arcuate shape, although some forms are relatively straight. Sutures are not visible in the first chambers; in later chambers, a depression in the shell surface marks the sutures. Wall surfaces are smooth. Some of the specimens' sutures are not clear at all. Having only flat surfaces (D'Orbigny, 1826; Fletcher, 1966; Loeblich and Tappan, 1964; Sliter, 1980).

Remarks. Wide variation in the number of chambers, the orientation of sutures, aperture shape. Broken and juvenile specimens made taxonomical classification difficult. Most common species is *D. communis*, but *D. debilis* and *D. eujuncida* are also present.

Chronostratigraphy. Permian to Recent (Loeblich and Tappan, 1964).

Order **Vaginulinida** Mikhalevich, 1993

Family **Vaginulinidae** Reuss, 1860

Genus *Lenticulina* Lamarck, 1804

Lenticulina muensteri (Roemer), 1839

1839 *Robulina münsteri* Roemer p.48, pl. 20, fig. 29 (*fide* Jendryka-Fuglewicz 1975)

1932 *Lenticulina münsteri* (Römer); Paalzow p. 101, pl. 5, figs. 23, 24, pl. 6, figs. 1,2 (*fide* Jendryka-Fuglewicz 1975)

1975 *Lenticulina muensteri* (Roemer); Jendryka-Fuglewicz p. 149, pl. 8, figs. 1-15, pl. 9, figs. 1-10, pl. 10, figs. 1-10, pl. 11, figs. 1-6

1989 *Lenticulina muensteri* (Roemer); Hart *et al.* p. 350, pl. 7.18, fig. 2

1989 *Lenticulina muensteri* (Roemer); Shipp p. 258, pl. 6.4.2, figs. 9, 10

Description. Test biconvex, planispiral, involuted although it can be evolute in specimens. Periphery angular, sub-angular or with keel (carinate). Chambers grow out from the proloculus area and increase in size. In transparent examples, the earlier chambers can be seen underneath younger chambers. Sutures project from the proloculus space, with sharp curved lines (although they can vary) that fold slightly backwards. Wall surface is smooth unless, for sutures, that can be raised, or not, leaving some specimens almost entirely flat. Size can change widely, and some examples reach hundreds of micrometres in length. The last chamber can be larger and have a distinctive shape. (Jendryka-Fuglewicz, 1975; Loeblich and Tappan, 1964; Roemer, 1841; Shipp, 1989; Hart et al., 1989).

Remarks. This is a very diverse species, which brings many features together. Some specimens display a smooth wall surface, but others have sutures with ribs of different heights; shapes also vary. Some are more elongate, whereas others are more inflated and globular; many juveniles and specimens at various stages of development make this species one of the most diverse.

Chronostratigraphy. Triassic to Recent (Loeblich and Tappan, 1964).

Order **Rosalinida** Delage and Hérouard, 1896

Superfamily **Gavelinelloidea** Hofker, 1956, stat. elevated Mikhalevich, 2013

Family **Gavelinellinae** Hofker, 1956

Genus *Gavelinella* Brotzen, 1942

Gavelinella barremiana Bettenstaedt, 1952

1952 *Gavelinella barremiana* Bettenstaedt (*fide* Bartenstein and Bettenstaedt, 1962)

1962 *Gavelinella barremiana* Bettenstaedt; Bartenstein and Bettenstaedt p. 282, pl. 37, fig. 7, 8

1989 *Gavelinella barremiana* Bettenstaedt; Hart *et al.* p. 334, pl. 7.10, figs. 1, 2

Description. Test trochospiral, biconvex, sides flattened. Specimens may have one convex and one concave side. Periphery rounded, slightly serrated by chamber sutures. Two or three whorls in adult specimens. Semi-evolute. All coils are visible in clear transparent specimens on the spiral side. Only last-whorl chambers are visible in the umbilical side. Chambers increasing in size from earlier to younger ones. The last chamber is more extensive than any previous chamber, with a distinctive half-moon shape. Earlier chambers look like a smaller, slimmer version of this motif. Sutures radiate from the umbilical area, bent backwards. A depression in between chambers marks them.

Calcareous wall. (Bartenstein and Bettenstaedt, 1962; Loeblich and Tappan, 1964; Hart et al., 1989)

Remarks. Sutures are sigmoidal in the specimens, and there are variations in the curvature; some of them curve almost ‘backwards’; it is common to find that the last chamber is broken, which may be due to rough processing.

Chronostratigraphy. Middle and Late Barremian for *G. barremiana* in deep-water outer sublittoral and bathyal facies prevalent in the central and northern North Sea (King et al., 1989).

Class **Globothalamea** Pawlowski, Holzmann and Tyszka, 2013

Subclass **Globigerinana** Mikhalevich, 1980

Order **Globorotaliida** Mikhalevich, 1980

Superfamily **Rotaliporoidea** Sigal, 1958

Family **Hedbergellidae** Loeblich and Tappan, 1961

Genus *Hedbergella* Brönnimann & Brown, 1958

Hedbergella infracretacea (Glaessner), 1937

1937 *Globigerina infracretacea* Glaessner (*fide* Microtax)

1977 *Hedbergella infracretacea* (Glaessner); Carter and Hart p. 35, pl. 3, figs. 18-20

1982 *Hedbergella delrioensis* Carsey; Burnhill p. 88, pl. 8, figs. 5, 6

1989 *Hedbergella infracretacea* (Glaessner); Hart *et al.* p. 346, pl. 7.16, figs. 1-3

1997 *Blefuscuiana infracretacea* (Glaessner); BouDagher-Fadel *et al*. p. 128, pl. 8.3, figs. 1-8

2020 *Hedbergella infracretacea* (Glaessner); Young *et al*. pf Microtax

Description. Test trochospiral, umbilicate, periphery rounded, globular chambers, around 5 or 4 in the last whorl on the umbilical side; sutures radial, straight; wall calcareous, surface smooth; (Burnhill, 1982; Glaessner, 1937; Loeblich and Tappan, 1964; BouDagher-Fadel et al., 1997; Hart et al., 1989; Young et al., 2017).

Remarks. Specimens show significant variation; some do not have clear and deep sutures. Coiling also changes from dextral to sinistral in specimens. The height of the trochospiral axis varies widely. The description for *Blefuscuiana infracretacea aptica* in literature is very similar to the one for *Hedbergella infracretacea*. However, as porticus and cones are not found in the specimens, they are kept in the genus *Hedbergella*. *H. delrioensis* was used in the literature for specimens that are described and look very much like *H. infracretacea*. Since the size of the specimens is small, it is better to use *H. infracretacea* (BouDagher-Fadel, 2012; Burnhill, 1982; Carter and Hart, 1977; Banner et al., 1993). Remarkably, both dextral and sinistral coiling is present in the samples.

Chronostratigraphy. Early Aptian for *H. infracretacea* in deep-water outer sublittoral and bathyal facies prevalent in the central and northern North Sea (King et al., 1989).

Class **Tubothalamana** Pawlowski, Holzmann and Tyszka, 2013

Subclass **Miliolana** Saidova, 1981

Order **Soritida** Schultze, 1854

Superfamily **Peneroplidea** Schultze, 1854

Family **Fischerinidae** Millandt, 1899

Genus *Vidalina* Schlumberger, 1900

Vidalina carpathica Neagu and Popescu, 1966

1966 *Vidalina carpathica* Neagu and Popescu p. 41, pl. 1, figs. 1-12

1979 *Vidalina carpathica* Neagu and Popescu; Gaździcki, Kozur and Mock p. 96, pl. 4, figs. 3-5

Description. Test large, up to 1,5 millimetres in diameter with proloculus followed by planispirally enrolled, involute, nonseptate, tubular second chamber, involute whorls resulting in umbonal thickening; wall calcareous, imperforate; aperture at the open end of the tube (Loeblich and Tappan, 1964).

Remarks. The state of preservation is not the best. The coiling and some of the chambers are still recognisable.

Chronostratigraphy. Upper Cretaceous (Loeblich and Tappan, 1964).

3.2.10 Conclusions

The North Sea Central Graben experienced low-energy, deep-water conditions during the Early Cretaceous; sediments of this age are represented by fine-grained lithologies and benthic microfossil assemblages of moderate diversity and low abundance. Microfossil assemblages reflect ongoing sea-level rise as witnessed by the increasing abundance of planktic foraminifera and consequently the decreasing relative proportion of benthic foraminifera from the Barremian into the Early Aptian.

Nannofossil assemblages support local marine conditions for much of the Barremian section. In contrast, the Upper Barremian and Lower Aptian display nannofossil taxa that may suggest warm water influx into the North Sea Basin.

Three foraminiferal biozones and thirty nannofossil biozones provide a robust framework for the Lower Cretaceous of the North Jens-1 well, which can be correlated more widely. However, to obtain a complete picture of the North Sea Basin evolution during this period, it would be necessary to examine the calcareous microfossil and nannofossil assemblages from shallower-water shelf areas of the basin.

Data Availability:

The original foraminiferal count data is available at the University of Birmingham eData site.

4 COMPARISON, CONCLUSIONS, AND OUTLOOK

4.1 Summary

This thesis project provides a suite of micropalaeontological data from four areas in the North Sea dating back to the Lower Cretaceous period. Four boreholes and one outcrop provided the samples, which were processed and analysed under micropalaeontological guidelines to recover fossil foraminifera. The recovered foraminiferal specimens were taxonomically studied, and biostratigraphic schemes were produced to characterise the studied areas. The microfossil populations provided insights into the palaeoenvironmental conditions of deep- and shallow-water areas in the North Sea basin for the Lower Cretaceous.

Chapter 1 is a concise introduction to the thesis. It lays out the objectives for the research around the biostratigraphic characterisation of the study areas under a unifying scheme. It also promises to target the fossil populations' palaeoenvironmental indicators to understand the foraminiferal assemblages at that time. It also provides a brief glimpse of the palaeontological evidence found in the literature that inspired this research: the idea that foraminifera diversified and thrived (with ups and downs) during the Jurassic and Cretaceous times. The Lower Cretaceous looked like a promising window to capture significant foraminiferal trends such as benthic calcareous radiation in shelves, agglutinated recovery, and exploration of deep-water niches and planktic first show appearance. The chapter briefly raised points related to the tectonic landscape and structural dynamism on which the sedimentary particles (including foraminiferal tests) were accumulated. The chapter touches on patterns of evolution observed in Lower Cretaceous foraminifera as they respond to environmental pressures of factors such as oceanic anoxic events. The chapter also briefly looked at the foraminiferal populations described in basins other than the North Sea for Lower Cretaceous times, as valuable comparisons can be drawn between them.

Chapters 2 and 3 delved deep into the data sets. Chapter 2 is devoted to the shallow water palaeoenvironment of the Lower Cretaceous Yorkshire shelf. It provided an abridged geological background of the Cleveland Basin and the geology of the Filey Bay section and raised the biostratigraphic work carried out by previous investigations, besides providing a brief overview of the methodology employed in this study. Next, the chapter presented the results regarding biostratigraphy and correlation between sites, a microfossil assemblage analysis of both sampling sites and multivariate analysis of these results. A series of palaeoenvironmental hypotheses were tested with detrended correspondence analysis, which confirmed the validity of the microfossil assemblage-subdivision based primarily on the predominant wall type. The microfossil data confirmed the dominance of benthic calcareous foraminifera over the microfossil population, as predicted in one of the initial hypotheses in this thesis, which stated that benthic calcareous taxa flourished in Lower Cretaceous marine shelves (in the objectives section, 1.1). Agglutinated foraminifera were relevant at intermittent intervals, perhaps, in accordance with the initial prediction on the objectives of this thesis, stating that agglutinated foraminifera would dominate and diversify in truly deep-water environments (which are not found at the North Sea Basin). Planktic foraminifera dominated the microfossil assemblages towards the mid-Cretaceous as the palaeoenvironment of deposition deepened over time, as predicted in the initial hypothesis on the objectives section (1.1). The results obtained from the micropalaeontological analysis of the study areas in chapter 2 provide a biostratigraphic model that allows correlation of the North Fordon and Filey Bay stratigraphic sections with other regions of the North Sea Basin. This is highly relevant, as the study areas provide almost continuous exposure of the boreal Lower Cretaceous, which is scarce in the North Sea and surrounding areas. Despite its long stratigraphic range, North Fordon G1 is an entirely underexplored borehole with nearly no published data. In addition to the microfossil results, the lithological data analysed for this project confirmed some of the palaeoenvironmental hypotheses for the Lower Cretaceous of the North Sea Basin, such as the increasing water-depth and the change from restricted to more open basinal settings.

Chapter 3 addresses the deeper water palaeoenvironment found in the graben sectors of the North Sea Basin. The first area of study of the chapter is the Britannia Field located in the triple junction of the Witch Ground Graben, the Central Graben, and the Viking Graben. The analysis introduces the regional geology before investigating the geologic and biostratigraphic background of the Britannia Field, followed by displaying methods, data, and results obtained from two boreholes, 16/26-B3 and 15/30-7 ST2. The section concludes with a palaeoenvironmental interpretation of the foraminiferal assemblages and their implications for the basin. The results obtained in this section confirm the trend forecasted in the objectives section (1.1) regarding planktic foraminifera, as they dominate the microfossil assemblages of the two Britannia boreholes towards the mid-Cretaceous geological stages. The whole foraminiferal assemblage suggested a transition from predominantly terrigenous to calcareous environments, indicating initially restricted conditions and open and connected areas afterwards. Nevertheless, the microfossil assemblages suggest a low-productivity environment, as highlighted by the low to moderate foraminiferal abundance and species richness displayed in general.

The second study area explained in this chapter is in the Valdemar Field in the Danish Central Graben. The regional geology and biostratigraphy of the site are considered before examining the methods used in the data from the North Jens-1 borehole. Nannofossil (input from an external researcher) and foraminiferal biostratigraphy are provided for the microfossil assemblages found in the core samples. A biostratigraphic scheme is put forward based on the results of foraminifera (based on King et al. (1989)) and external results from calcareous nannofossils (based on Bown (1998) and Jeremiah (2001)). The chapter concludes with a compact discussion of the palaeoenvironments inferred from the microfossil assemblages. The microfossil analysis' results confirm the initial premise set out in the objectives of this thesis (section 1.1) regarding planktic foraminifera, as they dominate the assemblages in the Lower and Upper Aptian stages. The hypothesis referring to benthic calcareous foraminifera is also, moderately, upheld as these taxa dominate the assemblage during the Barremian and most of the Upper Hauterivian stage. Agglutinated foraminifera are important during the Lower Hauterivian and Upper Barremian. However, they are not becoming more important as water depth increases towards the mid-Cretaceous. Their hypothesis, that they would thrive in deep-water Lower Cretaceous palaeoenvironments rose as an observation into agglutinated foraminiferal studies referenced in previous chapters, where agglutinated taxa thrived in deep-water such as flysch-type deposits. However, the Graben sectors of the North Sea Basin cannot be considered as true deep-water deposits; therefore, the agglutinated hypothesis from the objectives section (1.1) cannot be fully tested in this basin.

The final chapter summarises, concludes, and compares the results obtained from the different sample sets and possible future research views.

4.2 Result comparisons

The deep- and shallow-water microfossil assemblages display over twenty foraminiferal species in common. The shallow-water environment of the Yorkshire area shows greater species richness (over a hundred species counted crossing at geological stage boundaries, according to Figure 25) than the deep-water areas such as the Danish Central Graben and the triple junction of the Witch Ground, Central and Viking grabens.

STAGE BOUNDARY		GEOLOGICAL TIME (M.A.) after Gale et al. (2020)	BASED ON (after Gale et al. 2020)	# Sp. CROSSING BOUNDARY		
				NJ1	NFG1	FB
Upper Aptian	Lower Aptian	119.2	base of the *Tropaeum bowerbanki* ammonite	11		
Lower Aptian	Upper Barremian	121.4		13	14	
Upper Barremian	Lower Barremian	124.5	upper 1/3 *Paracrioceras elegans* ammonite zone	19	21	20
Lower Barremian	Upper Hauterivian	126.5		20	46	30
Upper Hauterivian	Lower Hauterivian	128.8	LO *Cruciellipsis cuvillieri* nannofossil zone	17	34	
Hauterivian	Upper Valanginian	132.6				21
Upper Valanginian	Undet Early Cret	135.1	middle of *P. hollwedensis* ammonite zone		11	19
Undet Early Cret	Upper Jura-Berrias				5	

Figure 25. Number of species crossing a few Lower Cretaceous stages' boundaries at the North Jens, North Fordon and Filey Bay sites. The absolute ages for the chronostratigraphic model are from Gale et al. (2020).

Despite sharing a small fraction of all the foraminiferal species recorded in the project, the species richness and abundance values display similar trends in all sites: oscillating values from Berriasian to Barremian, primarily due to benthic foraminifera, whereas high abundance and low species richness values for the Aptian and Albian stages are due to the influx of planktic foraminifera.

It is also helpful to look at evolutionary rates for geological stages common to the North Jens, Filey Bay and North Fordon sites. Data for the Britannia site is unsuitable for this type of analysis due to the uncertainties of species records resulting from poor fossil material preservation.

Figure 26 shows a plot for the average values of species richness, diversification rate and turnover rate for several geological stages of the Lower Cretaceous at the study area. It helps understand why abundance and species richness values remain relatively similar for all three sites. The reasons are simple: the appearance and disappearance of taxa on the fossil record on these stratigraphic sections follow a similar pattern exemplified by the diversification and turnover rates for the three sites. It is fair to say that North Jens and the Filey Bay section evolutionary rates behave similarly. North Fordon is also very similar, although it displays more variation, especially regarding species richness for the Upper Hauterivian and Lower Barremian. There, the values encountered are higher than the values for the rest of the assemblages. However, on average, it is a similar pattern for all three evolutionary variables, for all three sites, for most of the geological time under consideration. Diversification rate values highlight that the Valanginian and Hauterivian of the area display diversifying microfossil assemblages.

In contrast, negative values are shown for the Barremian and Aptian, which is evident in the assemblages' analysis in previous chapters, as species richness in benthic foraminifera crashed for most sites to give place to a planktic dominated assemblage with lower species richness.

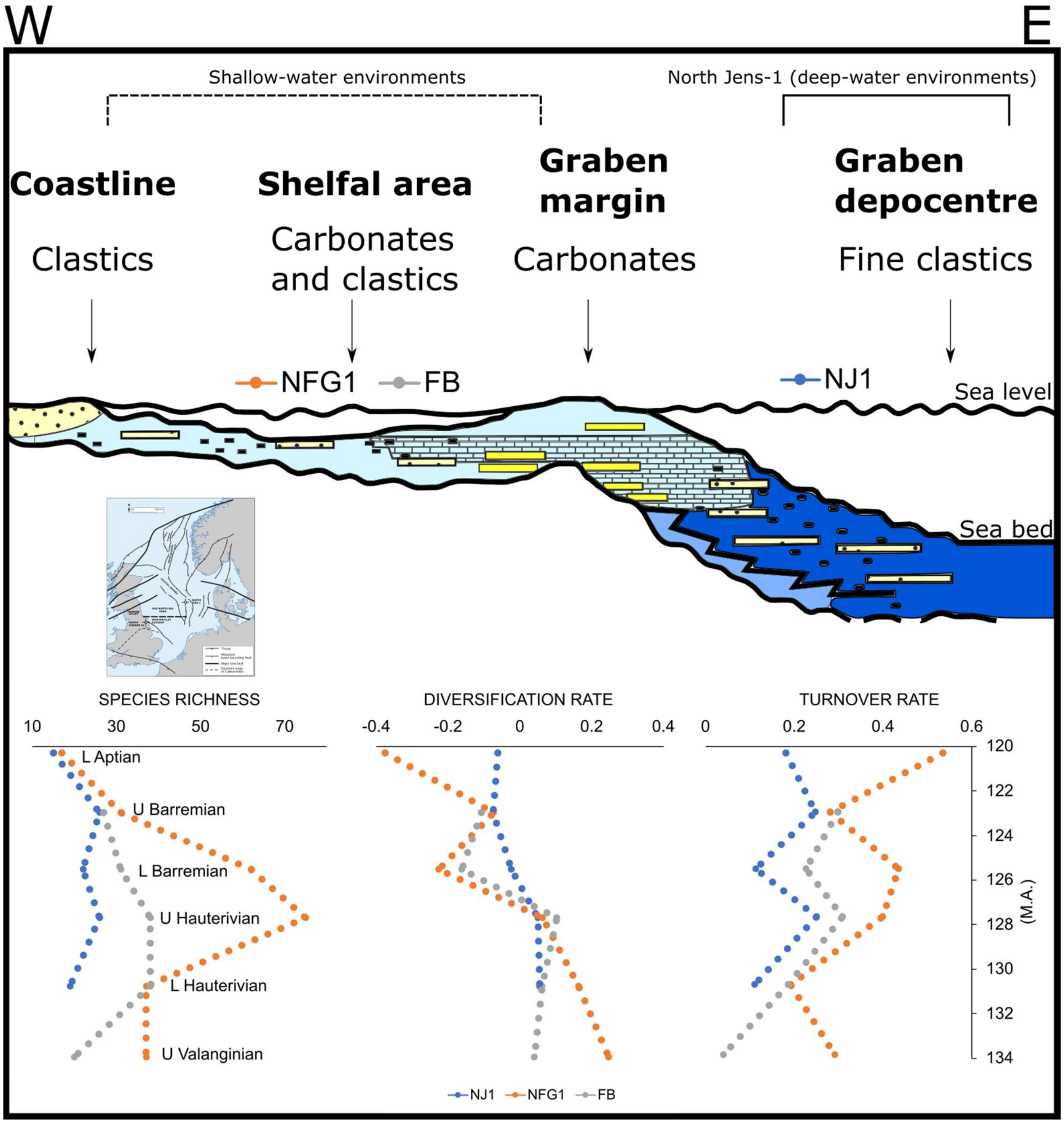


Figure 26. Average species richness, diversification rate, and turnover rate values for the North Jens-1, North Fordon G1 and Filey Bay data for Lower Cretaceous stages. Calculations follow the equations of Wei and Kennett (1986). Cross-section modified from Copestake et al. (2003).

The abundance patterns for benthic foraminifera follow similar trends in deep- and shallow- environments (Valhall, Tuxen and Sola/Carrack formations on one side and Speeton Clay and Hunstanton formations on the other side, accordingly) despite the difference in foraminiferal species populations highlighted in previous paragraphs.

Notice that Figure 26 represents the palaeogeographical configuration of the North Sea Basin starting in its western margin in the British Isles and moving towards the basin depocentre in the Central Graben. The projected location of the North Jens-1, North Fordon G1 and Speeton Clay section (at Filey Bay) is shown in the cross-section. Notice that subtle differences between shallow and deep palaeo water depth assemblages can be highlighted in the turnover rate and species richness. The North Jens-1 assemblage displays a lower turnover rate and species richness than the two other (shallower) sites. This may serve to confirm the assumption that North Jens-1 is a deeper water environment, and in consequence, foraminiferal assemblages display lower diversity and dynamicity.

The micropalaeontological results suggest that agglutinated foraminifera take a secondary role behind benthic calcareous for most of the Early Cretaceous (Berriasian to Barremian) in the study sites. However, in the Lower Barremian, agglutinated foraminifera dominate the benthic fraction of the assemblage at the North Fordon (samples 270' to 335' – 340' MD) and Filey Bay (sample at 316' of height) sites (see Figure 12 and Figure 13). A similar trend is seen in North Jens-1 as benthic foraminifera take a prominent role through the Lower Barremian and Hauterivian (2303 – 2328 m (7556' – 7639')) and almost completely disappear from the assemblage around the Barremian – Aptian boundary, somewhere stratigraphically above 2269 (7445') MD, just before the planktic foraminifera influx in the Basin. These events may imply brief episodes of basinal restriction amid a growing, open-oceanic ventilation trend throughout the Lower Cretaceous.

The hypothesis set out on the objectives section (1.1) concerning foraminiferal evolution for foraminiferal fossil groups divided by wall-type and life-mode (i.e., agglutinated versus calcareous and benthic versus planktic) were partially confirmed by this project’s results, as follows.

First, planktic taxa were shown to appear in high abundance towards the mid-Cretaceous in all four sampling sites. This is consistent with a wealth of literature around the topic, some of which was referenced in previous chapters. Of all the sites, the Britannia field boreholes contain the most comprehensive stratigraphic record yielding planktic foraminifera. The composite section between boreholes 16/26-B3 and 15/30-7 ST2 displays an important number of planktic foraminifera present from Hauterivian to Albian stages recovered from ditch cuttings. Unfortunately, several reasons, including poor preservation quality, low average abundance, and small test size, precluded a full range micropalaeontological analysis of the assemblages. Very few planktic (or benthic foraminifera) were allocated to named species. Most of the specimens were associated with a genus, although uncertainty remained; therefore, most were marked with a question mark (per taxonomical guidelines).

Nevertheless, the other sampling sites (North Jens, North Fordon and Filey Bay) display an interesting planktic footprint that allowed the author to identify five species within the genus *Hedbergella*. The planktic taxa show low species richness but high abundance values in all sampling sites. This is consistent with some views in the academic community (e.g., pforams@microtax (Young et al., 2017)) for planktic taxa similar to those found in the study area. However, other views (Banner and Desai, 1988; Banner et al., 1993) suggest a much larger number of species and genera for the planktic taxa of the Lower Cretaceous of the North Sea area. However, the author does not find some of the taxonomic criteria suggested by the former authors practical and useful for regular micropalaeontological work. The author considers that the former authors over split the planktic assemblages. Thankfully, data found in Young et al. (2017) provides a working taxonomy that reflected the diversity of the planktic foraminiferal assemblages.

Secondly, benthic calcareous taxa were shown to be flourishing in marine shelves of the study areas. Figure 22, Figure 20, Figure 12, and Figure 13 show the abundance and number of species (species richness) of benthic calcareous nature. Most of the diversification and turnover rates shown in Figure 26 are due to benthic calcareous and agglutinated foraminiferal first and last appearances in the studied stratigraphic sections (see Figure 27 and Appendix G).

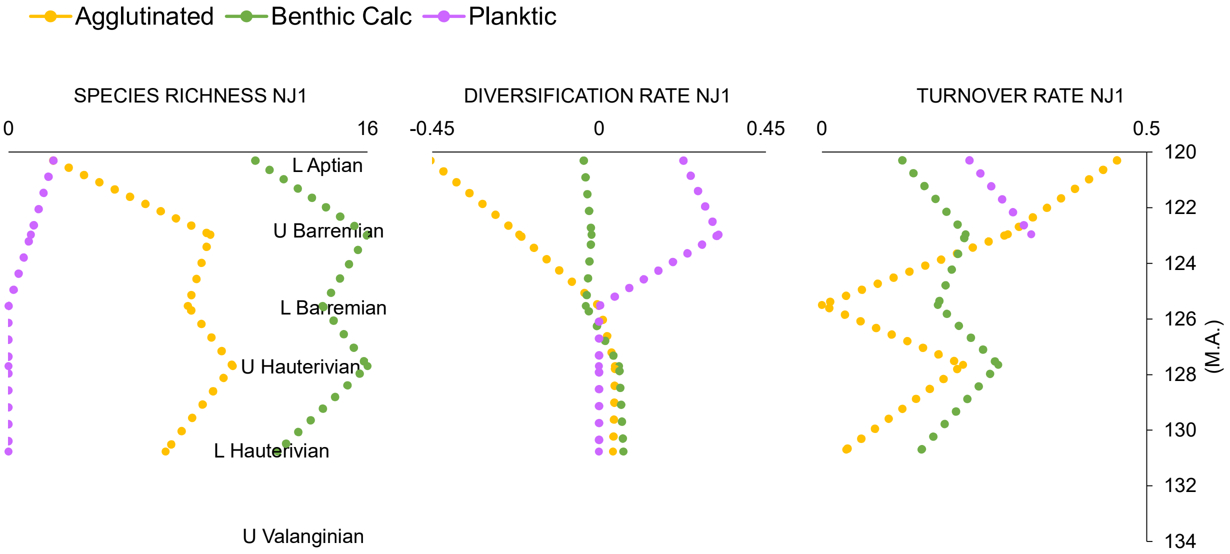


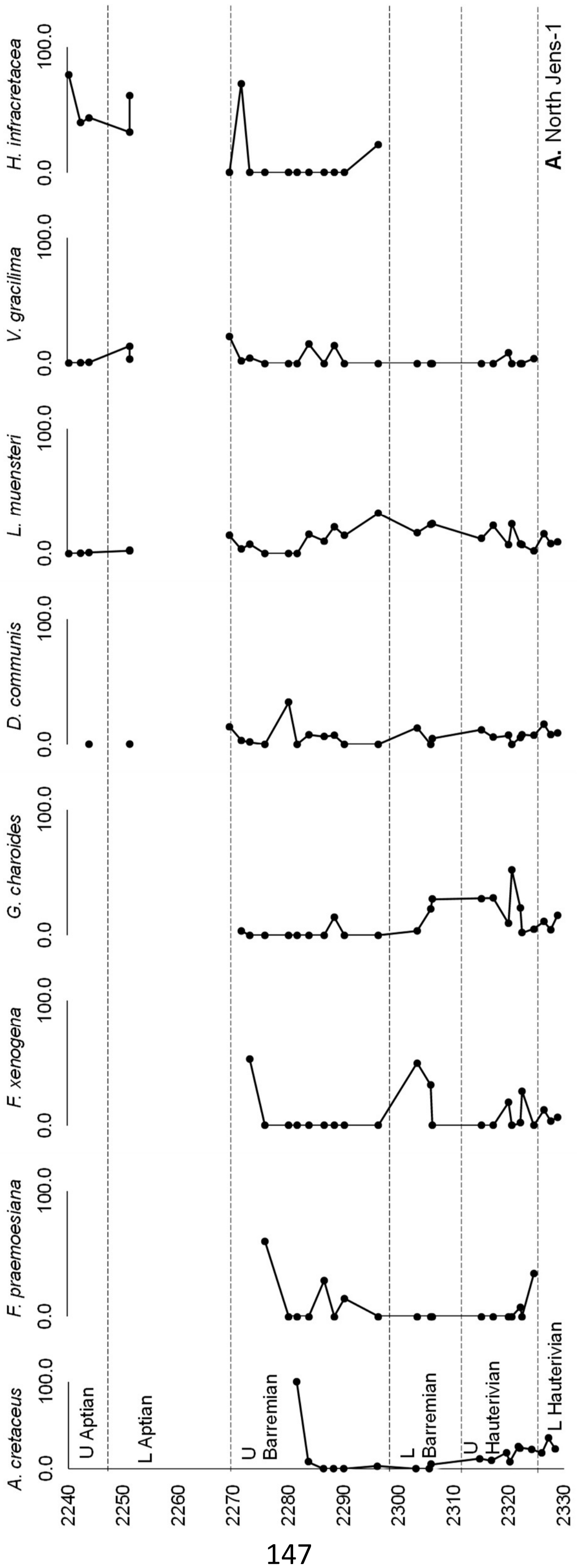
Figure 27. Species richness, diversification, and turnover rates for the foraminiferal assemblages of the North Jens-1 well according to wall type and life mode.

The hypothesis assumed that as the number of foraminiferal genera and species continued to increase (as suggested in the literature; for example, see Figure 1 and Figure 2), throughout the Upper Jurassic and Lower Cretaceous, the bulk of the species richness increase would be carried over by benthic calcareous taxa. Two assumptions were made; 1. that planktic foraminifera did not become abundant until mid-Cretaceous times, and 2. that agglutinated foraminifera expanded primarily into deep water niches; therefore, their micropalaeontological signature on shallow water bodies would be characterised by their absence or minimal contribution to the fossil assemblage. This hypothesis is partially confirmed, as benthic calcareous foraminifera thrived and dominated the foraminiferal assemblages for most of the Lower Cretaceous on the four study sites, as was made evident in previous chapters. North Fordon was the site that displayed the highest number of benthic calcareous foraminiferal species. However, all areas showed a moderate to high species richness.

Lastly, the hypothesis surrounding agglutinated taxa exploring and expanding into deep-water sedimentary environments could not be confirmed. The graben areas of the North Sea Basin did not reach water depths that would allow deep-water agglutinated foraminiferal assemblages to thrive. This was known at the outset of the project, as anybody would learn from a general North Sea Basin geological review. However, the author hypothesised that it might be possible to evidence a shift in the foraminiferal assemblages from shallow- (or even brackish or non-marine for the Berriasian stage) water agglutinated foraminifera towards increasingly DWAF-affinity assemblages, even on shallower sedimentary facies. Unfortunately, this was not the case; therefore, this part of the initial project's hypotheses could not be confirmed through the project results.

This study aimed at investigating the biostratigraphical distribution of foraminiferal groups throughout the Lower Cretaceous of the North Sea Basin and its margins, as outlined in section 1.1. The investigation results displayed in previous chapters have shown foraminiferal assemblages dominated by benthic foraminifera for the Berriasian, Valanginian, Hauterivian and part of the Barremian; and planktic foraminifera for part of the Barremian, Aptian and Albian in the study areas. The research has also shown that a basin-wide scheme such as King et al.'s (1989) schemes for the North and South areas of the North Sea Basin can be applied to the study areas with efficacy to generate multi-site correlations and build useful chronostratigraphic models.

A significant finding emerging from the research is that foraminiferal assemblages in the study areas can be characterised meaningfully by subdividing the assemblages by wall-type and life mode. That provides a traceable signature for the assemblage over geological time and changing palaeoenvironmental conditions. Evidence can be found in the study areas such as Filey Bay, North Fordon and North Jens; as water palaeo-depth increased from Berriasian to mid-Cretaceous, the assemblage changed.


A. North Jens-1
A. cretaceus
F. praemoesiana
F. xenogena
G. charoides
D. communis
L. muensteri
V. gracilima
H. infracretacea
0.0
100.0
U Aptian
L Aptian
U Barremian
L Barremian
U Hauterivian
L Hauterivian
2240
2250
2260
2270
2280
2290
2300
2310
2320
2330

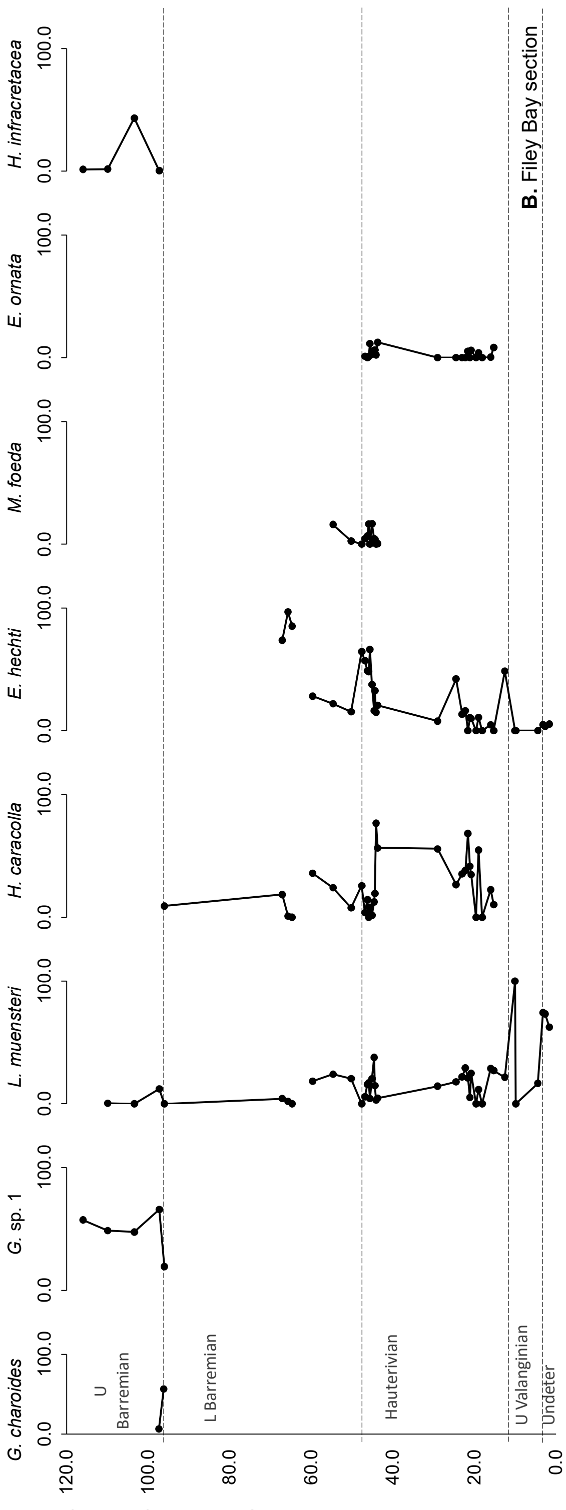


Figure 28. Eight most common fossil foraminiferal species at the A. North Jens, and B. Filey Bay sites.

Changes were tracked by palaeoecological indicators such as species richness and abundance, which showed that the variables that summarised most of the assemblage change were life mode (planktic versus benthic) and wall-type (calcareous versus agglutinated). A similar change, although less drastic, can be found when moving from shallow water (e.g., Yorkshire) to a deep water basinal setting (e.g., North Sea grabens).

The insights gained from this study may help expand the understanding of Lower Cretaceous foraminiferal evolution. Taken together, the findings may have helped to understand how benthic calcareous, agglutinated, and planktic foraminifera developed through the Lower Cretaceous as sea-level rose and the restricted conditions of the Early Cretaceous gave place to more connected seas, toward the mid-Cretaceous. The evolution of Lower Cretaceous foraminifera in the North Sea basin is linked to the palaeoenvironmental development of the basin. Rising sea-levels opened new ecological niches in the basin for foraminifera to colonise and expand. Restricted conditions in the earliest Cretaceous followed by opening and connectivity towards the mid-Cretaceous brought new foraminiferal species from the Tethyan province to compete with local species in the basin.

It is worth looking at the most abundant species at each sampling site and comparing among different locations. Figure 28 shows the eight most common species for (A) North Jens-1 and (B) Filey Bay section.

North Jens-1's assemblages (Figure 28 A) display four agglutinated and four calcareous walled foraminiferal species as the most abundant ones. This is interesting as it may suggest a slightly more relevant role for agglutinated foraminifera in the deeper areas of the North Sea graben. In contrast, the Filey Bay section's assemblages (Figure 28 B) display only one agglutinated species among the most abundant ones at the site. Only one planktic foraminiferal species, *H. infracretacea*, features in both locations by displaying high abundance. Only three species are highly abundant on both sites, the planktic *H. infracretacea*, the benthic calcareous *L. muensteri*, and the agglutinated *G. charoides*.

The stratigraphic range appears to be continuous for the species in North Jens-1 (Figure 28 A) for the Barremian and Hauterivian for almost all the most abundant fossil foraminifera species, seven in total. In contrast, the stratigraphic range seems more discontinuous, with only two species being abundant, during the same stratigraphic interval (Barremian and Hauterivian) in the Filey Bay section (Figure 28 B). This may indicate that the deeper water areas of the North Sea Central Graben had a slightly less disrupted sedimentation history than shallower areas such as those in the Yorkshire shelf.

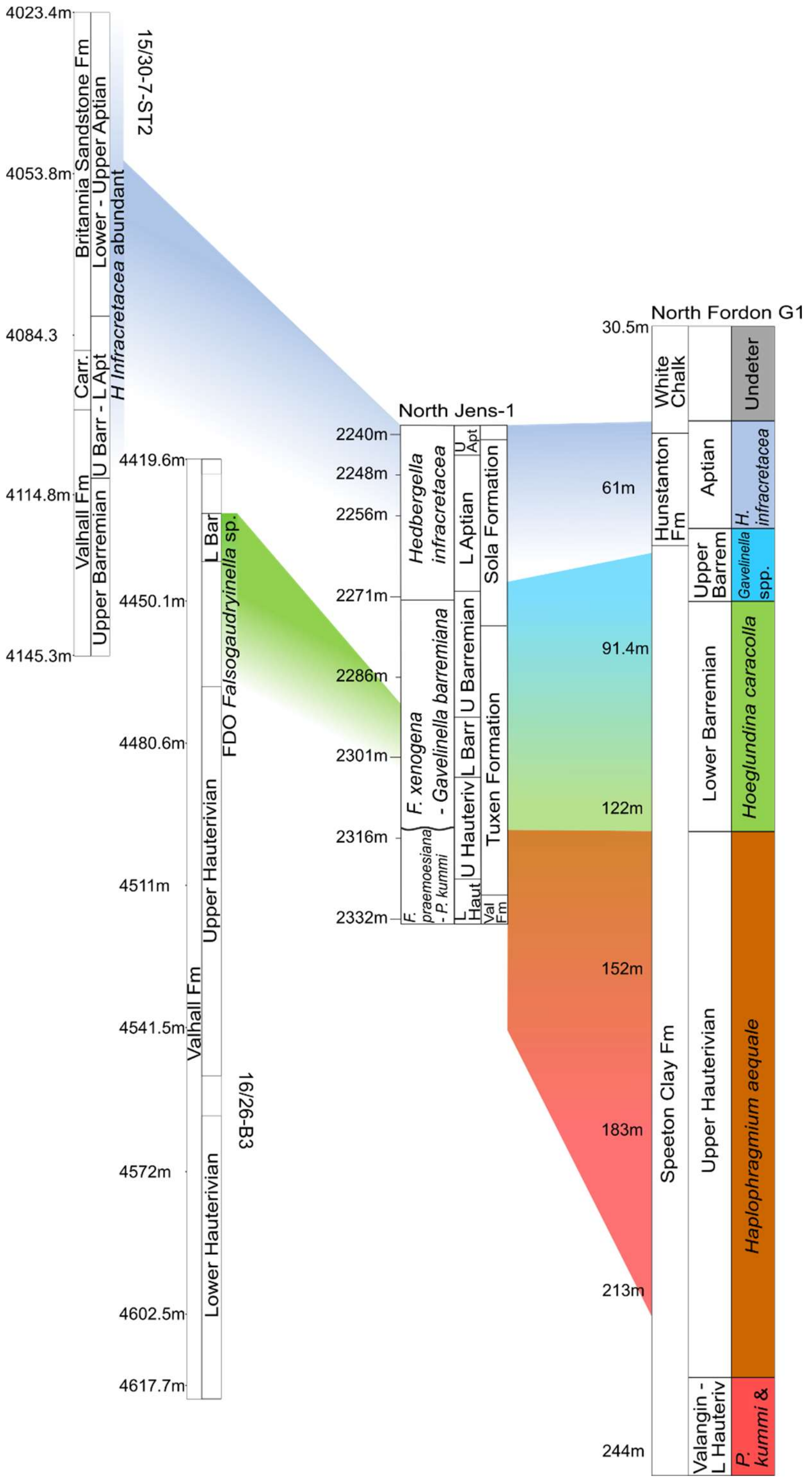


Figure 29. Simplified biostratigraphic correlation for three sites, 15/30-7 ST2 & 16/26-B3; North Jens-1; North Fordon G1. Some biozones for the Barremian and Aptian are highlighted in colours. They are based on King et al.'s (1989) model for the North and South areas of the North Sea.

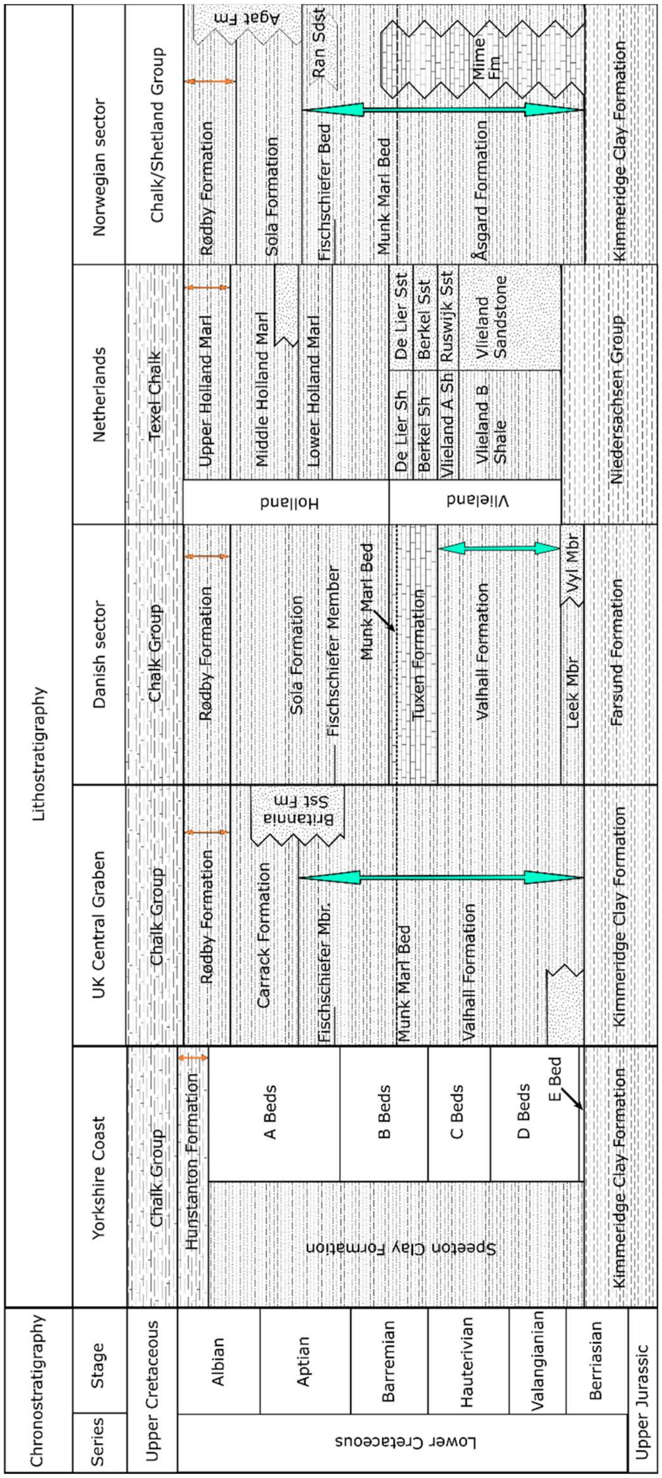


Figure 30. Lithostratigraphy of Lower Cretaceous Rocks in selected areas of the North Sea and surroundings. Modified from Oakman and Partington (1998); Rawson (2006); Copestake et al. (2003); Rawson et al. (1978).

The latter may have been subjected to the interplay between basinal sea-level and active local tectonic conditions.

There is a difference between the chronostratigraphic schemes suggested in this work (based on the biostratigraphic schemes put forward following the micropalaeontological work) and the chronostratigraphic schemes from the literature cited in previous chapters for the shallow- and deep-water areas. This dissimilarity is most prominent when comparing the chronostratigraphic information between Figure 29, Figure 10, Figure 11, Figure 20, and Figure 22, which show a different age for formations such as the Valhall Fm and Hunstanton Fm equivalents. Inconsistencies around the Valhall Fm in Figure 29 and Figure 30 can be explained by a degree of diachroneity in the stratigraphic formations and models from the North Sea Basin. The Valhall Fm, as described previously in chapter 3, was defined with different boundaries and geological span in several basins such as the Danish Central Graben, the triple junction of the Witch Ground, Central and Viking grabens, the Norwegian margin, etc. On these locations, the same name is used for rock packages with similar lithological character but slightly different geological ages. This is showcased in Figure 30 with coloured arrows. The green arrows highlight the chronological age differences for the Valhall Fm and equivalents, which is entirely normal behaviour for geological basins worldwide.

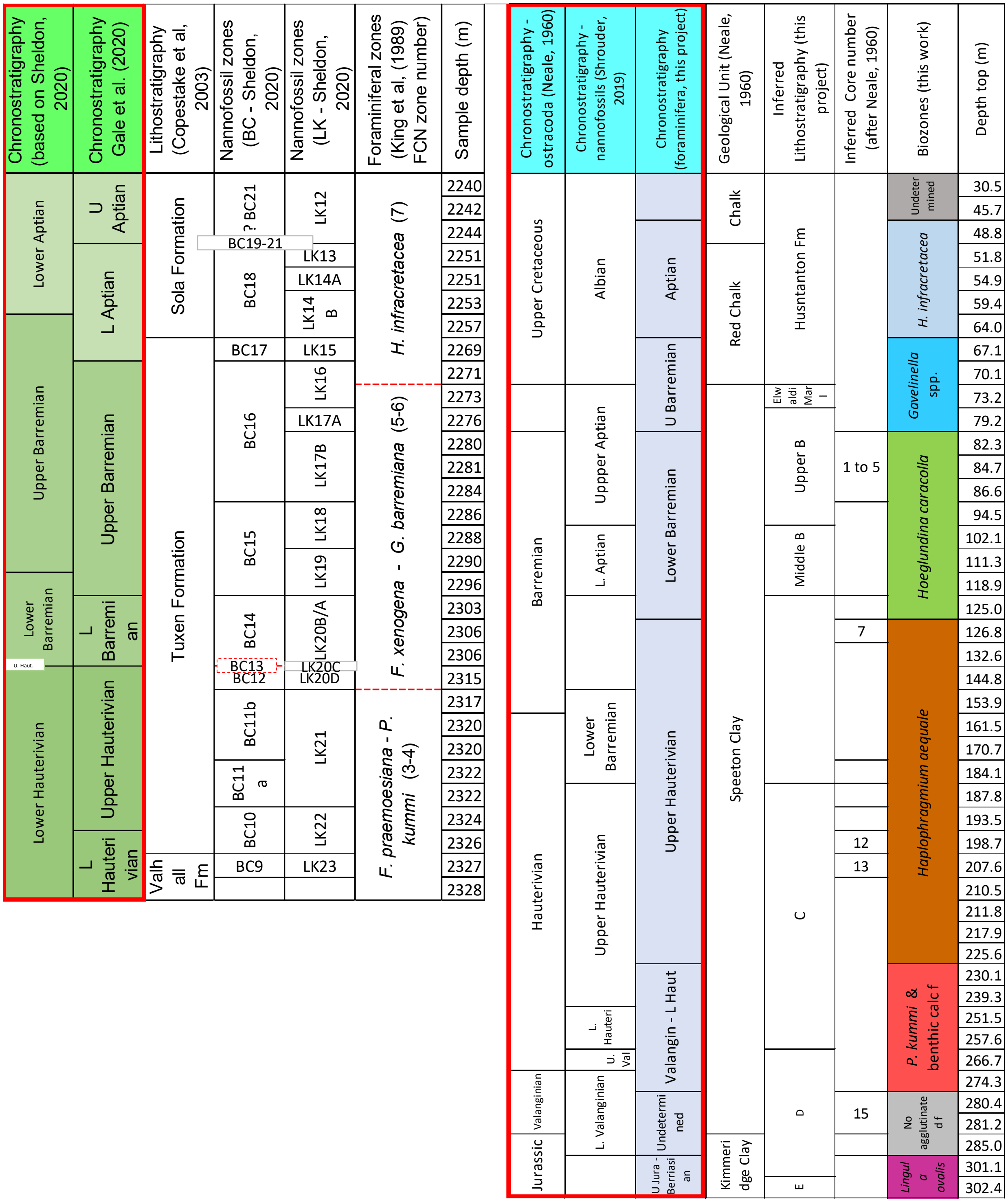


Figure 31. Modified from Figure 23 to highlight the challenges raising from mismatches between different biostratigraphical proxies such as nannofossil and foraminifera, in the case of North Jens-1

However, it adds uncertainty to the chronostratigraphic models in this project because the foraminiferal data come from different sectors of the North Sea Basin that will naturally show different chronostratigraphic ages for similar formations across the basin, making the correlation between sites more difficult.

In the case of the shallow-water Hunstanton Fm and its equivalents, such as the deeper-water Rødby Fm, the differences between the chronostratigraphic models put forward in this project and the literature can be explained as the result of combining different palaeontological proxies and biostratigraphic schemes. This project is based on the use of foraminifera for biostratigraphic models and uses calcareous nannoplankton to support age models whenever available. However, some of the models used in the literature referenced in previous chapters result from using different proxies like invertebrate microfossils (ammonites and belemnites) and other micropalaeontological proxies such as Ostracoda and palynology, not investigated for in the sample sets analysed in the laboratory for this project. North Jens-1's results, for instance, take major cues for the chronostratigraphic model from a very robust calcareous nannoplankton scheme produced by collaborators at GEUS. In this way, the foraminifera took a less prominent role in the chronostratigraphic model. However, for North Fordon and Filey Bay, the calcareous nannoplankton studies available were not extensive enough to provide a robust biostratigraphic framework; therefore, the chronostratigraphic model for the

Yorkshire area is based on foraminiferal biozones. Figure 31 on the left hand-side highlights the mismatch between two chronostratigraphic models that are based on different biostratigraphic proxies. The first one is a calcareous nannofossils model by Sheldon (pers. comm., 2020); the second one is based on the foraminiferal results of this project (areas highlighted by a red rectangle). Notice how the boundaries, extension of Lower Cretaceous stages changes from one model to the other. However, as suggested above, this project builds a biostratigraphic framework around foraminiferal biostratigraphy, which may be in minor conflict with other palaeontological proxies as evidenced in Figure 31.

On the right hand-side of Figure 31, it is possible to notice inside the red polygon mismatches between chronostratigraphy based on ages dictated by different palaeontological proxies such as ostracoda, calcareous nannofossils and foraminifera. These mismatches put in evidence, again, the challenges faced by builders of basinal chronostratigraphic models who wish them to be consistent and robust. Nevertheless, differences between models are minor, in the author's opinion; and biostratigraphic models are consistent with basin-scale schemes such as King et al. (1989).

4.3 Conclusions

The work undertaken in this study helps to expand the quantitative and qualitative understanding of Lower Cretaceous foraminiferal palaeoenvironments in the North Sea. It provides an expanded point of view into less well-known data sets (such as the Filey

Bay section and the Britannia Field) and provides a refreshed view of underexplored data sets (North Fordon G1, North Jens-1 boreholes).

The microfossils studied in this project from the Danish Central Graben, the Central Graben, and the Yorkshire shelf clearly indicate a marine environment throughout the Lower Cretaceous of the North Sea (although emerged areas were present (Copestake et al., 2003)) with a general trend from restricted to a more open marine environment as geological time progressed.

The microfossils suggest a shallow environment at the onset of the early Cretaceous and a deepening trend through the following Lower Cretaceous stages. Microfossil assemblages from shallower, earlier stages display palaeoenvironmental features suggesting a moderately restricted palaeoenvironment due to the slightly isolated basinal configuration of the North Sea basin as suggested by the impoverished benthic foraminiferal assemblages of the time. In contrast, later stages, towards the mid-Cretaceous, show microfossil assemblages suggesting deeper waters and a connection to open marine areas, pointing to a change in the environmental conditions of the North Sea Basin, as indicated by the planktic foraminifera influx. Both shelfal (Yorkshire) and bathyal environments (Central and Danish Graben) display a similar sea level trend suggesting a continuous connection between all the studied sites.

The micropalaeontological analysis led to a revised foraminiferal biostratigraphic scheme for the studied areas (Figure 29). These biozones were heavily based on King et al.'s (1989) schemes for northern and southern North Sea (FCN and FCS); however, they were adapted to each case, slightly modifying, skipping or adding new biozones wherever it was necessary. Nonetheless, the biostratigraphic schemes produced are primarily compatible with King et al. (1989), which allows for comparison with other datasets elsewhere in the basin.

As for the objectives set out at the beginning of this project, essential questions regarding the foraminiferal assemblages and dynamics of populations throughout the Lower Cretaceous of the North Sea remain. However, we improved the understanding of the biostratigraphy of the study sites by providing a scheme comprising zonal index foraminifera used in basin-wide micropalaeontological studies such as King et al. (1989).

Species richness and abundance were compared on each site, prompted by the primary goals stated at the beginning of this project. However, comparing their absolute values was not possible because of differences in the quality between the data sets. In essence, processing methods yielded different results on the various lithologies involved in the project and microfossil recovery quantities oscillated between sample sets. Therefore, low confidence is attributed to the absolute values of the ecological indexes. Instead, relative values of species grouped by diagnostic features such as wall-type are used as discriminant factors to subdivide microfossil populations into assemblages and to characterise palaeoenvironments of deposition – e.g., into restricted and open marine settings.

The preservation quality of the recovered fossil material is mediocre to poor, with exceptions such as well-preserved material from the Filey Bay section on the positive side and very poorly preserved material from the Britannia Field on the opposing side. Species identification was challenging in most sites. More advanced processing techniques may help obtain better results with these types of studies in the future.

Lithological information (Figure 30) provided invaluable help to understand the sedimentological type of regime under which the microfossils lived and were deposited on the seafloor. However, this project did not focus on lithological analysis.

4.4 Recommendations for further study

Microfossil material from other surrounding regions would complement the project results very well. Locations such as the north-west German Basin (Bartenstein and Bettenstaedt, 1962; Elstner and Mutterlose, 1996) provide Lower Cretaceous material that, if analysed, could provide additional insights into the evolution of the foraminiferal assemblages of the North Sea Basin and the rest of north-west Europe.

This project may benefit from a more robust independent age model for each locality. If calcareous nannoplankton biostratigraphy was available for each sample set, as it was for the North Jens-1 record, it would certainly provide a higher degree of confidence to the age models and chronostratigraphic schemes of the localities studied, such as North Fordon, Filey Bay and Britannia.

Implementing different processing techniques such as liquid nitrogen could benefit the laboratory phase of projects like this one. The time and effort put into sample processing were beyond what supervisors and the literature advised. Novel and perhaps, more effective processing techniques may provide better alternatives.

A complete suite of petrographical and geochemical studies may benefit the analysis of the North Sea's palaeoenvironments in future research endeavours.

End Pages

5 Appendices

Digital files of each appendix and additional files used to process and analyse the project results will be made available through the University of Birmingham Online Repository.

Sample depth (ft)	Sample	*Ammodiscus cretaceus*	*Ammodiscus cretaceus* var. oval	*Falsogaudryinella praemoesiana*	*Falsogaudryinella tealbiensis*	*Falsogaudryinella xenogena*	*Glomospira charoides*	*Glomospira gordialis*	*Haplophragmoides cushmani*	*Protomarssonella kummi*	*Rhabdammina cylindrica*	*Recurvoides* sp.	*Astacolus* sp.	*Conorboides hofkeri*	*Dentalina communis*	*Dentalina debilis*	*Dentalina distincta*	*Dentalina eujuncida*	*Eoguttulina oolithica*	*Frondicularia hastata*	*Gavelinella barremiana*	*Gavelinella* sp. 1	*Lagena hauteriviana hauteriviana*	*Lagena* sp.	*Lenticulina circumcidanea*	*Lenticulina forticosta*	*Lenticulina gaultina*	*Lenticulina inflata*	*Lenticulina muensteri*	*Lingulina hauteriviana*	*Marginulina costata*	*Paalzowella feifeli*	*Pseudonodosaria humilis*	*Pseudonodosaria vulgata*	*Pyrulina cylindroides*	*Trocholina feifeli*	*Valvulineria gracilima*	*Vidalina carpathica*	*Hedbergella aptiana*	*Hedbergella excelsa*	*Hedbergella infracretacea*	*Ostracoda*	Total Abundance
7350	NJ1-01																					3		1					1								4		170	10	667		856
7357	NJ1-02												4												1				1					1			1		232		157		397
7362	NJ1-03														2							4							5						1		5		315		260		592
7386	NJ1-06										1											5					2		7								43		151		100		309
7386	NJ1-07														1							3			1			4	8								13		124		249		403
7393	NJ1-10																																										0
7404	NJ1-12																																										0
7445	NJ1-13							1					2		2							3							2						1		3					2	14
7452	NJ1-14						2	2	1				2		2							3			2				2								1				42		59
7457	NJ1-15		1		10	35		1	2				1		1											1			5				3	3			3					3	66
7466	NJ1-16				2	6													1														1									1	10
7480	NJ1-18										1				1																		1									1	3
7485	NJ1-20	1																																									1
7492	NJ1-23	1	2					4							1														2				1				2						13
7501	NJ1-26					14			13						3					2	2					1			5				9									1	49
7507	NJ1-27						2	1					1		1						4								3								2					1	14
7513	NJ1-28					1		1													1							3	1														7
7533	NJ1-31	1						5													3								10	1				3	1						7		31
7556	NJ1-34					15	1	3							4											2			5													4	30
7564	NJ1-38					11	7										1							2					8				1			4						1	34
7565	NJ1-39	1					6	4			1				1														5					1	1			1					21
7594	NJ1-44	2					5	1			4	1			2														2													3	17
7601	NJ1-45	5	4				16	1		2	1				3	1							1						12				5			3						6	54
7610	NJ1-47	16	9	16			8	1			1		2	8	6				1										6							6	7					17	87
7612	NJ1-48	2					13	4																					6													2	25
7617	NJ1-49	14	1	5			12			2			1		3						1								4				3		1	5		3				4	55
7618	NJ1-51	28	11	32			2			14	1				9	4													8							5		2					116
7625	NJ1-52	35	5	53			8	3		2	1			1	11	1							2						3		1				5	16	6	3				13	156
7631	NJ1-53	10	5	7			6	2							9														9				1		4	3						13	56
7635	NJ1-55	78	27	8			10				2				17			1					4						18		2	6	4		15	15		17				30	224
7639	NJ1-56	53	29	15			36	2	11						21		2												22			5		1		21		10				10	228

Appendix A. North Jens-1 raw data from range chart.

Height (m)	Sample	Abundance	Ammodiscus cretaceus	Glomospirella gaultina	Arenobulimina chapmani	Protomarssonella sp. 1	Arenobulimina sp. 1	Protomarssonella aff. oxycona	Recurvoides sp. 1	Haplophragmoides aff. globosa	Glomospira charoides	Textularia foeda	Haplophragmoides nonionoides	Ammobaculites sp. 1	Trochamminoides cf. gudkouffi	Tritaxia pyramidata	Verneuilinoides necomiensis	Lagenammina lagenoides	Haplophragmium aequale	Ammobaculites subcretaceus	Bigenerina clavellata	Gaudryinella sherlocki	Haplophragmoides cushmani	Trochammina depressa	Ammovertella cellensis	Gavelinella sp. 1	Gavelinella barremiana	Gavelinella baltica	Gavelinopsis touranensis	Lenticulina muensteri	Dentalina communis	Lenticulina heiermanni	Lenticulina cf. jarvesi	Lenticulina pachynota	Marginulinopsis striatocostata	Vaginulina arguta	Ramulina spandeli	Lagena hauteriviana	Globulina prisca	Valvulineria gracillima	Gavelinella sp. 2	Gavelinella cf. barremiana	Ramulina fusiformis	Planularia crepidularis	Dentalina terquemi	Vaginulina striolata	Gavelinella intermedia	Marginulinopsis robusta	Nodosaria pyramidalis	Nodosaria sceptrum	Citharina pseudostriatula	Pseudonodosaria humilis	Lingulina sp.A (sensu Fletcher, 1966)	Hoeglundina caracolla	Epistomina hechti	Vaginulinopsis humilis praecursora	Lenticulina schlönbachi	Nodosaria cf. regularis	Lenticulina ouachensis wisselmanni	Conorboides lamplughi	Pseudonodosaria vulgata	Marginulinopsis foeda	Citharina sparsicostata	Marginulinopsis gracilissima	Lenticulina bronnii	Lagena hispida	Epistomina ornata	Lenticulina guttata	Gavelinella sigmoicosta	Lingulonodosaria nodosaria	Frondicularia inversa	Lenticulina saxonica	Citharina harpa	Frondicularia concinna	Lenticulina schreiteri	Marssonella kummi	Palmula malakialinensis	Dentalina debilis	Frondicularia hastata	Nodosaria obscura	Lenticulina circumcidanea	Tristix insignis	Frondicularia simplicissima	Nodosaria reightonensis	Tristix acutangula	Lagena cf. sulcata (sensu Fletcher 1966)	Hedbergella infracretacea	Hedbergella kuznetsovae	Hedbergella speetonensis	Ostracods	Gastropods	Recrystallised carbonates?	Pysitised burrows	Burrows	Bivalves	Pyritised foraminifera
116	3RC	371	24	2	8	13	5																			213	28	3	4																																																															5	58	8							
110	2RC	471		4	6	4		3	2	1																229	30	16	13	2	11	2	1	1	2	1	1	4	1	18	5	18	1																																																				8		87	2					1	
103.5	1RC	328			11																					156					3	1									4			2	1	2	6																																																	142			2				2	1	
97.4	A3	535	14		1						35															353	39			65	3		1	1											3	5		1	1	3	1	1	1																																							2	5		4						
96.2	A4	262	20	6							148	6	4	2	1											51																												24																																															
67.4	LB1A	404														1														17		5																		6				75	298	2																																							1				
66	LB1B	202																											4																								2	196																																						2		1			
65	LB1E	115																																															17						98																																						4				4	
64.3|LB2A|0|																																																																																															
60	LB3D	142	1	2								1					5	1												26		7		1												1		1	3					51	40		1	1																																			2			2			
55	LB4C	332	1									1				1														80	1			2	8	2	1	4						12				1	3	1				80	73				3	2	2	53	1																																						
50.6	LB5	39										1																		8		2		1				1	3									4						3	6		1		1		1	1		2	3	1																									1		5				
48	LB5D	31																													3																						8	20																																					1						
47.2	LB6	296										2				18	1		1											17	4	6	4	1		1		1						8	1	1			1			1		11	169		1		1			13					3	3	24	1	1	1																					11						1	?
46.6	C1A	133														1														21		5		1	2		1							1										19	65		1					9			1	2		2					1	1																			2		3				?
46.3	C1B	408	1									3					2		1	3										69	3	6	2	2	3	4	4	4						7	1			4	2						197		6		1	2		67		2	1		4	1	1				1		2	1	1																	26							?
46	C2A	329																		1										14	1			5	2									7					2					27	218		2						1	3	1		38	5	1					1																			2							?
45.5	C2B	425		2								2									1									87	9	6		3	4	2	3	5	1					12		1		5	2					7	160		16	3		4	2	71	1	3	1		12																										6	2						?
45	C2C	135										1																		51			1	4	1			1						7				5						17	22		3			1	1	6		2	1		8	1		1									1																2						3
44.8	C2D	304		1								2																		45	1	5	1	8	3		5	2						4		2						1			59	99		5		2	6		12	2	5	1		19	2	2		1		1	1	6				1												5							?
44.5	C2E	341																												10	1	6												1										262	51												8			1										1												2							?
44.1	C2F	304														2														14		2		2		2									1									172	63					6		1					38						1																										?
29.5	C6	77	2									3					1	1			1	1	1							11				1				2													1			43	6				1																							2									7		18				?
25	C7A	45																											8								1	2									2						12	19				1																															2		4				?
23.5	C7C	82	2									4				2	4	1												18								4										1						29	11													1													5											35	8			?
22.7	C7E	55	3																1											16	2			1	1									1										21	9																																						1			2			
22.1	C7F	19																											4	1																							13													1																																	?
21.6	C8B	218	1	1								20						7	9	7			3	15						11	4	5		1		2		6	2									2						91	23			3																			1				4									4	4	24				?
21.3	C9A	250										1				1				1				1						62	2			14	1			9	10					5										87	25		3		2		1				3		15	2		1			2						1			1								20		?				?
20.1|C9B|28|2|												|20|	|3|		|3|																																																																													
19.5	C9C	250	2									2					1		1						1					29		3			3			5						2				7						137	27		2		1	8				1			10	3												1		4									6	3	?				?
18.6	C9D	2	2																																																																																												4			
16.5	C11A	254																											73	2	9	2	5	3	1	5	7	5					4	1			8	2		1			57	12		2		5					3			1	14			1				3	24	2		1				1							28	2					?
15.8	C11B	48										5				2														13		1						1						3					1					5			1		1					2	1		4	5							3																	26							?
13.1	D2A	74	4																1											16	3	2			1									3											36									4	4																																		
10.6	D3A	1																											1																																																																		2			
10.4|D3B|1|1|																																																																																													|1|		
5	D5C	6																											1									1														1											1					1																						1						2			
3.75	D6A	515																											383	1	30	2	16	15			1	4									10			15	1			25		2		1		1			6	1						1																					2			2		2	Y
3.4	D6B	0																																																																																															
3.24	D6D	584																											428	3		5	4	28			15	10									2		3					21	3	2							27	1					2								1		1	21	5		1	1					1			1		2	Y
2.2	D6I	338																											211	8	11		8				8										12	6						18		3				2			13	1						3		6							1	24	1				2				1	1		2			Y
1.95	D6J	0																																																																																															

Appendix B. Filey Bay section raw data from range chart.

Inferred Lithostratigraphy (this project)					Gault					El wa			Upper B				Middle B															C									D				E
Depth top (ft)	100	150	160	170	180	195	210	220	230	240	260	270	278	284	310	335	365	390	410	416	435	475	505	530	560	604	616	635	652	681	690.5	695	715	740	755	785	825	845	875	900	920	922.5	935	988	992
Depth base (ft)	105	155	165	175	185	200	215	225	235	245	265	270	278	284	315	340	370	395	410	416	440	480	510	535	565	604	616	640	652	681	690.5	700	720	745	760	790	830	850	880	905	920	922.5	940	988	992
Picked forams	0	0	222	293	143	294	139	89	91	268	120	136	229	79	14	105	123	248	188	186	29	30	49	60	41	163	348	70	31	37	130	54	64	121	72	58	22	17	29	12	0	0	14	65	0
Falsogaudryinella xenogena			4		2	3	1			1	1		1			1		10	30	1						3																			
Falsogaudryinella alta			2		1	1				1								1																											
Textularia sp. 1			1																																										
Ammodiscus cretaceus				2								15	15	2		2	1				2					2	7	2	1					6	2	2				1					
Arenobulimina chapmani					8		2			2	1							1																		1									
Glomospira charoides							1			14	1	35	20		6	12	10	5					1	2	3			1					1	6	6		2	2	1						
Reophax minuta									1				8	1																															
Haplophragmoides nonionoides											1	26	70	5	4	6		2					3										2	6	2										
Trochammina cf. *depressa*												17	34	9		2			7	16								6	3			6	2	6	2								1		
Glomospirella gaultina												14	16	7			4	6	2	9	2	3	3	4	1			2			5	1	1	2	2	4			2						
Verneuilinoides neocomiensis												7	4	4		5	1		4		2		4	1	2						3	3	1	2				1							
Verneuilinoides cf. *neocomiensis*																						1																							
Haplophragmium sp. 1												2																				2			3										
Ammobaculites cf. *irregulariformis*												1				12								4	4			4				1		5	2										
Trochamminoides cf. *gudkouffi*												1	11	3	1	10					1	4	4	7	2			2			3	3		2	1	1		1							
Lituotuba sp. 1												3	13	7											1			1				1													
Haplophragmoides sp. 1												5		20							1			7									2	1											
Gaudryina dividens												10	11																																
Trochammina depressa													2			2			9	2	2	1				4							3	5											
Thalmannammina sp. 1													9	5		2								3				7								2							2		
Recurvoides sp. 1													9			10																													
Ammobaculites obliquus													5	4																															
Haplophragmoides aff. *globosa*														2	1							3	2	3	3							8	1		1										
Psammosphaera sp. 1														5						19				1	1			3																	
Gaudryinella aff. *sherlocki*														1		2				2						5																			
Textularia cf. *bettenstaedti*														1																															
Textularia foeda																7			2	20					1		1	3	1		2			2											
Tritaxia capitosa																2							2	1	2								1	6	6										
Ammobaculites sp. 1																2		3		17						1			2			1	2			1		1							
Tritaxia pyramidata																1		1	1					1				1						1		1									
Heterantyx cretosa																2								1																					
Falsogaudryinella sp. 1																1																													
Lagenammina lagenoides																		1								4									1	1									
Haplophragmium aequale																			2	24	1			1			5		3	1	3			3											
Trochammina sp. 1																			13	7		3																							
Glomospirella cf. *gaultina*																			2																										
Ammovertella cellensis																				1									1			1	3												
Ammobaculites subcretaceus																				20									1	1	2						1		1	1					
Ammobaculites cf. *subcretaceus*																					1	2	1																						
Textularia bettenstaedti																						1	1																						
Verneuilina muensteri																							1																						
Ammosphaeroidina sp. 1																								1																					
Haplophragmoides cushmani																										57	15				3														
Reophax sp. 1																										1																			
Ammobaculites reophacoides																											6						1												
Haplophragmium cf. *aequale*																												5																	
Trochamminoides sp. 1																												7																	
Protomarssonella cf. *kummi*																																			1										
Lagena hauteriviana			3														2	1		1	1					1				1	5	1		3	2	1									
Valvulineria gracillima			10	7	25		5	2	9					1		3	14	20					1	1							2	3	3			1									
Praebulimina sp. 1			2		4				1																																				
Gavelinopsis tourainensis			2														7																												
Gavelinella sp. 1				1	2			2			26				1	9	34	94				1	5	5	5								2	3	6	2	1		1	1					
Gavelinella baltica				1	1						1																																		
Gavelinella brielensis				2																																									
Lenticulina muensteri						7	20	6	12	27	3				1		9	17	12		3				1	1	11	1	1	13	40		2		2	8			2	1				20	
Lenticulina heiermanni						17																	1				6		5																
Hoeglundina caracolla								2										3			3	2	4	1					6	13	6	1	4		7	10	4	5	5	3			1		
Dentalina communis								2	3	2							1	4		1				1					1							1	1								
Gavelinella stelligera									7	76																																			
Gavelinella intermedia									2																																				
Marginulinopsis gracilissima										1										1							12	1		1	2			2									1		
Dentalina debilis										1																																			
Frondicularia simplicissima										2																																			
Nodosaria obscura										3																					1														
Nodosaria sceptrum										1																																	1		
Pseudonodosaria humilis										2																																			
Vaginulina mediocarinata										1																																			
Gavelinella cf. barremiana											3					2	12		4	10		1												5	1										
Gavelinella barremiana											2																																		
Lenticulina cf. *jarvesi*											2						1	1										1																	
Lenticulina sp. 1														1																															
Marginulinopsis striatocostata																	1									1				1	5													1	
Globulina prisca																	5	2	1								2																		
Pseudonodosaria radiata																		1																											
Epistomina hechti																			5	10	4	4	9	12	6	80	255	20	2	2		17	27	50	22	19	10	4	16	5			6		
Conorboides valendisensis																			50	6					1	1				3		1	2	3										25	
Epistomina ornata																			6						3						1			1											
Planularia crepidularis																			1											1	2														
Conorotalites intercedens																			1																										
Epistomina chapmani																			12	14																	2	2							
Epistomina spinulifera spinulifera																			22																										
Lenticulina cf. gaultina																			2																										
Nodosaria pyramidalis																				1						1	20												1					13	
Lingulina sp. A - sensu Fletcher (1966)																				1											1														
Lenticulina humilis praecursora																				2																									
Praebulimina cf. *reussi*																						1																							
Lenticulina ouachensis wisselmanni																									1								2	1											
Lenticulina pachynota																										1	1		1		5		1												
Lenticulina bronnii																											3				7														
Lenticulina schloenbachi																											2	1			6														
Nodosaria cf. regularis																											2						1												
Gavelinella cf. *intermedia*																												1				2													
Gavelinella cf. *stelligera*																												1				2													
Ramulina spandeli																													1		5				2										
Marginulinopsis foeda																													2		14					3									
Nodosaria reightonensis																															4														
Pseudonodosaria vulgata																															1														
Ramulina fusiformis																															2														
Marginulinopsis robusta																																					1						1	6	
Palmula malakialinensis																																											1		
Quinqueloculina antiqua																	1																												
Hedbergella infracretacea			198	274	100	265	104	71	53	113	52		1			1	1			1	6	2	7	3	4							3*													
Hedbergella kuznetsovae				6		1	6	4	3	19	23					8	19	75																											
Hedbergella speetonensis										2	4																																		
Heterohelix moremani														1		1						1													1			1							
Bivalves																							1			3	14																		
Gastropods																											2																		
Lingula ovalis - brachiopod																																												4	
Ostracods						2	1			2						2	2		2												2				2				2						

Appendix C. North Fordon G1 borehole raw data from range chart.

Inferred Lithostratigraphy (this project)	Biozones (this work)	Depth top (ft)	Depth base (ft)	Picked forams	Falsogaudryinella xenogena	Falsogaudryinella alta	Textularia sp. 1	Ammodiscus cretaceus	Arenobulimina chapmani	Glomospira charoides	Reophax minuta	Haplophragmoides nonionoides	Trochammina cf. depressa	Glomospirella gaultina	Verneuilinoides neocomiensis	Verneuilinoides cf. neocomiensis	Haplophragmium sp. 1	Ammobaculites cf. irregulariformis	Trochamminoides cf. gudkouffi	Lituotuba sp. 1
	Undetermined	100	105	0																
		150	155	0																
	H. infracretacea	160	165	222	4	2	1													
		170	175	293				2												
Gault		180	185	143	2	1			8											
		195	200	294	3	1														
		210	215	139	1				2	1										
	Gavelinella spp.	220	225	89																
		230	235	91							1									
El wa		240	245	268	1	1			2	14										
		260	265	120	1				1	1		1								
	Hoeglundina caracolla	270	270	136				15		35		26	17	14	7		2	1	1	3
Upper B		278	278	229	1			15		20	8	70	34	16	4				11	13
		284	284	79				2			1	5	9	7	4				3	7
		310	315	14						6		4							1	
		335	340	105	1			2		12		6	2		5			12	10	
Middle B		365	370	123				1		10				4	1					
		390	395	248	10	1			1	5		2		6						
		410	410	188	30								7	2	4					
	Haplophragmium aequale	416	416	186	1								16	9						
		435	440	29				2						2	2				1	
		475	480	30										3		1			4	
		505	510	49						1		3		3	4				4	
		530	535	60						2				4	1			4	7	
		560	565	41						3				1	2			4	2	1
		604	604	163	3			2												
		616	616	348				7												
		635	640	70				2		1			6	2				4	2	1
		652	652	31				1					3							
		681	681	37																
		690.5	690.5	130										5	3				3	
C		695	700	54									6	1	3		2	1	3	1
		715	720	64						1		2	2	1	1					
		740	745	121				6		6		6	6	2	2			5	2	
	P. kummi & benthic calc f	755	760	72				2		6		2	2	2			3	2	1	
		785	*790*	58				2	1					4					1	
		825	*830*	22						2										
		845	850	17						2					1				1	
		875	880	29						1				2						
		900	905	12				1												
D	No agglutinated f	920	920	0																
		922.5	922.5	0																
		935	940	14									1							
E	*Lingula ovalis*	988	988	65																
		992	992	0																

Depth top (ft)	Depth base (ft)	Haplophragmoides sp. 1	Gaudryina dividens	Trochammina depressa	Thalmannammina sp. 1	Recurvoides sp. 1	Ammobaculites obliquus	Haplophragmoides aff. globosa	Psammosphaera sp. 1	Gaudryinella aff. sherlocki	Textularia cf. bettenstaedti	Textularia foeda	Tritaxia capitosa	Ammobaculites sp. 1	Tritaxia pyramidata	Heterantyx cretosa	Falsogaudryinella sp. 1	Lagenammina lagenoides	Haplophragmium aequale	Trochammina sp. 1	Glomospirella cf. gaultina
100	105																				
150	155																				
160	165																				
170	175																				
180	185																				
195	200																				
210	215																				
220	225																				
230	235																				
240	245																				
260	265																				
270	270	5	10																		
278	278		11	2	9	9	5														
284	284	20			5		4	2	5	1	1										
310	315							1													
335	340			2	2	10				2		7	2	2	1	2	1				
365	370																				
390	395													3	1			1			
410	410			9								2			1				2	13	2
416	416			2					19	2		20		17					24	7	
435	440	1		2															1		
475	480			1				3												3	
505	510							2					2								
530	535	7			3			3	1				1		1	1			1		
560	565							3	1			1	2								
604	604			4						5				1				4			
616	616											1							5		
635	640				7				3			3			1						
652	652											1		2					3		
681	681																		1		
690.5	690.5											2							3		
695	700							8						1							
715	720	2		3				1					1	2							
740	745	1		5								2	6		1				3		
755	760							1					6					1			
785	*790*				2									1	1			1			
825	*830*																				
845	850													1							
875	880																				
900	905																				
920	920																				
922.5	922.5																				
935	940				2																
988	988																				
992	992																				

Depth top (ft)	Depth base (ft)	Ammovertella cellensis	Ammobaculites subcretaceus	Ammobaculites cf. subcretaceus	Textularia bettenstaedti	Verneuilina muensteri	Ammosphaeroidina sp. 1	Haplophragmoides cushmani	Reophax sp. 1	Ammobaculites reophacoides	Haplophragmium cf. aequale	Trochamminoides sp. 1	Protomarssonella cf. kummi	Lagena hauteriviana	Valvulineria gracillima	Praebulimina sp. 1	Gavelinopsis tourainensis	Gavelinella sp. 1	Gavelinella baltica	Gavelinella brielensis	Lenticulina muensteri
100	105																				
150	155																				
160	165													3	10	2	2				
170	175														7			1	1	2	
180	185														25	4		2	1		
195	200																				7
210	215														5						20
220	225														2			2			6
230	235														9	1					12
240	245																				27
260	265																	26	1		3
270	270																				
278	278																				
284	284														1						
310	315																	1			1
335	340														3			9			
365	370													2	14		7	34			9
390	395													1	20			94			17
410	410																				12
416	416	1	20											1							
435	440			1										1							3
475	480			2	1													1			
505	510			1	1	1									1			5			
530	535						1								1			5			
560	565																	5			1
604	604							57	1					1							1
616	616							15		6											11
635	640										5	7									1
652	652	1	1																		1
681	681		1											1							13
690.5	690.5		2					3						5	2						40
695	700	1												1	3						
715	720	3								1					3			2			2
740	745													3				3			
755	760												1	2				6			2
785	*790*													1	1			2			8
825	*830*		1															1			
845	850																				
875	880		1															1			2
900	905		1															1			1
920	920																				
922.5	922.5																				
935	940																				
988	988																				20
992	992																				

Depth top (ft)	Depth base (ft)	Lenticulina heiermanni	Hoeglundina caracolla	Dentalina communis	Gavelinella stelligera	Gavelinella intermedia	Marginulinopsis gracilissima	Dentalina debilis	Frondicularia simplicissima	Nodosaria obscura	Nodosaria sceptrum	Pseudonodosaria humilis	Vaginulina mediocarinata	Gavelinella cf. barremiana	Gavelinella barremiana	Lenticulina cf. jarvesi	Lenticulina sp. 1	Marginulinopsis striatocostata	Globulina prisca	Pseudonodosaria radiata	Epistomina hechti
100	105																				
150	155																				
160	165																				
170	175																				
180	185																				
195	200	17																			
210	215																				
220	225		2	2																	
230	235			3	7	2															
240	245			2	76		1	1	2	3	1	2	1								
260	265													3	2	2					
270	270																				
278	278																				
284	284																1				
310	315																				
335	340													2							
365	370			1										12		1		1	5		
390	395		3	4												1			2	1	
410	410													4					1		5
416	416			1			1							10							10
435	440		3																		4
475	480		2											1							4
505	510	1	4																		9
530	535		1	1																	12
560	565																				6
604	604																	1			80
616	616	6					12												2		255
635	640						1									1					20
652	652	5	6	1																	2
681	681		13				1											1			2
690.5	690.5		6				2			1								5			
695	700		1																		17
715	720		4																		27
740	745						2							5							50
755	760		7											1							22
785	*790*		10	1																	19
825	*830*		4	1																	10
845	850		5																		4
875	880		5																		16
900	905		3																		5
920	920																				
922.5	922.5																				
935	940		1				1				1										6
988	988																	1			
992	992																				

Depth top (ft)	Depth base (ft)	Conorboides valendisensis	Epistomina ornata	Planularia crepidularis	Conorotalites intercedens	Epistomina chapmani	Epistomina spinulifera spinulifera	Lenticulina cf. gaultina	Nodosaria pyramidalis	Lingulina sp. A - sensu Fletcher (1966)	Lenticulina humilis praecursora	Praebulimina cf. reussi	Lenticulina ouachensis wisselmanni	Lenticulina pachynota	Lenticulina bronnii	Lenticulina schloenbachi	Nodosaria cf. regularis	Gavelinella cf. intermedia	Gavelinella cf. stelligera	Ramulina spandeli	Marginulinopsis foeda
100	105																				
150	155																				
160	165																				
170	175																				
180	185																				
195	200																				
210	215																				
220	225																				
230	235																				
240	245																				
260	265																				
270	270																				
278	278																				
284	284																				
310	315																				
335	340																				
365	370																				
390	395																				
410	410	50	6	1	1	12	22	2													
416	416	6				14			1	1	2										
435	440																				
475	480											1									
505	510																				
530	535																				
560	565	1	3										1								
604	604	1							1					1							
616	616								20					1	3	2	2				
635	640															1		1	1		
652	652													1						1	2
681	681	3		1																	
690.5	690.5		1	2						1				5	7	6				5	14
695	700	1																2	2		
715	720	2											2	1			1				
740	745	3	1										1								
755	760																			2	
785	*790*																				3
825	*830*					2															
845	850					2															
875	880								1												
900	905																				
920	920																				
922.5	922.5																				
935	940																				
988	988	25							13												
992	992																				

Depth top (ft)	Depth base (ft)	Nodosaria reightonensis	Pseudonodosaria vulgata	Ramulina fusiformis	Marginulinopsis robusta	Palmula malakialinensis	Quinqueloculina antiqua	Hedbergella infracretacea	Hedbergella kuznetsovae	Hedbergella speetonensis	Heterohelix moremani	Bivalves	Gastropods	Lingula ovalis - brachiopod	Ostracods
100	105														
150	155														
160	165							198							
170	175							274	6						
180	185							100							
195	200							265	1						2
210	215							104	6						1
220	225							71	4						
230	235							53	3						
240	245							113	19	2					2
260	265							52	23	4					
270	270														
278	278							1							
284	284										1				
310	315														
335	340							1	8		1				2
365	370						1	1	19						2
390	395								75						
410	410														2
416	416							1							
435	440							6							
475	480							2			1				
505	510							7				1			
530	535							3							
560	565							4							
604	604											3			
616	616											14	2		
635	640														
652	652														
681	681														
690.5	690.5	4	1	2											2
695	700							3*							
715	720														
740	745														
755	760										1				1
785	*790*														
825	*830*				1										
845	850										1				
875	880														2
900	905														
920	920														
922.5	922.5														
935	940				1	1									
988	988				6									4	
992	992														

Appendix D. North Fordon G1 borehole data from range chart with biostratigraphic zones.

Depth ft	f pi	*B. aptiana orientali*	*B. rudis*	*pf unclassifie*	*bf unclassified*	Omini benthi	*Ammodiscus* sp	*Lenticulina* sp.	*Dentalina* sp.	*Glomospirella* sp.	*Valvulineria* sp.	*Gavelinella* sp.	Ostracods	*Bivalve*	*Falsogaudryinella* sp.
B-14420	6	3	1							1					
B-14450	78	20	6	rest		5	*3*	2	1		10	3		1	
B-14480															
B-14510	3		1					1				1			
B-14540															
B-14570	11	1				2		2	3	1		1			1
B-14600															
B-14630	36	1		1	5	3			1	2	1	4			2
B-14660															
B-14690	18					2		4			1	2	1		
B-14720															
B-14750	18	2			rest	2			2						
B-14780															
B-14810															
B-14840															
B-14870	21	1			rest	2		5		3					
B-14900															
B-14930															
B-14960															
B-14990	16				rest	3			2	2		3	2		
B-15020															
B-15050	2								4				1		
B-15080															
B-15110	0														
B-15140															
B-15170	0														

Appendix E. 16/26-B3 borehole raw data for part of the analysis.

B-14630'

Type	Number	Cell
Planktic	2	9
Benthic C	31	1-13
Benthic A	0	
	33	Total number

B-14570'

Type	Number	Cell
Planktic	1	1
Benthic C	10	1, 2
Benthic A	0	
	11	Total number

B-14690'

Type	Number	Cell
Planktic	0	
Benthic C	19	18-22
Benthic A	0	
	19	Total number

B-14990'

Type	Number	Cell
Planktic	3	13
Benthic C	16	13-15
Benthic A	0	
	19	Total number

B-14870'

Type	Number	Cell
Planktic	3	19
Benthic C	19	20-21
Benthic A	0	
	22	Total number

B-14750'

Type	Number	Cell
Planktic	3	25
Benthic C	18	26-27
Benthic A	0	
	21	Total number

B-15050'

Type	Number	Cell
Planktic	0	
Benthic C	6	1
Benthic A	0	
	6	Total number

B-14420'

Type	Number	Cell
Planktic	4	3
Benthic C	1	3
Benthic A	0	
	5	Total number

B-14450'

Type	Number	Cell
Planktic	59	6-7
Benthic C	19	8,14-16
Benthic A	0	
	78	Total number

B-14510'

Type	Number	Cell
Planktic	1	17
Benthic C	2	17
Benthic A	0	
	3	Total number

7-13530'

Type	Number	Cell
Planktic	3	2
Benthic C	0	
Benthic A	0	
	3	Total number

7-13470'

Type	Number	Cell
Planktic	3	11
Benthic C	1	
Benthic A	0	
	4	Total number

7-13330'

Type	Number	Cell
Planktic	20	19
Benthic C	4	20
Benthic A	0	
	24	Total number

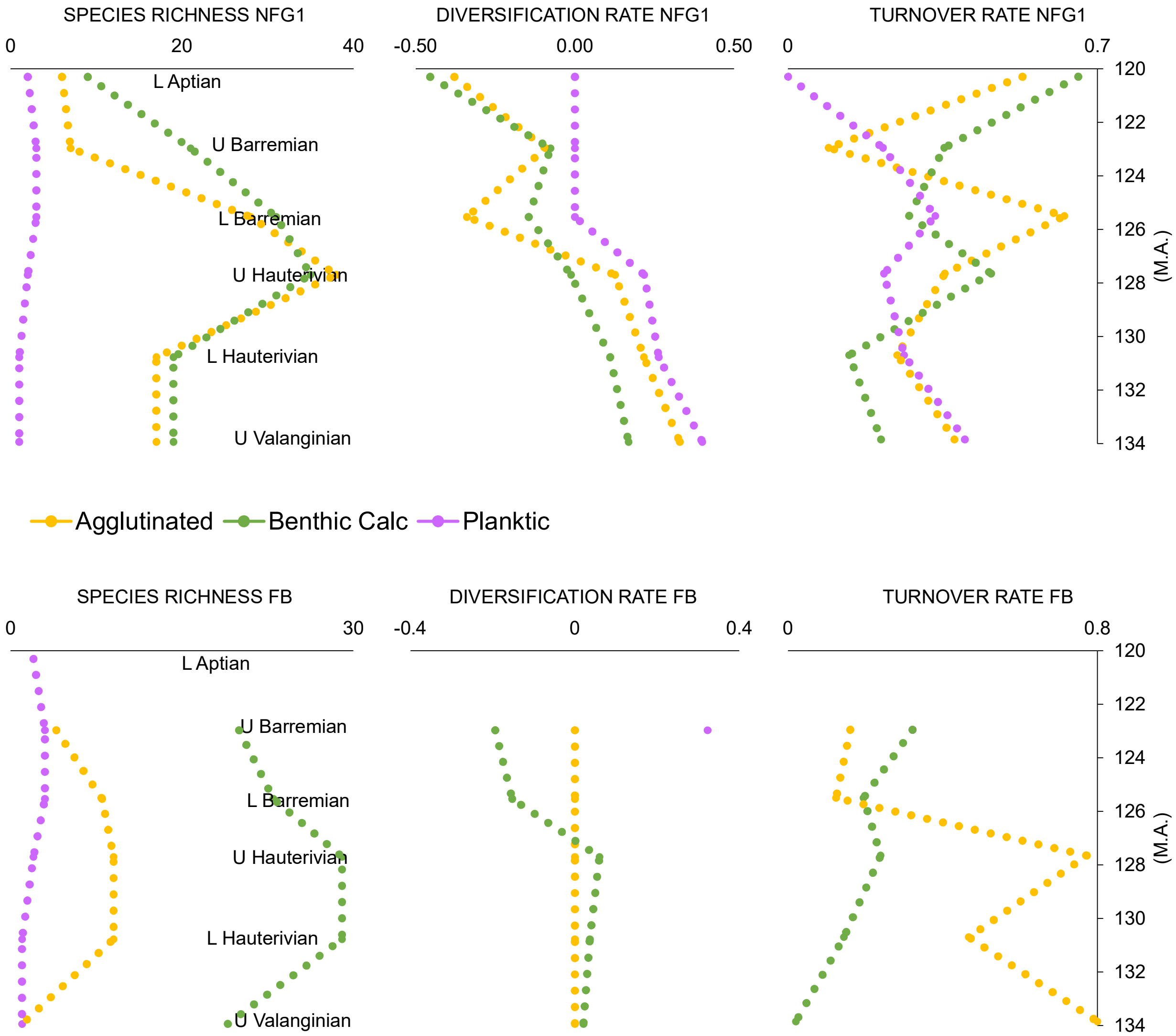
7-13260'

Type	Number	Cell
Planktic	11	28
Benthic C	1	29
Benthic A	0	
	12	Total number

7-13130'

Type	Number	Cell
Planktic	2	2
Benthic C	0	
Benthic A	0	
	2	Total number

Appendix F. Some of the data used to analyse the Britannia Field boreholes 16/26-B3 and 15/30-7 ST2. Data for the Britannia Field is scarcer than the other study sites.



Appendix G. Species richness, diversification, and turnover rate according to wall type and life mode for the microfossil assemblages of the North Fordon G1 and Filey Bay section.

6 Plates

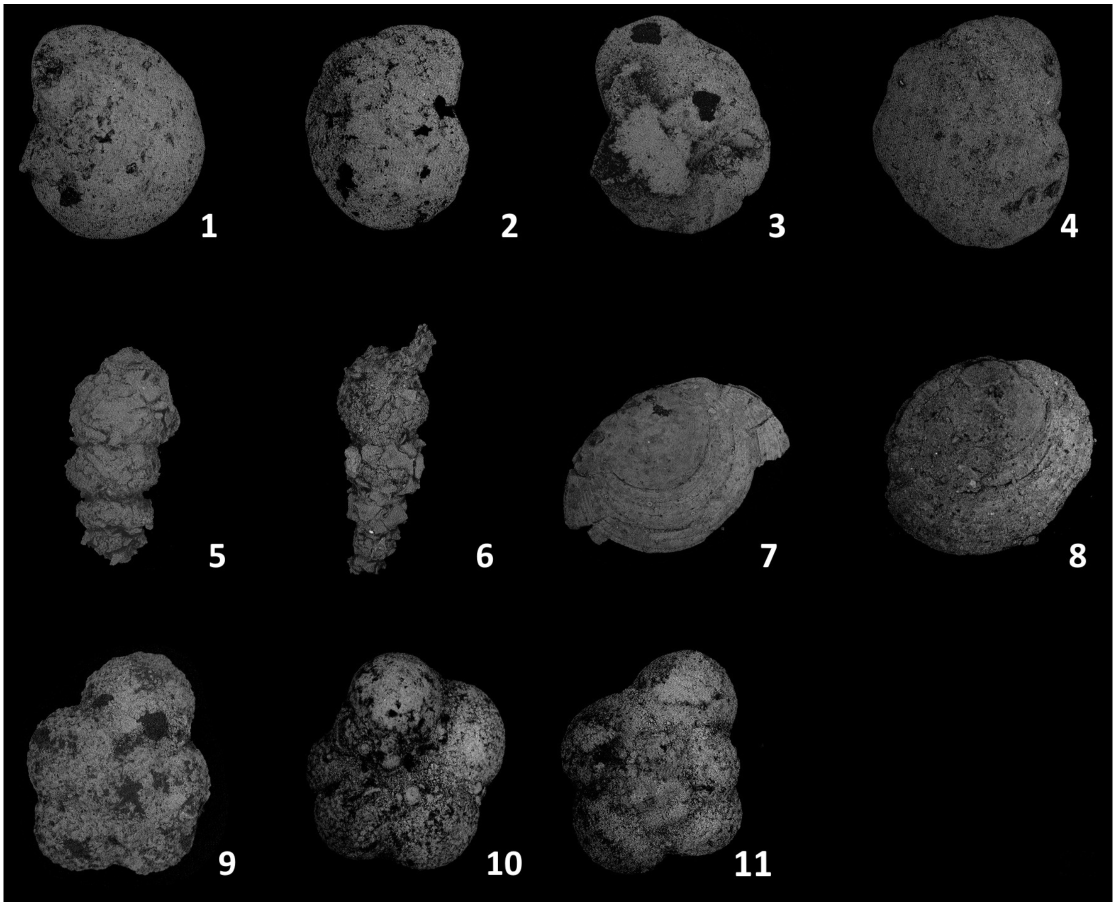


Plate 1. Measurements along the main axis or across the diameter, depending on the test's shape. 1 *G. barremiana* spiral side view, 200 µm (sample 2RC, FB); 2 *G. barremiana* spiral side view, 220 µm; 3 *G. barremiana* umbilical side view, 270 µm; 4 *G. barremiana* spiral side view, 240 µm. 5 *Reophax minuta* lateral view, 330 µm (sample 84.7 m (278'), NF); 6 *Reophax minuta* lateral view, 490 µm. 7 *Lingulina ovalis* dorsal valve view (?), 310 µm (sample 301 m (988'), NF); 8 *Lingulina ovalis* dorsal valve view(?), 360 µm. 9 *H. infracretacea* spiral side view, 290 µm; 10 *H. infracretacea* umbilical view, 400 µm (sample 1RC, FB); 11 *H. infracretacea* spiral side view, 290 µm. NF stands for North Fordon, FB for Filey Bay.

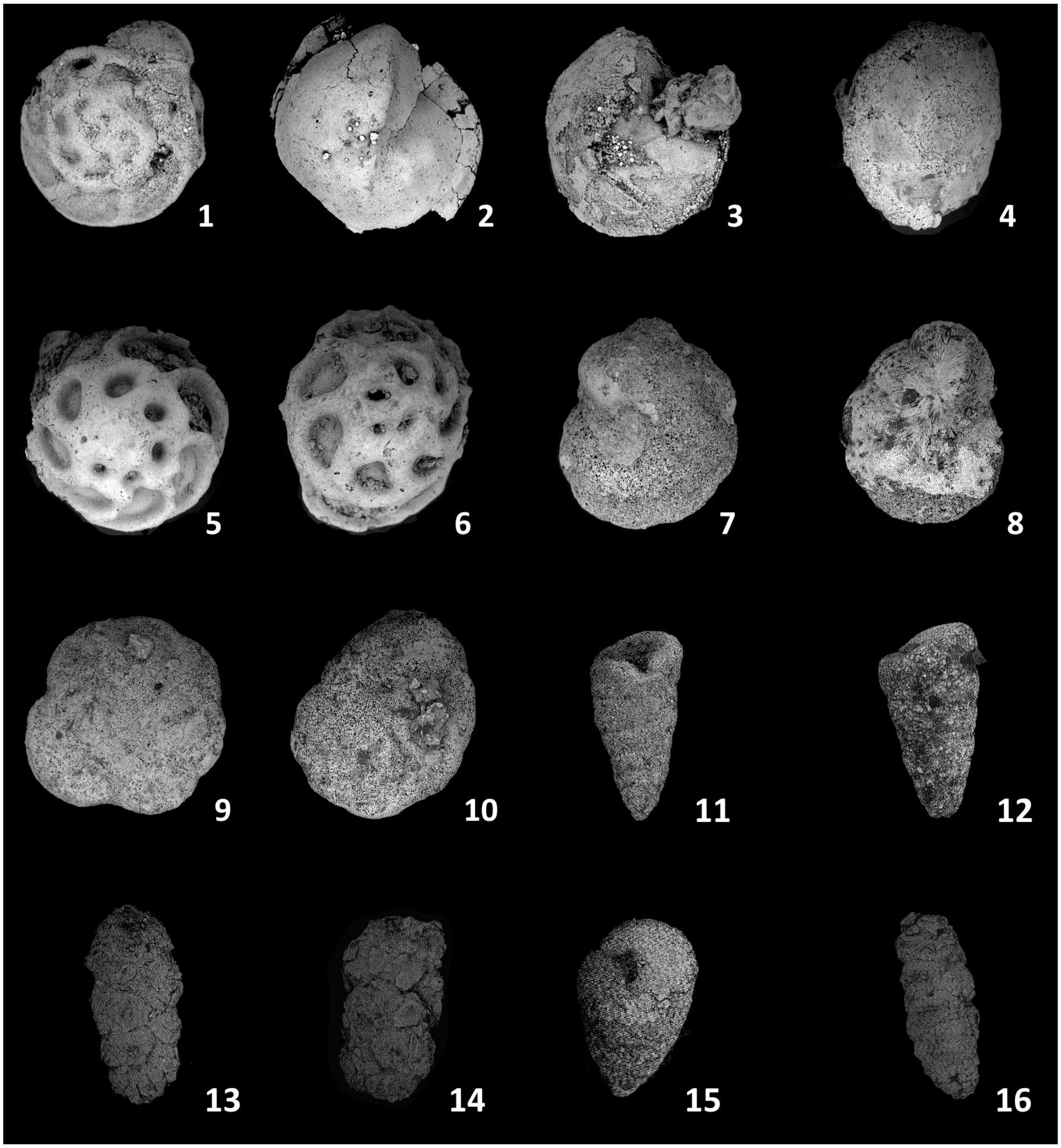


Plate 2. Measurements along the main axis or across the diameter, depending on the test's shape. 1 *Epistomina hechti* spiral side view, 310 µm (sample 127 m (416'), NF). 2 *E. hechti* umbilical side view, 310 µm; 3 *E. hechti* umbilical side view, 310 µm. 4 *Hoeglundina caracolla* spiral side view, 510 µm (sample C9C, FB). 5 *E. ornata* spiral side view, 760 µm (sample C2F, FB); 6 *E. ornata* spiral side view, 820 µm. 7 *G. sigmoicosta* umbilical side view, 440 µm (sample LB6, FB); 8 *G. sigmoicosta* umbilical side view, 360 µm. 9 *G. sigmoicosta* spiral side view, 420 µm; 10 *G. sigmoicosta* spiral side view, 510 µm. 11 *P. kummi* lateral view, 470 µm (sample C11A, FB); 12, *P. kummi* lateral view, 440 µm; 15 *P. kummi* top view at an angle, 310 µm. 13 *H. aequale* lateral view, 380 µm (sample C8B, FB); 14 *H. aequale* lateral view, 310 µm. 16 *G. dividens* lateral view, 420 µm (sample 84.7 m (278'), NF). NF stands for North Fordon, FB for Filey Bay.

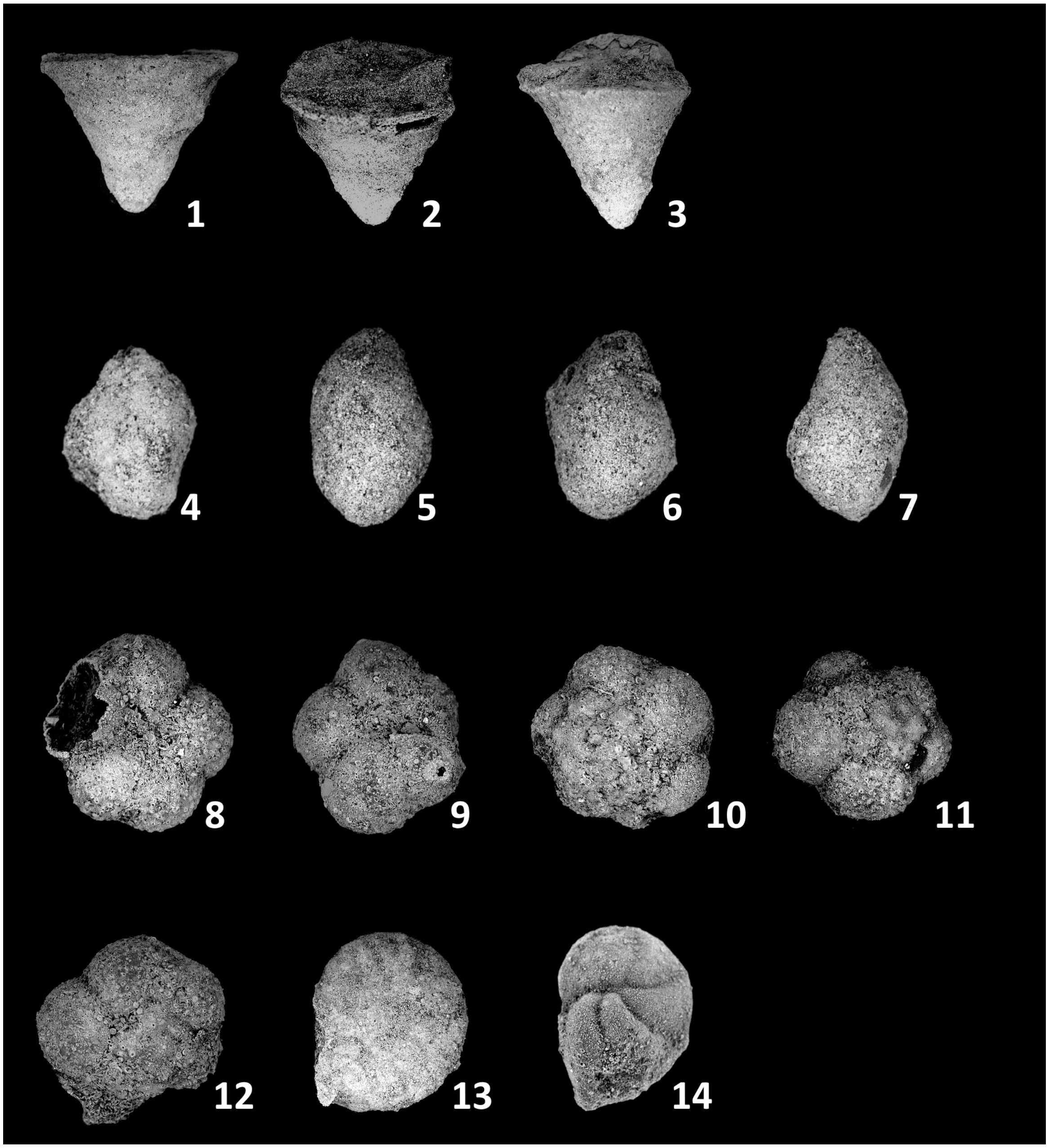


Plate 3. Measurements along the main axis or across the diameter, depending on the test's shape. 1 *P. kummi* lateral view, 1000 µm (sample 2324 m (7625'), NJ1); 2 *P. kummi* top view at an angle, 500 µm; 3 *P. kummi* top view at an angle, 1200 µm. 4 *F. praemoesiana* lateral view, 500 µm (sample 2320 m (7610'), NJ1); 5 *F. praemoesiana* lateral view, 600 µm; 6 *F. praemoesiana* lateral view, 700 µm; 7 *F. praemoesiana* lateral view, 600 µm. 8 *H. infracretacea* umbilical side view, 600 µm (sample 2271 m (7452'), NJ1); 9 *H. infracretacea* umbilical side view, 600 µm; 10 *H. infracretacea* spiral side view, 500 µm; 11 *H. infracretacea* spiral side view, 600 µm; 12, *H. infracretacea* spiral side view, 500 µm. 13 *G. barremiana* spiral side view, 900 µm (sample 2288 m (7507'), NJ1). 14 *L. muensteri* spiral side view, 1000 µm (sample 2328 m (7639'), NJ1).

7 List of Foraminiferal Species

- ***Ammobaculites* cf. *irregulariformis*** Bartenstein & Brand, 1951
  - ***obliquus*** Loeblich & Tappan, 1949
  - **sp.** Cushman, 1910
  - ***subcretaceus*** Cushman & Alexander, 1930
  - ***reophacoides*** Bartenstein, 1952
- ***Ammodiscus cretaceus*** (Reuss), 1845
- ***Ammosphaeroidina* sp.** Cushman, 1910
- ***Ammovertella cellensis*** Bartenstein & Brand, 1951
- ***Arenobulimina chapmani*** Cushman, 1936
  - **sp.** Cushman, 1927
- ***Astacolus* sp.** Montfort, 1808

- ***Bigenerina clavellata*** Loeblich & Tappan 1949
- ***Blefuscuiana aptiana orientalis*** BouDagher-Fadel, Banner, Gorbachik, Simmons, & Whittaker, 1996
  - ***rudis*** Banner, Copestake & White, 1993

- ***Citharina harpa*** (Roemer), 1841
  - ***pseudostriatula*** Bartenstein & Brand, 1951
  - ***sparsicostata*** (Reuss), 1863
- ***Conorboides hofkeri*** Bartenstein & Brand, 1951

intercedens	(Bettenstaedt), 1952
lamplughi	(Sherlock), 1914
valendisensis	(Bartenstein & Brand), 1951

Dentalina communis	(D’Orbigny), 1826
debilis	(Hantken), 1868
distincta	Reuss, 1860
terquemi	D’Orbigny, 1826

Eoguttulina oolithica	(Terquemi), 1874
Epistomina chapmani	Ten Dam, 1948
hechti	Bartenstein, Bettenstaedt & Bolli, 1957
ornata	Terquem, 1883
spinulifera spinulifera	(Reuss), 1863

Falsogaudryinella alta	Magniez-Jannin, 1975
praemoesiana	Kaminski, Neagu & Platon, 1995
sp.	Bartenstein, 1977
tealbyensis	Bartenstein, 1956
xenogena	Kaminski, Neagu & Platon, 1995
Frondicularia concinna	Koch, 1848
hastata	Roemer, 1842
inversa	Reuss, 1844

simplicissima	Ten Dam, 1946

Gaudryinella sherlocki	Bettenstaedt, 1952
Gaudryina dividens	Grabert, 1959
Gavelinella baltica	Brotzen, 1942
barremiana	Bettenstaedt, 1952
brielensis	
intermedia	Berthelin, 1880
sp.	Brotzen, 1942
sigmoicosta	(Ten Dam), 1948
stelligera	(Marie), 1941
Gavelinopsis touranensis	
Globulina prisca	(Reuss), 1863
Glomospira charoides	(Jones & Parker), 1860
gordialis	(Jones & Parker), 1860
Glomospirella gaultina	(Berthelin), 1880

Haplophragmium aequale	(Roemer), 1841; em. Bartenstein, 1952
sp.	Reuss, 1860
Haplophragmoides cushmani	Loeblich & Tappan, 1946
aff. *globosa*	Lozo, 1944
nonionoides	Reuss, 1863
sp.	Cushman, 1910

Hedbergella aptiana	Bartenstein, 1965
excelsa	Longoria, 1974
infracretacea	Glaessner, 1937
kuznetsovae	(Banner & Desai), 1988
speetonensis	(Banner & Desai), 1988
Heterantyx cretosa	(Ten Dam), 1950
Heterohelix moremani	(Cushman), 1938
Hoeglundina caracolla	(Roemer), 1841
Lagena hauteriviana	Bartenstein & Brand, 1951
hispida	Reuss, 1863
sp.	Walker & Jacob, 1798
cf. *sulcata*	Walker & Jacob, 1798 (sensu Fletcher 1966)
Lagenammina lagenoides	(Crespin), 1953
Lenticulina bronnii	(Roemer), 1841
circumcidanea	(Berthelin), 1880
forticosta	(Bettenstaedt), 1952
cf. *jarvesi*	
gaultina	(Berthelin), 1880
guttata	(Ten Dam), 1946
heiermanni	Bettenstaedt, 1952
humilis praecursora	(Bartenstein & Brand), 1951
inflata	(Reuss), 1860

muensteri	(Roemer), 1839
ouachensis wisselmanni	(Sigal), 1952
pachynota	(Ten Dam), 1946
saxonica	Bartenstein & Brand, 1951
schlönbachi	(Reuss), 1860
schreiteri	(Eichenberg), 1935
sp.	Lamarck, 1804
Lingulina hauteriviana	Fletcher, 1966
***Lingulina* sp.**	D'Orbigny, 1826 (sensu Fletcher, 1966)
Lingulonodosaria nodosaria	(Reuss), 1863
***Lituotuba* sp.**	Rhumbler, 1895
Marginulina costata	(Batsch), 1791
Marginulinopsis foeda	(Reuss), 1863
gracilissima	(Reuss), 1863
striatocostata	(Reuss), 1863
robusta	(Reuss), 1863
Marssonella kummi	Zedler, 1961
Nodosaria obscura	Reuss, 1845
pyramidalis	Koch, 1848
sceptrum	(Reuss), 1863
cf. *regularis*	Terquem, 1862

reightonensis	Fletcher, 1966

Paalzowella feifeli	(Paalzow), 1932
Palmula malakialinensis	(Espitalié & Sigal), 1963
Planularia crepidularis	(Roemer), 1842
***Praebulimina* sp.**	Hofker, 1953
cf. *reussi*	(Morrow), 1934
Protomarssonella kummi	Zedler, 1961
aff. oxycona	(Reuss), 1860
sp.	Desai & Banner, 1987
***Psammosphaera* sp.**	Schulze, 1875
Pseudonodosaria vulgata	(Bornemann), 1854
humilis	(Roemer), 1841
radiata	(Barnard), 1952
Pyrulina cylindroides	(Roemer), 1838

Quinqueloculina antiqua	(Franke), 1928

Ramulina fusiformis	Khan, 1950
spandeli	Paalzow, 1917
***Recurvoides* sp.**	Earland, 1934
Reophax minuta	Tappan, 1940
sp.	Montfort, 1808

Rhabdammina cylindrica	Glaessner, 1937

Textularia bettenstaedti	Bartenstein & Oertli, 1977
foeda	Reuss, 1846
sp.	De France, 1824
***Thalmannammina* sp.**	Pokorný, 1951
Tritaxia capitosa	(Cushman), 1933
pyramidata	(Reuss), 1863
Tristix acutangula	(Reuss), 1863
insignis	(Reuss), 1863
Trochammina depressa	Lozo, 1944
sp.	(Parker & Jones), 1859
Trochamminoides* cf. *goudkoffi	Dailey, 1970
sp.	Cushman, 1910
Trocholina feifeli	Paalzow, 1932

Vaginulina arguta	Reuss, 1860
mediocarinata	Ten Dam, 1950
striolata	Reuss, 1860
Vaginulinopsis humilis praecursora	(Bartenstein & Brand), 1951
Valvulineria gracillima	Ten Dan, 1947
Verneuilina muensteri	Reuss, 1854
Verneuilinoides neocomiensis	Myatlyuk, 1939

Vidalina carpathica Gaździcki, 1979

Lingula ovalis Reeve, 1841 (brachiopod)

8 List of References

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