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Foraminifera and sequence stratigraphy of the lower part of the Speeton Clay Formation (Lower Cretaceous) in N. E. England

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(With 9 figures)

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Abstract

The Speeton Clay Formation is exposed in the cliffs north of Flamborough Head in N. E. England. The formation ranges in age from Ryazanian to the Albian but is often poorly exposed in the sea cliffs and on the foreshore. In the lower part of the succession (Ryazanian – Barremian) the foraminiferal assemblage is dominated by long-ranging nodosariids although, at some levels, the fauna is dominated by monospecific assemblages of epistominiids. The diversity of the total foraminiferal assemblage varies throughout the succession, with the maximum diversity being recorded in the Late Hauterivian. Using information from (i) diversity, (ii) distribution of epistominiids, (iii) glauconite and (iv) pyrite it is possible to identify potential sequence boundaries in the Late Ryazanian (~138 Ma), Early Valanginian (~136 Ma), mid-Hauterivian (~129 Ma) and Early Barremian. These four events are very close in age to the events (K20, K30, K40 and K50) originally described by SHARLAND and co-workers in Arabia.

Keywords: Foraminifera, Speeton Clay Formation, Sequence Stratigraphy, taphonomy.

Introduction

The Speeton Clay Formation is about 100 metres thick at its type locality in Filey Bay (Fig. 1) but thickens inland to ~360 m in the Fordon No. 1 borehole about 4.4 km west of Speeton (DILLEY, in discussion of NEALE 1968). South of the present outcrop, seismic data indicate a thickness of ~1 km before thinning towards the Market Weighton High (KIRBY & SWALLOW 1987; RAWSON 2006). Off-shore, in the North Sea Basin thicknesses of 100–170 m are normally recorded (RAWSON et al. 1978; CAMERON et al. 1992, fig. 79) although <900 m are recorded near the Dowsing Fault Line (CAMERON et al. 1992). In the well-known Filey Bay succession all six Lower Cretaceous stages are represented although the Valanginian, Aptian and Albian successions are much reduced by non-sequences and erosional features. The dominantly argillaceous succession is badly affected by folding, faulting and landslides, and surfaces are frequently obscured by downwash. The most reliable sections are found on the foreshore when a combination of favourable tides and wind has removed beach sand and shingle.

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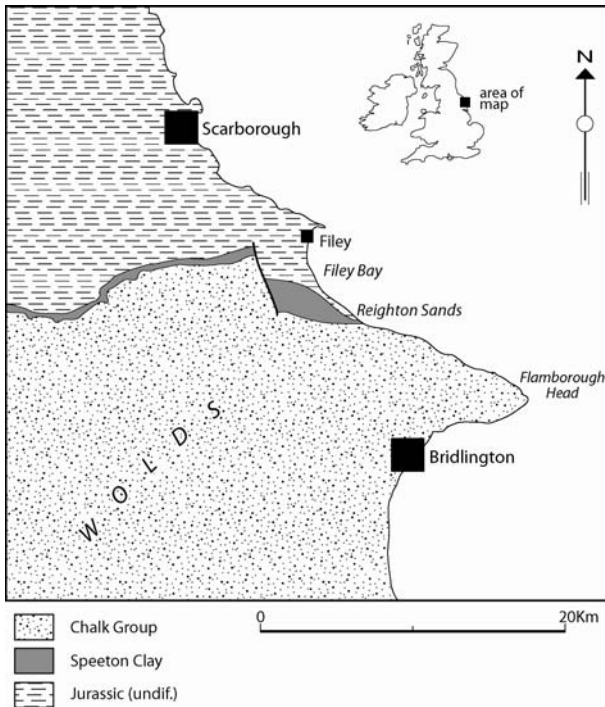


Fig. 1: Location of the Filey Bay succession of the Speeton Clay Formation in N. E. England.

Within the overall clay succession are thin, phosphatic nodule beds and concentrations of glauconite which may represent significant pauses in sedimentation. Some of the clays are distinctly mottled (by chondritiform burrow systems), while in places there are silt layers and distinctive colour changes. Some of these pale (more calcareous)/dark (less calcareous) rhythmic alternations are best seen in the top C Beds and lowest B Beds (near the Hauterivian/Barremian boundary) and may represent Milankovitch precession cycles (22,300 years: see RAWSON & MUTTERLOSE 1983).

One of the earliest descriptions of the Speeton Clay Formation was by LECKENBY (1859), closely followed by JUDD in 1868. Late in the nineteenth century LAMPLUGH (1889) subdivided the succession into four units, each of which was represented by a letter (A – D, with the D Beds at the bottom and the A Beds at the top). Each of the identified units was recognised by the presence of a diagnostic belemnite and so this lettering scheme was not a genuine lithostratigraphical sub-division of the formation. Bed E was identified as the thin phosphatic “Coprolite Bed” that forms the base of the succession and which rests non-conformably on the Kimmeridge Clay Formation (Upper Jurassic). Subsequent work by ENNIS (1937), NEALE (1960a, 1962a), KAYE (1964) and FLETCHER (1969) has refined the lithological subdivisions of the lettered units. The ammonite fauna has been described by LAMPLUGH (1924), NEALE (1962a), RAWSON (1971a, b, 1975), RAWSON et al. (1978), KEMPER et al. (1981) and DOYLE (1989) but taxa are relatively rare except in the Hauterivian. Belemnites, however, are relatively common throughout the succession and have been described by LAMPLUGH (1889, 1924),

SWINNERTON (1936), SPAETH (1971), PINCKNEY & RAWSON (1974), PINCKNEY (1975), RAWSON & MUTTERLOSE (1983), MUTTERLOSE et al. (1987) and MUTTERLOSE (1990).

The first systematic description of the foraminifera was by SHERLOCK (1914), who compared the fauna with the Gault Clay Formation of Folkestone (Kent, S. E. England), the Hils Clay of Germany (HECHT 1938; BARTENSTEIN & BETTENSTAEDT 1962), the Gault Clay Formation of Montcley, France (BERTHELIN 1880) and the Recent foraminifera collected during the HMS *Challenger* Expeditions. A later paper by KHAN (1962) compared the foraminifera of the Speeton Clay Formation with comparable successions in Germany, but the imprecise location of the samples used in this investigation has rendered this work of limited value.

The ostracod fauna, which is quite diverse and abundant, has been described by NEALE (1960b, 1962b, 1968, 1973, 1978). The calcareous nannofossil assemblage has been described by BLACK (1971), SISSINGH (1977), PERCH-NIELSEN (1979) and TAYLOR (1978a, b, 1982).

Distribution of the foraminifera

It has been suggested that water depths during the deposition of the lower part of the Speeton Clay Formation may have been less than 100 m (RAWSON 2006, p. 375). Some horizons, in the D Beds (e.g., D5) may either have been shallower as suggested by the presence of *Lingula*, or almost anoxic as indicated by the presence of abundant pyrite (including infilled burrow systems). In such shallow shelf successions the foraminiferal morphogroups present do not show the variability seen in, for example, the Brazilian Continental Margin (KOUTSOUKOS & HART 1990). Analysis of the fauna using alpha diversity and triangular diagrams (MURRAY 1991, pp. 313-322) has also proven to be ineffective in this succession. The dominant assemblage is one of relatively long-ranging nodosariids (especially *Lenticulina* and *Citharina*) with smaller numbers of agglutinated taxa. In some horizons the assemblage can, however, contain ~95 % *Epistomina* and/or *Hoeglundina*.

Our knowledge of the foraminifera is limited with the only major investigation being that of FLETCHER (1966) which remains largely unpublished. FLETCHER (1973) provided a summary of his research, presenting data on the distribution of the foraminifera in the Speeton Clay Formation (bed-by-bed), though no taxa were illustrated. Some of this information was used by HART et al. (1982, 1989) in a summary of Cretaceous foraminifera, which was supplemented by some additional collecting by MBH in 1977 and a study of borehole material in the collections of the late Professor J. W. NEALE (Hull University). The material used by FLETCHER, in the collections of Hull University, has also been consulted and this provided some of the specimens used to illustrate HART et al. (1982, 1989). The diversity information presented here is based on the species identifications of MBH, after consultation with Dr B. N. FLETCHER and Prof. J. W. NEALE. The samples prepared by FLETCHER were washed on a 75µm sieve, while the additional samples prepared by MBH used the "white spirit" method (BRASIER 1980) and were also washed on a 75µm sieve (the norm in the 1960s and 1970s). In 1988 CRITTENDEN (in an unpublished PhD thesis) described the fauna of the Speeton Clay Formation in the Southern North Sea Basin, although the bulk of the fauna was not illustrated by SEM photographs. BANNER & DESAI (1988) have described the planktic foraminifera from the Aptian and

Albian succession in N. E. England, although planktic taxa have not been described from the Ryazanian (Berriasian) to Barremian part of the Speeton Clay Formation.

Sequence Stratigraphy

Sequence stratigraphy was developed in the 1970s and, initially, used for the interpretation of seismic profiles. VAIL et al. (1977) developed the concept, extending it to allow the inclusion of borehole and outcrop data. The hypothesis was that short-term fluctuations in sea level generate “sequences” or “genetically related strata bounded by unconformities or their correlative conformities” (VAN WAGONER et al. 1988, p. 39). Sequence stratigraphy quickly developed a relatively complicated terminology of systems tracts. This “Exxon Model” of a sequence must not be confused with the “Galloway Model”, which uses the Maximum Flooding Surface (rather than the Sequence Boundary) as the key to sequence identification (GALLOWAY 1989a, b) or the “Einsle Model” which is based on the recognition of transgressive/regressive cycles (EINSLE & BAYER 1991).

The “Exxon Model” was used by EMERY & MYERS (1996) in their interpretation of sequences and the palaeontological signal that would be left in the fossil record (Fig. 2). As there are no planktic taxa in the lower levels of the Speeton Clay Formation in the Filey Bay section only the pattern left by the benthic taxa is relevant. In this, parts of the Lowstand Systems Tract (LST) would have a reduced diversity while the maximum diversity would be expected around the Maximum Flooding Surface (MFS) or “Zone of Maximum Flooding” (*sensu* MONTANEZ & OSLEGER 1993; STRASSER et al. 1994,

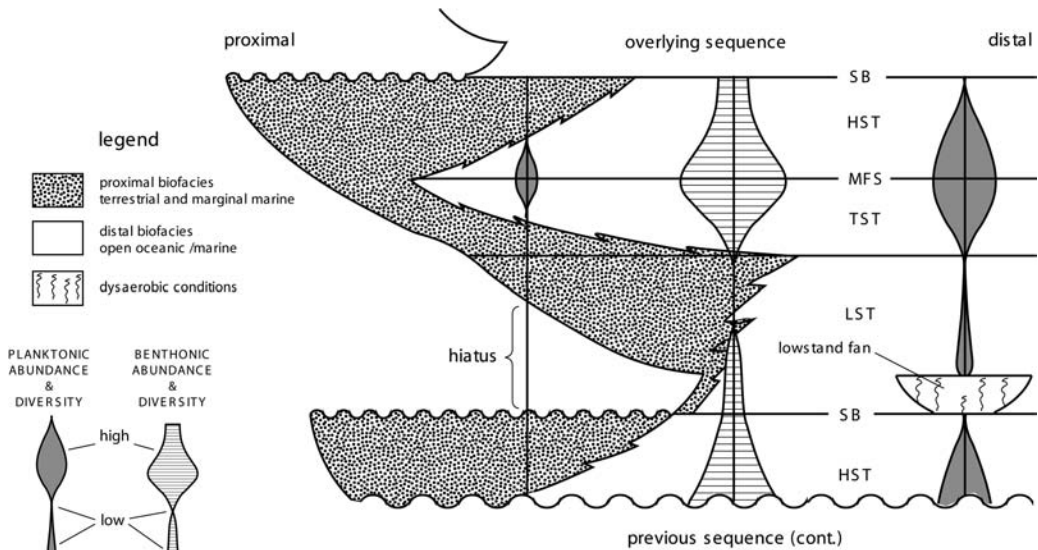


Fig. 2: The “Exxon Model” of a sequence (based on EMERY & MYERS 1996, fig. 6.14a) and the hypothetical distribution of benthic and planktic foraminifera. The planktic foraminifera are most abundant (and diverse) in the region of the MFS with deeper-water morphotypes being found in more distal regions while only surface-water morphotypes are to be found in more proximal environments.

1999; OLIVER 1998). The MFS coincides with the most landward distribution of diverse, open marine, plankton and a diversity maximum of benthic taxa. This approach has been used effectively in younger rocks, most notably in the Cenozoic sediments of the Gulf of Mexico (SHAFFER 1987, 1990; ARMENTROUT 1987, 1991; ARMENTROUT & CLEMENT 1990; ARMENTROUT et al. 1990, 1999; PACHT et al. 1990; VAIL & WORNARDT, 1990; VAN DER ZWAN & BRUGMAN 1999). Recently a number of other authors have extended this approach to the interpretation of Mesozoic successions (OLSSON 1988; CUBAYNES et al. 1990; SIMMONS et al. 1991; POWELL 1992; HART 1997, 2000; HENDERSON 1997; HENDERSON & HART 2000; OXFORD et al. 2000, 2004; SHARLAND et al. 2000).

The Speeton Clay Formation has been investigated, often indirectly, for its record of Early Cretaceous sequences and changes in sea level. Some of this research (MITCHELL & UNDERWOOD 1999; UNDERWOOD & MITCHELL 1999; RÜCKHEIM et al. 2006) has been focussed on the upper part of the formation which is Barremian to Albian in age. The lower part of the formation (Berriasian to Barremian in age) has been studied by RAWSON & RILEY (1982), COPESTAKE et al. (2003) and HOEDEMAEKER & HERNGREEN (2003). The interpretations of the latter authors appear to have been driven by parallel work on the Río Argos (S. E. Spain) succession by HOEDEMAEKER (1995) and HOEDEMAEKER & LEEREVELD (1995). The Río Argos succession investigated by Hoedemaeker (and P. R. Vail – though not listed as a co-author on the 1995 paper) is a very complete, fossiliferous succession dominated by limestone/marlstone cycles that are driven by Milankovitch periodicities (TEN KATE & SPRENGER 1989). It is quite difficult to follow the reasoning behind Hoedemaeker's selection of systems tracts and, in the paper with Leereveld, there is no indication of the sequence boundaries that appear in HOEDEMAEKER (1995, fig. 1). This interpretation identified major (= long term) sequence boundaries in the early to mid-Berriasian, late Berriasian, mid-Valanginian, mid-Hauterivian, late Hauterivian and early to mid-Barremian. These major events appear to be those used by HOEDEMAEKER & HERNGREEN (2003, foldout chart). HOEDEMAEKER & HERNGREEN (2003, p. 261) also indicate that Hoedemaeker had used the foraminiferal data of FLETCHER (1973) and the ostracod data of NEALE (1962b) in his (HOEDEMAEKER 1998, 2002) interpretation of the D Beds of the Speeton Clay Formation. This appears to be the only reference to the use of microfossils in the interpretation of the sequence stratigraphy in the lower part of the Speeton Clay Formation.

The MFS is usually identified as the most clay-rich part of the sequence (EMERY & MYERS 1996), often identified in well logs by the presence of a higher gamma-ray record. This clay-rich environment will leave a very different faunal signal, compared with silts or sands elsewhere in the succession. How this faunal signal is interpreted is now described.

Interpretation of the benthic fauna

Any fauna recorded in geological samples is the result of:

- The initial fauna that was living on or within the sediment;
- Post-mortem taphonomy (including transport in and transport out);
- Diagenesis and compaction;
- Changes during burial and geological time; modern weathering and exhumation (if not collected from the subsurface); and
- Errors introduced during sampling, processing and analysis.

In order to understand the processes involved in the distribution of benthic foraminifera within sequences we have investigated the controls on a modern assemblage and then attempted to understand the anticipated post-depositional changes.

Plymouth Sound – a modern analogue

In Plymouth Sound, a large drowned valley system on the Devon/Cornwall boundary in S. W. England we have, over a number of years, collected sea floor samples from fixed sites and documented the changes in the benthic foraminifera from 1973 onwards and over annual cycles (1994–1996 and 2007–2008). All samples collected in this on-going project were placed in buffered formalin on the boat and then washed and stained with rose Bengal (to identify the “living” foraminifera) within a few hours. In Figure 3 it can be seen that the sites cover a range of substrates, including sand, sand waves, shell gravel, mixed mud/sand/gravel and mud. When the diversity and annual production are calculated for these sample sites the data are quite interesting (Fig. 4). Sample 9

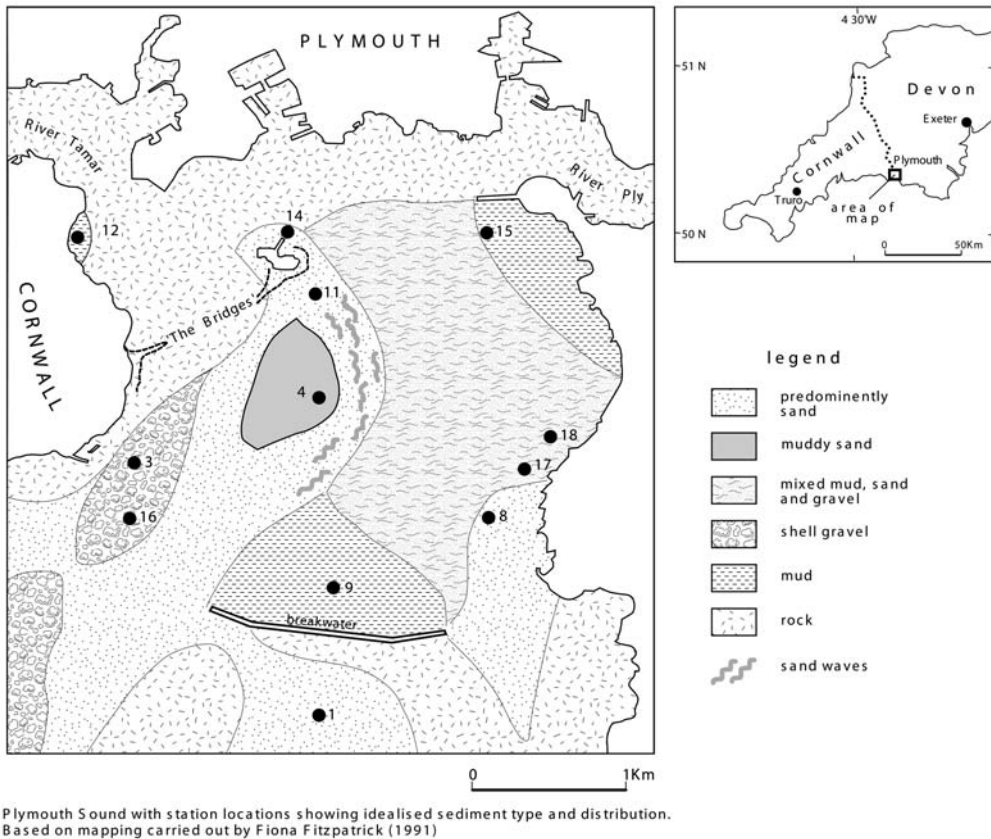


Fig. 3: Sediment distribution map of Plymouth Sound and the location of some of the sampling sites used in the monthly analysis (1994–1996) of the benthic foraminifera (after CASTIGNETTI et al. 2000)

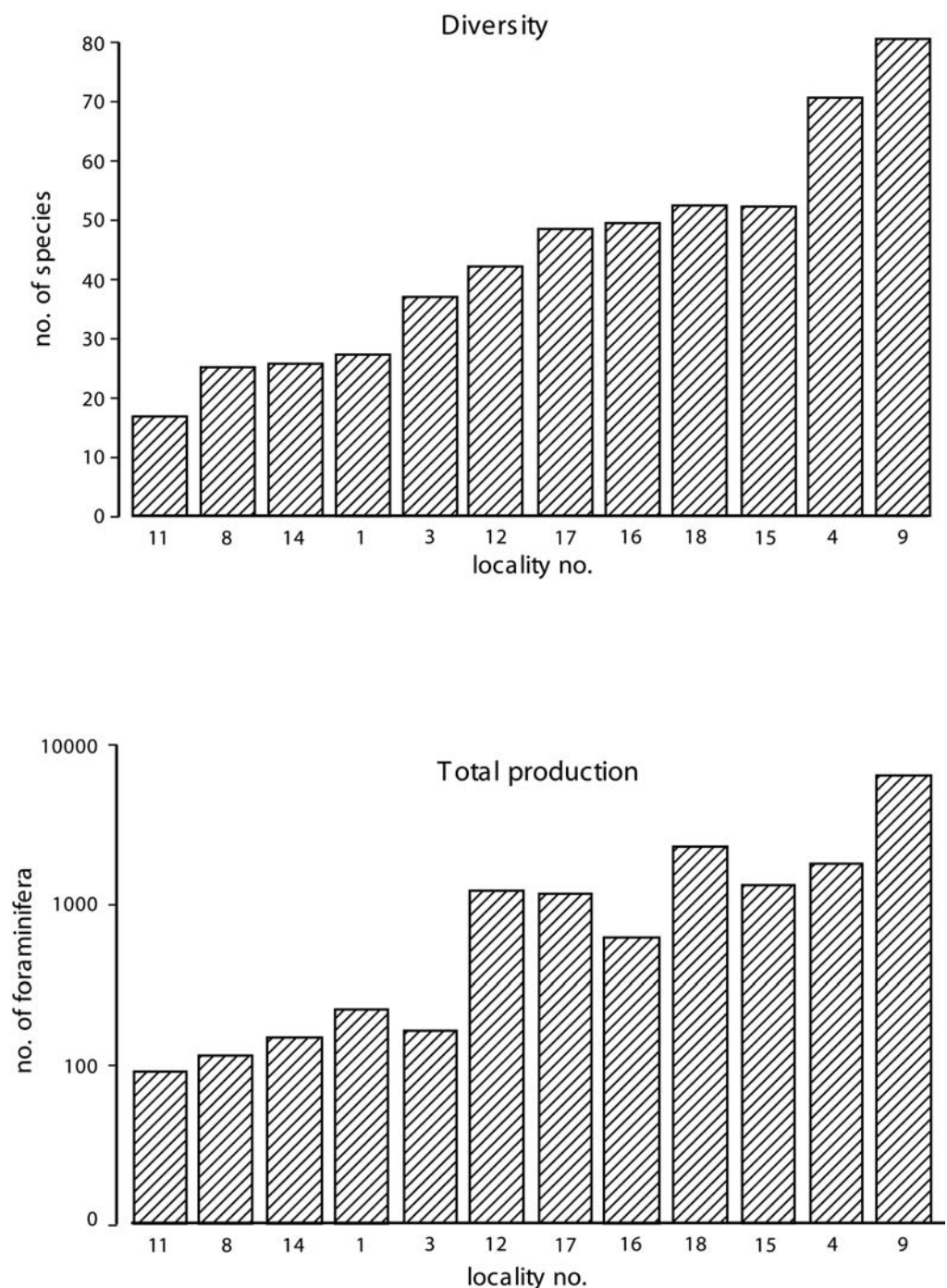


Fig. 4: Graphical plots of annual species diversity and annual total production of benthic foraminifera for the sites indicated in Figure 3 (after CASTIGNETTI 1997). Note the logarithmic scale for the numbers of foraminifera in the graph for Total Production.

(mud) records the highest diversity while the sand wave environment is the lowest with other sand environments also recording low values. The graphs for total annual production, though not quite identical, provide a very similar pattern between the mud (highest) and sands (lowest).

As in all ecological studies the controls on the fauna are complex but it is clear that in the nutrient-rich clays there is an abundant, diverse fauna with the nutrient-poor sands supporting only a poor, *in-situ* living fauna. It is also clear that the faunas in the clay-rich environments will be enhanced by the slow rate of sedimentation and that any micropalaeontological sample from a geological succession must include a significant number of yearly standing crops compared with the dilution effect of the higher rates of sedimentation in the more sand-rich environments. Compaction will further accentuate this situation with clays often being subjected to 50 % reduction in thickness as water is removed. This compaction can be evidenced in the Speeton Clay Formation by the generally compressed nature of the agglutinated taxa (e.g., *Ammobaculites*, *Haplophragmoides*, etc.).

In recent years a number of investigations of the preservation potential of foraminifera have been undertaken by MURRAY (1989), ALVE & MURRAY (1995) and MURRAY & ALVE (2000). It is particularly noted by MURRAY & ALVE (2000) that high diversity agglutinated assemblages can be derived from high diversity assemblages dominated by calcareous taxa through the selective dissolution of the calcareous component over time. This process will particularly impact on the aragonitic taxa and, in the Jurassic and Cretaceous, the epistominids will often only be recorded in the dense, clay-rich parts of the succession that have acted as aquacludes to ground water movement (Fig. 5). In some parts of this, and other, clay successions epistominids are also preserved as pyrite steinkerns or, even when the outer test survives, an infilling of pyrite. Deposition of pyrite within the tests of foraminifera is normally limited to organic-rich clay environments.

Using the model shown in Figure 5 it is relatively simple to argue that the EMERY & MYERS (1996, fig. 6.14a) interpretation of faunas in an idealised sequence is correct and that, in geological settings, we should expect both variation in diversity, quality of preservation (including collapsed agglutinated taxa) and a presence/absence of aragonitic taxa.

Foraminifera in the Speeton Clay Formation

As indicated above, the lower part of the Speeton Clay Formation contains a quite diverse assemblage of benthic foraminifera. The fauna is dominated by *Lenticulina* spp. many of which are well-known across Eastern England, the North Sea Basin (CRITTENDEN 1988) and North Germany (see HECHT 1938; BARTENSTEIN & BETTENSTAEDT 1962). Other wide-ranging, diagnostic taxa are members of the Superfamily Ceratobuliminacea (*Epistomina* and *Hoeglundina*); both of which have aragonitic tests. As shown in Figure 6, many of these aragonitic species are relatively well-preserved, although many are in-filled with pyrite (also an indicator of organic-rich, clay environments).

When the species diversity data for the lower part of the Speeton Clay Formation are plotted (Fig. 7) it is evident that there are two main "cycles". One is Lower to mid-

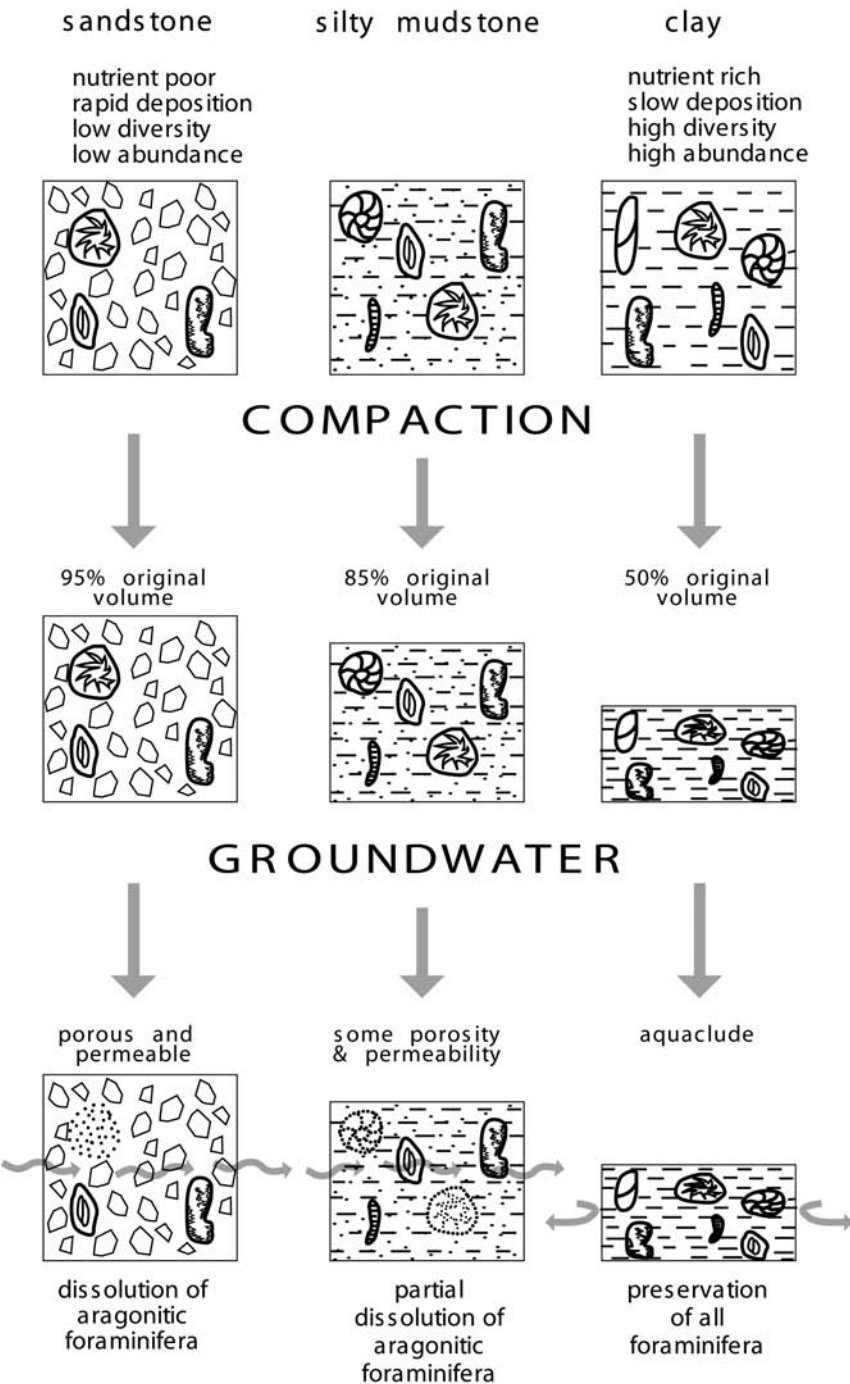


Fig. 5: Theoretical model for the history of a "sample" from deposition to final collection, showing the effects of taphonomy, compaction and dissolution by groundwater flow (after OXFORD et al. 2004).

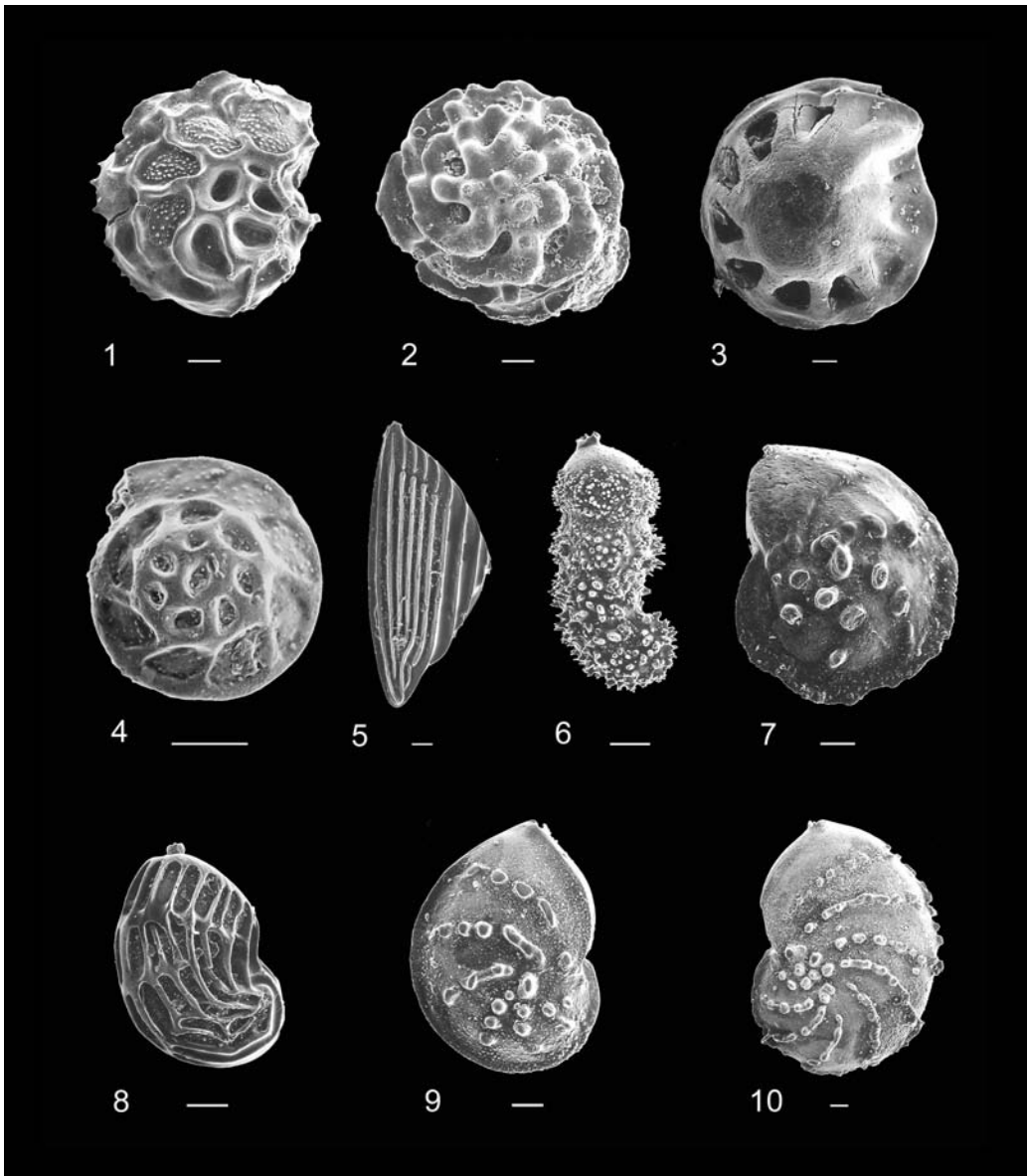


Fig. 6: Representative species of foraminifera from the Speeton Clay Formation, Filey Bay, N. E. England. (1) *Epistomina ornata* (ROEMER), Hauterivian (Bed C4); (2) *Epistomina ornata* (ROEMER), Hauterivian (Bed C4); (3) *Hoeglundina caracolla* (ROEMER), Barremian (Bed LB4D); (4) *Epistomina hechti* BARTENSTEIN & BOLLI, Barremian (Bed LB2); (5) *Citharina harpa* (ROEMER), Hauterivian (Bed C4E); (6) *Marginulinopsis foeda* (REUSS), Hauterivian (Bed C4C); (7) *Lenticulina eichenbergi* BARTENSTEIN & BRAND, Hauterivian (Bed C7); (8) *Lenticulina schreiteri* (EICHENBERG), Hauterivian (Bed C2F); (9) *Lenticulina guttata* (TEN DAM); and (10) *Lenticulina guttata* (TEN DAM), Hauterivian (Bed C3). All of the scale bars represent 100 μ m. The figured specimens (and other material from the Speeton Clay Formation) are in the Micropalaeontology Collections (under the heading "Stratigraphic Index of Fossil Foraminifera") of the University of Plymouth.

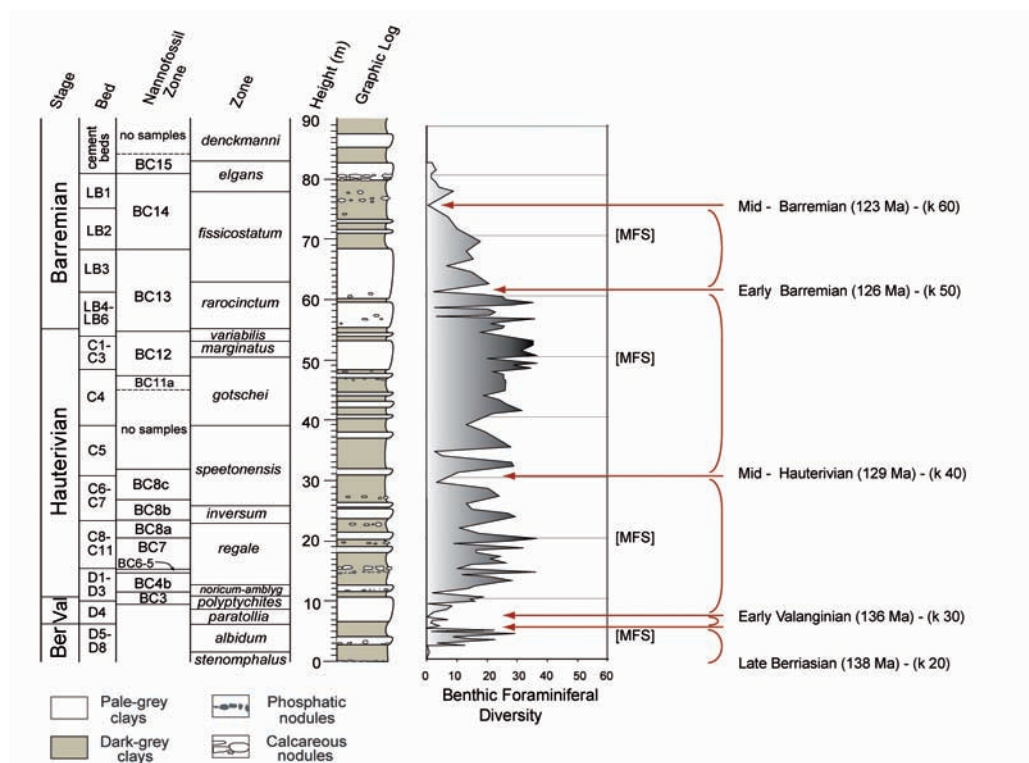


Fig. 7: The Speeton Clay Formation in the Filey Bay succession, including lithostratigraphy, biostratigraphy, species diversity of benthic foraminifera and interpretation of the sequence stratigraphy. The “no samples” marked in the calcareous nannofossil column refers (here and in Figs 8, 9) to samples solely for nannofossil work and not samples for stable isotopes or foraminifera.

Hauterivian with another in the mid-Upper Hauterivian, with a (?) sequence boundary in the mid-Hauterivian (~129 Ma) which appears close to the SHARLAND et al. (2001) K40 event. This is, almost certainly, the mid-Hauterivian event identified by RAWSON & RILEY (1982) and close to the mid-Hauterivian discontinuity identified by HOEDEMAEKER & HERNGREEN (2003). The end of the upper cycle appears to be in the Early Barremian (~126 Ma), with another sequence boundary a little higher in the mid-Barremian (~123 Ma). Both of these events appear to be close to K50 and K60 of the SHARLAND et al. (2001) model and some of the sequence boundaries and maximum flooding events identified by COPESTAKE et al. (2003).

There is a fairly prominent maximum flooding event in the latest Berriassan/Ryazanian (*Peregrinoceras albidum* Zone) followed by a regression or sequence boundary in the earliest Valanginian (~136 Ma = K30). While we have no desire to overplay what the foraminiferal distribution tells us, it does appear to be the case that the major cycles (sequences) are in some agreement with other Lower Cretaceous data. The pattern recorded by the foraminifera also confirms why the ammonites are largely seen in the Hauterivian as that appears to be the most “open” marine part of the succession

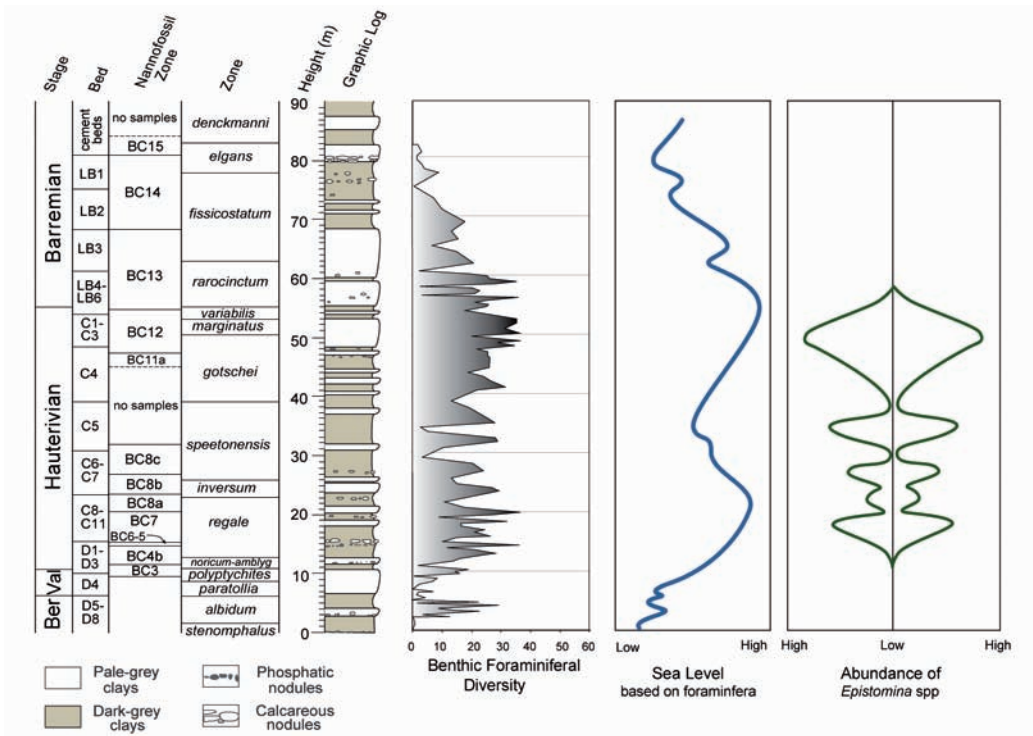


Fig. 8: The Speeton Clay Formation in the Filey Bay succession, including lithostratigraphy, biostratigraphy, diversity of benthic foraminifera, suggested sea level changes and schematic distribution of *Epistomina* and *Hoeglundina*.

(Fig. 8). This is supported by the distribution of the aragonitic foraminifera, which reach their maximum levels of abundance in the Hauterivian and earliest Barremian. The distribution of *Epistomina* and *Hoeglundina* in the sequences identified here is comparable to that recorded by OXFORD et al. (2004) in the Oxfordian (Jurassic). Using the diversity data and the known distribution of taxa (FLETCHER 1973; HART et al. 1989) it is possible to interpret the sea level changes in a general way (Fig. 7). There is, in this interpretation, a relatively close correspondence with some of the transgressive/regressive cycles identified by DE GRACIANSKY et al. (1998, chart 4).

Stable isotope stratigraphy

Figure 9 shows the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data (from PRICE et al. 2000; MCARTHUR et al. 2003), together with the diversity curve. The carbon isotope profile shows a clear trend through the studied section from $\delta^{13}\text{C}$ values around 0.0‰ during the early Valanginian (*Paratollia*–*Polyptychites* beds) to more positive values during the early Hauterivian interval. Such an abrupt change in $\delta^{13}\text{C}$ values, a characteristic feature of a stratigraphic break, maybe correlated with the late Valanginian-early Hauterivian positive carbon isotope event observed by WEISSERT (1989). The Valanginian positive carbon isotope excursion

has been related to episodes of platform drowning within Tethys whereby the leaching of nutrients on coastal lowlands during a rise in sea-level resulted in increased ocean fertilization, productivity and an expansion of the oxygen minimum zone (e.g., WEISSERT 1989). This, in turn, leads to global sea-waters enriched in $\delta^{13}\text{C}$. Such a trend is consistent with the sea level curve based on foraminiferal diversity data and the known distribution of taxa. What is more difficult to reconcile is the oxygen isotope data and sea level curve. Increasingly negative $\delta^{18}\text{O}$ carbonate values can be related to elevated temperatures in environmental settings where continental ice volume is at a minimum and evaporation or freshwater input are minor factors. Hence assuming that these conditions apply, from the Valanginian through into the Hauterivian oxygen isotope values become more positive, possibly indicative of cooling and decrease to more negative values in the Barremian (i.e., warming). The postulated sea level curve would, however, appear to suggest the opposite and this discrepancy has yet to be resolved. It may simply be a function of the scale of the relatively minor sea level changes involved. The mid-Barremian is also a time of plate re-adjustment in North West Europe (e.g., opening of the Bay of Biscay).

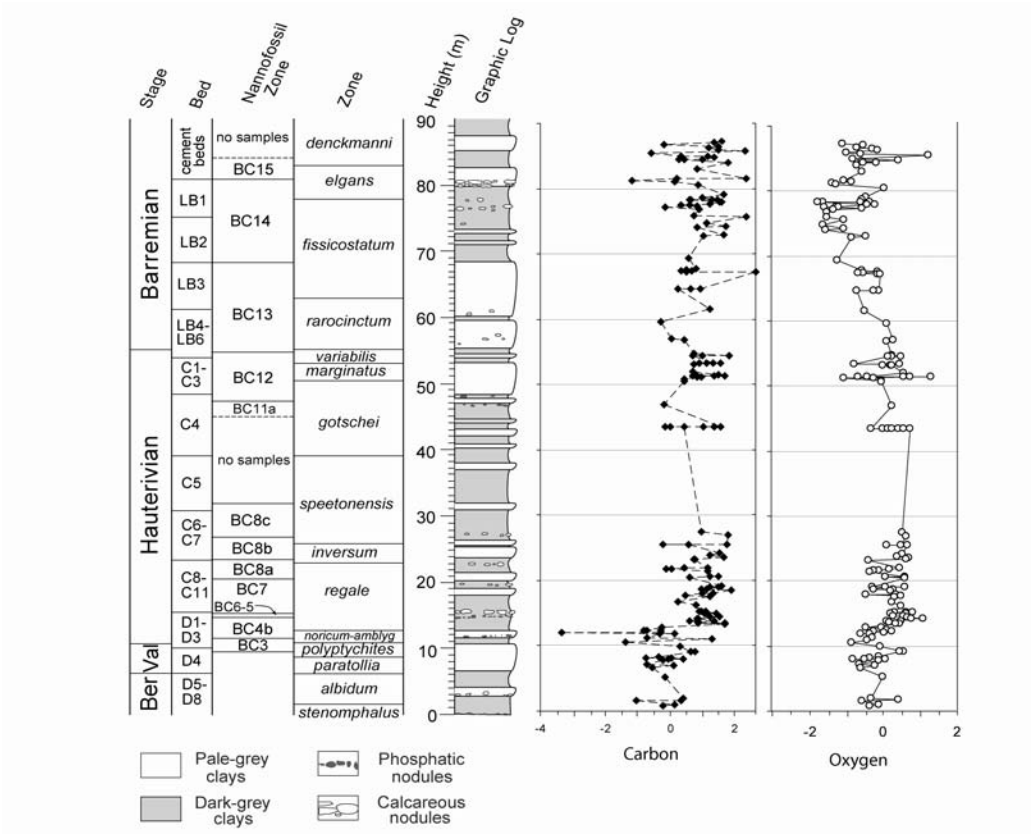


Fig. 9: The Speeton Clay Formation in the Filey Bay succession, including lithostratigraphy, biostratigraphy and the carbon and oxygen stable isotope data (from PRICE et al. 2000; McARTHUR et al. 2003).

Summary

The distribution of benthic foraminifera in the Speeton Clay Formation does appear to record the major sequences (sequence boundaries and “zones” of maximum flooding). While not perfect, the resulting pattern does seem to show some agreement with other interpretations of the succession. The recorded pattern has been discussed in the light of on-going research on modern environments and a model is presented for discussion. The very “spiky” nature of the diversity curve is what was found by OXFORD et al. (2004) in Oxfordian strata on the Dorset Coast and it either represents “noise” in the diversity graph or, more significantly, parasequences that would require very close sampling to resolve.

Acknowledgements

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