Foraminiferal assemblages from the late Lower and Middle Cenomanian of Speeton (North Yorkshire, UK): relationships with sea-level fluctuations and watermass distribution

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ABSTRACT - Twenty-seven marl samples from the late Lower and Middle Cenomanian of Speeton (North Yorkshire, UK) have been studied and six benthic foraminiferal assemblages (A to F) have been recognized by cluster analysis. These assemblages can be classified according to their constituent agglutinated foraminifera. Assemblages characterized by high abundances of non-calcareous agglutinates (A and E) have low numbers of planktics and are associated with cold-water pulse faunas of mid Russian affinity (belemnites, brachiopods and bivalves). These are interpreted as representing a cold North Sea watermass. Assemblages characterized by high abundances of planktics (B and C) are associated with pulse faunas that lack cold-water elements and are interpreted as representing a warm watermass. The foraminiferal assemblages are also related to sea-level fluctuations and individual assemblages were probably depth controlled. The assemblages can, therefore, be used to construct a sea-level curve and this agrees with the placement of critical sequence stratigraphic surfaces (e.g. sequence boundaries and flooding surfaces). Journal of Micropalaeontology, 15: 37-54.

INTRODUCTION
The early Middle Cenomanian event like the Cenomanian-Turonian boundary event (CTBE) represented a time of major environmental change (e.g. Paul et al., 1994; Mitchell et al., in press). Both events were associated with the influx of certain faunai elements (e.g. the belemnite Actinocamax and the bivalves Oxyostra seminudum (Dames) and Lyropecten (Aequipecten) arlesiensis (Woods)), a stable carbon isotope excursion and changes in sea-level (Paul et al., 1994; Mitchell et al., 1996; Robaszynski et al., in press). Previous studies on foraminiferal changes have largely concentrated on the Cenomanian–Turonian boundary event (e.g. Jefferies, 1962; Jarvis et al., 1988). This event was characterized by extinctions of both benthic and planktic foraminifera. The mechanism usually used to explain these extinctions is the expansion of the oxygen minimum zone (Sclanget et al., 1987; Jarvis et al., 1988). Previous studies on the late Lower and early Middle Cenomanian have included those of Burnaby (1961) and Paul et al. (1994, which included a summary of the results presented here).

In this paper the foraminiferal succession from the late Lower to late Middle Cenomanian of Speeton is presented. The data obtained are analysed using various statistical techniques and the results compared with the palaeoceanographic changes that occurred during this interval.

The section at Speeton
During the late Lower and Middle Cenomanian, Speeton was situated in the Cleveland Basin on the southern margin of the Southern North Sea Basin (Fig. 1). To the south lay the East Midlands Shelf and beyond this the Anglo-Paris Basin. The section studied here is situated below Buckton Cliffs [grid ref. TA 183 747] and is part of the Ferriby Chalk Formation (Wood & Smith, 1978). Section details have previously been given by Hill (1888), Wright (1968), Jeans (1980), Paul et al. (1994) and Gale (1995).

Lithostratigraphy
The section consists of alternations of thin flaser-marlS and micritic to calcarenitic, well-cemented limestones. The marls are thin, usually about 1 cm in thickness, but occasionally up to 10 cm in thickness. They have been piped down by burrows in places indicating that they are primary sedimentary phenomena and are not purely due to pressure solution. The limestones are generally coccolith-rich micrites with sparse shell fragments (predominantly inoceramid prisms and foraminifera) although two units of gritty (calcarenitic) chalk are present (the Totternhoe and Nettleton stones). Stained acetate peels indicate that the limestones have a ferroan calcite cement.

A lithostratigraphic numbering scheme for the chalk at Speeton (prefixed by SLC – Speeton Lower Chalk, above the Red Chalk – see Mitchell 1995) is shown in Fig. 2 (a key to the symbols on the graphic log is shown in Fig. 3). The succession contains a number of distinctive lithological units, these are as follows:

SLC6: six massive weathering chalk beds SLCA to F (Jeans’ (1980) 6-chalk unit).
SLC8: a conspicuous massive weathering chalk bed.
SLC10A: a thin massive weathering chalk bed.
SLC11: the Totternhoe Stone (or Grey Bed of Hill, 1888), with a prominent, thick marl (SLC11A) at the base and another (SLC11C) near the top.
SLC13: prominent marl.
SLC15: prominent marl.
SLC17: the Nettleton Stone (SLC17B, a grey weathering calcarenitic chalk) overlying a prominent marl (SLC17A, the Nettleton Pycnodonte Bed of Gaunt et al., 1992).

Marl–chalk cycles (couples) in the Cenomanian of the Anglo-Paris Basin are currently interpreted as productivity cycles under Milankovitch climatic control (Hart, 1987; Ditchfield & Marshall, 1989; Leary & Ditchfield, 1989; Gale,
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1995). Individual, or distinctive groups of, couplets have been correlated both within the Anglo-Paris Basin (Gale, 1990) and between different basins in NW Europe (Mitchell, unpublished data; Gale, 1995) using a variety of distinctive faunal, geochemical and lithological markers. Gale (1995) demonstrated, by comparing numbers of rhythms verses radiometric dates, that these rhythms were likely to represent the Milankovitch (21 ka) precession cycle. He introduced a numbering system for these rhythms and the applicable portion of this scheme as applied to Speeton is shown in Fig. 2.

Biostratigraphy
Biozonal schemes based on ammonites, inoceramid bivalves and planktic foraminifera have been applied to the Cenomanian of NW Europe, while several other groups (belemnites, brachiopods and oysters) have been used as biostratigraphic markers. These schemes, with regard to Speeton, are discussed below.

Ammonites. Unfortunately ammonites are rare and often poorly preserved at Speeton but, where present, are invaluable. A poorly preserved example of Mantelliceras dixoni Spath was collected from bed SLC6F (Fig. 2) and this indicates the M. dixoni Zone of the Lower Cenomanian. Occasional, well-preserved ammonites are found in bed SLC11C; these include Acanthoceras rhotomagense (Brongniart), Turrilites costatus Lamarrck and Sciponoceras baculoides (Mantell). This assemblage is characteristic of the T. acutus Subzone of the A. rhotomagense Zone. In southern England, ammonites of this subzone appear in couplet B43 (Paul et al., 1994) and the base of SLC11C (couplet C1) at Speeton can be provisionally taken as the base of the A. rhotomagense Zone. There is no ammonite evidence for the early Middle Cenomanian Cunningtoniceras inerme Zone at Speeton but based on couplet correlation with southern England (Mitchell, unpublished data; Paul et al., 1994) the base of this zone (and thus the base of the Middle Cenomanian) is provisionally placed in couplet B38. Diagnostic Middle Cenomanian ammonites have not been found above SLC11C and neither the Turrilites acutus Subzone or the Acanthoceras jukesbrownei Zone can be recognized at present.

Inoceramids. Inoceramid bivalves have been widely used in correlating the Cenomanian of NW Europe and this group of bivalves is common at Speeton. Zonal schemes have been developed by Keller (1982), Tröger (1989) and Wiedmann et al. (1989), while Gale (1990, 1995) has related the inoceramid succession to his couplet-based Cenomanian timescale. The distribution of inoceramids is shown in Fig. 2. Inoceramus virgatus Schlüter occurs abundantly from SLC6A to SLC6F. This bioevent was recognized by Ernst et al. (1983) in NW Germany and represents Gale’s (1995) B-division in the M. dixoni Zone (couplets B13–B18). Inoceramus schoenodori Heinz occurs in beds SLC11A and SLC11C, the presence of this species in the former bed agrees with its placement in the C. inerme Ammonite Zone. Fragments of inoceramids tentatively identified as Inoceramus atlanticus (Heinz) occur in the upper part of bed SLC16 while occasional well-preserved specimens occur in the Nettleton Pycnodonte Bed (bed SLC17A). Identifiable inoceramids have not been found in the Nettleton Stone at Speeton, but the earliest examples of Inoceramus pictus Sowerby appear in the chalk bed immediately above the Nettleton Stone (Fig. 2).

Foraminifera. Planktic foraminifera, particularly the genus Rotalipora, have been used to correlate Tethyan Cenomanian successions (Robaszynski & Caron, 1979). Unfortunately, in NW Europe many of the important planktic species are rare or absent, although a few species that occur at Speeton have proved to be useful (Paul et al., 1994). Rotalipora ex gr. reicheli Mornod has a limited distribution in Tethyan regions (Robaszynski & Caron, 1979). At Speeton R. ex gr. reicheli occurs in small numbers in the marl at the base of SLC10C and relatively commonly in the prominent marl in mid bed SLC14 (Fig. 2). The former occurrence finds a parallel in southern England where R. ex gr. reicheli occurs in the marls of couplets B40 and B41 (Mitchell & Carr, in prep.), and not with the acme occurrence in couplets B34–B36 (as implied by Paul et al., 1994, p. 726). The concentration of R. ex gr. reicheli in bed SLC14 is particularly significant since similar concentrations have been recognized at this level at South Ferriby (Mitchell, unpublished data) and possibly also from Bornholm, Denmark (Hart, 1979). This pulse of R. ex gr. reicheli in the early T. acutus Subzone may prove to be a valuable faunal marker in the Middle Cenomanian. The absence of Rotalipora below SLC10B means that the base of the R. reicheli Zone is undefined at present. Rotalipora cushmani (Morrow) appears in bed SLC13 at Speeton and marks the base of the R. cushmani Zone (Fig. 2).

Carter and Hart (1977) recognized a significant increase in

Fig. 1. Map showing locations of sections mentioned in the text.
Fig. 2. Lithostratigraphy, macrofossil biostratigraphy, planktic foraminiferal biostratigraphy, sequence stratigraphy, stable isotope stratigraphy and inferred ammonite zonation of the late lower and middle Cenomanian at Speeton. See Fig. 3 for key to symbols on graphic log.

Foraminifera from the Cenomanian of Yorkshire, UK

| Zones | Lower Cenomanian | Middle Cenomanian |
|-------|-----------------|-------------------|
| Ammonites (inferred) | | |
| Inoceramids | | |
| Planktic foraminifera | | |

| Identification | Common | Abundant |
|----------------|--------|---------|
| Mantellliceras dixoni | Acanthoceras photomagense | Turritellites costatus |
| Sciponoceras diluculoides | Inoceramus virgatus | Inoceramus schoendorfi |
| Inoceramus atlanticus | Inoceramus pictus | Rotalipora ex gr. reicheli |
| Rotalipora cushmani | Actinoceras primus | Belemnocamax boweri |
| Orthisia mantelliana | Terebratulina proxistriata | Gravisiphonca graviana |
| Pycnodonte sp. | Concentrations | |
the proportion of planktic foraminifera in the mid-Cenomanian. They suggested that this represented a significant break in the succession and called it the ‘mid-Cenomanian non-sequence.’ This has proved to be a useful marker horizon (Carter & Hart, 1977; Paul et al., 1994) at the base of couplet C11 (Fig. 2) for which the non-interpretative term PB break has been applied as there is no apparent break at this level (see Paul et al., 1994).

Other faunal groups. Some other fossil groups are important stratigraphically, these include belemnites, brachiopods and oysters. The belemnite Actinocamax primus Arkhangelsky is restricted to bed SLC11C (i.e. lower couplet C1) at Speeton (Fig. 2). This species occurs in lower couplet C1 throughout NW Europe (Paul et al., 1994; Gale, 1995). At Speeton this belemnite is accompanied by common examples of the small belemnite Belenocamax boweri Crick which ranges from bed SLC11C to bed SLC12A (couplets C1–C2). This species occurs at the same level throughout NE England and in northern Germany (Christensen et al., 1992).

The rhynchonellid brachiopod Orhynchia mantelliana (J. de C. Sowerby) occurs at three levels at Speeton (Fig. 2). The three concentrations of this species are well recorded elsewhere in NW Europe (e.g. Jeans, 1980; Gale, 1990, 1995; Paul et al., 1994) but show minor diachroneity. For instance, the lowest concentration (see Gale, 1995 for details) occurs in couplets B22–B23 at Speeton, B21 at Southerham (Sussex) and B19–22 at Baddeckenstedt (Lower Saxony, Germany). These concentrations of Orhynchia at Speeton are also characterized by the appearance of other brachiopods that are otherwise absent: Terebratulina protostriatula Owen in the lowest pulse and T. protostriatula and Grassirhynchia grsiana (d’Orbigny) in the middle pulse (Fig. 2).

Concentrations of oysters have also been used as biostratigraphic markers. Small Pycnodonte sp. occur at two levels within the succession studied: beds SLC13 and SLC17A. The latter horizon (the Nettleton Pycnodonte Bed of Gaunt et al., 1992) can be traced into Germany (the Pycnodonte event of Ernst et al., 1983) and southern England (base of ‘Jukes Browne’s bed VII,’ Jukes-Browne & Hill, 1903; Gale, 1995).

Sequence stratigraphy
The sequence stratigraphy of the Cenomanian of the Anglo-Paris Basin has recently been documented in detail by Robaszynski et al. (in press). They recognized six horizons (onlap surfaces) which onlap the basin margins, locally onto Palaeozoic basement. Sequence boundaries preceding these onlap surfaces were placed at levels where there was a significant increase in the proportion of clay (increased acid insoluble residues).

Jeans (1980) recognized a series of fining-upwards cycles in the Cenomanian of northeast England. Each cycle commenced with a thin winnowed calcarenitic chalk, often containing glauconitized reworked pebbles, and was followed by a thicker succession of coccolith-rich chalk. It is the bases of these fining-upwards cycles that correspond with the onlap surfaces recognized by Robaszynski et al. (in press). Portions of three of these cycles are in the section considered in this paper, with the Totternhoe Stone and Nettleton Stone representing the lower portions of two of these cycles. On the East Midlands Shelf (e.g. South Ferriby, Hunstanton, etc.) the Totternhoe Stone rests on an erosion surface cut into the Lower Cenomanian and contains examples of A. primus (indicating lower couplet C1) and reworked chalk pebbles at its base (Jeans, 1980; Gaunt et al., 1992; Mitchell, unpublished data; Paul et al., 1994). At Speeton, however, A. primus occurs in the upper part of the Totternhoe Stone (i.e. bed SLC11C), the lower part showing a passage downwards into coccolith-rich chalks (transition in SLC10C). The base of SLC11C is interpreted as the onlap surface while the calcarenitic chalks below represent part of the lowstand deposits. In the absence of clastic (clay) input into the Cleveland Basin, sequence boundaries are difficult to recognize at Speeton and correlative horizons are suggested in Fig. 2 from the work of Robaszynski et al. (in press) in the Anglo-Paris Basin.

Stable isotope geochemistry
Stable isotopes of carbon (δ13C) have been used as a powerful stratigraphic tool (Scholle & Arthur, 1980; Gale et al., 1993; Jenkyns et al., 1994; Paul et al., 1994; Mitchell et al., 1996). Within the interval considered in this paper, two short-term carbon stable isotope (δ13C) excursions are present, superimposed on a long-term general increase in background δ13C (Fig. 2). The long-term δ13C curve correlates with progressive sea-level rise during the Cenomanian (Hancock, 1989; Gale, 1995) and can be explained through increased storage of organic carbon in deep water masses or burial of organic carbon (Mitchell et al., 1996). The short-term excursions are associated with sequences boundaries and/or onlap surfaces (Mitchell & Paul, 1994; Mitchell et al., 1996). The lower excursion (MCE I) is represented by two positive peaks (MCE Ia and Ib) which occur in the same couplets (peaks in B41 and C1) throughout all sections studied to date (Paul et al., 1994, Gale, 1995, Mitchell et al., 1996). The lower excursion occurs in the lowstand deposits while the upper peak occurs in the early transgressive deposits just above the onlap surface. The upper excursion (MCE II) is represented by a small negative excursion associated with lowstand deposits at Speeton. Short-term carbon excursions in the Cenomanian have been explained through changes in carbon cycling related to variations in nutrient fluxes controlled by sea-level fluctuations (Mitchell et al., 1996).
TECHNIQUES AND METHODS

Sampling and processing
Trial attempts demonstrated that the chalks at Speeton are too strongly cemented to process for their foraminifera. In contrast, the marls are easily processed. About 200 g of each marl (27 samples in total) was carefully collected in the field to avoid contamination. The samples were then placed in suitable containers and processed by freeze-thawing with water until disaggregated (usually two to three freeze-thaw cycles). The residues were then sieved through standard meshes. In each case at least 300 specimens were picked from the 250–500 μm size fraction. In all cases the number of specimens recovered from the 500–1000 μm size fraction was significantly smaller (by two orders of magnitude) than those present in the 250–500 μm size fraction. Because of the problem of combining size fractions that are not completely picked, all statistical studies were carried out on the 250–500 μm size fraction. Furthermore all species in the 500–1000 μm fraction were also present in the 250–500 μm size fraction. All benthic foraminiferal data are expressed as percentages of the total benthic fauna in the 250–500 μm size fraction.

Foraminiferal taxonomy follows Loeblich & Tappan (1987) with additional data from Carter & Hart (1977), Barnard & Banner (1980), Hart et al. (1989) and Meyn & Vespermann (1994), amongst others. Representative taxa are illustrated on Plate 1 and Fig. 5.

Statistical techniques and indices
While living foraminiferal assemblages provide information on biomass (i.e. species living together), fossil assemblages provide information only on species that are preserved on biomass (it species living together), fossil assemblages completely picked, all statistical studies were carried out on the 250–500 μm size fraction. In modern oceans P stands for the proportion of the total benthic fauna that are planktic foraminifera in the 250–500 μm size fraction. Because the number of taxa in a sample is dependent on the number of specimens picked. Furthermore, simply expressing the number of species present gives no information on the population structure (i.e. relative abundance of different species). In this paper three methods are used to investigate diversity. Graphical methods are frequently advocated since these provide all the information contained in the population (see Maguran, 1988 for details). In particular, rank/abundance (cumulative percentage using a complimentary logarithmic scale vs. species rank) plots can be used to differentiate communities.

The logarithmic series model was introduced by Fisher et al. (1943). This model has been widely applied to foraminiferal assemblages (see Murray, 1973, 1991) and the α-diversity index is applicable as a measure of species richness where the model holds. Values can be read from plots on previously prepared graphs (see Murray, 1991 for details). Values typically range from 5 to 20 on recent normal marine shelves and 5 to 25 in slope or bathyal environments (Murray, 1991, p. 291).

The Shannon index (H′), based on information theory, is also relatively popular (Peet, 1974; Maguran, 1988). This is sensitive to both species richness and the underlying species abundance distribution. Values typically fall within the range 1–3.5 (May, 1975) with higher values representing both greater species richness and greater evenness in the species abundance distribution. For modern assemblages, H′ ranges from 0.6 to 2.75 on modern shelves and 0.75 to 4.1 on slopes (Murray, 1991, p. 289).

Triangle diagrams. Triangle diagrams represent a method of plotting three variables on the same graph (strictly the relative variation) and have been widely used in foraminiferal studies. Three triangles are used here: the suborder (test structure: agglutinated vs. calcareous hyaline vs. calcareous porcellaneous) diagram (see Murray, 1973, 1991, for details); the feeding strategy (herbivores vs. detritivores vs. suspension feeders) diagram (see Jones & Charnock, 1985); and a diagram showing the variation in agglutinates (introduced here). The latter diagram uses the NCA, the Mars scaffold/Tritylia/Pseudoextutilia and the Pleucena/Arenostubulum on the vertices (see below).

Cluster analysis. Cluster analysis is a collective term for a variety of agglomerative hierarchical methods that operate on a matrix of similarities among a set of samples (Digby & Kempton, 1987). Different clustering criteria give rise to different cluster diagrams. Complete linkage (or furthest member) cluster analysis tends to produce a large number of very compact spherical clusters, and this method of clustering has been used here. The dataset used here is particularly suitable for cluster analysis as all but one of the species range throughout the stratigraphical interval investigated. Cluster analysis, by itself, does not justify the clusters produced, but the technique can be easily integrated with other techniques such as principal component analysis (PCP).

Principal component analysis. Principal component analysis (PCP) is an indirect ordination method that creates a new set of orthogonal axes with axes ranked to contain the maximum amount of variance possible in the sample.
(Krzanowski, 1988). For instance, in a data set of $n$ samples containing say $N$ species (i.e. $N$ dimensions expressed as orthogonal axes, where $N \leq n$), a PCP analysis creates a new set of orthogonal axes (the eigenvectors) such that eigenvector 1 contains the greatest variance possible within the sample by one variable, eigenvector 2 the next greatest amount of variance, etc. In this manner the variation in the sample can be approximated by a smaller number of dimensions.

RESULTS AND STATISTICAL ANALYSES

The distribution of the benthic foraminifera recovered in this study is shown in Fig. 4, a list of all the benthic taxa recorded is given in Table 1 and representative taxa are shown in Plate 1 and Fig. 5. A spindle diagram showing the variation in the relative abundance of the most important taxa is shown in Fig. 6. Up section, there is a gradual reduction in the proportion of NCA taxa (particularly Ammodiscus cretaceous and Hyperammina gaulitinu (samples

![Fig. 4. Distribution of benthic foraminifera from the late Lower and Middle Cenomanian at Speeton. Successive occurrences joined. See Fig. 3 for key to symbols on graphic log.](image-url)
TEXTULARIANA
Non-calcareous agglutinated (NCA) taxa
Hyperammina gaultina Ten Dam. Bartenstein & Bolli 1986, pl. 1, figs 14-17.
Ammomiscus cretaceus (Reuss). King 1989, pl. 9, fig. 3.
Ammodiscus sp. 386 of Kuhnt & Moullade. 1991, pl. 4, fig. C.
Giomospirella gaultina (Berthelin). Loeblich & Tappan 1987, pl. 38, figs. 3-4.
Haplophragmoides nonioninoides (Reuss). Meyn & Vespermann 1994, pl. 1, figs. 1-8.
Pelostina sp.
Ammoverteolina sp.
Turritellella sp.

Verneullinaceae
Plectina coenomanica Carter & Hart. Hart et al. 1989, pl. 7.2, fig. 10.
Plectina mariae (Franke). Carter & Hart 1977, pl. 2, fig. 8.
Gaudryina austriana Cushman. Carter & Hart 1977, pl. 1, fig. 10.
Spiroplectinata plana (Gorbenko). Loeblich & Tappan 1987, pl. 143, figs. 6-8.
Eggerellina brevis Marie. Jarvis et al. 1988, fig. 10(f).
Eggerellina mariae Ten Dam. Hart et al. 1989, pl. 7.2, figs. 1-2.
Tristaxis pyramidalata Reuss. Hart et al. 1989, pl. 7.3, figs 2-3.

Ataxophragmidiae
Arenobuliminu advenu Bartenstein & Bolli 1986, pl. 1, figs 14-17.
Arenobuliminu elongata Barnard & Banner 1980, pl. VI, figs. 2-4.
Arenobuliminu pseudalbiana Barnard & Banner 1980, pl. VII, figs. 15-16.
Hagenowella elevata (d’Orbigny). Barnard & Banner 1953, pl. 8, figs. 11A-D.
Ataxophragmium depressum (Perner). Jarvis et al. 1988, fig. 10(c).
Pseudotextulariella cedota (Cushman). Hart et al. 1989, pl. 7.2, figs 11-12.

Textulariaceae
Marssonella trocho (d’Orbigny). Barnard 1962, text-fig. 3.
Marssonella sp. nov. A.
Dorothia gravata Berthelin. Bartenstein & Bolli 1986, pl. 1, figs 38-39.
Dorothia filiformis (Berthelin). Hart et al. 1989, pl. 7.1, figs 11-12.
Dorothia sp. nov. A.
Textularia chapmani Laücker. Hart et al. 1989, pl. 7.3, fig. 1.
Textularia sp. nov. A.
Textularia sp. nov. B.

ROTALINA
Chistolomellacea
Gavelinella berthelini (Keller). Jarvis et al. 1988, figs 11k, 1.
Gavelinella reussi Khan. Khan 1950, pl. 2, figs 17-18.
Gavelinella cenomanica (Broten). Hart et al. 1989, pl. 7.10, figs 9-11.
Gavelinella intermedia (Berthelin). Hart et al. 1989, pl. 7.11, figs 7-9.
Lingulogavelinellia tornaripes (Broten). Carter & Hart 1977, pl. 1, figs 31-32.
Lingulogavelinella globosa (Broten). Carter & Hart 1977, pl. 1, figs 12-14.
Lingulogavelinella jarzecae (Vasilenko). Carter & Hart 1977, pl. 1, figs. 29-30.
Gyroidinoides parva Khan. Khan 1950, pl. 2, figs 12-14, 19.

Nodosariaceae
Lenticulina muensteri (Roemer). Meyn & Vespermann 1994, pl. 24, figs. 1-17.
Trachyproloculina frunkei Ten Dam. Bartenstein & Kovačević 1982, pl. 3, fig. 19.
Astacolus schloenbach (Reuss). Meyn & Vespermann 1994, pl. 42, figs. 1-6.
Astacolus humilis (Reuss) Meyn & Vespermann 1994, pl. 39, figs. 6-17.
Astacolus sp. nov. A.
Frondiculina gaultina Reuss. Chapman 1894a, pl. III, fig. 7.
Frondiculina perovata Chapman. Chapman 1894a, pl. IV, fig. 5.
Psilocithurella recta (Reuss). Bartenstein & Bolli 1986, pl. 6, figs. 7-8.
Psilocithurella striolata (Reuss). Bartenstein & Bolli 1986, pl. 6, fig. 10.
Planulacea strombecki (Reuss). Bartenstein & Bolli 1966, pl. 2, figs 111-114.
Planulacea biochii Berthelin. Chapman 1894b, pl. VIII, fig. 14.
Laevicinalina gracilis (d’Orbigny. Bartenstein & Bolli 1986, pl. 3, figs 4-6.
Laevicinalina subguttifera Bartenstein. Bartenstein & Bolli 1986, pl. 3, fig. 13.
Laevicinalina cylindroides Reuss. Bartenstein & Bolli 1986, pl. 2, figs. 38-39.
Laevicinalina cf. nana (Reuss). Meyn & Vespermann 1994, pl. 7, figs. 8-16.
Pyramidulina paupercula (Reuss). Bartenstein & Bolli, 1986, pl. 5, figs. 30-31.
Pseudonodosaria humilis (Roemer). Bartenstein. Bartenstein & Bolli 1977, pl. 6, figs. 9-12.
Nodosaria nuda (Reuss). Meyn & Vespermann 1994, pl. 6, figs. 4-9.
Dentalina sp.
Guttulina sororia (Reuss). Barnard 1962, Text-figs. 6a-b.
Globulina prisca (Reuss). Bartenstein, Bettenstaedt & Bolli 1966; pl. 3, figs 24-25.
Oolina globosa (Monyagi). Chapman 1893, pl. VIII, figs. 1a-b.
Ballopora laevi (Sollas). Bartenstein & Bolli 1986, pl. 3, fig. 16.
Ramulina aculeata Wright fusiform variety. Bartenstein, Bettenstaedt & Bolli 1966, pl. 4, figs 316-329.
Ramulina aculeata Wright. Bartenstein & Bolli 1986, pl. 3, figs 29-32.
Ramulina grandis (Fuchs). Bartenstein & Bolli 1986, pl. 3, figs 39-40.

MILIOBLINA
Spiroloculina papiracea (Burrows, Sherborn & Bailey). Carter & Hart 1977, pl. 1, fig. 6.

Table 1. List of all benthic foraminiferal taxa recorded from the late Lower and Middle Cenomanian at Speeton.
1–9), although *A. cretaceous* reappears in samples 12–18. *Plectina* and *Arenobulimina* become the most important taxa between these two pulses of NCA taxa (i.e. in samples 9–11). Above sample 15 certain calcareous agglutinated (*Triaxia pyramidata*) and calcareous hyaline (*Gavelinella reussi, Gyroidinoides parva* and *Lenticulina muensteri*) taxa increase in numbers (Fig. 6).

Dissolution can be rejected as the major control on the foraminiferal assemblages for the following reasons:

(i) all the marls sampled throughout the section are visually very similar;

(ii) calcareous taxa occur throughout;

(iii) Acid resistant taxa (*Arenobulimina* and NCAs) show quite different abundance patterns suggesting primary control on the assemblages;

(iv) samples with high proportions of NCA taxa contain very well preserved planktic foraminifera (e.g. sample 8).

**Triangular diagrams (test structure and feeding strategy)**

All the samples plot within the normal marine field on the test structure diagram (Fig. 7A). On the feeding strategy

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**Explanation of Plate 1.**

Representative agglutinated foraminifera from Speeton. Figs 1–2. *Plectina cenomanica* Carter & Hart, sample 11 (*×88*); Fig. 3. *Plectina mariae* (Franke), sample 11 (*×58*). Fig. 4. *Spiroplectinata plana* (Gorbachenko), sample 23 (*×54*). Fig. 5. *Triaxia pyramidata* Reuss, sample 23 (*×60*). Fig. 6. *Arenobulimina pseudobulimina* Barnard & Banner, sample 11 (*×88*). Figs 7–8. *Arenobulimina obtusa* Cushman, sample 11 (*×93*). Figs 9–10. *Pseudoxuariella cretosa* (Cushman), sample 11 (*×50*). Fig. 11. *Ataxophragmium depressum* (Pernier), sample 22 (*×68*). Fig. 12. *Hyperammina gaulina* Ten Dam, sample 2 (*×47*). Fig. 13. *Ammodiscus cretaceus* (Reuss), sample 2 (*×58*). Fig. 14. *Dorothia gradata* Berthelin, sample 23 (*×54*). Fig. 15. *Marssonella trochos* (d'Orbigny), sample 23 (*×83*). Fig. 16. *Eggerellina brevis* Marie, sample 23 (*×104*).
Fig. 6. Spindle diagram showing the percentage abundance of the more important benthic foraminifera from the late Lower and Middle Cenomanian at Speeton. See Fig. 3 for key to symbols on graphic log.

diagram samples 1–7 plot in the upper bathyal field and samples 8–27 plot in the shelf field (Fig. 7B).

**Diversity**

Figure 8 shows a rank/abundance plot for all the samples and shows that there are significant variations in population structure. Five groups can be recognized (1 to 5) and these are shown in Fig. 9. All curves approximate to the log series model and this justifies the use of Fisher's α-diversity index. The graph illustrating Fisher's α-diversity index shows two peaks (Fig. 9): a minor one in samples 7–10 and a more significant one in samples 21–25. The Shannon index (H') graph shows a similar pattern (Fig. 9). Additionally sample 12 shows high values of both α and H' (Fig. 9).
Cluster analysis
A complete linkage cluster analysis for all samples of benthic foraminifera is shown in Fig. 10. The samples cluster into six assemblages labelled A to F and the stratigraphic distribution of these is shown in Fig. 9. The relative abundance of the important benthic species (together with P% which was not used in the clustering) is shown in Fig. 11. Assemblages may most easily be classified by the dominant agglutinated foraminiferal species found in each assemblage.

A. Ammodiscus–Hyperammina assemblage.
B. Tritaxia assemblage.
C. Tritaxia–Marssonella assemblage.
D. Tritaxia–Marssonella–Dorothia assemblage.
E. Marssonella–Pseudotextulariella–Ammodiscus assemblage.
F. Arenobuliminia–Plectina assemblage.

It is also significant that assemblages B and C have significantly higher percentages of Lenticulina muensteri, Gyroidinoides parva, Gavelinella reussi, Lingulogavelinella globosa and L. tormarpensis than the other assemblages, assemblage B always having more than assemblage C. This equates directly with P% and suggests coeval changes in both planktic and benthic foraminiferal communities.

Principal Component Analysis (PCP)
The results of a PCP on the benthic foraminifera from Speeton is shown in Table 2. The PCP shows that 75% of the variance is represented by the first three eigenvectors. The first eigenvector accounts for 44.7% of the variance and shows a strong positive correlation with Hyperammina gaultina and Ammodiscus cretaceus and moderate negative correlations with Tritaxia pyramidata, Lenticulina muensteri and many of the Gavelinella species. The second eigenvector accounts for 19.1% of the variance and shows strong negative correlations with Arenobuliminia advena and
Plectina cenomanana and moderate positive correlations with Triaxia pyramidata, Pseudotextulariella cretosa, Marssonella trochus and Gavelinella berthelini. The third eigenvector accounts for 11.4% of the total variance and shows a positive correlation with Triaxia pyramidata, Gavelinella reussi and Lenticulina muensteri, strong negative correlations with Pseudotextulariella cretosa and Marssonella trochus and moderate negative correlations with Plectina and Arenobuliminina advena. In terms of the agglutinates, the first eigenvector may be interpreted as representing the proportion of NCAs in the assemblage, the second, the ratio between the Arenobuliminina–Plectina and the Tritaxia–Pseudotextulariella–Marssonella groups and the third, the ratio between the Tritaxia and the Pseudotextulariella–Marssonella groups.

Figure 12 shows the six assemblages recognized in the cluster analysis plotted on a rotated three-dimensional plot using the first three eigenvectors as axes. This clearly separates assemblages A, E and F. Figure 13 shows the variation represented by the first two eigenvectors as a triangular diagram (vertices: NCA, Arenobuliminina + Plectina, Marssonella + Triaxia + Pseudotextulariella) and separates assemblages A and F from all the other assemblages. Figure 14 shows the variation represented by
The distribution of modern planktic foraminifera is controlled by both water depth and the distribution of assemblages. The third eigenvector (proportion of Tritaxia amongst Tritaxia, Marsonella and Pseudotextularia) plotted against different watermasses foraminifera from Speeton. It is therefore surface water with a reversal in this trend at the Cenomanian (Carter et al., 1994). Previous work on the distribution of planktic foraminifera in the Cenomanian (Carter & Hart, 1977) has largely concentrated on water depth. The PB break clearly represents a dramatic change in the mid-Cenomanian. Long-term oxygen isotope curves through the Cenomanian (Jenks et al., 1994) suggest a progressive warming of surface water with a reversal in this trend at the Cenomanian-Turonian boundary event. It is therefore possible that the appearance of abundant large planktic foraminifera at the PB break might be related to surface warming or the progressive northerly movement of a warm watermass.

Both long-term changes in the foraminiferal abundances and the foraminiferal assemblages (A–F) can be related to changes in sea-level. During the Cenomanian there was a progressive rise in sea level which saw the spread of chalk deposition across the whole of England (Hancock, 1989, Robaszynski et al. in press). This is reflected in the progressive increase in δ13C (Mitchell et al., 1996). At Speeton the foraminiferal assemblages show a change from NCA-dominated assemblages in the late Lower Cenomanian to planktic-dominated assemblages in the late Middle Cenomanian.

**INTERPRETATION**

The distribution of modern planktic foraminifera is controlled by both water depth and the distribution of different watermasses (e.g., temperature, salinity, nutrients, Murray, 1995). Previous work on the distribution of planktic foraminifera in the Cenomanian (Carter & Hart, 1977) has largely concentrated on water depth. The PB break clearly represents a dramatic change in the mid-Cenomanian. Long-term oxygen isotope curves through the Cenomanian (Jenks et al., 1994) suggest a progressive warming of surface water with a reversal in this trend at the Cenomanian-Turonian boundary event. It is therefore possible that the appearance of abundant large planktic foraminifera at the PB break might be related to surface warming or the progressive northerly movement of a warm watermass.

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This change in the foraminiferal assemblages can be related to more open oceanic circulation with increases in eustatic sea-level (King et al., 1989). Although the high NCA samples (1 to 7) plot in the upper bathyal field in the feeding strategy triangular plot (Fig. 7B), the low \(\alpha\)-diversity (\(\alpha = 2.5-5.0\)) of these samples does not suggest an upper bathyal environment (compare Murray, 1991, p. 291). These assemblages were probably controlled by nutrient supply rather than water depth (see discussion in Jones & Charnock, 1985, p. 312-313).

At Speeton, the correlatives of the sequences recognized by Robaszynski et al. (in press) do not show alternations of NCA- and planktic-dominated assemblages that characterize long-term sea-level change. Instead, these show smaller-scale variations with the appearance of different benthic foraminiferal assemblages. The late Lower to early Middle Cenomanian sequence (Sequence 3 of Robaszynski et al. in press) is characterized by three foraminiferal assemblages (Fig. 15). The highstand deposits are characterized by assemblage A (NCA dominated) which passes to assemblages D and F in the lowstand deposits. The lowstand is also associated with an increase in diversity from \(\alpha = 2.5-5.0\) in the high stand deposits to \(\alpha = 5-7\) in the low stand deposits.

The Middle Cenomanian sequence (Sequence 4 of Robaszynski et al. in press) is characterized by a succession of foraminiferal assemblages (Fig. 15). The transgressive deposits are characterized by assemblages E and D, the highstand deposits by assemblages C and B and the lowstand deposits by a return to assemblage C. Diversity is

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**Fig. 12.** Plot of six assemblages recognized in the cluster analysis on the rotated first three eigenvectors.

**Fig. 13.** Triangle diagram (based on PCP analysis). Note distinction of assemblages A and F from the cluster analysis.

**Fig. 14.** Scatterplot showing \(T \% \frac{(\text{Tritaxia})(\text{Tritaxia + Marssonella + Pseudotextulariola})}{100}\) against NCA %, showing distinction of cluster assemblages.
low in the transgressive deposits ($\alpha = 2.5-5.0$) reaches a peak in the highstand deposits ($\alpha = 7-8$) and falls again in the lowstand deposits ($\alpha = 3$).

Burnaby (1961) discussed the depth of the benthic foraminifera from the Chalk Marl of Cambridgeshire. By comparison with living species he suggested a depth range for four taxa from the Chalk Marl. *Arenobulimina* spp. were interpreted as living in very shallow water, *Textularia* in intermediate water depths and *Gyroidinoides* and *Tritaxia* in deep water. These results are consistent with the sequence stratigraphy and foraminiferal assemblages from Speeton. In Fig. 15 a sea-level curve is constructed assuming that the foraminiferal assemblages (A–F) were depth related. This model agrees with the independently derived sequence stratigraphic surfaces (sequence boundaries and flooding surfaces), although the sequence boundary in sequence 3 (of Robaszyński et al. in press) would be better placed a little higher in couplet B39. It is perhaps significant that the highest diversities are found in the lowstand deposits in sequence 3 and the highstand deposits in sequence 4 and not in the transgressive deposits.

**DISCUSSION**

Jefferies (1962) studied the faunas of the *plen us* marls in detail and recognized the appearance of species with central Russian affinity (*Actinocamax, Aequipecten, Lyropecten*)
arlesiensis, Oxytoma seminudum). He considered these to represent a cold-water migration event. In the early Middle Cenomanian a succession of similar, or the same, taxa characterized by a cold surface water oxygen isotope signal (see Paul et al., 1994, fig. 5). The influx of the brachiopod Orbihynchia (together with other brachiopods of Anglo-Paris Basin affinity in the Cleveland Basin) is also associated with these belemnite/bivalve incursions.

With progressive temperature rise during the Cenomanian (Jenkyns et al., 1994) major changes can be recognized in certain faunal groups. Cold water faunal incursions (belemnites, bivalves and brachiopods) are restricted to the interval below the PB break, where foraminiferal assemblages are characterized by high proportions of NCAs. Above the PB break these cold-water faunal elements are absent and incursions are characterized only by oysters, while foraminiferal assemblages are characterized by high proportions of planktics. The PB break is interpreted as a significant level where a northern watermass with high proportions of NCAs was replaced by a southern watermass with high proportions of planktic foraminifera. A model of this general form was used by Reid (1976) to explain gross faunal changes in the whole of the Upper Cretaceous of the United Kingdom.

CONCLUSIONS

During the late Lower Cenomanian, the Cleveland and the Anglo-Paris basins had different foraminiferal assemblages and both basins lacked significant planktic taxa. The Anglo-Paris Basin was characterized by a diverse calcareous benthic assemblage including abundant Tritaxia and Gavelinella, while the Cleveland Basin contained a restricted fauna dominated by NCA foraminifera.

The sea-level fall in the early Middle Cenomanian produced a major change in the bentic fauna of the Cleveland Basin showing a transition through assemblage D (Tritaxia–Marssonella–Dorothia) to the shallow water assemblage F (Arenobulimina–Plectina) and an increase in benthic foraminiferal diversity. Associated with these foraminiferal assemblages is the appearance of a series of pulse faunas of central Russian affinity. These occur both in the Anglo-Paris Basin and in the Cleveland Basin but, in the latter, include pulse faunas of Anglo-Paris Basin affinity. It seems apparent that such incursions were times of faunal migrations due to the relatively low sea-level and the relatively southerly extension of a cool North Sea watermass.

As sea-level rose again, foraminiferal faunas underwent progressive changes in the Cleveland Basin through assemblages E to B. Assemblage E is related to the North Sea watermass and contains relatively high proportions of NCAs. Assemblage C marks the sudden appearance of vast numbers of planktic taxa characteristic of a warm water mass. The sudden influx of planktic foraminifera is synchronous across England (Paul et al., 1994) and displaces the pulse faunas of mid Russian affinity. This migration of planktic foraminifera is associated with an increase in diversity of benthic foraminifera in the Cleveland Basin. All this together suggests the rapid movement of a southerly watermass northwards displacing colder water faunas. In the Cleveland Basin planktic foraminifera increase in numbers up to assemblage B and thenceforth decrease in numbers towards the next sea-level fall in the late Middle Cenomanian. This sea-level fall is not associated with the entry of pulse faunas of cold water type but only with oyster events since both the Anglo-Paris and the Cleveland basins were under the influence of the warm water mass.

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