Coastal Coccolithophores (Guest Ed. R.W. Jordan)
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Calcareous nannofossils from a Late Cretaceous nearshore setting

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Abstract Unexpectedly rich and diverse associations of calcareous nannofossils are reported from Upper Cretaceous sediments of northern Germany. Samples from the Cenomanian–Campanian yielded well-preserved calcareous nannofossils, with an average of 52 to 81 species per sample. The most common taxa were *Biscutum*, *Zeugrhabdotus*, *Watznaueria, Tranolithus* and *Prediscosphaera*, which exceeded 60% in each assemblage. The sediments were deposited in a coastal nearshore setting, at water-depths of ≤40m. The material was collected from glauconite-rich marls that contain small amounts of quartz. These nearshore deposits, lying 10–20km from the former coastline, interfinger with hemipelagic chalks and limestones, which reflect the widely distributed sediments of the Late Cretaceous.
We postulate that this Late Cretaceous nearshore environment, represented by glauconite-rich marls, and with diverse and abundant calcareous nannofossil assemblages, has no modern analogue. Our data suggest a Late Cretaceous 'water world' scenario, where open oceanic conditions prevailed, even in nearshore settings.

Keywords Calcareous nannofosils, Late Cretaceous, NW Germany, nearshore sediments

1. Introduction

During a drilling campaign in 2003–2015, the Geological Survey of North Rhine Westfalia cored Cenomanian to Campanian sediments in 13 wells in NW Germany (Fig. 1; Dölling et al., 2018). These cores recovered glauconite-rich marls, which were deposited 0–10km north of the former coast, under shallow-marine conditions. The glauconite, cross-bedding in some of the glauconite beds, the macrofauna and ichnofossils suggest a shallow-water environment, which did not exceed 10–40m water-depth. Unconformities in some of the cores, which were drilled a maximum of 10 km apart, indicate the relief of the Carboniferous basement onto which the Late Cretaceous sea transgressed. A very shallow-marine nearshore setting was likely, with runoff from the nearby hinterland supplying dissolved iron for the glauconite formation, but not a substantial input of coarse-grained components.

Unexpectedly, these deposits provided well-preserved and diverse calcareous nannofossil assemblages. All samples showed moderate to very good preservation. Moderate preservation, indicated by minor calcite overgrowth of the nannofossils, was observed in the carbonate-rich, less sandy and less glauconite-rich sediments. Scanning electron microscope (SEM) images show minor etching and/or overgrowth in two of the cores (Oberhausen, Duisburg).

To our knowledge, this is the first time that highly-diverse and abundant nannofossil assemblages have been described from a relatively very shallow-water setting. Here, we present the initial data from our findings and attempt to place the new observations into a supraregional context.

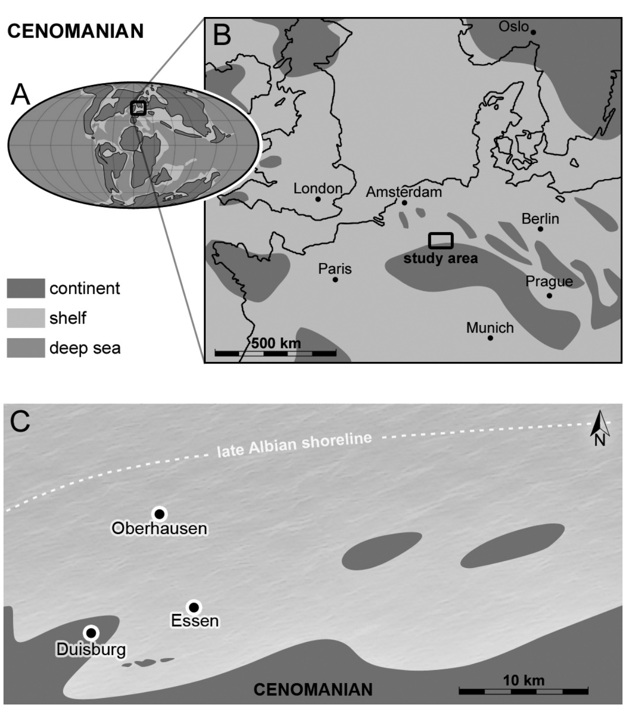


Figure 1: **A**. Palaeogeographic map of the Cenomanian (modified after Scotese, 2014). **B**. Northern and central Europe in the Cenomanian (modified after Ziegler, 1990). **C**. Palaeogeographic map of the study area in the Cenomanian, showing the studied sections and the palaeocoastline (Albian, after Frieg et al., 1990)

2. Regional geology

Throughout the Triassic–Early Cretaceous, NW Germany formed the northern part of the continental Rhenish Massif, where Carboniferous rocks were exposed and eroded (Hiss, 1995). With the global sea-level rise starting in the Late Albian, the area was flooded from the north, and marine conditions prevailed throughout the Cenomanian–Campanian. The trace of the Late Cretaceous shoreline was well documented by shallow-water, nearshore sediments, cropping out over a distance of 150km in a west–east direction. In the more hemipelagic settings, some 10–20km north of the former coastline, the Late Cretaceous global sea-level maximum is evidenced by the widespread occurrence of chalks, limestones and marls. These carbonates contain rich and diverse calcareous nannofossil assemblages, well known from other areas around the world via the Deep Sea Drilling Project and later programmes.

A proximal c. 10km-wide belt along the former coastline in the south is dominated by marls with high amounts of glauconite and, to a lesser extent, quartz sand. The glauconite-rich marls rest unconformably on Upper Carboniferous sand- and siltstones. The heterochronous onset of Early Cenomanian sedimentation, and the presence of local unconformities in some of the cores, which are a maximum of 10km apart, suggest the relief of the Carboniferous basement onto which the Late Cretaceous sea transgressed. Local swells, formed by weathering-resistant Carboniferous sandstone ridges, emerged 4–10m above the Cretaceous sea level. These small cliffs, which alternated with shallow marine lagoonal settings, are known from four outcrops (Mülheim, Bochum, Fröndenberg, Bremen-Ense) located in the Cenomanian coastal belt of the study area (Kukuk, 1938; Hiss et al., 2008; Linnert & Mutterlose, 2012). The richness in glauconite and the relatively low amount of quartz grains indicate a siliciclastic-starved marine coastal setting and a flat palaeorelief of the hinterland. The micro- and macrofaunas – which, among other things, include sea urchins – are fully marine. A very shallow-marine nearshore setting is likely, with runoff from the nearby hinterland supplying dissolved iron for the glauconite formation. Cross-bedding has been observed in the glauconite-rich Middle Turonian interval in the Oberausen core. The high proportion of matrix is interpreted as having resulted from muddy coastal waters of the inner shelf, with water-depths of about 0–20m (Hiss, 1985; Wilmsen et al., 2005). The continuous occurrence of bioturbation indicates well-oxygenated bottom-water conditions. Authigenic glauconite formation likely occurred under reducing microenvironments in the uppermost part of the sediment column (Robert, 2009). The three wells that supplied the material for this study penetrated the glauconite-rich nearshore succession of Cenomanian to Campanian age (Dölling et al., 2018; Püttmann et al., 2018).

3. Material and methods

Three wells (Duisburg, Essen, Oberhausen; Fig. 1), which are dominated by sandy, glauconitic marls, recovered sediments of Early Cenomanian to Early Campanian age. Calcareous nannofossils were studied using an Olympus BH-2 light-microscope (LM) at 1250x and 1500x magnification. In a first step, 154 smear-slides were biostratigraphically screened to establish an initial stratigraphic framework for the three cores (Püttmann et al., 2018). Sample processing followed Perch-Nielsen (1985), species identification followed a combination of Burnett et al. (1998) and Nannotax3, with references therein.

The aim of this study was to first obtain data on the nannofossil assemblage compositions in these nearshore sediments. A total of six samples were selected from different stratigraphic levels (Lower Cenomanian, UC1b; Lower Turonian, UC7; Upper Turonian, UC9a; Middle to Upper Coniacian, UC10–11a; Upper Santonian, UC12; Lower Campanian, UC13), to represent most of the Late Cretaceous. Relative abundances of specific taxa were then investigated in settling-slides by counting at least 300 specimens per slide. For settling-slide preparation, see Geisen et al. (1999).

4. Results

All six samples studied showed moderate to very good nannofossil preservation (Fig. 2). Moderate preservation, indicated by minor calcite overgrowth of the nannofossils, was observed in the carbonate-rich, less sandy and less glauconite-rich sediments. The sand- and glauconite-rich samples of the Cenomanian and Turonian yielded very well-preserved calcareous nannofossils. SEM images demonstrate only minor etching and/or overgrowth in the Oberhausen core (Fig. 2).

An average of 52 to 81 species per sample were encountered throughout the three cores, with a maximum of 81 species being identified in the Oberhausen core (at 252.20m). The diversity of the assemblages is documented by images of selected, well-preserved specimens (Plates 1, 2). Coccoliths smaller than 5µm, such as *Zeugrhabdotus erectus*, *Corollithion signum* and *Tranolithus minimus*, occur frequently, and somewhat support the absence of dissolution.

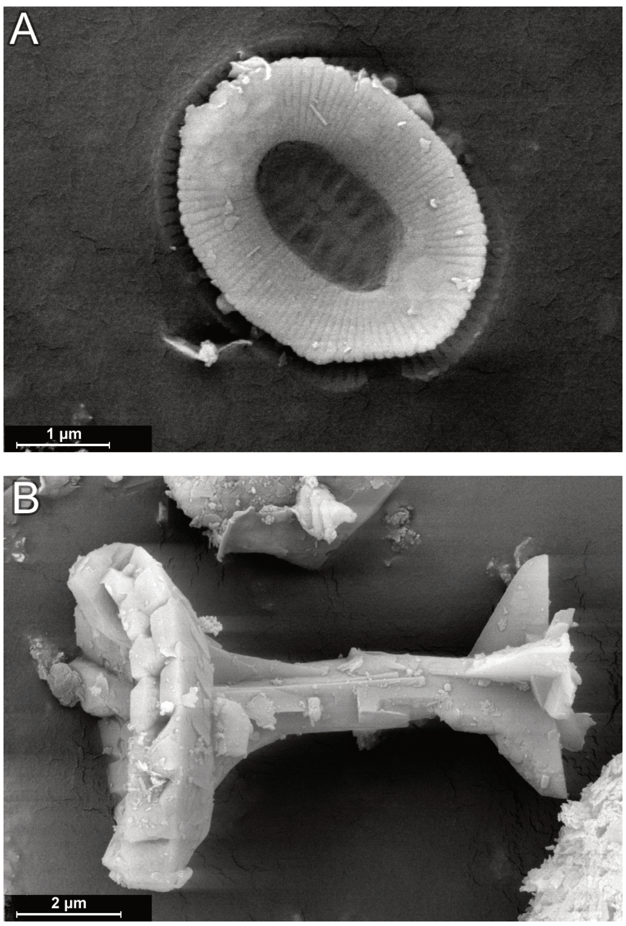


Figure 2: SEM images of well-preserved calcareous nannofossils from the Oberhausen core. **A**. *Repagulum parvidentatum*, UC8b (258.21m, Middle Turonian). **B**. *Prediscosphaera cretacea*, UC9a (246.46m, Upper Turonian)

Counts of the relative abundances of the most common taxa, which jointly comprised >60% in each given assemblage, resulted in the dataset shown in Figure 3. The sample from the Lower Cenomanian is dominated by *Biscutum* spp. (23.6%), *Zeugrhabdotus* spp. (18.27%), *Watznaueria* spp. (15.0%), *Tranolithus* spp. (10.0%) and *Prediscosphaera* spp. (3.7%). The abundance patterns observed in the Lower Turonian sample include *Biscutum* spp. (11.0%), *Zeugrhabdotus* spp. (16.4%), *Watznaueria* spp. (14.6%) and *Prediscosphaera* spp. (10.1%). The sample from the Upper Turonian consists of *Biscutum* spp. (18.2%), *Watznaueria* spp. (15.5%), *Tranolithus* spp. (9.8%), *Prediscosphaera* spp. (8.4%) and *Staurolithites* spp. (7.6%). Most common in the Middle Coniacian sample are *Biscutum* spp. (13.0%), *Tranolithus* spp. (12.7%), *Watznaueria* spp. (11.1%), *Zeugrhabdotus* spp. (9.8%) and *Eiffellithus* spp. (7.1%). The sample from the Upper Santonian yielded *Biscutum* spp. (24.1%), *Prediscosphaer*a spp. (10.0%), *Tranolithus* spp. (9.7%), *Watznaueria* spp. (9.7%) and *Zeugrhabdotus* spp. (7.8%). The uppermost sample – Lower Campanian – provided *Biscutum* spp. (23.1%), *Tranolithus* spp. (10.6%), *Prediscosphaera* spp. (9.9%), *Watznaueria* spp. (8.7%) and *Zeugrhabdotus* spp. (8.3%).

5. Discussion

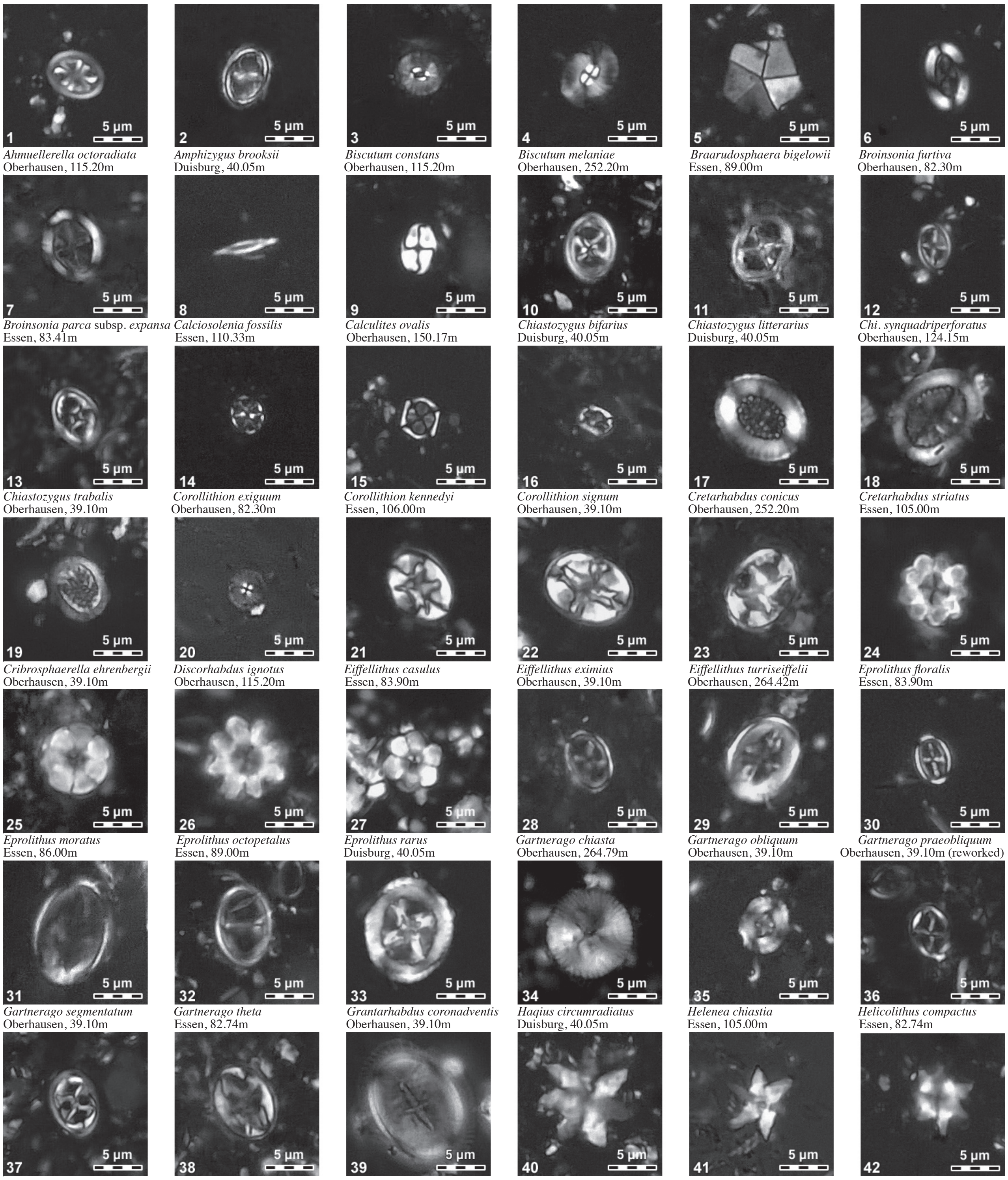
The good preservation of the calcareous nannofossils encountered can be explained by a combination of factors. These include: 1) the rarity of coarse-grained siliciclastics and a high amount of clay (and glauconite), giving the sediments a low porosity, so that pore-water circulation was restricted; 2) shallow depositional water-depths in a warm lagoonal environment; 3) an absence of diagenetic overprint, due to a low overburden and subsequent Cenozoic uplift; and 4) a low amount of organic matter in the deposits, which is known to accelerate post-depositional carbonate dissolution (Self-Trail & Seefelt, 2005).

Studies of nannofossil assemblages from coastal/nearshore palaeoenvironments from the geological past are rare. In contrast to the present day, much more widespread epicontinental shelf seas existed during the Jurassic, Cretaceous, Paleocene and Eocene for calcareous nannofossils to inhabit. The widespread sedimentation of chalks under neritic/hemipelagic conditions (water-depths of ≤200m, coastal distance of ≥50km) resulted from this. There is no modern analogue for such a setting; currently, shelf-break fronts prohibit the mixing of nearshore and open-ocean waters, and thus prevent a strong influx of calcareous nannofossils into the shallow seas (Hay, 2008). In the Late Cretaceous, a wide variety of calcareous nannofossil species occupied the epicontinental seas, where they could exist in rock-forming abundances.

Early nannofossil studies of Mesozoic sediments differentiated between neritic (shelf) and pelagic (open-ocean) calcareous nannofossil assemblages. Most taxa

Plate 1

LM images of nannofossils from the Duisburg, Essen and Oberhausen cores

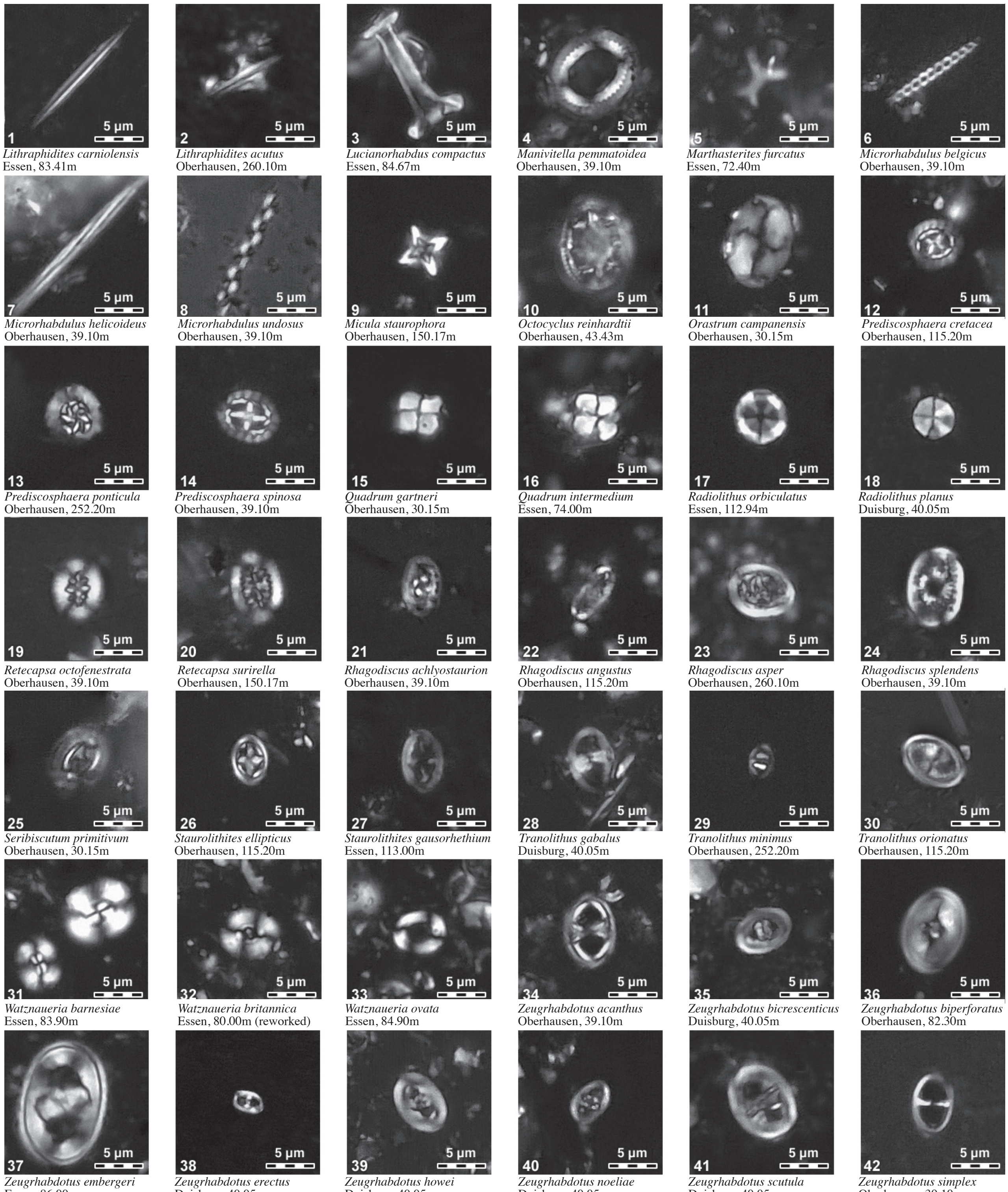


1 *Ahmuellerella octoradiata* Oberhausen, 115.20m
2 *Amphizygus brooksii* Duisburg, 40.05m
3 *Biscutum constans* Oberhausen, 115.20m
4 *Biscutum melaniae* Oberhausen, 252.20m
5 *Braarudosphaera bigelowii* Essen, 89.00m
6 *Broinsonia furtiva* Oberhausen, 82.30m
7 *Broinsonia parca* subsp. *expansa* Essen, 83.41m
8 *Calciosolenia fossilis* Essen, 110.33m
9 *Calculites ovalis* Oberhausen, 150.17m
10 *Chiastozygus bifarius* Duisburg, 40.05m
11 *Chiastozygus litterarius* Duisburg, 40.05m
12 *Chi. synquadriperforatus* Oberhausen, 124.15m
13 *Chiastozygus trabalis* Oberhausen, 39.10m
14 *Corollithion exiguum* Oberhausen, 82.30m
15 *Corollithion kennedyi* Essen, 106.00m
16 *Corollithion signum* Oberhausen, 39.10m
17 *Cretarhabdus conicus* Oberhausen, 252.20m
18 *Cretarhabdus striatus* Essen, 105.00m
19 *Cribrosphaerella ehrenbergii* Oberhausen, 39.10m
20 *Discorhabdus ignotus* Oberhausen, 115.20m
21 *Eiffellithus casulus* Essen, 83.90m
22 *Eiffellithus eximius* Oberhausen, 39.10m
23 *Eiffellithus turriseiffelii* Oberhausen, 264.42m
24 *Eprolithus floralis* Essen, 83.90m
25 *Eprolithus moratus* Essen, 86.00m
26 *Eprolithus octopetalus* Essen, 89.00m
27 *Eprolithus rarus* Duisburg, 40.05m
28 *Gartnerago chiasta* Oberhausen, 264.79m
29 *Gartnerago obliquum* Oberhausen, 39.10m
30 *Gartnerago praeobliquum* Oberhausen, 39.10m (reworked)
31 *Gartnerago segmentatum* Oberhausen, 39.10m
32 *Gartnerago theta* Essen, 82.74m
33 *Grantarhabdus coronadventis* Oberhausen, 39.10m
34 *Hagius circumradiatus* Duisburg, 40.05m
35 *Helenea chiastia* Essen, 105.00m
36 *Helicolithus compactus* Essen, 82.74m
37 *Helicolithus trabeculatus* Oberhausen, 39.10m
38 *Helicolithus turonicus* Essen, 80.00m
39 *Kamptnerius magnificus* Oberhausen, 39.10m
40 *Kokia kayae* Essen, 89.00m
41 *Lithastrinus grillii* Oberhausen, 39.10m
42 *Lithastrinus septenarius* Essen, 74.00m

are common to both settings, with only a few genera (e.g. *Nannoconus*, *Micrantholithus*, *Braarudosphaera*) having neritic affinities (Thierstein, 1976; Roth & Krumbach, 1986; Applegate et al., 1989). These taxa inhabited inner- to middle-shelf settings on a supraregional scale. Alternatively, nannoconids may have preferred clear, clean

Plate 2

LM images of nannofossils from the Duisburg, Essen and Oberhausen cores



1 *Lithraphidites carniolensis* Essen, 83.41m
2 *Lithraphidites acutus* Oberhausen, 260.10m
3 *Lucianorhabdus compactus* Essen, 84.67m
4 *Manivitella pemmatoidea* Oberhausen, 39.10m
5 *Marthasterites furcatus* Essen, 72.40m
6 *Microrhabdulus belgicus* Oberhausen, 39.10m
7 *Microrhabdulus helicoideus* Oberhausen, 39.10m
8 *Microrhabdulus undosus* Oberhausen, 39.10m
9 *Micula staurophora* Oberhausen, 150.17m
10 *Octocyclus reinhardtii* Oberhausen, 43.43m
11 *Orastrum campanensis* Oberhausen, 30.15m
12 *Prediscosphaera cretacea* Oberhausen, 115.20m
13 *Prediscosphaera ponticula* Oberhausen, 252.20m
14 *Prediscosphaera spinosa* Oberhausen, 39.10m
15 *Quadrum gartneri* Oberhausen, 30.15m
16 *Quadrum intermedium* Essen, 74.00m
17 *Radiolithus orbiculatus* Essen, 112.94m
18 *Radiolithus planus* Duisburg, 40.05m
19 *Retecapsa octofenestrata* Oberhausen, 39.10m
20 *Retecapsa surirella* Oberhausen, 150.17m
21 *Rhagodiscus achlyostaurion* Oberhausen, 39.10m
22 *Rhagodiscus angustus* Oberhausen, 115.20m
23 *Rhagodiscus asper* Oberhausen, 260.10m
24 *Rhagodiscus splendens* Oberhausen, 39.10m
25 *Seribiscutum primitivum* Oberhausen, 30.15m
26 *Staurolithites ellipticus* Oberhausen, 115.20m
27 *Staurolithites gausorhethium* Essen, 113.00m
28 *Tranolithus gabalus* Duisburg, 40.05m
29 *Tranolithus minimus* Oberhausen, 252.20m
30 *Tranolithus orionatus* Oberhausen, 115.20m
31 *Watznaueria barnesiae* Essen, 83.90m
32 *Watznaueria britannica* Essen, 80.00m (reworked)
33 *Watznaueria ovata* Essen, 84.90m
34 *Zeugrhabdotus acanthus* Oberhausen, 39.10m
35 *Zeugrhabdotus bicrescenticus* Duisburg, 40.05m
36 *Zeugrhabdotus biperforatus* Oberhausen, 82.30m
37 *Zeugrhabdotus embergeri* Essen, 86.00m
38 *Zeugrhabdotus erectus* Duisburg, 40.05m
39 *Zeugrhabdotus howei* Duisburg, 40.05m
40 *Zeugrhabdotus noeliae* Duisburg, 40.05m
41 *Zeugrhabdotus scutula* Duisburg, 40.05m
42 *Zeugrhabdotus simplex* Oberhausen, 39.10m

waters, not necessarily reflecting nearshore conditions (Mutterlose & Bottini, 2013).

Linnert & Mutterlose (2015) described relatively rich nearshore assemblages from the Lower Turonian of the current study area. High relative abundances of eutrophic taxa, such as *Biscutum constans* (max. 16.2%)

and *Tranolithus orionatus* (max. 12.7%) suggest an elevated palaeofertility. This is consistent with a nearshore setting, where nutrients would have been provided via fluvial input from the nearby landmass. In our dataset, increased abundances of *Biscutum* spp. (max. 24.2%, Upper Santonian) and *T. orionatus* (max. 11.9%, Middle to Upper Coniacian) support this hypothesis for the entire Cenomanian–Campanian interval.

Our findings relate to a very specific Late Cretaceous scenario. The Late Cretaceous sea-level rise resulted in a breakdown of the shelf-break fronts, which could no longer be maintained. Chalks were then deposited in the broad epicontinental seas, which became an integrated part of the oceanic realm. Hemipelagic conditions were established, and oceanic calcareous plankton invaded the epicontinental seas. At the same time, warm and humid conditions prevailed. In specific coastal settings, in the absence of a significant input of coarse-grained clastics due to low inland relief and perhaps dense vegetation, sediment starvation occurred. Present-day mangrove swamps, typical in warm, humid environments between 25°N and 25°S, might perhaps be the closest to a modern

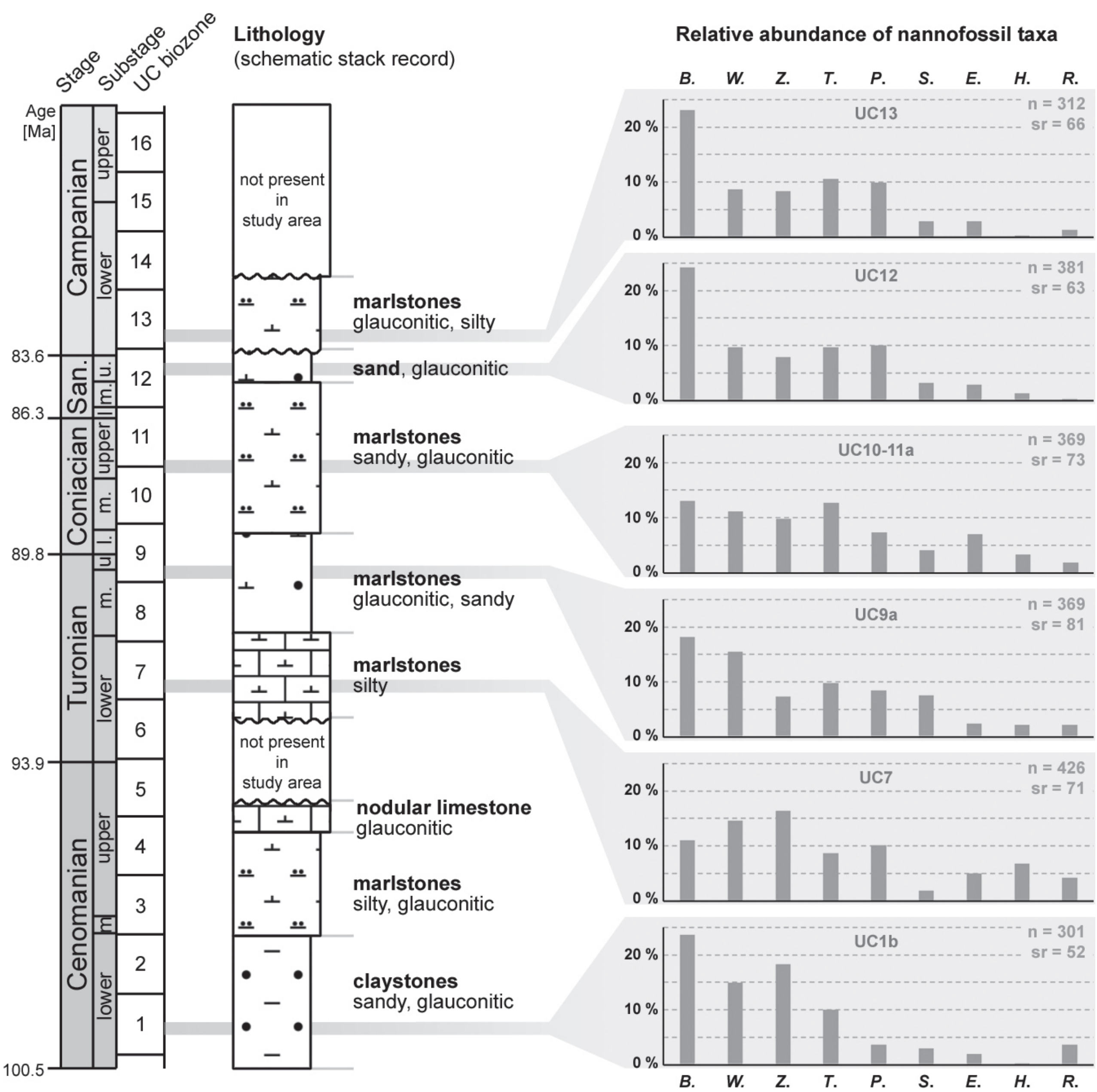


Figure 3: Relative abundances of the most common taxa. *B.* – *Biscutum* spp., *W.* – *Watznaueria* spp., *Z.* – *Zeugrhabdotus* spp., *T.* – *Tranolithus* spp., *P.* – *Prediscosphaera* spp., *S.* – *Staurolithites* spp., *E.* – *Eiffellithus* spp., *H.* – *Helicolithus* spp., *R.* – *Rhagodiscus* spp., n – number of specimens counted, sr – species richness. UC – Upper Cretaceous nannofossil zones of Burnett et al. (1998), absolute ages after Gradstein (2012)

analogue. Our Late Cretaceous nearshore setting was characterised by a calcareous open-ocean signal (i.e. from calcareous nannofossils) and glauconite, forming in a sediment-starved environment.

6. Conclusions

To our knowledge, this is the first time that well-preserved Late Cretaceous calcareous nannofossils have been reported from a very shallow-marine nearshore setting of 0–10km from the coast. The assemblages are highly diverse and very abundant, and contain common nearshore taxa. We postulate that this Late Cretaceous glauconite-rich marl environment, with its diverse and abundant calcareous nannofossil assemblages, has no modern analogue. Our data suggest a Late Cretaceous 'water world' scenario, where open-ocean conditions prevailed in this palaeocoastal setting.

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