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Stratigraphic and palaeoenvironmental analysis of the Rupelian–Chattian transition in the type region: evidence from dinoflagellate cysts, foraminifera and calcareous nannofossils[☆]

Stefaan Van Simaey^{a,*}, Ellen De Man^b, Noël Vandenberghe^a,
Henk Brinkhuis^c, Etienne Steurbaut^{a,b}

^a *Historical Geology, University of Leuven, Redingenstraat 16, Leuven B-3000, Belgium*

^b *Royal Belgian Institute of Natural Sciences, Vautierstraat 29, Brussels B-1000, Belgium*

^c *Laboratory of Paleobotany and Palynology, Utrecht University, Budapestlaan 4, Utrecht 3584 CD, The Netherlands*

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Abstract

Quantitative analysis of organic-walled dinoflagellate cysts (dinocysts), foraminifera and calcareous nannofossils from boreholes in Belgium and Germany enables the recognition of biotic events and reconstruction of environmental change in the late Rupelian and early Chattian in their type region the southern North Sea Basin. Compared to the early Rupelian, depositional conditions (neritic) do not seem to have substantially changed during the late Rupelian. The microfossil groups studied indicate relatively cold-water conditions in an outer-shelf environment. The boundary between the (lower) Rupelian stratotype section and the Upper Rupelian subsurface succession can be recognized by the first occurrence (FO) of *Saturnodinium pansum* and the last occurrence (LO) of *Enneadocysta pectiniformis* (dinocysts). The traditional Rupelian–Chattian (R–C) boundary definition, at the base of the benthic foraminiferal *Asterigerinoides guerichi* acme known as the *Asterigerina* Horizon, is upheld here. In terms of dinocyst biostratigraphy, it coincides with the FO of *Artemisiocysta cladodichotoma* and the recurrence of *Pentadinium imaginatum*, falling within the middle of the NP24* nannofossil zone (* points to the substitute zonation for the North Sea Basin). The traditional R–C boundary coincides with an abrupt return of shallow warm-water conditions and represents a third-order sequence boundary. The R–C boundary is overlain by transgressive Chattian deposits, which correspond to a distinct warming event. This pulse may correlate with the globally detected Late Oligocene Warming Event, which has an approximate age of 26 Ma. A mid-Chattian hiatus coincides with the NP24*/NP25* boundary and with the simultaneous disappearance of several dinocyst taxa. A detailed literature study proved that the LO of the planktonic foraminiferal genus *Chiloguembelina* is globally diachronous. Hence, the validity of this *Chiloguembelina* extinction as a global R–C boundary criterion can be questioned. This study offers new perspectives for the search for a R–C boundary Global Stratotype Section and Point (GSSP). © 2004 Elsevier B.V. All rights reserved.

Keywords: Rupelian–Chattian boundary; North Sea Basin; Dinoflagellate cysts; Benthic foraminifera; Calcareous nannofossils

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* Corresponding author. Fax: +32-16-32-64-01.

E-mail address: stefaan.vansimaey@geo.kuleuven.ac.be (S. Van Simaey).

1. Introduction

The greater North Sea Basin is the home of the type sections of eight out of the nine internationally selected Paleogene stages. It is one of the best documented passive margin systems worldwide in terms of Paleogene sedimentary facies history, biostratigraphy and sequence stratigraphic interpretation. Although the stratigraphical data allow high-resolution correlations throughout the basin, their calibration to the integrated time scale of Berggren et al. (1995) remains controversial at certain levels. Many of the younger Paleogene calibration problems arise from the effects of global climatic cooling, culminating at the onset and within the Oligocene, as the Earth began to shift from its pre-

Oligocene greenhouse state to its present icehouse state. The global cooling forced taxa to migrate towards lower latitudes. As a consequence, many of the biotic events used in standard late Eocene–Oligocene biostratigraphy are latitudinally diachronous (e.g., Cavalier, 1979; Wei and Wise, 1990; papers in Berggren and Prothero, 1992; Brinkhuis and Visscher, 1995). Moreover, some of the biotic events used in these standard zonations are not recorded at high latitudes, as temperature barriers delimited the distribution of taxa (e.g., the nannofossil *Sphenolithus ciperoensis*, the first occurrence (FO) of which defines the NP23/NP24 boundary, is absent in the North Sea Basin; Müller, 1986).

Other correlation and calibration problems arise from the restricted marine setting of the greater North

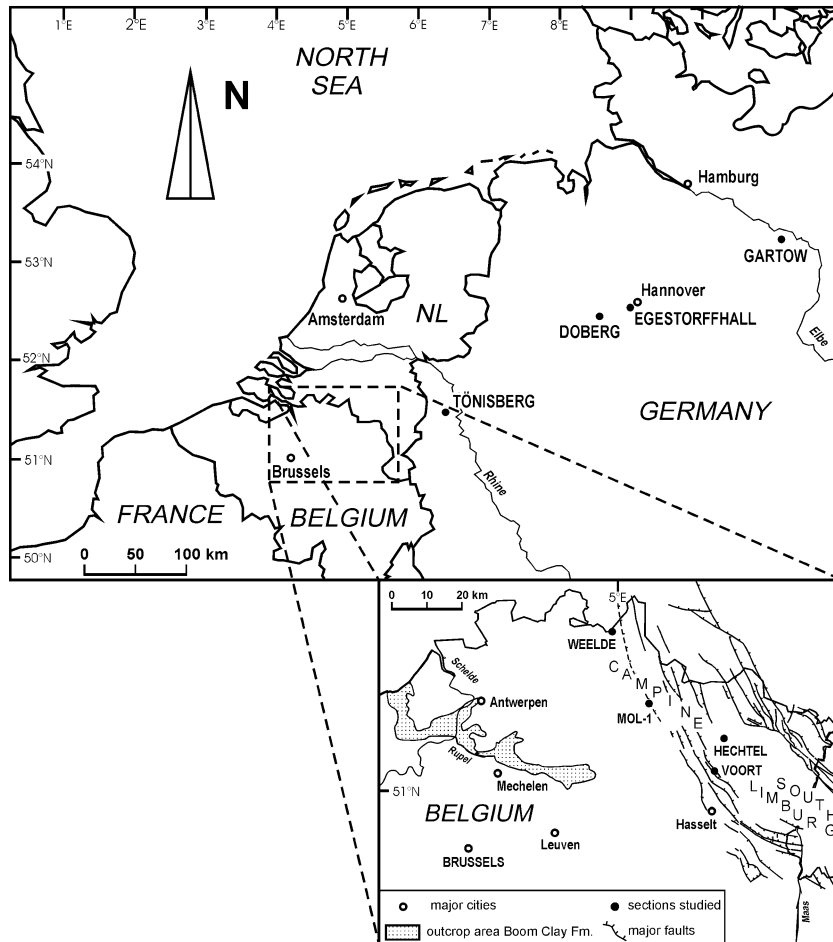


Fig. 1. Location of the sections studied. The position of each borehole or locality is given in Table 1. (NL: The Netherlands)

Sea Basin during much of the Paleogene. The semi-enclosed configuration, enhancing anoxia in certain subregions, was not favourable for carbonate preservation, thus hampering traditional biostratigraphy and oxygen isotope analysis on the basis of calcareous biotic remains. In certain areas like the southern border of the basin, sediments underwent severe diagenesis, causing the destruction of original geomagnetic signatures and geochemical signals.

Here, we aim at (1) clarifying existing mid-Oligocene correlation problems and (2) elucidating palaeoenvironmental changes associated with the Rupelian–Chattian (R-C) boundary in the type region through integrated quantitative micropalaeontological analysis, involving foraminifera, calcareous nannofossils and dinocysts. For this purpose, several surface and subsurface sections throughout the Rupelian and Chattian type region in Belgium and Germany have been investigated (Fig. 1). This study may contribute to choosing a R-C boundary Global Stratotype Section and Point (GSSP).

2. The Rupelian and Chattian stages

2.1. The Rupelian stage

The Rupelian stage was introduced by Dumont (1849). The main body of this stratigraphic unit is composed of clays cropping out along the river Rupel in northwest Belgium (Fig. 1). Today, these clays are lithostratigraphically referred to as the Boom Clay Formation. The latter consists of a detrital, grey silty clay or clayey silt with rather consistent chemical and mineralogical properties throughout the entire succession. The most striking feature of the Boom Clay is its rhythmic alternation of grain size, land-derived organic matter and carbonate contents. The rhythms occur in well-defined sequences and are consistent throughout the outcrop area. This succession of rhythms has a characteristic geophysical log response (Vandenberghe et al., 1997, 2001).

In the outcrop area north and west of the river Rupel, the Boom Clay Formation has an approximate total thickness of 43 m and can be subdivided into three lithological units, in ascending order, the Belsele-Waas Member, the Terhagen Member and the Putte Member. In the subsurface of the Campine, northeast of the

outcrop area (Fig. 1), the total thickness of the Boom Clay Formation increases rapidly up to 150 m. Based on detailed geophysical well-log correlations and some micropalaeontological data, Vandenberghe et al. (2001) concluded that the outcrop section in the stratotype area correlates only with the lower part of the Boom Clay Formation in the subsurface of northeast Belgium. The remaining 100-m-thick upper part of the Boom Clay in the Campine subsurface is therefore younger and has never been systematically investigated. Van den Broeck (1884, 1893) identified clayey sands, now described as Eigenbilzen Formation, on top of the Boom Clay in the Campine area. Based on the similar lithology, grain size rhythmicity and stratigraphic position below the Chattian Voort Sands, both the Boom Clay Formation and the Eigenbilzen Formation have always been included in the Rupel Group and thus belong to the Rupelian stage. Van Straelen (1923) introduced the term ‘Voort Sands’ to indicate dark green glauconite-rich fine sand, rich in macrofossils (mainly bivalves and gastropods), known from the Campine subsurface. Based on the same foraminiferal assemblage as the early part of the Chattian sands of Germany, the Voort Sands have always been attributed to the Chattian stage (Willems et al., 1988, p. 186). The top of the Rupelian and the base of the Chattian in northeast Belgium are bounded by a minor unconformity (Vandenberghe et al., 1998).

The Rupelian stratotype has been the topic of many (micro)palaeontological, sedimentological and geochemical studies. Stover and Hardenbol (1994) carried out a detailed study on the dinocysts of the Boom Clay Formation. Overviews of the calcareous nannofossil and benthic foraminiferal studies have been given in Steurbaut (1986, 1992) and Grimm and Steurbaut (2001), respectively. Hooyberghs (1983); Hooyberghs et al. (1992) investigated the planktonic foraminifera. He recognized planktonic foraminiferal zones P18 to P21 of Blow (1969), although no zonal boundaries could be identified since some of the zonal markers were not encountered or had a peculiar range. Macrofossil studies have essentially focused on bivalves (Glibert, 1955, 1957), decapods (Verheyden, 2002) and fish remains (Steurbaut and Herman, 1978). Vandenberghe (1978) studied the sedimentology. The Milankovitch cyclicity and cyclostratigraphy of the Boom Clay Formation have been investigated by Van Echelpoel and Weedon (1990) and Vandenberghe et

al. (1997). The geochemical signature has been studied by Laenen (1997) and the magnetostratigraphy by Lagrou (2001). Vandenberghe et al. (2001) used calibrated well logs to correlate the Rupelian stratotype in north Belgium with the Lower Rhine area in Germany and southern Limburg in the Netherlands. However, all these studies only dealt with the Rupelian stratotype in the outcrop area (northwest Belgium), which only covers the lower part of the Rupelian stage. In order to analyse the R–C transition in the type region and make recommendations towards the definition of a suitable GSSP for the R–C boundary, it is necessary to analyse the as-yet poorly known younger upper part of the Rupelian in the stratotype area.

2.2. The Chattian stage

The Chattian stage was introduced by Fuchs (1894) to denote and describe the upper Oligocene sediments near Kassel, Doberg and Sternberg in Germany and at Ormoy in the Paris Basin. As Fuchs (1894) did not give information on specific localities and sections, Görge (1957) selected the Doberg near Bünde in Westfalen as the stratotype for the Chattian stage, a decision subsequently approved by Anderson et al. (1971) (Fig. 1; Table 1). The stratotype section has an overall thickness of approximately 67 m and consists of glauconite-rich sandy marls to marly sands, with some beds being more clayey. Macrofossils are very abundant, with gastropods, bivalves and echinoderms being the most common groups. Based on evolutionary trends within two strains of pectinids, the Chattian

Table 1

Location of the boreholes and outcrop sections studied (BF = benthic foraminifera, D = dinocysts)

Borehole	Mapsheet	Studied interval	Number of samples	Group studied
Weelde	8E159	341–231.16 m	32	BF + D
Mol	31W221	200.15–152.73 m	17	D
Voort	62W226	89–73 m	7	D
Hechtel	47E192	250–173 m	14	D
Doberg	TK 3817	7–67 m	7	D
Egestorffhall	TK 253624	70.45–66.8 m	5	BF
Gartow	TK 2934	298.20–215 m	12	(in progress)

was originally subdivided into a lower Eochattian (= “Untere Doberg Schichten”) and upper Neochattian (= “Obere Doberg Schichten”) (Hubach, 1957). Later, Anderson (1961) refined this twofold subdivision on the basis of pectinid ranges, introducing three units, Chattian A and Chattian B grouped into the Eochattian substage, and Chattian C, corresponding to the Neochattian substage.

Because of its rich macrofossil assemblage and its assessment as a neostatotype, the Doberg section has been the topic of many palaeontological, sedimentological and geochemical investigations. A full record of the different macrofossil groups studied is given in Anderson et al. (1971). Micropalaeontological investigations include studies of benthic foraminifera (Indans, 1965; Grossheide and Trunkó, 1965; Kaefer and Oekentorp, 1970), calcareous nannofossils (Martini and Müller, 1975) and dinocysts (von Benedek, 1975).

The lowermost layers at the very base of the Chattian sequence at Doberg are known as the *Asterigerina* Horizon, named after the bloom of the benthic foraminifer *Asterigerinoides guerichi*. This distinct bloom can be recognized in the entire North Sea Basin (Indans, 1958; Ellermann, 1958; Doppert and Neele, 1983; Ulleberg, 1987; King, 1983, 1989). Coeval with this event are the first occurrences (FOs) of the benthic foraminifera *Elphidium subnodosum* and *Protelphidium roemeri*. This early Eochattian (= Chattian A) is still within nannoplankton zone NP24, while Chattian B and C belong to zone NP25. Note that these zonal attributions are not based on the standard zonal definitions of Martini (1971) or Bukry (1973, 1975) used in the magnetobiochronologic framework of Berggren et al. (1995) (see Section 4.4 for a more detailed discussion). Authigenic glauconite grains from the *Asterigerina* Horizon in the Astrup borehole (northwest Germany) were dated through K–Ar dating at 26.2 ± 0.5 Ma. (Gramann et al., 1980).

2.3. The Rupelian–Chattian boundary in the type region

Since a Global Stratotype Section and Point (GSSP) between the Rupelian and Chattian stage has not yet been defined, uncertainties remain about where to place this boundary. It has been suggested that the definition of a chronostratigraphic unit should

place emphasis on the selection of the boundary stratotype of its lower boundary; its upper boundary is then defined as the lower boundary of the overlying unit. Therefore, the lower boundary stratotypes of successive chronostratigraphic units define their time spans (Salvador, 1994). According to this concept, the boundary between the Rupelian and Chattian stage coincides with the base of the Chattian stage. The base of the stratotype of the Chattian unit as defined at Doberg coincides with the FOs of the benthic foraminifera *Elphidium subnodosum* and *Protelphidium roemeri*, which are coeval with the onset of the bloom of *Asterigerinoides guerichi*. These distinct events are widespread in the North Sea Basin, allowing the recognition of the R-C boundary in its type region.

2.4. The Rupelian–Chattian boundary and the standard time scale

In their 1985 version of the integrated Cenozoic time scale, Berggren et al. subdivided the Oligocene into a lower Rupelian stage and an upper Chattian stage. They also stated that the boundary between these two stages is biostratigraphically linked with the last occurrence (LO) of the planktonic foraminiferal genus *Chiloguembelina* and with the NP23/NP24 boundary, which are associated with Chron C10n at an estimated age of 30 Ma (Fig. 2). This boundary characterisation was principally based on Ritzkowski's (1982) observations in northwest Germany. He stated that contrary to the previous correlation model of Hardenbol and Berggren (1978), the highest occurrence of *Pseudohastigerina* is not a suitable R-C boundary criterion because it falls within the middle of the Rupelian (=Rupel 3 division of Spiegel, 1965). The highest occurrence of *Chiloguembelina*, being positioned at the top of the Rupelian (=Rupel 4 division of Spiegel, 1965), was proposed as new R-C boundary criterion by Ritzkowski (1982). The magnetobiochronologic correlations proposed by Berggren et al. (1985) were based on studies of DSDP cores (Poore et al., 1982; Miller et al., 1985) and the Contessa section in central Italy (Lowrie et al., 1982). According to Berggren et al. (1985, p. 173), magnetobiostratigraphic data from the DSDP sections support correlation of the last appearance datum (LAD) of *Chiloguembelina* with a level low in zone NP24 and the authors "would agree that the Rupelian–Chattian boundary is closely linked with the

TIME (Ma)	Berggren et al. (1995)				CHRONS	POLARITY	Berggren et al. (1985)																	
	EPOCH	AGE	P-zones	NP-zones			NP-zones	P-zones																
23	MIOCENE	EARLY	M1b	NN2	C6Bn	■	NN1	'N4'																
24			M1a	NN1	C6Br				C6Cn															
25	OLIGOCENE	LATE	CHATTIAN	P22	NP25	■	NP25	P22																
26									P21	NP24	C7n	■	NP24	P21										
27											b				NP24	C8n	■	NP24	b					
28																a				NP24	C8r	■	NP24	a
29																					C9n			
30		P20	NP23	C10n	■	NP23	P19/ P20																	
31		P19		NP23				C11n	■	NP23	P19/ P20													
32		P18	NP22		C12n	■	NP22	P18																
					(1)																			
					(2)																			

Fig. 2. The integrated magnetobiochronologic time scale for the Oligocene of Berggren et al. (1995) compared with the magnetobiochronology of Berggren et al. (1985). The magnetic polarity for both time scales is the same. The P-zones in Berggren et al. (1995) refer to the plankton zones of Berggren and Miller (1988), while the P-zones in Berggren et al. (1985) refer to Blow (1969), Berggren and Van Couvering (1974) and Hardenbol and Berggren (1978). In both scales, the NP-zones refer to the calcareous nannoplankton zones of Martini (1971). (1): NP22/NP23 boundary at low to middle latitudes; (2): NP22/NP23 boundary at southern high latitudes.

LAD of *Chiloguembelina* and the NP23/NP24 boundary." However, the close link with the nannofossil NP23/NP24 boundary in this new reconstruction of the time scale slightly differs from the previously published nannofossil results of Martini (1971), von Benedek and Müller (1974) and Martini and Müller (1975). The latter stated that not only the top, but also a considerable part of the Upper Rupelian Clay (=Rupel 4 division of Spiegel, 1965) as well as the overlying Eochattian (=Chattian A) had to be incorporated into zone NP24. It is also clear that Berggren's straightforward correlation between the highest occurrence of *Chiloguembelina* and Chron C10n is not unequivocally supported by the data (see Fig. 3 and comments below).

The revised Cenozoic geochronology and chronostratigraphy of Berggren et al. (1995) combines a large

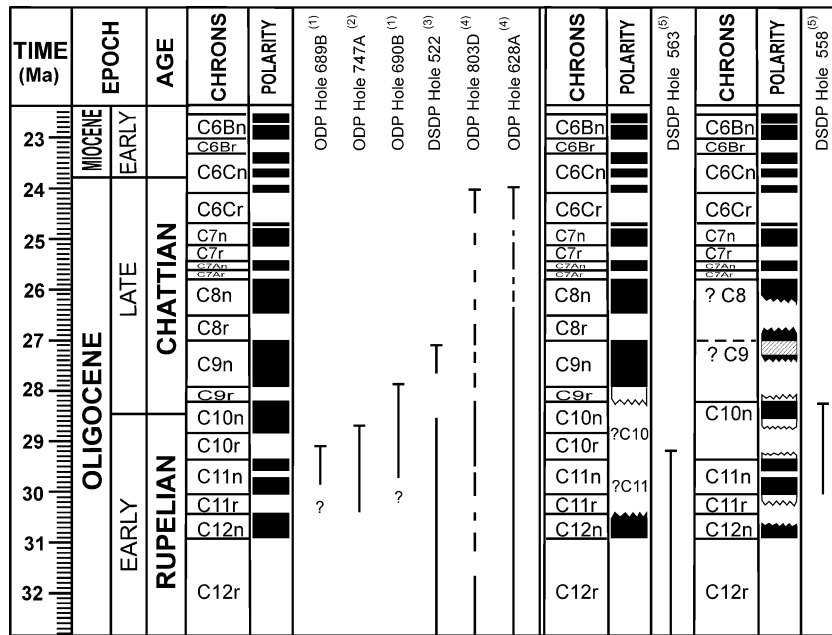


Fig. 3. Last appearance datum of *Chiloguembelina* spp. illustrated for different ODP and DSDP sites. (1) Stott and Kennett (1990); (2) Berggren (1992); (3) Poore et al. (1982); (4) Leckie et al. (1993); (5) Miller et al. (1985). Positive or negative inclination values indicate normal (shaded) or reversed (open) magnetic polarity; slashes indicate uncertain polarity. Magnetic polarity zones bounded by zigzag patterns (DSDP sites 558 and 563) are due to poor or no core recovery.

amount of magneto- and biostratigraphic data with new radiometric ages and has become the most applicable integrated magnetobiochronologic time scale for the Cenozoic. The frameworks of both the 1985 as well as the 1995 time scales are outlined in Fig. 2. In the revised time scale of Berggren et al. (1995), compared to Berggren et al. (1985), only a single biostratigraphic criterion is maintained to characterize the R-C boundary, namely, the last appearance datum of (common) chiloguembelinids, formalized as the P21 a/b boundary and calibrated to (mid) Chron C10n with an estimated age of 28.5 Ma.

Analyses of well-calibrated DSDP (Poore et al., 1982; Miller et al., 1985) and ODP boreholes (Stott and Kennett, 1990; Berggren, 1992; Leckie et al., 1993) demonstrate that the last appearance datum of chiloguembelinids, used worldwide to recognize the R-C boundary, is far less consistent than generally accepted. Combined evidence clearly indicates that the extinction of chiloguembelinids is not isochronous within magnetochron C10n and is most likely controlled by palaeolatitude and palaeobiogeography (Fig. 3). Berggren et al. (1995) were aware of this

problem and agreed that “whether this datum (=mid Chron C10n) refers to extinction or strong reduction remains a moot point” (Berggren et al., 1995, p. 173).

Besides the difficulties arising when using the extinction of chiloguembelinids as a criterion for recognizing the R-C boundary, there are also discrepancies with its age assessment. K–Ar dating on authigenic glauconites from the *Asterigerina* Horizon in northwest Germany revealed an absolute age of 26.2 ± 0.5 Ma (Gramann et al., 1980) while magneto-chronological estimates for the boundary suggested an approximate age of 28.5 Ma (Berggren et al., 1995). Thus, the radiometric dating of the base of the Chattian stratotype (26.2 Ma) differs by at least 1.8 Ma from the boundary age in Berggren’s revised time scale.

3. Material and methods

Samples for palynological (dinocyst) analysis were taken in the cored boreholes Mol-1 and Weelde at about 3-m intervals, covering the upper part of the Boom Clay Formation, the Eigenbilzen Sand Formation and

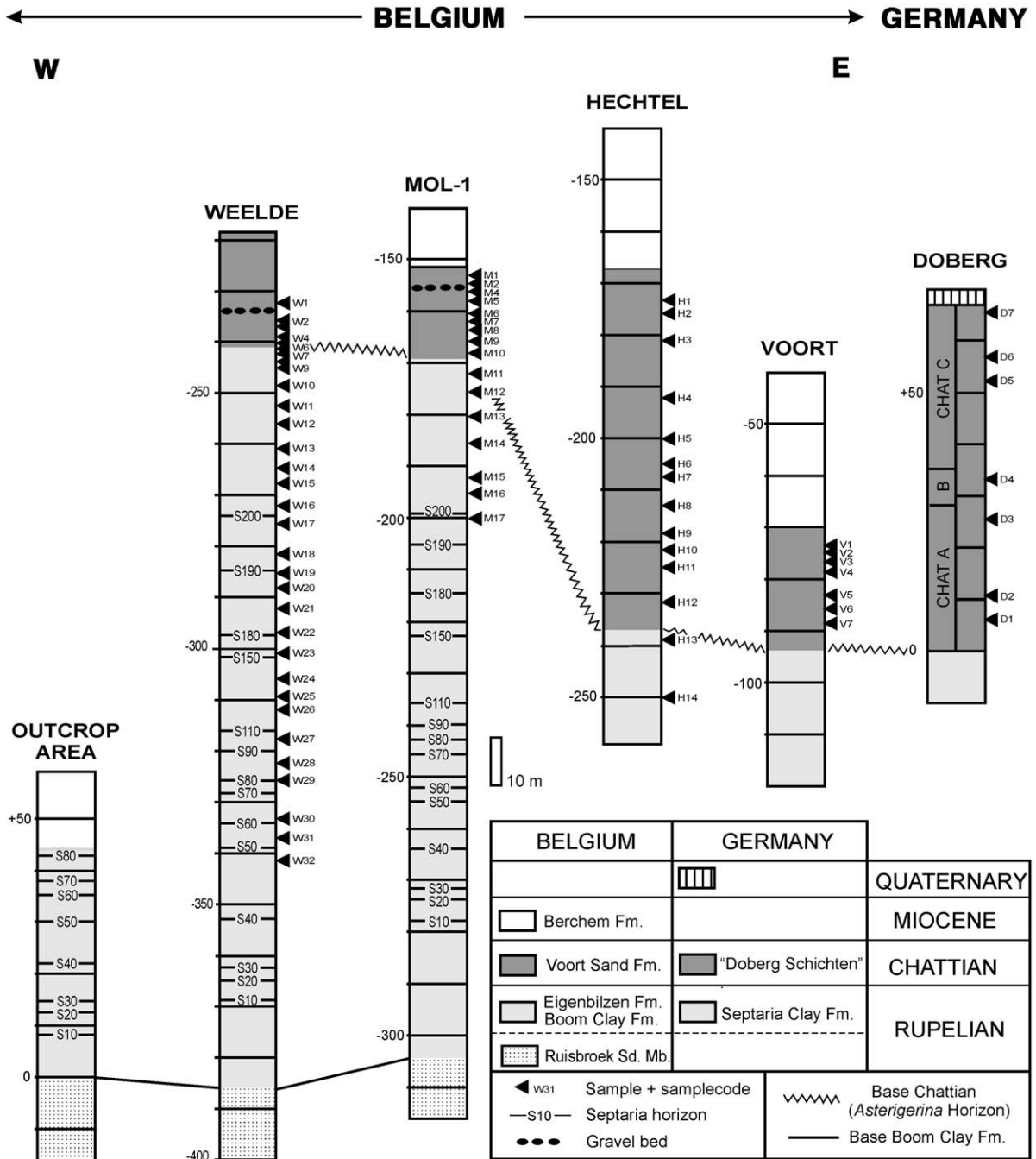
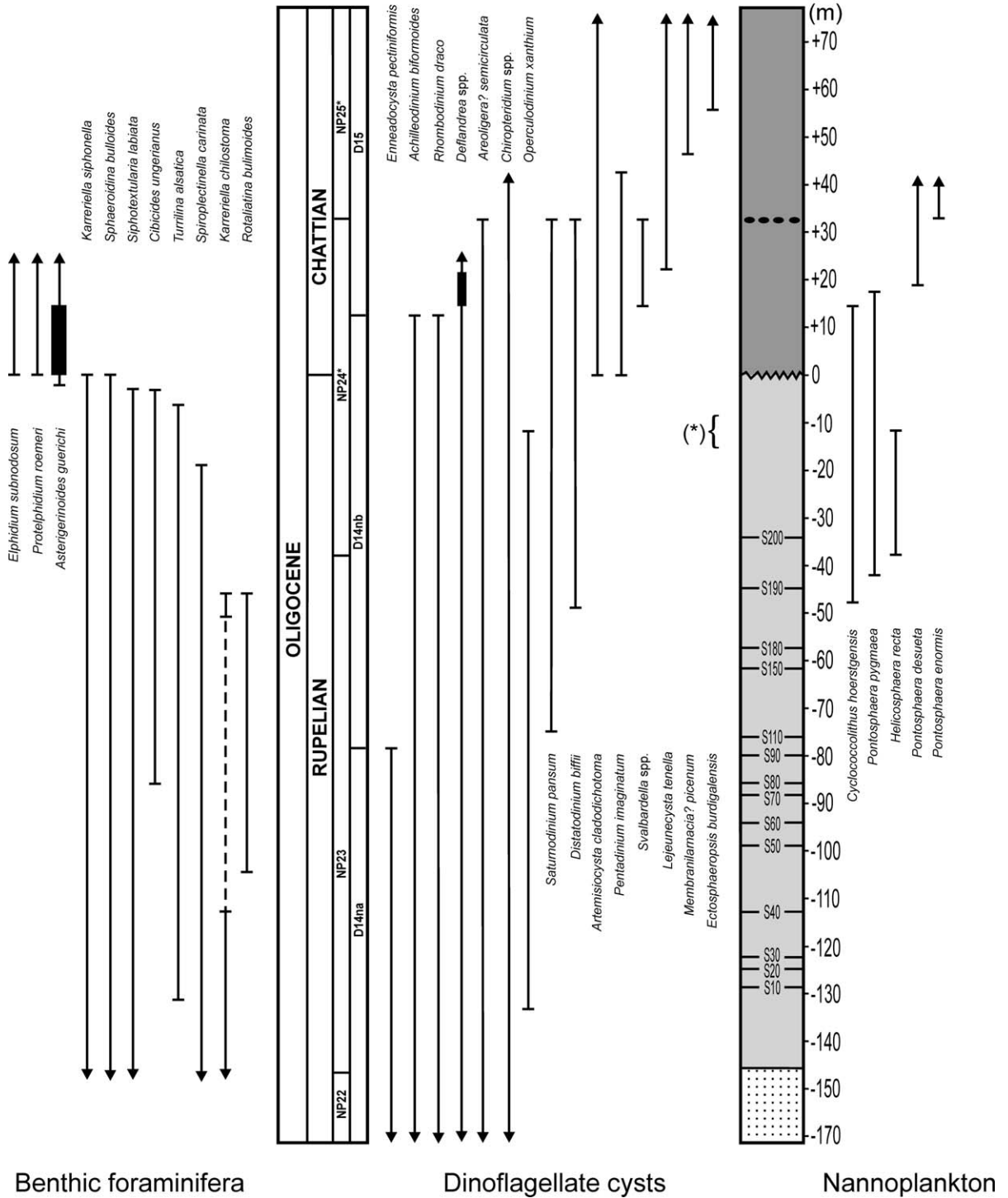


Fig. 4. Correlation between the five studied sections and the outcrop area of the Boom Clay Formation in its type locality. The Doberg section is subdivided into Chattian A and B (Eochattian) and Chattian C (Neochattian), as indicated in Anderson et al. (1971). Sample positions are given in Excel spreadsheet 1.

COMPOSITE SECTION



the Voort Sand Formation (Fig. 4). The lowermost sample was taken just below septaria level S-50, in order to assure an overlap with the outcrop area and previous studies on dinocysts (essentially Stover and Hardenbol, 1994). The Chattian stratotype section at Doberg was reinvestigated using samples collected during a fieldtrip guided by Gramann et al. (1969). This material was completed by a set of samples of the Chattian Voort Sand Formation from the Hechtel and Voort boreholes in northeast Belgium and by samples from the R-C transect in the Gartow borehole in northwest Germany. For location and details of the sections studied, see Fig. 1 and Table 1. The benthic foraminiferal investigation is based on 25 samples from the Weelde borehole, which were also used for dinocyst analysis. This material is completed by reference samples from the Mol-1 and Hechtel boreholes (northeast Belgium) and the Egestorffhall borehole 104 (northwest Germany). Sample positions are given in Fig. 4 and in Excel spreadsheet 1. The calcareous nannofossil data are from an investigation of a continuous series of samples from the Weelde and Mol-1 boreholes, the Doberg section and the calcareous parts of the Voort and Hechtel boreholes (Sturbaut, work in progress).

The boreholes are calibrated on the basis of geophysical well-log correlation and biostratigraphy. They have been integrated into a composite section (Fig. 5). The *Asterigerina* Horizon is designated as reference level 0. The lowermost dinocyst sample studied here is located at –98.6 m in this composite section, the lowermost benthic foraminiferal sample 30 m higher, at –69.6 m.

Foraminifera were processed for microfaunal analysis by soaking samples of equal weight (250 g) in a 10% solution of a phosphate-containing detergent (“Sun”), followed by wet sieving through a 63- μm sieve. The fraction above 120 μm was analysed quantitatively, taking into account planktonic and benthic foraminifera, bolboforma and sponges. The planktonic foraminifera were not identified to species level, but only calculated into the P/B index (=number planktonic foraminifera/number benthic foraminifera),

a proxy for ocean-water influx. Photographs were taken on a Philips XL30 environmental scanning electron microscope.

Palynological techniques were applied to approximately 50 g of sediment per sample and involved treatment with cold 25% HCl, digestion for 2 days in HF (40%), followed by repeated hot baths (80 °C) in 25% HCl. The samples were rinsed to neutrality between each step. No oxidation, heavy liquid separation or ultrasonic treatment was applied. All residues were homogenized by stirring and sieved through nylon filters with a mesh size of 15 μm . For those residues particularly rich in amorphous organic matter, subsamples were sieved through 30- μm filters in order to concentrate the dinocysts. Both fractions were stained with Safranin O and mounted with glycerine jelly. Relative abundances were calculated from 300 specimen counts from the 15- μm slides. One or two slides from the 30- μm fraction were scanned for rare species or especially well-preserved specimens. Photographs were taken on a ZEISS Axioskop-2 light microscope equipped with a Sony DSC-S75 camera.

Standard procedures as described in Sturbaut and King (1994) were used for the preparation of the samples and for the qualitative and quantitative analyses of the calcareous nannofossil assemblages. About 2 cm^2 of glass slide was examined for each sample.

The dinocyst material is stored in the collection of the Laboratory of Stratigraphy, section Historical Geology, University of Leuven, Belgium, the calcareous nannofossils and foraminifera in the collections of the Royal Belgian Institute of Natural Sciences (Brussels, Belgium).

4. Results and interpretation

4.1. Planktonic foraminifera

Planktonic foraminifera make up only 4% of the total number of foraminifera (in 25 samples). They are extremely rare in most of the samples, as shown by

Fig. 5. Composite section for the Rupelian–Chattian transitional layers in the stratotype area. The composite section was constructed by using the thickest (most complete) Rupelian and Chattian profiles, respectively, in the Weelde and Hechtel boreholes. Both boreholes were linked by using the base of the *Asterigerina* Horizon (=base of the Chattian); this level has been selected as zero level. The most important benthic foraminifera, dinocyst and nannoplankton events, completed with data by Grimm and Sturbaut (2001) and Stover and Hardenbol (1994), are projected to this section. *Indicates the interval with silicified biserial planktonic foraminifera. See Fig. 4 for legend.

the very low P/B index throughout the studied sections (between 0 and 0.03; see Excel spreadsheet 2). In the uppermost part of the Rupelian (samples W10, W11), the entire planktonic foraminiferal assemblage consists of silicified moulds. A minor part of these moulds are biserial and here provisionally attributed as “*Chiloguembelina*.” Similar records of these silicified “*Chiloguembelina*” are recorded from the German Rupel 4 division in the Egestorffhall borehole 104 (this study). We suggest that these silicified biserial foraminifera do not represent in situ chiloguembelinids, but are reworked heterohelicidae. This is based on scanning electron microscope (SEM) analyses which showed that all specimens have an early planispiral stage, a simple symmetrical aperture and a striate wall (see Plate I(7)–(8)); all features are characteristic for Late Cretaceous heterohelicidae. As the siliceous moulds occur within normal calcareous foraminiferal associations, their presence cannot be due to in situ silicification, but to reworking of previously silicified forms. It needs to be verified whether the *Chiloguembelina* records of Ritzkowski (1982) in the German Rupel 4 division have the same nature as the silicified moulds encountered in the Upper Rupelian in this study. This is necessary to delineate the true range of *Chiloguembelina* in the stratotype area of the Rupelian.

4.2. Benthic foraminifera

4.2.1. General comments

The lowermost 40 m of the Rupelian section exposed in the type area was analysed by Grimm and Steurbaut (2001). Our study starts about 25 m higher, at –69.6 m in the composite section (Fig. 5). To attain a coherent data set for the Oligocene, we have incorporated the significant biostratigraphic events of Grimm and Steurbaut (2001) in our study (Fig. 5).

Throughout the transect investigated, several non-calcareous intervals can be distinguished. Calcareous

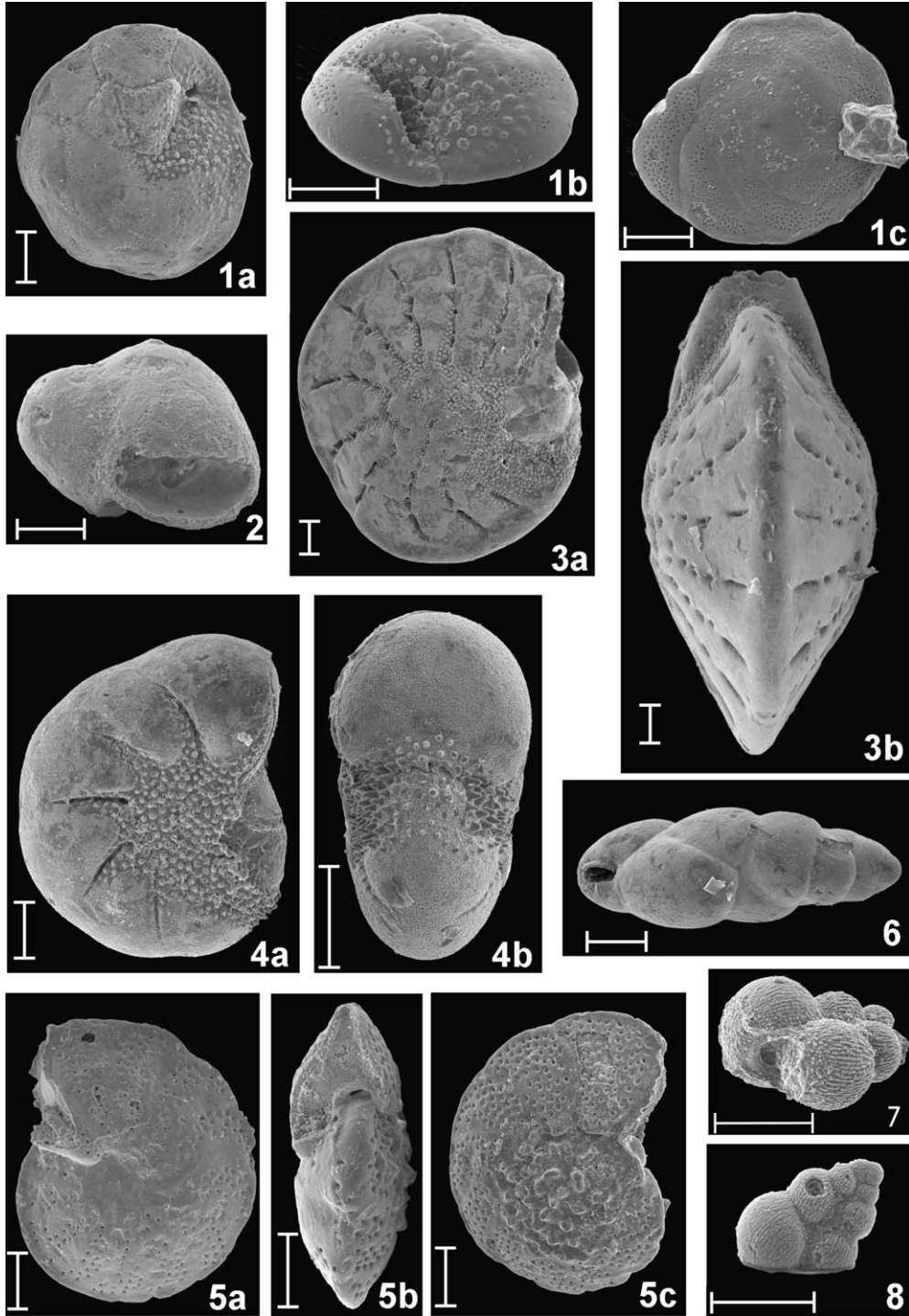
fossils in the lower part of the section are often pyritized and poorly preserved, while their preservation in the upper part is moderate to good. Lithological differences such as the alternation of clay and silt do not seem to influence the microfaunal associations.

The foraminiferal fauna is very poor throughout the entire section (0–400 specimens per 100 g sediment). Benthic foraminifera make up for 96% of the total foraminiferal specimens. The diversity of the fauna is very low, with only 5–34 benthic foraminiferal taxa per 100 counted specimens (Fig. 6 and Excel spreadsheet 2). In total, 55 benthic foraminiferal taxa could be identified. Agglutinated foraminifera occur rather consistently throughout the Upper Rupelian, sometimes making up for 70% of the total assemblage. They are virtually absent in the Chattian Voort Sands (Excel spreadsheet 2).

4.2.2. Biofacies and marker species

Compared to Grimm and Steurbaut (2001), some LOs have to be reconsidered. Both *Karrerella chilostoma* and *Spiroplectinella carinata* were found in the Upper Rupelian, the former with low frequencies in a single level (1%), the latter in much higher frequencies as known from the Lower Rupelian. These high values, however, could be due to differential dissolution of calcareous foraminifera, increasing the relative proportion of agglutinated taxa. Two pulses of *Cibicides ungerianus* (Plate I(5)) are recorded, the lowest pulse virtually coinciding with the LOs of *Rotaliatina bulimoides* (Plate I(2)) and *Karrerella chilostoma*. The LO of *C. ungerianus* occurs at the very top of the Rupelian section and is closely associated with the LOs of *Siphotextularia labiata*, *Bolivina* spp., *Alabamina tangentialis*, *Sphaeroidina bulloides*, *Nodosaria spinescens*, *Karrerella siphonella* and *Lagena* spp. *Bulimina elongata* (Plate I(6)) has maximum abundances (up to 23%) in these topmost Rupelian levels (Fig. 5 and Excel spreadsheet 2). *Asterigerinoides guerichi* (Plate I(1)) first occurs, although in low numbers, around 2

Plate I. (1) *Asterigerinoides guerichi* (Franke 1912), sample W8. (a) Ventral side, (b) peripheral side, (c) dorsal side. (2) *Rotaliatina bulimoides* (Reuss 1851), Sample W21, side view. (3) *Elphidium subnodosum* (Roemer 1838). Sample W1. (a) Side view, (b) peripheral side. (4) *Protelphidium roemeri* (Cushman 1936), Sample W1. (a) Side view, (b) peripheral side. (5) *Cibicides ungerianus* (d'Orbigny 1846), Sample W9. (a) Dorsal side, (b) peripheral side, (c) ventral side. (6) *Bulimina elongata* (d'Orbigny 1846), Sample W8, side view. (7) Reworked heterohelicidae, Sample W11 apertural view. (8) Reworked heterohelicidae, Sample –70.65 m, Egestorffhall borehole 104, side view. Bar = 100 µm.



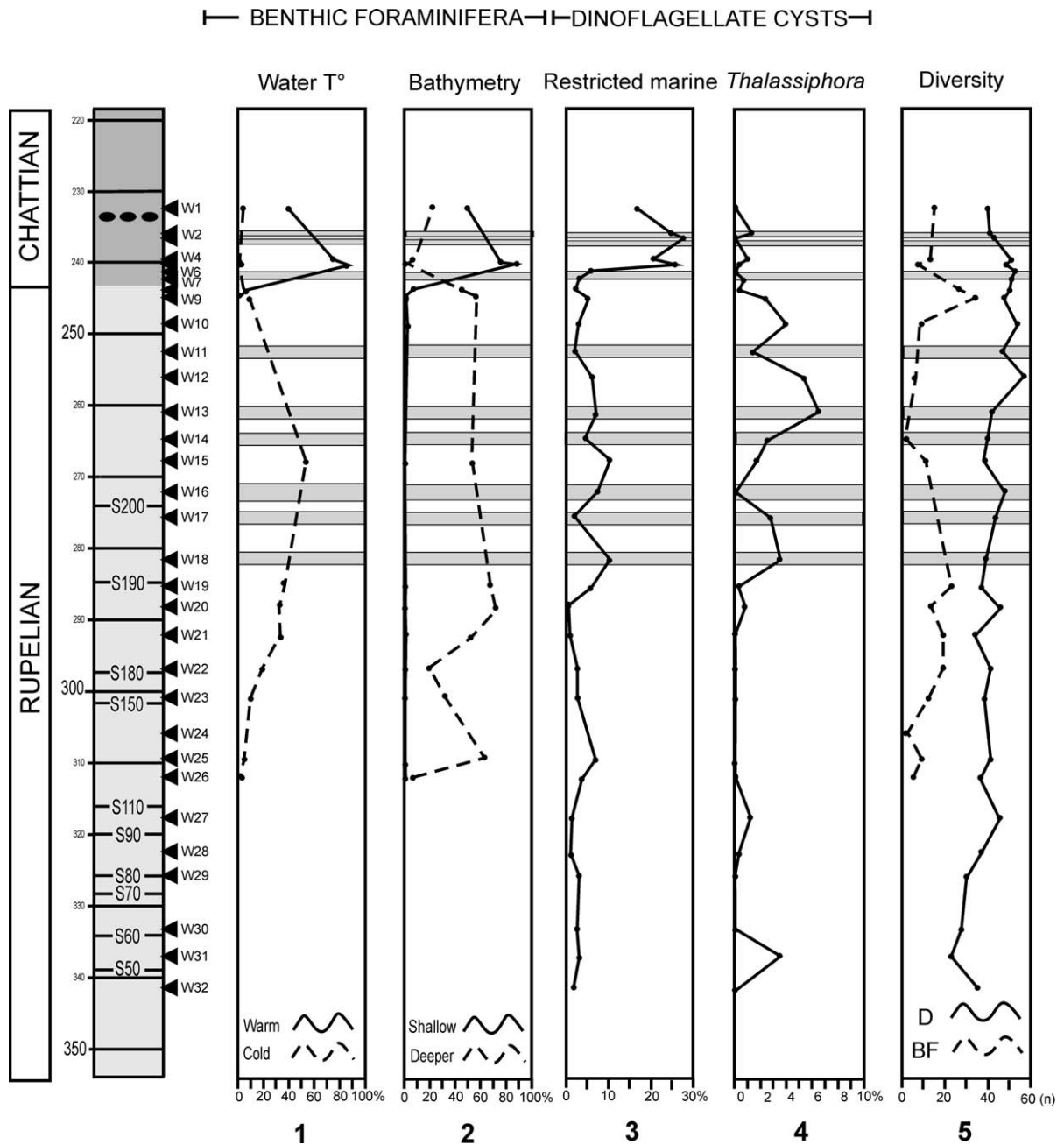


Fig. 6. Distribution of benthic foraminiferal and dinocyst eco-groups throughout the Weelde borehole. Taxa belonging to each group are given in Table 2. Values are in percentages, except in column 5, where absolute counts of both dinocysts (D) and benthic foraminifera (BF) species are plotted. Sample depths are given in Excel spreadsheet 1. Light grey zones indicate non-calcareous levels.

m below the top of the Rupelian. It reaches maximum abundances (70–90%) at the base of the Voort Sand Formation. The onset of the *Asterigerinoides guerichi*

bloom (= *Asterigerina* Horizon) coincides with the FOs of *Elphidium subnodosum* (Plate I(3)) and *Protelphidium roemeri* (Plate I(4)). These species become

more important higher up in the Chattian section, with abundances of up to 7% and 10%, respectively (see Fig. 5 and Excel spreadsheet 2).

4.2.3. Biostratigraphy: interpretation and correlation

Calcareous microfossil correlations between the North Sea Basin and the international zonation schemes appear problematic for the Rupelian–Chattian interval because many of the biotic events are latitudinally diachronous. Nevertheless, benthic foraminifera are quite useful for regional correlation. In the following, the biostratigraphically significant events are summarized and compared to existing zonation schemes for the Oligocene of the North Sea Basin.

Correlations of the Belgian Basin with the Rhenish area (Germany) are well established for the lower part of the Rupelian (von Daniels et al., 1994; Grimm and Steurbaut, 2001; Vandenberghe et al., 2001). The most obvious correlation horizon for the R–C transitional layers is the bloom of *Asterigerinoides guerichi*. Other biostratigraphic events occur in the same chronological order in the Belgian sections (this study), as well as in the German sections (Indans, 1958; Ellermann, 1958): a few metres below its actual bloom, *Asterigerinoides guerichi* has its first occurrence, coinciding with the LO of *Cibicides ungerianus*. Higher up, coeval with the onset of the *Asterigerina* Horizon, *Elphidium subnodosum* and *Protelphidium roemeri* have their FO. The remaining part of the R–C interval provides very little foraminiferal-based correlation criteria due to the scattered distribution of calcareous horizons.

Benthic foraminifera allow a detailed subdivision of the Lower Rupelian in North Germany (Spiegler, 1965). The application of this zonation scheme to the Belgian lower Oligocene outcrop area is possible (von Daniels et al., 1994). However, the identification of the Rupel 4 division in Belgium is controversial. The latter is characterized by the lowest (common) occurrence of *Cibicides ungerianus* and by the income of a diverse benthic foraminiferal assemblage. The presence of *C. ungerianus* in S-80 (–82 m in the composite section, Fig. 5) is only known from unpublished data of Doppert (1979) and Ritzkowski (1980). This would imply that the studied Rupelian section (from –69.5 m in the composite section) falls entirely within the Rupel 4 division. According to Spiegler (1965), the Rupel 4

division can be divided into two subzones on the base of the presence of *Plectofrondicularia seminuda* in the lower subzone. Since this species was not encountered here, no further subdivisions could be made for the Belgian Upper Rupelian.

King (1983, 1989) correlated the Lower Rupelian deposits of the outcrop area to offshore sections in the North Sea Basin. He used the highest occurrence of *Rotaliatina bulimoides* to approximate the R–C boundary. However, the LO of this species is recorded 42.6 m below the actual R–C boundary, as defined in its type area. *Karrerella chilostoma*, the highest occurrence of which defines the top of zone NSA 8, seems to disappear much earlier in Belgium, as it is not encountered in the Chattian sections studied.

4.3. Dinocysts

4.3.1. General comments

In general, the palynological samples examined are dominated by dinocysts and bisaccate pollen. A diverse and well-preserved dinocyst assemblage was recovered from the Upper Rupelian and Lower Chattian in north Belgium. The most diversified Rupelian assemblage consists of 58 taxa; the most diversified Chattian sample contains 61 taxa. Reinvestigations of the dinocyst assemblage from the Chattian stratotype show that the Doberg section (northwest Germany) is characterized by a rather low diversity (between 15 and 34 species per sample) and confirm earlier findings (von Benedek, 1975) that no representatives of the Order Peridinales occur (see Excel spreadsheet 3–6).

Based on the highest occurrence of common *Phthano-peridinium filigranum* and *Fibrocysta axialis* and confirmed by geophysical well-log correlations, it is possible to correlate the lowermost sample of our study (W32) with a level around 33 m in the Boom Composite Section of Stover and Hardenbol (1994, figure 7). The highest sample (62 m) in their Boom composite section corresponds with a level between samples W27 and W26 in this study. This correlation is based on the FO of *Saturnodinium pansum* (Plate IV(4)) and confirmed by geophysical well logs. Nevertheless, to attain a coherent data set for the Oligocene, we have incorporated the significant biostratigraphic events of Stover and Hardenbol (1994) in this study (Fig. 5).

A literature study on Oligocene dinocysts shows that the ranges of the following taxa encountered have

biostratigraphic significance (see also Fig. 5), viz: the FO of *Saturnodinium pansum*, that virtually coincides with the LO of *Enneadocysta pectiniformis*. Other important Upper Rupelian marker species are *Distatodinium biffii* (Plate III(1)), of which the FO is recorded at approximately 45 m below the R-C boundary in the composite section, and *Operculodinium xanthium* (Plate III(3)), which disappears around 10 m below the R-C boundary. The very base of the Chattian in the type region is characterized by the first occurrence of *Artemisiocysta cladodichotoma* (Plate II(4)) and by the recurrence of *Pentadinium imaginatum* (Plate IV(3)). Associated with the base of the Chattian is the highest occurrence of both *Rhombodinium draco* (Plate IV(1)) and *Achilleodinium biformoides* (Plate II(2)). About 14 m above the R-C boundary, a narrow interval occurs with some rare *Svalbardella* spp. (Plate III(3)). The base of this interval virtually coincides with the start of the *Deflandrea* spp. acme (ca. 10%) (Plate III(2)). The recurrence of *Lejeunecysta tenella* (Plate IV(5)) is recorded a few metres higher up, still within the *Svalbardella* interval. The three markers, *Distatodinium biffii*, *Saturnodinium pansum* and *Areoligera semicirculata* (Plate II(1)) disappear simultaneously at about +35 m in the composite section (see Fig. 5 and in Excel spreadsheet 3–6). The top of the Chattian is marked by the successive appearance of *Membranilarnacia? picena* (at +47 m) (Plate III(4)) and *Ectosphaeropsis burdigalensis* (at +56 m) (Plate IV(6)). The appearance of these taxa is apparently earlier at these latitudes than in the Mediterranean, where these events mark the earliest Miocene (Biffi and Manum, 1988; Brinkhuis et al., 1992; Zevenboom et al., 1994).

4.3.2. Biostratigraphy: interpretation and correlation

An intraformational gravel bed is encountered within the Voort Sand section. This narrow interval (ca. 5 cm) in both the Weelde and Mol-1 borehole consists of coarse quartz grains and fine gravel (less than 1 cm in

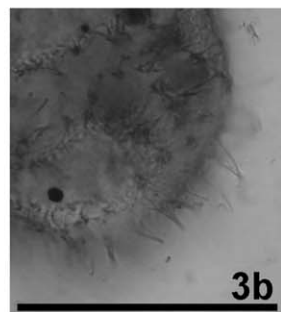
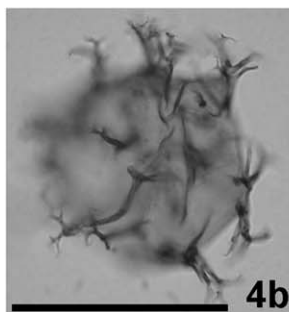
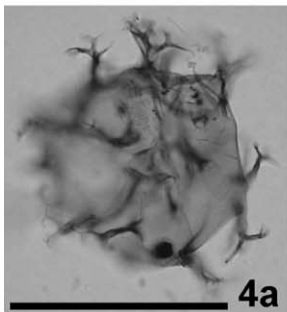
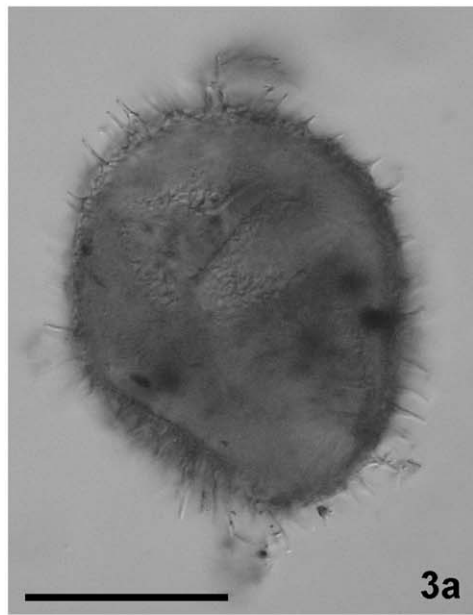
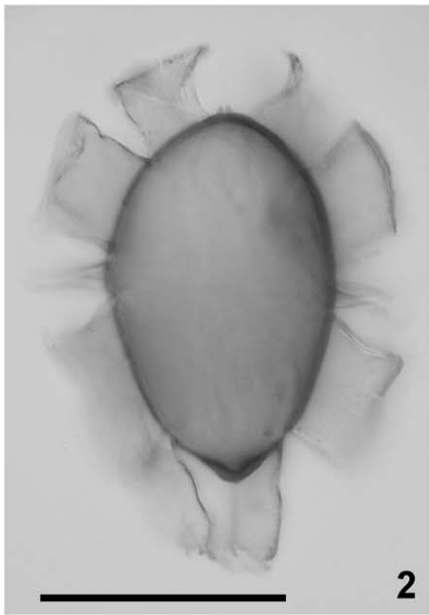
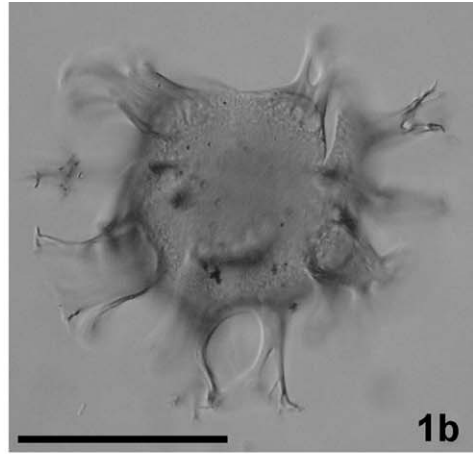
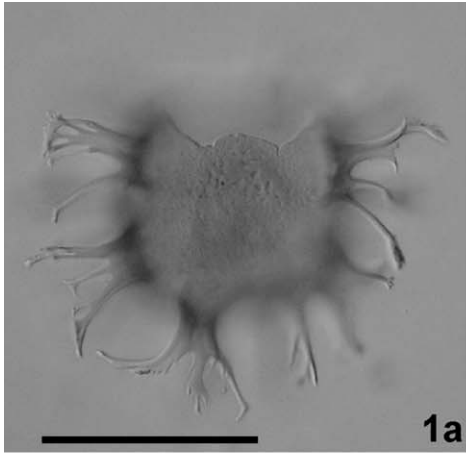
diameter). Both *Distatodinium biffii*, *Saturnodinium pansum* and *Areoligera semicirculata* have their highest occurrence just below this bed, while *Membranilarnacia? picena* has its lowest occurrence above this level. A Chattian hiatus can be assumed; the gravel layer could represent a transgressive lag deposit.

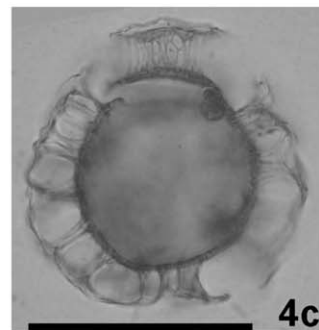
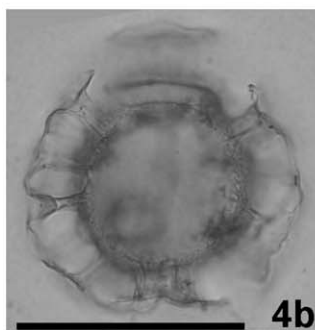
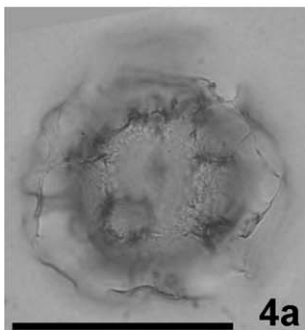
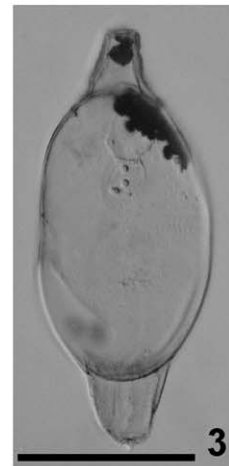
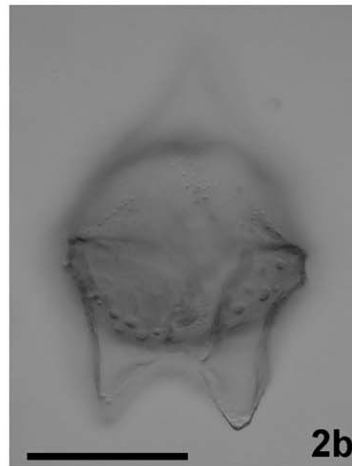
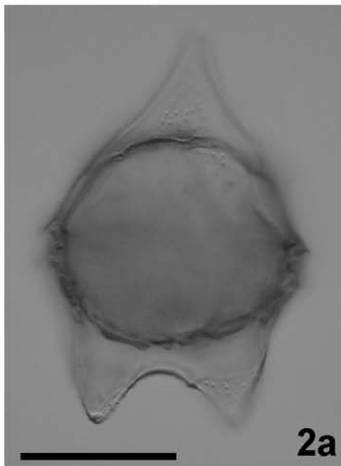
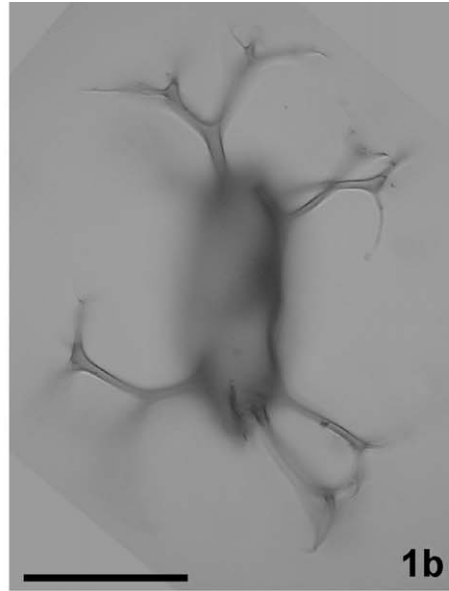
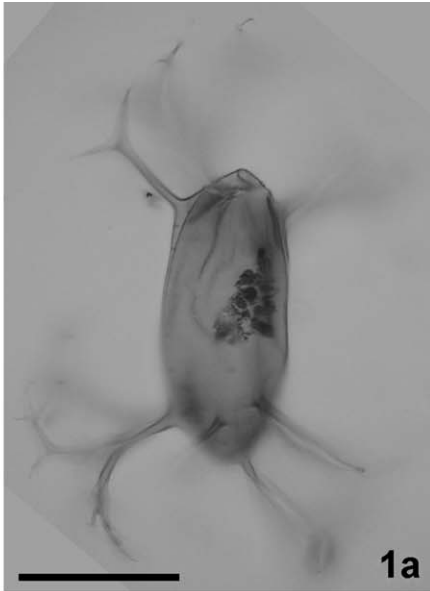
Costa and Manum (1988) proposed a high-resolution dinocyst zonation for the Cenozoic of the North Sea Basin. This zonation was subsequently modified by Köthe (1990) based on data from northwest Germany. The resulting zonation was found to be much better applicable to our study area. The boundary between Köthe's subzones D14na and D14nb can be recognized in the middle of the Rupelian section based on the last common occurrence of *Enneadocysta pectiniformis*. This event coincides with the FO of *Saturnodinium pansum* (Fig. 5). The boundary between D14nb and D15 coincides with the highest occurrence of *Rhombodinium draco*. This boundary correlates with a level within the *Asterigerina* Horizon. The base of zone D15 is thus younger than the base of the Chattian (see also Köthe, 1990).

Correlation between the Tönisberg profile (von Benedek, 1972) and the Belgian sections is established by applying the same chronological order of highest occurrences of *Enneadocysta pectiniformis*, *Rhombodinium draco*, *Deflandrea* spp., *Areoligera semicirculata* and *Chiropteridium* spp. and of lowest occurrences or recurrences of *Pentadinium imaginatum*, *Svalbardella* spp. and *Lejeunecysta tenella*. Moreover, in both sections, the highest occurrence of *Deflandrea* spp. is characterized by a distinct acme. *Artemisiocysta cladodichotoma* has a single occurrence below the *Asterigerina* Horizon (approx. 15 m) in both the Tönisberg borehole as well as in the Mol-1-borehole. The consistent range of this species, however, starts at the base of the Chattian.

The LO of *Enneadocysta pectiniformis* is dated at 29.3 Ma for Northern Hemisphere mid-latitudes (Hardenbol et al., 1998; Williams et al., in press). The FO of *Saturnodinium pansum* (which virtually coincides with

Plate II. (1) *Areoligera semicirculata* (Morgenroth 1966) Stover and Evitt 1978. Sample W16, slide S-88 (1) 30 µm, [H42-2]. (a) Low focus, ventral view, (b) high focus, dorsal view. (2) *Achilleodinium biformoides* (Eisenack 1954) Eaton 1976. Sample M13, slide S-134 (1) 30 µm, [H44-2] optical section. (3) *Operculodinium xanthium* (Benedek 1972) Stover and Evitt 1978. Sample W13, slide S-91 (1) 30 µm, [O58-4]. (a) Low focus, dorsal view, (b) detail of hollow processes. (4) *Artemisiocysta cladodichotoma* (Benedek 1972). Sample M3, slide S-152 (2) 30 µm, [Y51-2]. (a and b) Slightly differing high foci. Bar = 50 µm.





the last common occurrence of *Enneadocysta pectiniformis*) is believed to have an approximate age of 29.4 Ma (Williams et al., in press). According to Williams et al. (in press), the last appearance datum of *Achilleodinium bififormoides* has an age of 26 Ma, and the highest occurrences of both *Saturnodinium pansum* and *Distatodinium biffii* are at, respectively, 24.5 and 24.3 Ma. The LO of *Achilleodinium bififormoides* in the sections studied was encountered within the top of the *Asterigerina* Horizon. The extinctions of both *Saturnodinium pansum* and *Distatodinium biffii* in the sections studied occur in the same level. However, this may not represent their true extinction level, as the abovementioned gravel bed and the associated hiatus do not permit the determination of their true ranges. Until now, *Distatodinium biffii* was believed to be an exclusively Chattian species. The FO of this species was linked to the R-C boundary as defined in the magneto-biochronologic time scale of Berggren et al. (1995) in central Mediterranean sections (Wilpshaar et al., 1996). This study shows that the FO of this species is already encountered in the Upper Rupelian strata in the North Sea Basin. *Svalbardella* spp. have a distinct influx in the Mediterranean just above the FO of *Distatodinium biffii* (Wilpshaar et al., 1996). Whether the LO of *Deflandrea* spp. is a true extinction or rather a regional phenomenon is debatable. Although this genus has never been recorded in post-Oligocene sections in the Northern Hemisphere (Manum, 1976; Manum et al., 1989; Köthe, 1990; Poulsen et al., 1996), it is known to range into the earliest Miocene successions of the Mediterranean Basin (Powell, 1986; Brinkhuis et al., 1992; Zevenboom et al., 1994).

4.4. Calcareous nannofossils

4.4.1. Identification of the standard nannoplankton zones in the Oligocene of northwest Europe

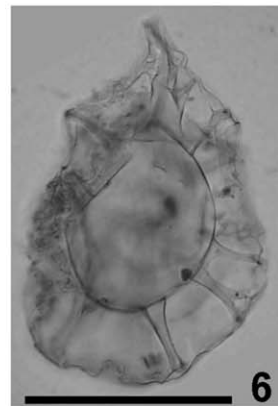
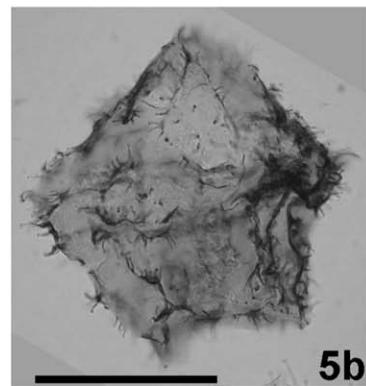
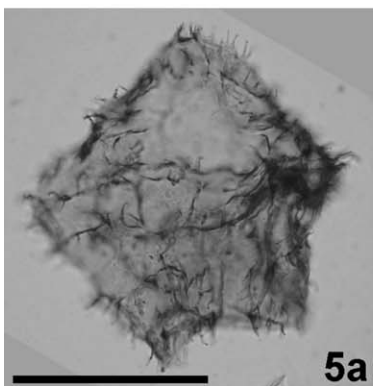
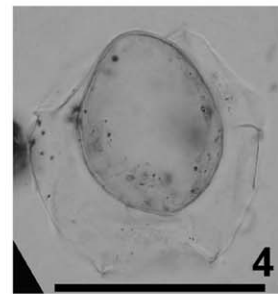
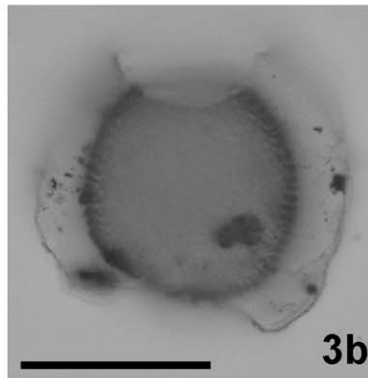
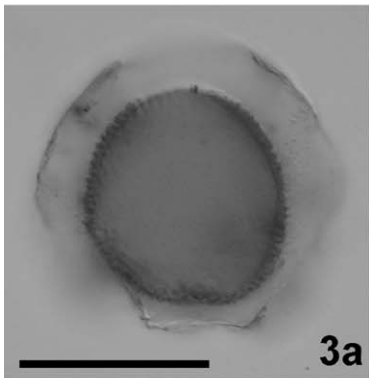
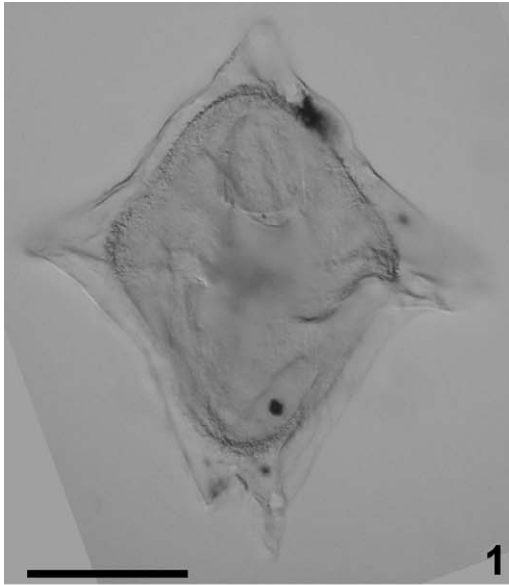
Martini's (1971) standard Paleogene calcareous nannofossil zonation (traditionally abbreviated to NP zones) is adopted without any comment in most of the compilations on the geology and stratigraphy of the

Cenozoic of the North Sea Basin (e.g., Tobien, 1986; Vinken, 1988). However, this zonation has led to dubious and even erroneous correlations and age determinations in the Oligocene of northwest Europe, because of the difficulties in applying the original boundary definitions. Information on the presence of zones NP23, NP24 and NP25 in the Oligocene of Belgium and northwest Germany is controversial and needs some further discussion.

The Boom Clay Formation has been assigned to NP23 by several authors on the basis of the absence of *Reticulofenestra umbilica* (Bramlette and Wilcoxon, 1967; Müller, 1970; Roth, 1970; Martini, 1971; Steurbaut, 1986, 1992; Verbeek et al., 1988). This was based on the recognition of Martini's original boundary definition: the highest occurrence of *R. umbilica* marking the boundary between NP22 and NP23. However, it must be emphasized that the attribution to NP23 only relates to parts of the exposed Boom Clay, since no comprehensive nannofossil investigation of the entire Boom Clay has yet been carried out.

The recognition of zone NP24 in the higher parts of the Boom Clay (Verbeek et al., 1988) and in the Septaria Clay Formation in Germany (Müller, 1970; von Daniels et al., 1994) has to be considered with caution. This is due to the fact that the standard definition for the NP23/NP24 boundary cannot be applied in the North Sea Basin. As *Sphenolithus ciperoensis* is absent and *Sphenolithus distentus* is extremely rare in the Oligocene of that region, the NP23/NP24 and the NP24/NP25 boundaries, defined by the FO of the former and the LO of the latter, respectively, cannot be recognized as such. Other bio-events have been proposed as substitutes for the NP23/NP24 boundary, among which are the lowest occurrence of *Cyclicargolithus abisectus* and the lowest occurrence of *Helicosphaera recta*. According to most authors, these are believed to coincide in the North Sea Basin (Martini and Müller, 1975, 1986; Müller, 1970, 1971, 1978, 1986; Perch-Nielsen, 1985). However, the FO of *Cyclicargolithus abisec-*

Plate III. (1) *Distatodinium biffii* Brinkhuis et al., 1992. Sample M6, slide S-129 (1) 30 µm, [R47-3]. (a) low focus, (b) high focus. (2) *Deflandrea phosphoritica* complex. Sample M6, slide S-129 (2) 30 µm, [Q70-3]. (a) optical section, (b) high focus. (3) *Svalbardella cooksoniae* Manum 1960. Sample H11, slide S-149 (2) 30 µm, [B36-1] optical section. (4) *Membranilarnacia? picena* Biffi and Manum 1988. Sample H3, slide S-146 (1) 30 µm, [C33-2]. (a–c) Slightly differing high foci. Bar = 50 µm.



tus, which has frequently been used in North Sea Basin biostratigraphy, is sometimes difficult to pinpoint. This is because parts of the Oligocene clays are decalcified. In addition, this species is represented by relatively small specimens (7–8 µm) in the lower part of its range, which in poorly preserved material may be confused with *Cyclicargolithus floridanus*. On the contrary, the FO of *Helicosphaera recta*, which seems to be synchronous throughout the North Sea Basin, is easily detectable and seems to have good biostratigraphic potential (Müller, 1970, p. 90). Therefore, we introduce an alternative zone NP24* for the North Sea Basin, the base of which is defined by the FO of *Helicosphaera recta*, and which is believed to coincide with or to be very close to the base of standard zone NP24.

von Benedek and Müller (1974) and Martini and Müller (1975) selected the lowest occurrence of *Pontosphaera enormis* as a substitute for identifying the NP24/NP25 boundary in the North Sea Basin because of the rare and inconsistent occurrences of *Sphenolithus distentus* and *Sphenolithus ciperoensis*. This concept is adopted here. The annotation NP25* denotes that a slightly revised zonal boundary definition is used here, which may deviate only little from the standard definition.

4.4.2. Rupelian–Chattian boundary events

The calcareous nannofossil investigation of various borehole sections in Belgium allows for the first time delimitation of the ranges of the marker species *Helicosphaera recta* and *Pontosphaera enormis*. The upper part of the Boom Clay Formation and the overlying Eigenbilzen Sand Formation, representing the Upper Rupelian, and the lower part of the Chattian Voort Sands belong to zone NP24*. The boundary NP23/NP24* coincides with the level of approximately –37 m in the composite section. The overlying zone NP25* has been identified in the upper part of the Voort Sands of the Weelde borehole. Calibration on the basis of dinocyst dis-

tributions allows a precise positioning of the NP24*/NP25* boundary at approximately +33 m in the composite section (Fig. 5).

The Upper Rupelian in northwest Belgium is characterized by Prinsiaceae-dominated nannofossil associations. Especially large-sized taxa, such as *Cyclicargolithus abisectus* and *Dictyococcites bisectus*, occur with abundances generally exceeding 70% of the association. *Coccolithus pelagicus* (<5%) and *Pontosphaera* spp. (<2%) are generally present, although never abundant. The general composition of the associations does not change much throughout this interval. A few forms appear stepwise upsection. Among the biostratigraphically significant events are the lowest occurrences of *Cyclococcolithus hoerstgensis*, *Pontosphaera pygmaea* and *Helicosphaera recta* at –48, –42 and –37 m, respectively, in the composite section. The R-C boundary is not marked by an abrupt change in nannofossil species diversity, but by considerable changes in species abundances. The associations in the lowermost part of the Chattian, known as the *Asterigerina* Horizon, differ from those of the Upper Rupelian by a major decrease in large Prinsiaceae (*Cyclicargolithus abisectus* and *D. bisectus* together less than 20%), by a considerable increase in *C. pelagicus* (from <5% to about 15%) and in small Prinsiaceae (from ca. 10% to 20%) and by the influx of reworked Cretaceous coccoliths (around 10%). Nearly all species cross the R-C boundary. The only species differences across the boundary are due to recurrences of *Lithostromation perdurum* and *Trochoaster simplex*, although in very low numbers. The typical Upper Rupelian taxa *P. pygmaea* and *C. hoerstgensis* are consistently present in the lower part of the Chattian. They disappear around +16 m above the boundary in the composite section. Their highest occurrences are very close to the lowest occurrence of the typical Chattian marker *Pontosphaera desueta* (Martini and Müller, 1975).

Plate IV. (1) *Rhombodinium draco* Gocht 1955. Sample Gartow – 276 m, slide S-164 (1) 30 µm, [Z34-1] optical section. (2) *Wetzeliella gochti* Costa and Downie 1976. Sample W16, slide S-88 (1) 15 µm [W34-3], optical section. (3) *Pentadinium imaginatum* (Benedek 1972) Stover and Hardenbol, 1994. Sample M8, slide S-151 (1) 30 µm, [C40-4]. (a and b) Slightly differing high foci. (4) *Saturmodinium pansum* (Stover 1977) Brinkhuis et al., 1992. Sample H14, slide S-101 (1) 15 µm, [G46-4] optical section. (5) *Lejeunecysta tenella* (Morgenroth 1966) Wilson and Clowes 1980. Sample H2, slide S-104 (1) 15 µm, [B65-2]. (a) low focus, (b) high focus. (6) *Ectosphaeropsis burdigalensis* Londeix and Jan Du Chêne 1988. Sample H2, slide S-104 (2) 30 µm, [R26-2] optical section. Bar = 50 µm.

Pontosphaera enormis and *Helicosphaera euphratis* appear 15 m higher up in the Voort Sand Formation, just above an intraformational gravel bed. Between the highest occurrences of *P. desueta* and *Pontosphaera enormis*, the associations become progressively richer in small Prinsiaceae (up to 40%), in *Pontosphaera* spp. (up to 25%) and in *Zygrhablithus bijugatus* (18%) (Fig. 5).

4.5. Combined biostratigraphic events

The most complete sections throughout the R-C transect, respectively, the Weelde and Hechtel boreholes, are combined into a composite section on which the biostratigraphic events were projected (Fig. 5). As known from the stratotype, the base of the Chattian can be recognized by a bloom of the benthic foraminifer *Asterigerinoides guerichi*. This biostratigraphic event coincides with the FOs of benthic foraminifera *Elphidium subnodosum* and *Protelphidium roemeri*. The major dinocyst events associated with the *Asterigerina* Horizon are the LOs of both *Rhombodinium draco* and *Achilleodinium biformoides* and the FO of *Artemisio-cysta cladodichotoma*. Additional biostratigraphically important dinocyst events are the last common occurrence of *Enneadocysta pectiniformis*, virtually coinciding with the FO of *Saturnodinium pansum* in the upper part of nannofossil zone NP23 (Upper Rupelian) and the recurrence of *Lejeunecysta tenella* in the lower part of the Chattian, within upper NP24*. *Areoligera semicirculata*, *Distatodinium biffii* and *Saturnodinium pansum* simultaneously disappear at the NP24*/NP25* nannofossil zonal boundary. These events coincide with a pebble bed, reflecting a mid-Chattian hiatus. This study allows for the first time the delimitation of the ranges of the marker nannofossil species *Helicosphaera recta* and *Pontosphaera enormis* in the Belgian Basin. The upper 42 m of the Upper Rupelian and the lower 35 m of the Chattian belong to zone NP24*.

5. Palaeoenvironmental change in the Rupelian type region

Based on a literature survey (Phleger, 1960; Murray and Wright, 1974; Murray, 1976, 1991; Grimm, 1994), eco-groups of benthic foraminifera and dinocysts have been identified in order to characterize

palaeoenvironmental conditions (Table 2). The “deeper water” and “shallow water” eco-groups are proxies for palaeobathymetry, while the “warm water” and “cold water” eco-groups can be used to assess the palaeotemperature. Both dinocyst taxa *Deflandrea* spp. (Plate III(2)) and *Wetzeliiella* spp. (Plate IV(2)) are believed to be tolerant of lagoonal, estuarine and/or brackish environments (Köthe, 1990) and thus may indicate restricted marine conditions (Brinkhuis, 1994; Powell et al., 1996). The taxa *Deflandrea* spp. and *Wetzeliiella* spp. are peridinioids. It has been proposed that their motile stages have similar life strategies to present-day *Protoperidinium*, heterotrophic dinoflagellates mainly feeding on phytoplankton and on bacterially decayed material (see Brinkhuis et al., 1992; Powell et al., 1996, and many others). The acritarch taxon *Paralecaniella* spp. is thought to be a brackish-water indicator (Elsik, 1977; Powell et al., 1996; Schioler et al., 1996). These three organic-walled phytoplankton taxa were used to characterize a “restricted marine” eco-group which favoured nutrient-rich, hyposaline, shallow-water conditions (Fig. 6, Table 2).

Within the benthic foraminifera, the deeper water eco-group, with high percentages of *Angulogerina* spp. and *Lenticulina* spp., dominates the Upper Rupelian assemblages. In addition, high percentages of both *Lenticulina* spp. and *Pullenia* spp. in the lower part of the section indicate cold-water conditions (Fig. 6, columns 1 and 2); Table 2). High values for both the deep-water and cold-water eco-groups favour a distinct outer-shelf character for the Upper Rupelian in the southern North Sea Basin. The distribution of benthic foraminifera throughout the Upper Rupelian section reveals some scattered non-calcareous levels. These coincide with high percentages of the dinocyst *Thalassiphora pelagica* (Fig. 6, column 4). Mass occurrences of *T. pelagica* have been reported from low-oxygen depositional environments in Lower Rupelian clays in northwest Germany (Köthe, 1990). This feature is also known from the Massignano section in central Italy (Vonhof et al., 2000) and from the Mainz Embayment (Pross, 1997, 2001) where the relative abundance of *T. pelagica* inversely correlates with the availability of benthic oxygen. High percentages of *T. pelagica* coincide with poorly ventilated water masses and anaerobic conditions on the sea floor (Köthe, 1990)

Table 2

Benthic foraminiferal and dinocyst eco-groups defined by environmental sensitive taxa

Eco-group	Taxa	References	Remarks	
<i>Benthic foraminifera</i>				
Deeper water	<i>Angulogerina</i> spp. ⁽¹⁾			
	<i>Bolivina</i> spp. ⁽¹⁾		taxa indicating	
	<i>Eponides umbonatus</i> ⁽¹⁾		“outer shelf to bathyal, or	
	<i>Globocassidulina subglobosa</i> ⁽¹⁾		>150 m”.	
	<i>Gyroidina soldanii</i> ^(2,3)			
	<i>Karreriella chilostoma</i> ⁽¹⁾			
	<i>Karreriella siphonella</i> ⁽¹⁾			
	<i>Lenticulina</i> spp. ⁽¹⁾			
	<i>Martinotiella communis</i> ⁽¹⁾			
	<i>Melonis affinis</i> ⁽¹⁾			
	<i>Pullenia</i> spp. ⁽¹⁾			
	<i>Siphotextularia labiata</i> ⁽²⁾			
	Shallow water	<i>Asterigerinoides guerichi</i> ⁽¹⁾	(1) Murray, 1991	taxa indicating inner shelf or
		<i>Elphidium subnodosum</i> ^(1,3)	(2) Murray, 1976	< 50 m
<i>Quinqueloculina</i> spp. ⁽¹⁾		(3) Phleger, 1960		
<i>Protelphidium roemeri</i> ⁽¹⁾		(4) Murray and Wright, 1974		
Warm water	<i>Asterigerinoides guerichi</i> ⁽¹⁾		taxa indicating	
	<i>Elphidium subnodosum</i> ⁽¹⁾		“subtropical to tropical or	
	<i>Protelphidium roemeri</i> ⁽²⁾		warm temperate”	
Cold water	<i>Eponides umbonatus</i> ⁽¹⁾			
	<i>Gyroidina soldanii</i> ⁽²⁾			
	<i>Karreriella chilostoma</i> ⁽¹⁾		taxa indicating	
	<i>Karreriella siphonella</i> ⁽¹⁾		cold or <10 °C	
	<i>Lenticulina</i> spp. ⁽¹⁾			
	<i>Melonis affinis</i> ⁽¹⁾			
	<i>Pullenia</i> spp. ⁽¹⁾			
	<i>Siphotextularia labiata</i> ⁽²⁾			
	<i>Turrilina alsatica</i> ⁽⁴⁾			

Table 2 (continued)

Eco-group	Taxa	References	Remarks
<i>Dinocysts and acritarchs</i>			
Restricted marine	<i>Paralecaniella</i> spp. ^(1,4)	(1) Elsik, 1977	taxa indicating
	<i>Deflandrea</i> spp. ^(2,3,4)	(2) Köthe, 1990	“lagoonal, estuarine or
	<i>Wetzeliiella</i> spp. ⁽²⁾	(3) Brinkhuis, 1994	brackish tolerant”
		(4) Powell et al., 1996	

and eutrophic surface conditions (Vanhof et al., 2000). Since the epeiric Rupelian Sea was more or less an enclosed basin, with only few marine inlets to the north and temporarily to the south, freshwater influx from the drainage areas could have facilitated the formation of a pycnocline, separating less saline surface waters from higher saline deeper waters (Pross, 2001; Pross and Schmiedl, 2002). This stratified water column could have caused temporarily anoxic conditions on the sea bottom, during which only very limited benthic life was possible.

The base of the Chattian is characterized by high percentages of tropical to subtropical benthic foraminifera (Fig. 6, column 1; Table 2). Higher up in the Chattian, warm temperate species dominate, associated with subtropical species. Estimated palaeotemperatures, based on the composition of benthic foraminiferal communities from the Doberg stratotype, revealed annual average temperatures between 14 and 19 °C (Kohnen, 1995). The increase of the “warm-water” eco-group is associated with inner-shelf foraminiferal assemblages with species favouring tidal marshes, lagoons and estuaries (Fig. 6, column 2; Table 2). The abrupt increase in the “restricted marine” paly-nomorph eco-group, with high amounts of the brackish-water taxon *Paralecaniella* spp. (>20%), suggests hyposaline shallow-water conditions at the base of the Chattian (Fig. 6, column 3; Table 2). This major palaeoenvironmental change is also well documented by the nannofossil association. The increase in numbers of both *Pontosphaera* spp. and *Zygrhablithus bijugatus*, and the recurrence of *Braarudosphaera bigelowii* at the base of the Chattian imply a landward shift of the depocenter. Changes in surface water temperatures are less evident from the dinocyst asso-

ciations. The newly appearing *Artemisiocysta cladodichotoma* and the recurrence of *Pentadinium imaginatium* at the base of the Chattian may well be seen to reflect relatively warm conditions. These, however, co-occur with a few specimens of the apparently cold-water species *Svalbardella* spp. (Head and Norris, 1989). The occurrence of the latter are, therefore, considered to be evidence of reworking, but this phenomenon also indicates brief colder conditions preceding the Chattian rise in sea level. Further study on this aspect is in progress.

A striking feature at the R-C boundary in the southern North Sea Basin is thus the major change in palaeotemperature and palaeobathymetry. Shallow marine to restricted marine subtropical species at the base of the Chattian are in strong contrast with the deeper marine and cooler Upper Rupelian benthic fauna. This biotic change is associated with an important shift in lithology, from clayey silts in the Rupelian to glauconite-rich fine sands in the Chattian. The sharp lithological contact between the Rupelian and Chattian deposits and the abrupt water mass change suggests a major break in sedimentation. This study further substantiates the assignment of the R-C boundary in the North Sea Basin to represent a major third-order sequence boundary. Deposits of the early Chattian transgression unconformably overlie the Rupelian strata. Our study indicates that the early Chattian transgression was associated with a widespread major warming event, recognized by means of benthic foraminifera. Both the *Asterigerinoides* bloom and the occurrence of the macro-foraminifer *Myogipsina septentrionalis* (not encountered in this study, but known from the Lower Chattian stratotype at Doberg; Anderson et al., 1971) indicate tropical to subtropical conditions. Further investigations should demonstrate whether this warming pulse can be correlated with the Late Oligocene Warming Event, recognized from oxygen isotope studies on DSDP and ODP boreholes (Zachos et al., 2001). This Late Oligocene Warming Event has an approximate age of 26 Ma. Although stable isotope data from the stratotype area (which could possibly support this view) are not yet available, an age of 26 Ma has already been suggested on the basis of K–Ar datings on glauconites from the base of the Chattian in the North Sea Basin (Gramann et al., 1980).

6. Conclusions

The investigation of dinocysts, foraminifera and calcareous nannofossils from a series of borehole sections in Belgium and Germany enables the recognition of biotic events and the reconstruction of environmental change in the late Rupelian and early Chattian in their type region, the southern North Sea Basin. This investigation completes previous micropalaeontological studies of the Lower Rupelian stratotype section (Steurbaut, 1992; Stover and Hardenbol, 1994; Grimm and Steurbaut, 2001). It upholds the generally accepted position of the R-C boundary at the base of the *Asterigerina* Horizon or at the base of the Voort Sand Formation.

The R-C boundary is marked by a decrease in benthic foraminiferal species diversity and a major bloom of *Asterigerinoides guerichi* (>70%), known as the *Asterigerina* Horizon. This bloom coincides with major changes in dinocyst and nannofossil species abundances and appears to be due to the installation of a shallow, warm-water depositional regime. As this aspect is also known from the base of the Chattian stratotype at Doberg, it allows the identification and correlation of the R-C Stage boundary throughout the North Sea Basin. Due to their endemic nature, the *Asterigerinoides guerichi* bloom, as well as most of the lowest and highest nannofossil occurrences, cannot be calibrated with the international magnetobio-chronologic time scale. Dinocysts may solve this calibration problem, being apparently slightly less affected by latitudinal variations, occurring in shallow as well as in deep marine settings and allowing detailed interregional correlations.

Planktonic foraminifera are rare throughout the Upper Rupelian (generally <1% per sample). In the foraminiferal assemblage of the uppermost part of the Rupelian in Belgium and Germany, silicified moulds of biserial planktonic foraminifers were present. These moulds are considered not to be in situ chiloguembelinids but reworked Late Cretaceous heterohelicidae. It needs to be verified whether the *Chiloguembelina* records of Ritzkowski (1982) in the German Rupel 4 division have the same nature as the silicified moulds encountered in this study. This is necessary to delineate the true

range of *Chiloguembelina* in the stratotype area of the Rupelian.

Calcareous nannofossils and foraminifera are not continuously distributed throughout the Upper Rupelian and Chattian, because of the presence of alternating carbonate-rich and non-calcareous intervals. Nevertheless, the alternative North Sea Basin nannofossil zones NP24* and NP25* could be recognized for the first time in the Belgian Basin.

The basal Chattian deposits in the North Sea Basin represent a major transgressive systems tract unconformably overlying the Rupelian stratotype. This unconformity corresponds to a hiatus between the top of the Rupelian and the base of the Chattian transgression and represents a third-order sequence boundary. The Chattian transgression coincides with a widespread and distinct warming event. This warming pulse is tentatively correlated with the Late Oligocene Warming Event. If this correlation is correct, the early Chattian transgression has an approximate age of 26 Ma, which is in agreement with earlier K–Ar datings on glauconites from the base of the Chattian in the North Sea Basin.

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Appendix A. Identified taxa

The taxa included in the present study are listed alphabetically below. Taxa illustrated in Plates 1–4 are marked with an asterisk.

Foraminiferids

- Alabamina tangentialis* (Clodius 1922)
Angulogerina spp.
Angulogerina gracilis (Reuss 1851)
Angulogerina gracilis (Reuss) var. *tenuistriata* (Reuss 1851)
 **Asterigerinoides guerichi* (Franke 1912), Plate I(1)
Bolivina spp.
Bolivina antiqua d'Orbigny 1846
Bolivina dilatata (Reuss 1850)
Bulimina alsatica Cushman and Parker 1937
 **Bulimina elongata* d'Orbigny 1846, Plate I(6)
Cibicides lobatulus (Walker and Jacob 1798)
Cibicides tenellus (Reuss 1865)
 **Cibicides ungerianus* (d'Orbigny 1846), Plate I(5)
 **Elphidium subnodosum* (Roemer 1838), Plate I(3)
Hansenisca soldanii (d'Orbigny 1826)
Karrerella chilostoma (Reuss 1852)
Karrerella siphonella (Reuss 1851)
Lagena spp.
Lagena isabella (d'Orbigny 1839)
Lagena tenuis (Borneman 1855)
Lenticulina spp.
Melonis affinis (Reuss 1851)
Nodosaria spp.
Nodosaria hirsuta d'Orbigny 1846
Nodosaria spinescens (Reuss 1851)
Nodosaria vertebralis (Batch 1781)
 **Protelphidium roemeri* (Cushman 1936), Plate I(4)
Pullenia bulloides (d'Orbigny 1846)
Pullenia quinqueloba (Reuss 1851)
Quinqueloculina spp.
Quinqueloculina akneriana d'Orbigny 1846
Quinqueloculina juleana d'Orbigny 1846
 **Rotaliatina bulimoides* (Reuss 1851), Plate I(2)
Siphotextularia labiata (Reuss 1861)
Sphaeroidina bulloides d'Orbigny 1826
Spiroplectinella spp.
Spiroplectinella carinata (d'Orbigny 1846)
Spiroplectinella deperdita (d'Orbigny 1846)
Turrilina alsatica Andreae 1884
Valulineria petrolei (Andreae 1884)

Dinoflagellate cysts

- **Achilleodinium bififormoides* (Eisenack 1954) Eaton 1976,
 Plate II(2)
Adnatosphaeridium multispinosum Williams and Downie 1966
-

(continued on next page)

Appendix A (continued)

Dinoflagellate cysts

- Apteodinium australiense* (Deflandre and Cookson 1955) Williams 1978
- **Areoligera semicirculata* (Morgenroth 1966) Stover and Evitt 1978, [Plate II\(1\)](#)
- Caligodinium amiculum* Drugg 1970
- Chiropteridium* spp.
- Chiropteridium galea* (Maier 1959) Sarjeant 1983
- Chiropteridium lobospinosum* Gocht 1960
- Cleistosphaeridium* spp.
- Cleistosphaeridium diversispinosum* Davey et al. 1966
- Cleistosphaeridium placacanthum* (Deflandre and Cookson 1955) Eaton et al. 2001
- Cribroperidinium* spp.
- Cribroperidinium guiseppi* (Morgenroth 1966)
- Cribroperidinium tenuitabulatum* (Gerlach 1961) Helenes 1984
- Dapsilidinium* spp.
- Dapsilidinium pastielsii* (Davey and Williams 1966) Bujak et al. 1980
- Dapsilidinium pseudocolligerum* (Stover 1977) Bujak et al. 1980
- **Deflandrea phosphoritica* complex, [Plate III\(2\)](#)
- Deflandrea heterophlycta* Deflandre and Cookson 1955
- Deflandrea phosphoritica* Eisenack 1938
- Deflandrea phosphoritica* var. *spinulosa* Alberti 1959
- **Distatodinium biffii* Brinkhuis, Powell and Zevenboom, 1992, [Plate III\(1\)](#)
- Distatodinium paradoxum* (Brosius 1963) Eaton 1976
- **Ectosphaeropsis burdigalensis* Londeix and Jan Du Chêne 1988, [Plate IV\(6\)](#)
- Enneadocysta pectiniformis* (Gerlach 1961) Stover and Williams 1995
- Fibrocysta axialis* (Eisenack 1965) Stover and Evitt 1978
- Filipsphaera filifera* Bujak 1984
- Gerlachidium aechmophorum* (Benedek 1972) Benedek and Sarjeant 1981
- Glaphyrocysta microfenestrata* complex
- Glaphyrocysta microfenestrata* (Bujak 1976) Stover and Evitt 1978
- Glaphyrocysta texta* (Bujak 1976) Stover and Evitt 1978
- Glaphyrocysta semitecta* (Bujak 1980) Lentin and Williams 1981
- Homotryblium* spp.
- Homotryblium floripes* (Deflandrea and Cookson 1955) Stover 1975
- Homotryblium tenuispinosum* Davey and Williams 1966
- Homotryblium vallum* Stover 1977
- Hystriocholpoma cinctum* Klumpp 1953
- Hystriocholpoma pusillum* [Biffi and Manum, 1988](#)
- Hystriocholpoma rigaudiae* Deflandre and Cookson 1955
- Hystriocholpoma salacia* Eaton 1976
- Impagidinium pallidum* Bujak 1984
- Impagidinium* spp.
- Lejeunecysta hyalina* (Gerlach 1961) Artzner and Dörhöfer 1978
- **Lejeunecysta tenella* (Morgenroth 1966) Wilson and Clowes 1980, [Plate IV\(5\)](#)

Appendix A (continued)

Dinoflagellate cysts

- Lingulodinium machaerophorum* (Deflandre and Cookson 1955) Wall 1967
- **Membranilarnacia? picena* [Biffi and Manum, 1988, Plate III\(4\)](#)
- Membranophoridium aspinatum* Gerlach 1961
- Operculodinium tiara* (Klumpp 1953) Stover and Evitt 1978
- **Operculodinium xanthium* (Benedek 1972) Stover and Evitt 1978, [Plate II\(3\)](#)
- Palaeocystodinium golzowense* Alberti 1961
- **Pentadinium imaginatum* (Benedek 1972) [Stover and Hardenbol, 1994, Plate IV\(3\)](#)
- Pentadinium laticinctum* Gerlach 1961
- Pentadinium lophophorum* (Benedek 1972) Benedek et al. 1982
- Phthanoperidinium comatum* (Morgenroth 1966) Eisenack and Kjellström 1971
- Phthanoperidinium filigranum* (Benedek 1972) Lentin and Williams 1976
- Polysphaeridium zoharyi* (Rossignol 1962) Bujak et al. 1980
- Reticulatosphaera actinocoronata* (Benedek 1972) Bujak and Matsuoka 1986
- **Rhombodinium draco* Gocht 1955, [Plate IV\(1\)](#)
- **Saturnodinium pansum* (Stover 1977) Brinkhuis, Powell and Zevenboom, 1992, [Plate IV\(4\)](#)
- Selenopemphix armata* Bujak 1980
- Selenopemphix nephroides* Benedek 1972
- Spiniferella cornuta* (Gerlach 1961) [Stover and Hardenbol, 1994](#)
- Spiniferites–Achomosphaera* complex
- **Svalbardella cooksoniae* Manum 1960, [Plate III\(3\)](#)
- Tectatodinium pellitum* Wall 1967
- Thalassiphora pelagica* (Eisenack 1954) Eisenack and Gocht 1960
- Tityrosphaeridium cantharellus* (Brosius 1963) Sarjeant 1981
- Tuberculodinium vancampoe* (Rossignol 1962) Wall 1967
- Wetzeliella articulata* Eisenack 1938
- **Wetzeliella gochtii* Costa and Downie 1976, [Plate IV\(2\)](#)
- Wetzeliella symmetrica* Weiler 1956

Acritarchs

- **Artemisiocysta cladodichotoma* Benedek 1972, [Plate II\(4\)](#)
- Cyclopsiella elliptica* Drugg and Loeblich 1967
- Cyclopsiella granosa* (Matsuoka 1983) Head et al. 1992
- Cymatiosphaera bujakii* De Coninck 1986
- Paralecaniella indentata* (Deflandre and Cookson 1955) Cookson and Eisenack 1970

Calcareous nannofossils

- Braarudosphaera bigelowii* (Gran and Braarud 1935) Deflandre 1947
- Coccolithus pelagicus* (Wallich 1877) Schiller 1930
- Cyclicargolithus abisectus* ([Müller, 1970](#)) Wise 1973
- Cyclicargolithus floridanus* (Roth and Hay in Hay et al. 1967) Bukry 1971
- Cylococcolithus hoerstgensis* [Müller, 1970](#)
- Dictyococcites bisectus* (Hay, Mohler and Wade 1966) Bukry and Percival 1971

Appendix A (continued)

Calcareous nannofossils

- Helicosphaera recta* Haq 1966
Lithostromation perdurum Deflandre 1942
Pontosphaera spp.
Pontosphaera desueta (Müller, 1970) Perch-Nielsen 1984
Pontosphaera enormis (Locker 1967) Perch-Nielsen 1984
Pontosphaera pygmaea (Locker 1967) Bystrická and Lehotayová 1974
Reticulofenestra umbilica (Levin 1965) Martini and Ritzkowski 1968
Sphenolithus ciperoensis Bramlette and Wilcoxon, 1967
Sphenolithus distentus (Martini 1965) Bramlette and Wilcoxon, 1967
Trochoaster simplex Klumpp 1953
Zygrhablithus bijugatus (Deflandre in Deflandre and Fert 1954) Deflandre 1959

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