A southern North Sea Miocene dinoflagellate cyst zonation

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Abstract

An integrated stratigraphical analysis emphasizing organic-walled dinoflagellate cyst (dinocyst) distribution has been carried out on multiple boreholes penetrating the Miocene in the subsurface of the Netherlands (southern North Sea Basin). The bulk of the investigated successions is attributed to the Breda Formation, a regional lithostatigraphical unit most complete in the south-eastern part of the Netherlands. In concert with a first regional integrated bio (chrono) sequence-stratigraphical framework, fourteen informal dinocyst zones for the southern North Sea Miocene (SNSM), and three subzones are proposed for the Breda Formation. By also integrating (chrono)stratigraphic information from Mediterranean and North Atlantic dinocyst studies a first ever detailed age-model is here proposed for the Miocene in the subsurface of the Netherlands.

Keywords: southern North Sea, the Netherlands, Miocene, Breda Formation, biostratigraphy, sequence stratigraphy, palynology, organic-walled dinoflagellate cysts

Introduction

Perhaps surprisingly, a comprehensive detailed stratigraphic synthesis of the marginal marine Late Oligocene (Chattian) and Neogene successions of the southern North Sea Basin is not yet established. Despite intense exploration in older deposits, Neogene (bio) chronostratigraphy is only available in very broad terms at best (e.g., Doppert et al., 1975; Van den Bosch, 1975; NAM and RGD, 1980; Letsch and Sissingh, 1983; Zagwijn, 1989; Van den Berg, 1996; Van Adrichem Boogaert and Kouwe, 1997; Verbeek et al., 2002). In the Netherlands, the bulk of the regionally thick Miocene succession is currently assigned to a single lithostratigraphical unit, the Breda Formation. This unit locally overlies the Veldhoven Formation of presumed Chattian to earliest Miocene age, or older deposits. Overlying strata have been assigned to the

marine Oosterhout and fluviatile Kieseloölite formations, or to yet to be defined units (notably in the Dutch offshore sectors; NAM and RGD, 1980; Van Adrichem Boogaert and Kouwe, 1997). Detailed age-assessment of all of these Neogene deposits is still largely lacking and lateral relationships are unclear.

The few attempts of stratigraphic calcareous microplankton studies of the shallow marine Breda Formation have been frustrated by absence and/or poor preservation of index-taxa. Recent studies have however indicated that organic-walled dinoflagellate cysts (dinocysts) are abundant and diverse throughout most of the succession. Elsewhere application of Neogene dinocyst biostratigraphy has led to significant improvement in dating and paleoenvironmental understanding (e.g., Powell, 1986; Head et al., 1989; Brinkhuis et al., 1992; Zevenboom, 1995; De Verteuil and Norris, 1996; Head 1998, Dybkjaer and

Rasmussen, 2000; Louwye, 2002), and there is every potential to achieve the same for the Breda Formation.

A study of multiple wells, spanning large parts of the Neogene in the subsurface of the Netherlands (Fig. 1) indeed indicates that a suite of dinocyst events consistently occurs in the Miocene of the southern North Sea Basin. Integrating quantitative palynological data with wire-line, lithological, and foraminifera and bolboforma studies, a first integrated bio (chrono) sequence-stratigraphical framework has recently been established (RGD, TNO-NITG, LPP internal reports; Munsterman, manuscript in preparation). Here we discuss the resulting dinocyst zonation for the Miocene.
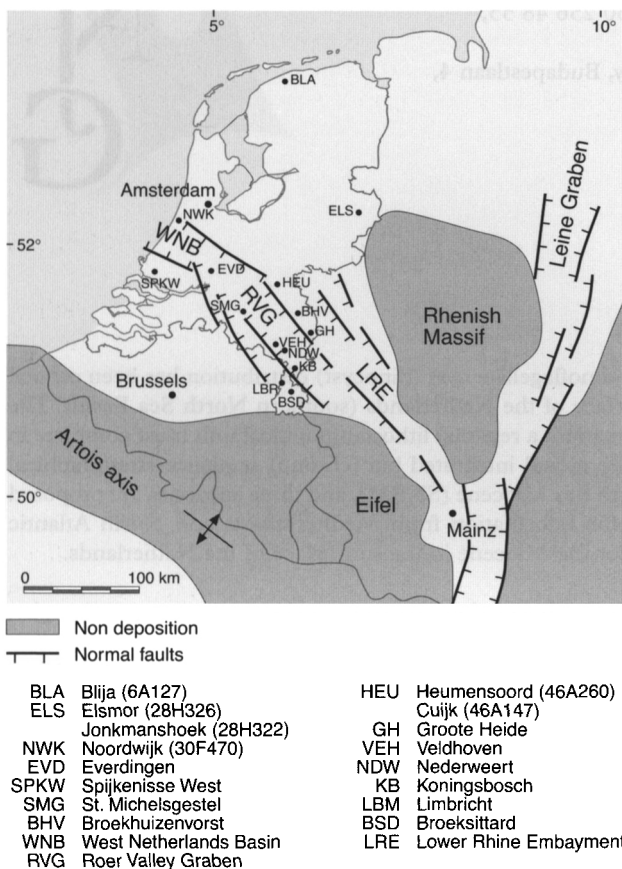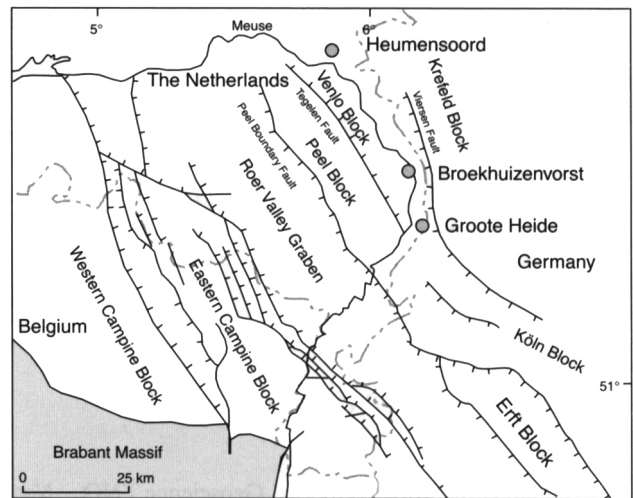

Fig. 2. Structural framework of the area (after map of Geluk et al., 1994).

in the southwest (Zagwijn, 1989; Geluk, 1990; Ziegler, 1990; 1994; Van den Berg, 1994, see Figs. 1 and 2).

The Roer Valley rift system is differentiated into several tectonic units, and is filled with up to 2000 m thick, largely Neogene shallow marine to continental deposits. To the northwest the graben broadens into the West Netherlands Basin (Fig. 1). Blocks of intermediate subsidence flank the Roer Valley Graben on both sides (Fig. 2). In the southwest these areas are the Eastern and Western Campine Blocks, while the Venlo, Peel and Köln Blocks are recognized in the northeast (Geluk et al., 1994). The deepest part of the Venlo-Peel Block is often referred to as the Venlo Graben (Van den Berg, 1994). The Peel Block has been uplifted ~1000 m along the NW-SE oriented Peel Boundary Fault. The Tegelen Fault divides the Peel Block and the Venlo Block (Van Adrichem Boogaert and Kouwe, 1997). The Viersen Fault is the principal displacement zone that separates the Venlo Block and the northeastern Krefeld Block (see Fig. 2).

The Cenozoic successions of the Lower Rhine Embayment and southern part of the North Sea Basin were deposited in a paleoenvironmental setting ranging from coastal plain, deltaic to shallow marine (littoral and epineritic; Zagwijn, 1989). Up until the Rupelian there was minimal differential subsidence (Geluk, 1990). The entire area subsided uniformly, although intermittently, notably in the Eocene, inversion movements and erosion occurred. The uplift in the southeastern Netherlands was caused by the Pyrenean tectonic phase (Letsch and Sissingh, 1983). The earliest syn-rift deposits in the Rhine Graben have been dated as 'Late Eocene' (Geluk, 1990). The rift system started to develop in the Alpine foreland and propagated northwards (and southwards) to accommodate the stress from the Alpine-Mediterranean orogenic system.

Non deposition

Normal faults

BLA	Blija (6A127)	HEU	Heumensoord (46A260)
ELS	Elsmor (28H326)		Cuijk (46A147)
	Jonkmanshoek (28H322)	GH	Groote Heide
NWK	Noordwijk (30F470)	VEH	Veldhoven
EVD	Everdingen	NDW	Nederweert
SPKW	Spijkenisse West	KB	Koningsbosch
SMG	St. Michelsgestel	LBM	Limbricht
BHV	Broekhuizenvorst	BSD	Broeksittard
WNB	West Netherlands Basin	LRE	Lower Rhine Embayment
RVG	Roer Valley Graben		

Fig. 1. Overview of the Rhine Graben system in northwest Europe (after Ziegler 1990).

Geological and paleoenvironmental setting

A complex Cenozoic rift system of approximately 1100 km long extends from the west coast of the Netherlands through West Germany and southeastern France into the western Mediterranean (Fig. 1). The Roer (Ruhr) Valley (or 'central Graben') rift system forms the main structural-physiographic unit of the so-called Lower Rhine Embayment, bordered by the Rhenish Massif in the east and by the Brabant Massif

During the Rupelian the rifting progressively moved northward and the Rhine and Leine grabens developed a narrow seaway between the Alpine foredeep and the North Sea Basin (Vinken, 1988). In the Chattian the rifting became evident in the SE Netherlands (Geluk, 1994). It developed via an older fracture system, reactivating e.g., the Peel Boundary Fault. The rifting was accompanied by sinistral strike-slip faulting, moving the Roer Valley southwards relative to the Peel Horst. The faulting resulted in differential subsidence in the area of the Roer Valley and adjacent blocks. A strong eustatic sea level drop apparently occurred at the Rupelian-Chattian boundary (e.g., Hardenbol et al., 1998; Van Simaeys et al., in press). This fall led to substantial erosion of the top sets of the latest Rupelian highstand system tracts. The Veldhoven Formation, representing shallow marine Chattian deposits, is only present in a relatively small area, i.e. in the central and SE Netherlands (Letsch and Sissingh, 1983; Zagwijn, 1989). The Roer Valley Graben and the Lower Rhine Embayment developed as nearshore depocenters during the younger Oligocene. In northern, western and eastern Netherlands the marine Chattian is believed to be largely absent, mainly due to non-deposition (synsedimentary erosion) and/or to later erosion (Zagwijn, 1989).

During the Neogene, marginal marine successions (all assigned to the Breda Formation) again covered most of the Netherlands, with the exception of the outermost southwestern, southeastern and eastern parts. After the Burdigalian rise in sea level, the area of marine sedimentation increased compared to the Chattian. During the Early Miocene, the Leine Graben and part of the Roer Valley Graben were affected by inversion, possibly related to the onset of the thermal uplift of the Rhenish Massif, which included volcanic activity in the Siebengebirge (Teichmüller, 1972; Sissingh, 2003). Volcanic activity peaked during the Early Miocene (Lippolt, 1983), while also increase in differential movements (Savian tectonic phase) during this time have been proposed for the Roer Valley Graben and the Peel Block areas, although subsidence rates in the graben apparently did not accelerate before the Pliocene (Zijerveld et al., 1992).

The relatively slow subsidence in combination with overall warm and humid climates led to considerable peat accumulation during the late Early to early Late Miocene in parts of the Roer Valley Graben area (e.g., Utescher et al., 2000). During the Late Miocene, besides the Roer Valley Graben, a second depocenter developed, i.e. the Zuiderzee Basin. Sediments supplied by the fluvial systems from the uplifting (Alpine) hinterland were trapped in the two marine depocenters. Therefore these sequences may be absent or very condensed more distally (Zagwijn, 1989). The position of the coastline varied from extending beyond the present German border to a more western position into the southeastern Netherlands, shifting over more than 100 km, also influenced by the strong Miocene eustatic sea level fluctuations.

The northwestern progradation of the paleo-Rhine (and Meuse; Van den Berg, 1996) delta continued in the southeastern part of the Netherlands during the Late Miocene and Pliocene, leading to the deposition of the fluvial Kieseloölite Formation (See: http://www.nitg.tno.nl/nomenclator/Shallow/nl/fluviatiel/kiezel/ map/html). These deposits laterally interfinger with the marine successions of the Oosterhout and younger Maassluis formations (See: e.g. http://www.nitg.tno.nl/nomenclatorShallow/nl/marien/oosterhout/map.html). The main sediment accumulation shifted from the Zuiderzee area towards the main axis of the North Sea Basin. Although shallowing and shifting to the northwest, a prodelta depocenter was maintained in the Roer Valley Graben during the Pliocene (Fig. 1).

As stated above, the Breda Formation is represented virtually everywhere in the subsurface of the Netherlands. According to its current definition (NAM and RGD, 1980; Van Adrichem Boogaert and Kouwe, 1997) the formation consists of glauconitic sands, sandy clays and clays. In many places a glauconitic-rich layer occurs at the base, which has become the criterion for recognition of the base of the formation. In this respect the original definition of the Breda Formation, which initially also included strata from below this glauconitic-rich layer (Doppert et al., 1975), has been slightly amended. The thickness of the Breda Formation varies strongly from less than 1 to more than 700 m (TNO-NITG internal reports). The upper limit of the Breda Formation is currently taken at the uppermost occurrence of greensands or clays rich in glauconite. It is overlain by the fluviatile, coarse grained deposits of the Kieseloölite Formation in the southeastern part of the Netherlands (Fig. 3). Elsewhere the upper boundary has been placed at the transition to the marine Oosterhout Formation, which is less glauconitic, grey-coloured and sometimes rich in shells (crags).

In the central and southeastern Netherlands the formation rests on the Upper Oligocene-Lower Miocene Veldhoven Formation. The lower boundary of the Breda Formation coincides with the transition from the Middle to the Upper North Sea Group. Elsewhere the Breda Formation unconformably rests on the Rupel Formation (Lower Oligocene) or, locally, on even older deposits. The lower boundary of the Breda Formation is difficult to establish in part of the
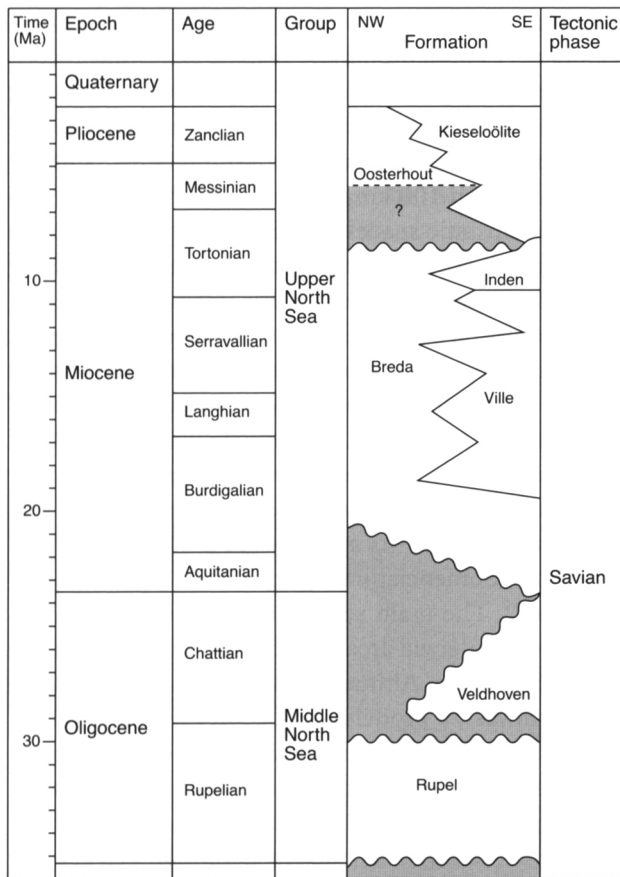
Fig. 3. Litho-chronostratigraphic chart for the southern Netherlands and adjacent area in Germany.

Roer Valley Graben and on the Peel/Venlo Blocks, since the transition from the glauconitic beds of the Veldhoven Formation into the greensands of the Breda Formation is gradual. Typically, therefore, in the Breda-type borehole Groote Heide from 1992, the Veldhoven Formation was not recognized. The Breda Formation, then recognized between 99.75-632 m at Groote Heide, was considered to overlie the Rupel Formation. Borehole Groote Heide was proposed as the lectostratotype section for the Breda Formation by the TNO-NITG (internal report 1998), and replaces its type, borehole Rijsbergen (50A0154), interval 174-234 m below surface, which is only 60 m along hole and incomplete. The Breda Formation at the southern Venlo Block is extensive and complete (TNO-NITG internal reports).

Material and methods

One hundred and ten airlift samples from well Groote Heide, interval 85-689 m were selected and analysed (see distribution chart on NJG webpage). The same set of samples was examined for foraminifera and bolboforma (TNO-NITG internal reports). The transition from glauconitic clays to glauconitic sands (and

silts) at 496.70 m depth is considered to represent the base of the Breda Formation. The top of the formation is recognized at 99.75 m depth, on the basis of the transition to coarse-grained sands which are associated with the Kieseloölite Formation.

Other wells (Fig. 1) on the Venlo Block have been included in the macro- and microfossil studies to offer a framework for identification of patterns between the succession of dinocyst events and for the recognition of trends in lithofacies and sequence stratigraphy. All samples have been palynologically processed at the Laboratory of Palaeobotany and Palynology at the University of Utrecht using standard techniques, involving HCl and HF digestion, no oxidation, 15 µm sieving, and preparation of at least two residue slides. Dinocyst taxonomy is according to that cited in Williams et al. (1998).

This paper is principally concerned with the recognition of stratigraphically consistent Miocene dinocyst events and chronostratigraphic assessment. The chronostratigraphic evaluation of the dinocyst events is based on the available Late Oligocene-Miocene palynological contributions in NW Europe (e.g., Gerlach, 1961; Morgenroth, 1966; Benedek, 1972; Piasecki, 1980; Sarjeant, 1984; Powell, 1986; Herngreen, 1987; Biffi and Manum, 1988; Londeix and Jan du Chene, 1988; Manum et al., 1989; Mudie, 1989; Brinkhuis et al., 1992; Powell, 1992; Strauss and Lund, 1992; Lentin, 1993; Lund et al., 1993; Stover and Hardenbol, 1993; Versteeg and Zevenboom, 1995; Zevenboom, 1995; De Verteuil and Norris, 1996; Stover et al., 1996; Louwye and Laga, 1998; Williams et al., 1998; Williams and Manum, 1999; Dybkjaer and Rasmussen, 2000; Louwye, 1999; 2000; Lund and Heilmann-Clausen, 2001; Van Simaeys et al., in press), and also considers the recent global compilation by Williams et al. (2004). The latter study makes use of paleomagnetic and/or calcareous plankton biostratigraphic calibration of dinocyst events, mainly derived from Mediterranean and Southern Ocean studies, based on the numerical timescale of Berggren et al. (1995). Resulting age-assessments for the southern North Sea Basin, further discussed below, have been cross-validated by correlation to recognized sea-level fluctuations using the sequence and a chrono-stratigraphic chart for NW Europe of Hardenbol et al. (1998). Recognition of the Dutch third-order Neogene sequences is based on changes in e.g., sporomorph/dinocyst ratios, the percentages of bisaccates (to the total sum sporomorphs), relative proportion of eco-dinocyst groups (e.g., sensu Brinkhuis, 1994), foraminifera associations and the γ-ray log expressions (Munsterman, manuscript in preparation).

Results

The composition of the dinocyst assemblages is highly variable (Figs. 4-21) although typically, several intervals are characterized by a dominance of a single taxon (e.g., *Homotryblium floripes-plectilum* group), due to restricted marine conditions. In general, however, representatives of *Dapsilidinium*, *Hystrichokolpoma*, *Lingulodinium*, *Operculodinium*, *Spiniferites* and *Systematophora* are common in most samples. The sporomorph content is dominated by bisaccates. Overall preservation is good, although the relatively low percentages of protoperidinioid species may be taken to indicate mild (insitu) oxidation (cf. Reichart and Brinkhuis, 2003).

Roughly fifty Late Oligocene-Miocene dinocyst events are consistently recognized between investigated boreholes (Fig. 1), while up to 17 third-order eustatic sea level sequences have been recognized on the basis of our integrated studies so far. Informal (interval) dinocyst zones for the Late Oligocene (3 zones) are presented elsewhere (Van Simaeys et al., submitted.) The fourteen Miocene zones are described below (Fig. 22). The zones are typically defined by the highest (HO) and lowest occurrence (LO) of taxa.

SNSM1 (southern North Sea Miocene 1) zone

Definition
The interval from the HO of *Distatodinium biffii* to the HO of *Chiropteridium* spp. (Fig. 4).

Characteristics
Several typical Paleogene taxa have their HO in this zone that spans the Oligocene/Miocene boundary, viz: *Deflandrea phosphoritica*, *Glaphyrocysta* spp., *Hystrichokolpoma cinctum*, *Hystrichokolpoma* sp. cf. *H. oceanicum* of Wilpshaar et al. (1996), and *Membranophoridium aspinatum*. *Membranilarnacia? picena* (Fig. 5) becomes more consistent throughout, while *Ectosphaeropsis burdigalensis* (Fig. 9) has its LO within this zone. Taxa that are more common include *Cordosphaeridium cantharellum*, *Polysphaeridium zoharyi*, *Spiniferites* spp., *Systematophora placacantha* and *Thalassiphora pelagica*. *Paralecaniella indentata* relative numbers increase while the *Homotryblium floripes/plectilum* group may be abundant.

Lithostratigraphy
Middle North Sea Group; Veldhoven Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age
Latest Chattian-early Aquitanian.

Reference section
Heumensoord (46A0260), interval 358-395 m.

Additional reference sections
Broekhuizenvorst (52E0114), interval 261-276 m; Groote Heide (58F0064), interval 440.2-485.7 m.

Remarks
This zone is more or less equivalent to the *Chiropteridium galea* Interval Zone (DN1) of De Verteuil and Norris (1996). Powell (1986) recorded the HO of *Chiropteridium galea* from the lower NN2 Zone at the Lemme section, Northwest Italy (~22.2 Ma; Berggren et al., 1995).

This zone is subdivided into three subzones SNSM1a, SNSM1b and SNSM1c.

SNSM1a (southern North Sea Miocene 1a) subzone

Definition
The interval from the HO of *Distatodinium biffii* to the HO of *Glaphyrocysta* spp.

Characteristics
The HO of *Deflandrea phosphoritica* and the highest consistent occurrence (HCO) of *Hystrichokolpoma cinctum* are recorded in this zone. *Ectosphaeropsis burdigalensis* has it's LO within this subzone. *Homotryblium floripes/plectilum* may appear in abundant numbers (up to 40%). *Paralecaniella indentata* is common. Other dinocysts recorded in higher abundances are *Operculodinium* spp., *Polysphaeridium zoharyi*, *Spiniferites* spp., and *Systematophora placacantha*.

Age
Latest Chattian - earliest Aquitanian.

Reference section
Heumensoord (46A0260), interval 368-395 m.

SNSM1b (southern North Sea Miocene 1b) subzone

Definition
The interval from the HO of *Glaphyrocysta* spp. to the lowest consistent occurrence (LCO) of *Membranilarnacia? picena* (Fig. 5).

Characteristics
Homotryblium floripes/plectilum and *Paralecaniella* are common. *Operculodinium piaseckii* has its LO in this subzone.

Age
Early Aquitanian.

Reference section
Broekhuizenvorst (52E0114), interval 261-276 m.

SNSM1c (southern North Sea Miocene 1c) subzone

Definition
The interval from the LCO of *Membranilarnacia? picena* to the HO of *Chiropteridium* spp.

Characteristics
Hystrichokolpoma cinctum, *Hystrichokolpoma* sp. cf. *H. oceanicum* and *Membranophoridium aspinatum* have their HO in this subzone. *Homotryblium floripes/ plectilum* achieves high relative abundances (up to 55%).

Age
Early Aquitanian.

Reference section
Groote Heide (58F0064), interval 440.2-462.75 m. Additional reference section: Heumensoord (46A0260), interval 358-367 m.

SNSM2 (southern North Sea Miocene 2) zone

Definition
The interval from the HO of *Distatodinium biffii* to the HO of *Membranilarnacia? picena* (Fig. 5).

Characteristics
The interval is marked by the HO of *Homotryblium vallum* and the LOs of *Cousteaudinium aubryae* (Fig. 8) and *Hystrichosphaeropsis obscura* (Fig. 14). Taxa that are quantitatively well-represented include *Apteodinium* spp., *Dapsilidinium* spp., *Distatodinium paradoxum* (Fig. 12), *Homotryblium floripes/plectilum*, *Lingulodinium machaerophorum*, *Polysphaeridium zoharyi*, *Spiniferites* spp., *Systematophora placacantha* and *Reticulatosphaera* actinocoronata.

Lithostratigraphy
Middle North Sea Group; Veldhoven Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age
Late Aquitanian - (earliest) early Burdigalian.

Reference section
Groote Heide (58F0064), interval 403.7-437.2 m.

Remarks
The HO of *Membranilarnacia? picena* is reported from the *Nematosphaeropsis downiei* Interval Zone at the Contessa section, northern Italy (Zevenboom, 1995). Its chronostratigraphic position is there calibrated magnetostratigraphically against C6N (~19.6 Ma; Berggren et al., 1995).

SNSM3 (southern North Sea Miocene 3) zone

Definition
The interval from the HO of *Membranilarnacia? picena* (Fig. 5) to the HO of *Cordosphaeridium cantharellum* (Fig. 6).

Characteristics
Caligodinium pychnum and *Leptodinium italicum* have their HOs in this zone. Common are *Batiacasphaera* spp., *Dapsilidinium* spp., *Lingulodinium machaerophorum*, *Operculodinium* spp., *Reticulatosphaera actinocoronata* and *Spiniferites* spp.

Lithostratigraphy
Middle North Sea Group; Veldhoven Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age
Early-middle Burdigalian.

Reference section
Groote Heide (58F0064), interval 317.8-400.7 m.

Remarks
Zevenboom (1995) recorded the HO of *Cordosphaeridium cantharellum* in his *Selenopemphix brevispinosa* Interval Subzone of the *Hystrichokolpoma reductum* Interval Zone in the *Cortemilia* section, northern Italy. The event is there calibrated against the top of Chron C5Dr (~17.6 Ma; Berggren et al., 1995).

SNSM4 (southern North Sea Miocene 4) zone

Definition
The interval from the HO of *Cordosphaeridium cantharellum* to LO of *Labyrinthodinium truncatum* (Fig. 16).

Characteristics
Sumatradinium soucouyantiae appears in this zone, while the LOs of *Barssidinium graminosum* and *B. wrennii* are noted as well. The associations are dominated by *Apteodinium spiridoides*, *Batiacasphaera* spp., *Operculodinium centrocarpum*, *Spiniferites* spp. and *Systematophora placacantha*. *Paralecaniella* and

Pediastrum may reach common to abundant values in the associations.

Lithostratigraphy
Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe 1997).

Age
Late Burdigalian or early Langhian (see Discussion).

Reference section
Groote Heide (58F0064), interval 296.5-314.8 m.

Remarks
This zone comprises the DN3 Zone of De Verteuil and Norris (1996). *Sumatradinium soucouyantiae* apparently has a younger LO in the North Sea Basin compared to the records from the U.S. Atlantic margin (DN 2 zone, De Verteuil and Norris, 1996). This may be due to climatic differences since *Sumatradinium* spp. are typical tropical taxa.

SNSM5 (southern North Sea Miocene 5) zone

Definition
The interval from the LO of *Labyrinthodinium truncatum* (Fig. 16) to the LO of *Unipontidinium aquaeductum* (Fig. 11).

Characteristics
Cerebrocysta poulsenii, '*Imperfectodinium bulbosum*' (Zevenboom, 1995, ms) and '*Palaeocystodinium ventricosum*' (Fig. 15) (Zevenboom, 1995, ms) have their LO in this zone. *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Reticulatosphaera actinocoronata*, *Systematophora placacantha* (Fig. 7) and *Spiniferites* spp. are common in this zone. The colonial freshwater alga *Pediastrum* is abundant, while the acritarch *Paralecaniella* may be common.

Lithostratigraphy
Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age
Langhian.

Reference section
Groote Heide (58F0064), interval 275.3-291.6 m.

Remarks
The zone is identical to the *Labyrinthodinium truncatum* Interval Zone of Zevenboom (1995). The LO of *Labyrinthodinium truncatum* at the Cessole

section, northern Italy, is calibrated against in the basal part of subchron C5Bn2n (~15.2 Ma; Zevenboom, 1995). De Verteuil and Norris (1996) proposed that the LO of *Labyrinthodinium truncatum* approximates the Burdigalian-Langhian transition (~16.4 Ma). In their discussion, De Verteuil and Norris (1996) refer to possible calibration against the planktonic foraminifera upper N8 or N9 Zone and calcareous nannofossil NN5 Zone. Our integrated biochrono-sequence stratigraphy places the event at 15,8 Ma in the southern North Sea Basin.

SNSM6 (southern North Sea Miocene 6) zone

Definition
The interval from the LO of *Unipontidinium aquaeductum* (Fig. 11) to the HO of *Cousteaudinium aubryae* (Fig. 8).

Characteristics
The lowest appearances of *Gramocysta verricula* (Fig. 20) are recorded at the top of this zone. The assemblage is dominated by *Batiacasphaera hirsuta*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Polysphaeridium zoharyi*, *Reticulatosphaera actinocoronata*, *Spiniferites* spp. and *Systematophora placacantha* (Fig. 7).

Lithostratigraphy
Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age
Latest Langhian.

Reference section
Broekhuizenvorst (52E0114), interval 178-197 m.

Additional reference section
Heumensoord (46A0260), interval 284-306 m.

Remarks
The LO of *Unipontidinium aquaeductum* is calibrated against the upper part of C5Bn2n (~ 15.1 Ma) in Italy (Zevenboom, 1995), while the HO of *Cousteaudinium aubryae* is calibrated against the base of C5Bn1n (~14.9 Ma).

SNSM7 (southern North Sea Miocene 7) zone

Definition
The interval from the HO of *Cousteaudinium aubryae* (Fig. 8) to the HO of '*Palaeocystodinium ventricosum*' Zevenboom (1995, ms) (Fig. 15).

Characteristics

An index-event for this zone is the LO of '*Headinium miocenicum*' Zevenboom, 1995, ms., while *Apteodinium spiridoides* has its HO in this zone. *Batiacasphaera, Labyrinthodinium, Lingulodinium, Operculodinium, Systematophora* and *Spiniferites* spp. are common in this zone. *Paralecaniella* spp. are common as well.

Lithostratigraphy

Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age

Early-middle Serravallian.

Reference section

Groote Heide (58F0064), interval 217.8-251.9 m.

Additional reference section

Broekhuizenvorst (52E0114), interval 133-173 m.

Remarks

The HO of '*Palaeocystodinium ventricosum*' is reported by Zevenboom (1995) from the middle part of his *Operculodinium eirikianum* Interval Subzone of the *Hystrichosphaeropsis pontiana* Interval Zone, at the Cassinasco section, northern Italy. There, this event is calibrated against the base of Chron C5Ar (~13 Ma).

SNSM8 (southern North Sea Miocene 8) zone

Definition

The interval from the HO of '*Palaeocystodinium ventricosum*' (Fig. 15) Zevenboom (1995, ms) to the HO of *Unipontidinium aquaeductum* (Fig. 11).

Characteristics

Batiacasphaera sphaerica, Dapsilidinium spp., *Habibacysta tectata, Labyrinthodinium truncatum, Lingulodinium machaerophorum, Palaeocystodinium golzowense, Polysphaeridium zoharyi, Reticulatosphaera actinocoronata, Spiniferites* spp. and *Systematophora placacantha* (Fig. 7) comprise the majority of the dinocysts in the associations of this zone.

Lithostratigraphy

Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age

Middle Serravallian.

Reference section

Heumensoord (46A0260), interval 250-256 m.

Additional reference section

Groote Heide (58F0064), interval 199.3-202.3 m.

Remarks

Zevenboom (1995) correlated the HO of *Unipontidinium aquaeductum* to base C5An (~12.4 Ma).

SNSM9 (southern North Sea Miocene 9) zone

Definition

The interval from the HO of *Unipontidinium aquaeductum* (Fig. 11) to the LO of *Achomosphaera andalousiensis* (Fig. 17).

Characteristics

Batiacasphaera hirsuta, Habibacysta tectata, Hystrichokolpoma rigaudiae, Lingulodinium machaerophorum, Operculodinium centrocarpum, Reticulatosphaera actinocoronata, Spiniferites ramosus and *Systematophora placacantha* are common in this zone, as is *Paralecaniella indentata*.

Lithostratigraphy

Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age

Middle-late Serravallian.

Reference section

Heumensoord (46A0260), interval 220-241 m.

SNSM10 (southern North Sea Miocene 10) zone

Definition

The interval from the LO of *Achomosphaera andalousiensis* (Fig. 17) to the HO of *Cerebrocysta poulsenii* (Fig. 18).

Characteristics

Spiniferites spp. dominate the associations of this zone. Common are *Habibacysta tectata, Hystrichokolpoma rigaudiae* and *Operculodinium centrocarpum*.

Lithostratigraphy

Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age

Middle-late Serravallian.

Reference section

Groote Heide (58F0064), interval 193.90-196.30 m.

Remarks

This zone is the equivalent of the *Achomosphaera andalousiensis* (Aan) Interval Zone of Zevenboom (1995). In Italy, the LO of *Achomosphaera andalousiensis* is calibrated magnetostratigraphically with the upper part of the subchron C5An (~12.2 Ma) by Zevenboom (1995). The HO of *Cerebrocysta poulsenii* is calibrated against basal C5r (~11.7 Ma) in Italy (Zevenboom, 1995).

SNSM11 (southern North Sea Miocene 11) zone

Definition
The interval from the HO of *Cerebrocysta poulsenii* (Fig. 18) to the HO of *Cannosphaeropsis passio* (Fig. 19).

Characteristics
Cannosphaeropsis passio first appears in this zone. *Paralecaniella* may dominate the associations. *Habibacysta tectata*, *Lingulodinium*, *Operculodinium* and *Spiniferites* spp. are common.

Lithostratigraphy
Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age
Late(st) Serravallian - earliest Tortonian.

Reference section
Groote Heide (58F0064), interval 144.8-193.55 m.

Additional reference section
Heumensoord (46A0260), interval 160-211 m.

Remarks
This zone comprises the *Cannosphaeropsis passio* Zone (DN 7) De Verteuil and Norris (1996). Zevenboom (1995) reported the HO of *Cannosphaeropsis passio* from the top of subchron C5Cr (~11 Ma) on the basis of the Italian sections.

SNSM12 (southern North Sea Miocene 12) zone

Definition
The interval from the HO of *Cannosphaeropsis passio* (Fig. 19) to the HO of *Palaeocystodinium golzowense*.

Characteristics
Locally *Gramocysta verricula*, *Labyrinthodinium truncatum* and *Selenopemphix brevispinosum* are common values. In general, *Habibacysta tectata*, *Hystrichokolpoma rigaudiae*, *Lingulodinium machaerophorum*,

Operculodinium spp., *Reticulatosphaera actinocoronata*, and *Spiniferites* spp. are abundant in this zone.

Lithostratigraphy
Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age
Early-middle Tortonian.

Reference section
Groote Heide (58F0064), interval 124.8-141.8 m.

Additional reference section
Heumensoord (46A0260), interval 140-156 m.

Remarks
The HO of *Palaeocystodinium golzowense* is calibrated against subchron C4An (~8.7 Ma) in Italy (Zevenboom, 1995). This matches the findings of De Verteuil and Norris (1996).

SNSM13 (southern North Sea Miocene 13) zone

Definition
The interval from the HO of *Palaeocystodinium golzowense* to the HO of *Systematophora placacantha* (Fig. 7).

Characteristics
Selenopemphix armageddonensis (Fig. 21) first appears in this zone. Common are *Batiacasphaera* spp., *Habibacysta tectata*, 'Headinium miocenicum', *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Reticulatosphaera actinocoronata*, *Selenopemphix* (including *S. brevispinosum* and *S. dionaeacysta*) and *Spiniferites* spp.

Lithostratigraphy
Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age
Middle Tortonian.

Reference section
Groote Heide (58F0064), interval 106.8-120.8 m.

Additional reference section
Heumensoord (46A0260), interval 125-134 m.

Remarks
Zevenboom (1995) calibrated the HO of *Systematophora placacantha* against the C4r/C4n transition (~8.1 Ma) in Italy.

SNSM14 (southern North Sea Miocene 14) zone

Definition
The interval from the HO of *Systematophora placacantha* (Fig. 7) to the HO of *Labyrinthodinium truncatum*.

Characteristics
Gramocysta verricula (Fig. 20) has its HO within this zone. Dinocysts with a Miocene or even earlier origin like *Cordosphaeridium minimum*, *Hystrichosphaeropsis obscura*, *Melitasphaeridium choanophorum* and *Reticulatosphaera actinocoronata* are still present. These taxa continue to occur above the HO of *Labyrinthodinium truncatum*.

Lithostratigraphy
Upper North Sea Group; Breda Formation (Van Adrichem Boogaert and Kouwe, 1997).

Age
Late Tortonian.

Reference section
Heumensoord (46A0260), interval 109-121 m.

Fig. 4. *Chiropteridium galea*. GH 635.5-637.7 m. Central body 62 × 84 µm.
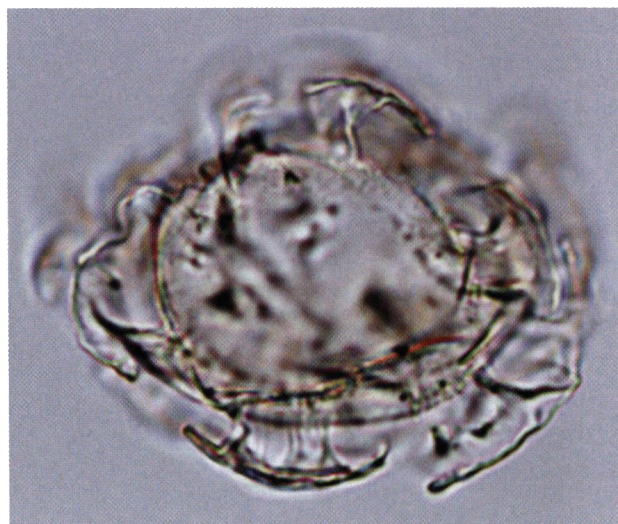
Fig. 5. *Membranilarnacia? picena*. GH 421.7-424.7 m. Overall dimensions 51 × 63 µm.
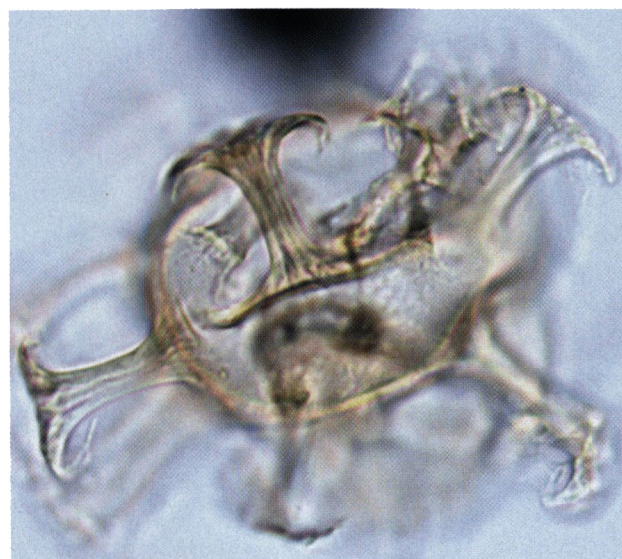
Fig. 6. *Tityrosphaeridium cantharellus*. GH 403.7-406.7 m. Central body 45 × 62 µm; processus 25 µm.
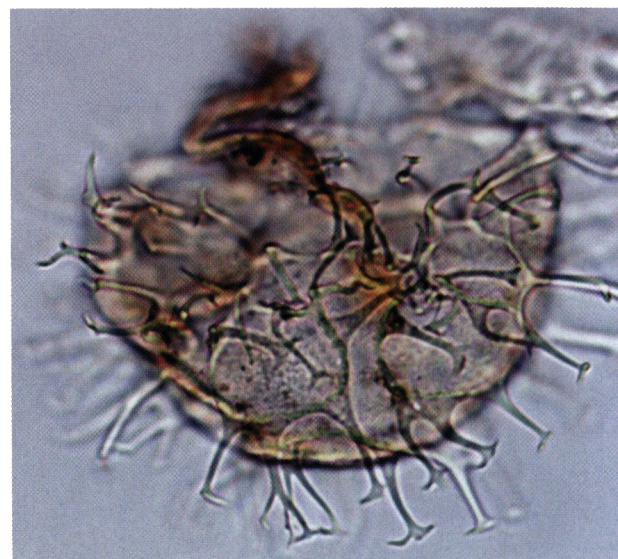
Fig. 7. *Systematophora placacantha*. GH 379.7-382.7 m. Central body diameter 78 µm.

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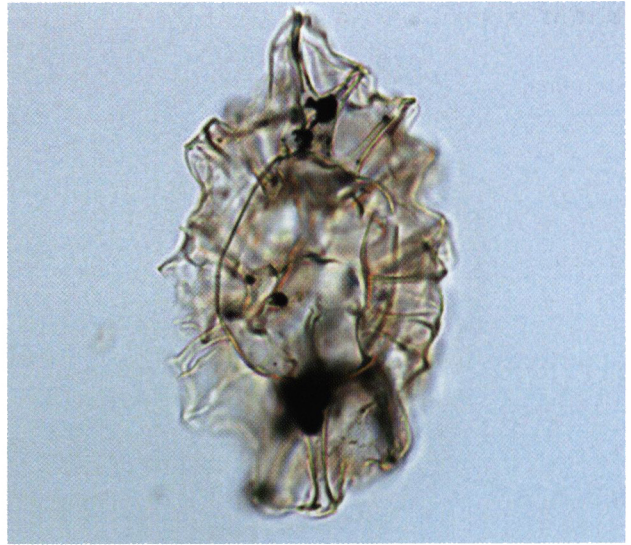Fig. 8. *Cousteaudinium aubryae*. GH 434.2-437.2 m. Diameter periblast 85 μm.

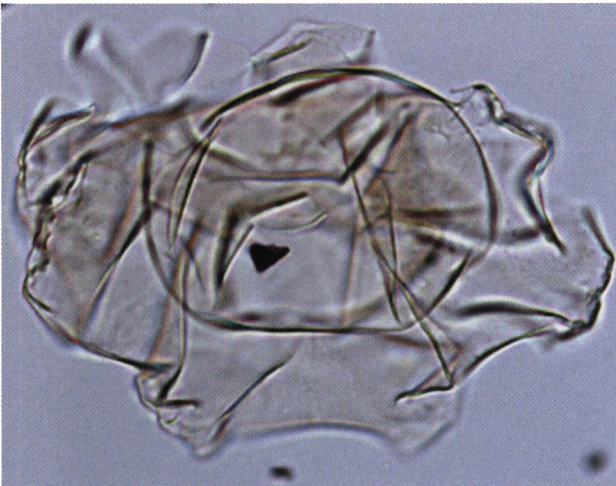Fig. 9. *Ectosphaeropsis burdigalensis*. GH 427.7-431.2 m. Overall dimensions 98 × 56 μm.

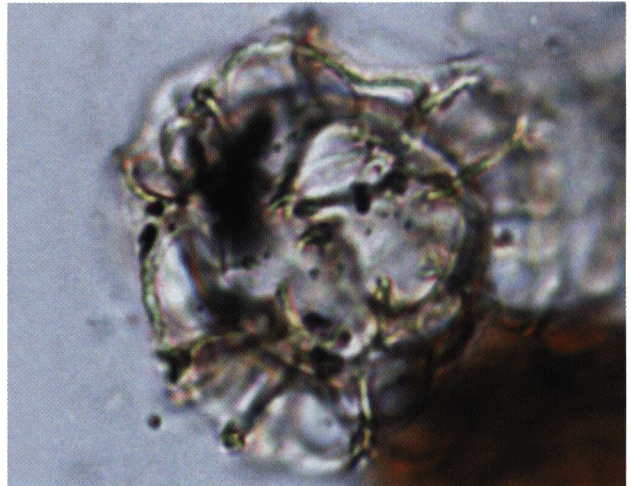Fig. 10. *Cousteaudinium aubryae*. GH 311.8-314.8 m. Dimensions periblast 69 × 103 μm.

Fig. 11. *Unipontidinium aquaeductum*. GH 210.3-211.4 m. Central body 32 × 30 μm; overall diameter 47 μm.

Fig. 12. *Distatidonium paradoxum*. GH 415.7-418.7 m. Central body 51 × 29 μm.

Fig. 13. *Distatodinium cavatum*. GH 493.4-496.7 m. Endocyst 48 × 29 μm; pericyst 51 × 36 μm.
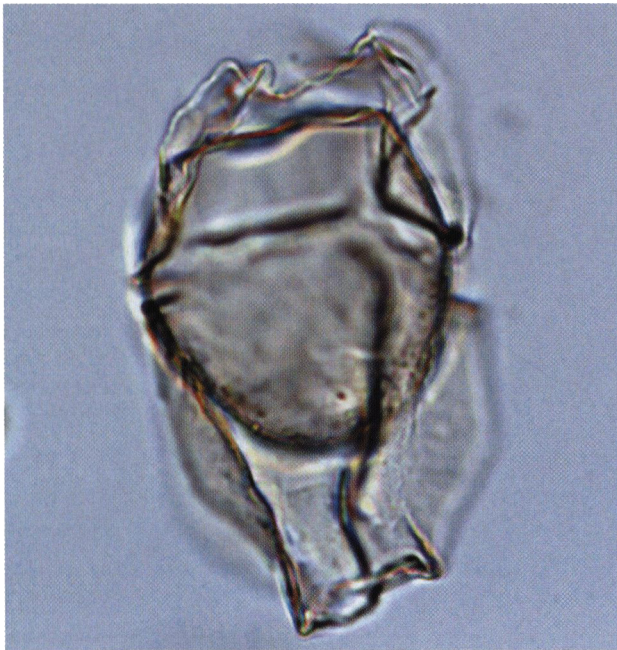
Fig. 14. *Hystrichosphaeropsis obscura*. GH 397.7-400.7 m. Overall dimensions 84 × 45 µm.

Fig. 15. *Palaeocystodinium ventricosum*. GH 208.1-210.3 m. Overall dimensions 112 × 40 µm.

Fig. 16. *Labyrinthodinium truncatum* subsp. *modicum*. GH 275.3-278.3 m. Central body diameter 36 µm.

Fig. 17. *Achomosphaera andalousiense*. GH 110.8-112-8 µm. Central body 34 × 25 µm; processus 17 µm.

Age assessment and comparisons with other Northern Hemisphere Neogene dinocyst zonations

So far, only the studies of Zevenboom and co-workers on the continuous Neogene successions from central and northern Italy provide the single, internally consistent, quasi-continuous dinocyst zonal scheme for the Miocene that has first-order paleomagnetic and biostratigraphic calibration (e.g., Zevenboom et al., 1994; Zevenboom, 1995; 1996, and Montanari et al., 1997).

Although unfortunately large portions of his thesis remain unpublished in the mainstream literature, we principally rely on this work for age-calibration, as indicated above. This despite indications that Cenozoic dinocyst distribution is principally controlled by variations in sea surface temperature, oceanic circulation, and/or differing latitudinal positions (e.g., Brinkhuis et al., 1998, 2003a,b; Sluijs et al., submitted). Since the Mediterranean was strongly influenced by Atlantic circulation throughout the Cenozoic, we consider its dinocyst record to be largely representative for the North
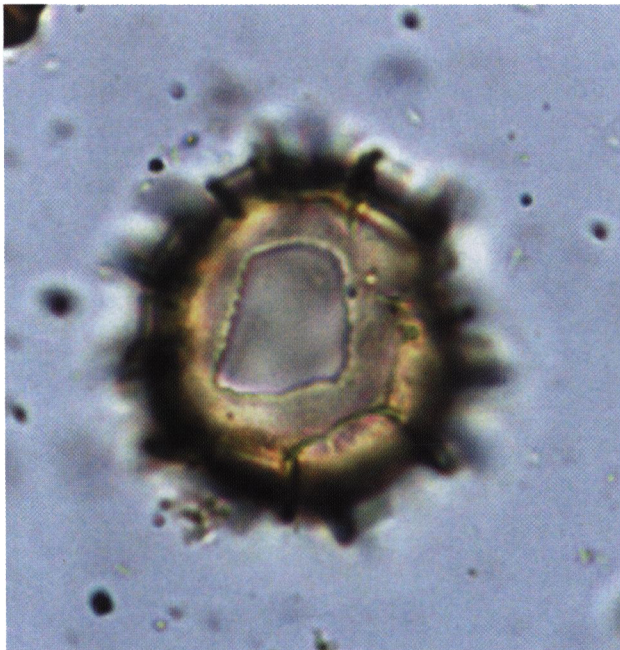
Fig. 18. *Cerebrocysta poulsenii*. GH 208.1-210.3 m. Overall dimensions 38 × 35 μm.

Fig. 19. *Cannosphaeropsis passio*. GH 159.8-163.3 m. Overall dimensions 81 × 73 μm.

Fig. 20. *Gramocysta verricula*. GH 166.3-169.3 m. Overall dimensions 70 × 62 μm.

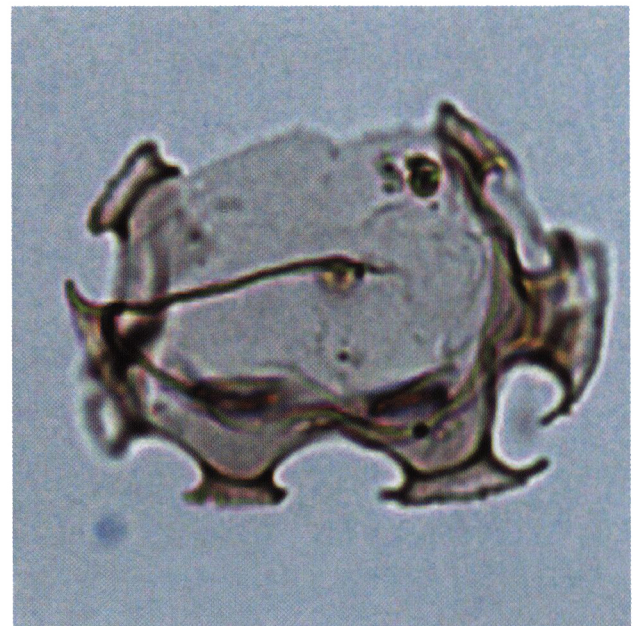Fig. 21. *Selenopemphix armageddonensis*. GH 118.8-120.8 m. Cental body diameter 39 μm.

Sea Basin as well. We therefore applied Zevenboom's principal findings, but evaluate, and deviate only where indications are that index datums are clearly controlled by the more northern latitudinal position of our study region, in part already discussed above (Fig. 22).

The single other meaningful Miocene zonal scheme is developed for the eastern North Atlantic margin by De Verteuil and Norris (1996). Having a similar latitudinal position as the southern North Sea Basin, the succession of index dinocyst events seems relevant for our study. Yet, De Verteuil and Norris' study suffers

from poor age calibration. We discuss relationships with these zonal schemes below, involve other studies where relevant, and evaluate our age-assessments for the southern North Sea Miocene zones (Fig 22).

North and central Italy (Zevenboom, 1995)

Most of the index dinocyst events recognized by Zevenboom and co-workers in the central Mediterranean have now also been recorded in the southern North Sea Basin, and are employed in our proposed

zonal scheme as discussed above. Some events considered in the Mediterranean zonation have however not been adopted here. This in view of e.g., obvious diachronicity (e.g., the LO of *Ectosphaeropsis burdigalensis* and *M?. picena*), and/or obvious strong environmental control over the distribution of certain taxa, in this case mainly oceanic taxa like e.g., *Nematosphaeropsis downiei*.

Zevenboom (1995) determined a mid-Burdigalian LO of *Hystrichosphaeropsis obscura* (Fig. 14). Subsequent studies (Montanari et al., 1997; Coccioni et al., 1997 and Dybkjaer and Rasmussen, 2000) extended its LO to the lower part of the Burdigalian. De Verteuil and Norris (1996) record this taxon down into their DN2, and even questionably into their DN1 Zone. This suggests an Aquitanian LO of *H. obscura*. Our study appears to confirm this aspect, since the event is recorded within the SNSM2 Zone.
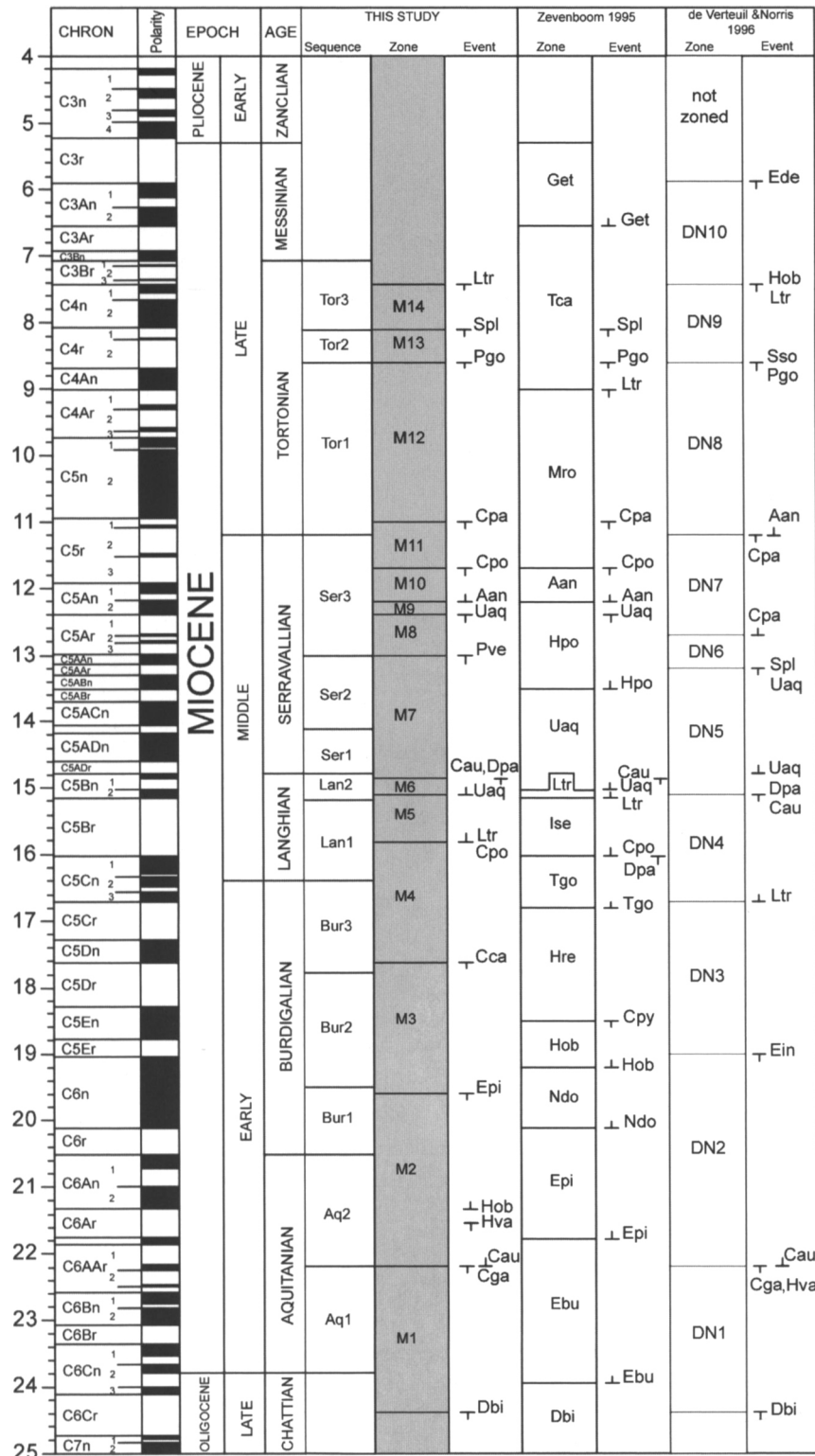

Fig. 22. Miocene timescale of Berggren et al. (1995) showing the chronostratigraphic position of the dinocyst zonation of Zevenboom 1995, De Verteuil & Norris, 1996 and this study.

The LO of *Cousteaudinium aubryae* (*Thalassiphora gonoperforata* nom. nud. Rusbült and Strauss, 1992; Tgo Interval Zone of Zevenboom, 1995) is apparently recorded earlier in the North Sea than in Italy (uppermost Burdigalian; Cortemilia section). In this paper the event is determined in the SNSM2 Zone. This further confirms early appearances reported from in the late Aquitanian in Belgium (Louwye et al, 2000), and Virginia and Maryland (De Verteuil and Norris, 1996).

Contrary to the succession of events in Italy, where Cerebrocysta poulsenii (as '*Imperfectodinium septatum*' of Zevenboom, 1995) has an earlier occurrence (LO) than *Labyrinthodinium truncatum*, in the Netherlands both events coincide. In Nieder Ochtenhausen (Strauss et al., 2001) *Labyrinthodinium truncatum* apparently even appears before *Cerebrocysta poulsenii*. The North Sea LO of *Labyrinthodinium truncatum* appears to correlate with the early Langhian 1 mfs (~15.8 Ma) of Hardenbol et al. (1998; Munsterman, manuscript in preparation). *Hystrichosphaeropsis pontiana* (Hpo Interval Zone, Zevenboom, 1995) is irregularly present in the Dutch shallow marine settings. The age of the event appears to roughly correspond to that postulated by Zevenboom (1995) for the Mediterranean. The HO of *Labyrinthodinium truncatum* in the Netherlands (late Tortonian) is apparently younger than in Italy (lower part of subchron C4An, middle Tortonian; Mazzapiedi section, Zevenboom, 1995). The assessment for the southern North Sea Basin is based on the superposition of events and on our classification in sequences (Trt-3; internal RGD, NITG-TNO, LPP reports; Munsterman, manuscript in preparation). *Galeacysta etrusca* (base Get Interval Zone, Zevenboom 1995) is absent in the marine associations of the Netherlands.

Eastern North Atlantic margin (De Verteuil and Norris, 1996)

De Verteuil and Norris (1996) described ten informal dinocyst zones for the Miocene coastal plain sediments of the Salisbury Embayment (Maryland and Virginia). The chronostratigraphic assessment of their zones is indirectly based on sparce records of calcareous nannofossils and planktonic foraminifers. Approximately half of the dinocyst events used to define their zones are also applied in our study. The chronostratigraphic datums for the HO of *Distatodinium biffii* and the HO of *Chiropteridium galea* in the Netherlands are in accordance with those from the mid-Atlantic margin (DN1 Zone, De Verteuil and Norris, 1996).

The HO of *Exochosphaeridium insigne* (DN2, De Verteuil and Norris, 1996) is not applied here, because the taxon is infrequently present in Dutch wells from the late Aquitanian to the Burdigalian. On the other hand *Membranilarnacia? picena* is not discerned at the eastern Atlantic margin. The LO of *Cousteaudinium aubryae* in the southern North Sea matches that of the eastern Atlantic margin. In the study of De Verteuil and Norris (1996) the LO of *Cousteaudinium aubryae* (Fig. 10) and the HO of *Homotryblium vallum* coincide. Our results from the Dutch wells argue for a slightly younger chronostratigraphic position in the Aquitanian for the HO of *Homotryblium vallum* (Fig. 22). The genus *Homotryblium* is known to be strongly environmentally controlled (e.g. Brinkhuis, 1994; Dybkjaer, 2004).

Cordosphaeridium cantharellum (= *Tityrosphaeridium cantharellus* sensu Williams et al., 1998) has a consistent HO in the Dutch part of the North Sea (SNSM 3 Zone, Bur-3 sequence). There is some uncertainty regarding the chronostratigraphic position of the HO of this taxon in different North Atlantic and adjacent basins (De Verteuil and Norris, 1996). The last occurrence in the North Sea is younger than that reported from the eastern Atlantic margin, and seems to match the magnetically calibrated event in North Italy (top C5Dr; Zevenboom, 1995).

The LO of *Labyrinthodinium truncatum* is discussed in the remarks on zone SNSM 5 above. In Dutch, German and U.S. studies the HO of *Cousteaudinium aubryae* and *Distatodinium paradoxum* (DN 4 Zone in De Verteuil and Norris, 1996) appear to coincide, marking the top of the Langhian. In the southern North Sea area the HO of *Cousteaudinium aubryae* is chosen for definition of the SNSM6 zone, because this event appears more consistent than the HO of *Distatodinium paradoxum* (Fig. 12). De Verteuil and Norris (1996) and Strauss et al. (2001) present the HO of *Distatodinium paradoxum* as being older than the LO of *Unipontidinium aquaeductum*. In the Dutch (this study), Belgian (Louwye et al., 2000) southern North Sea and Norwegian-Greenland Sea (Poulsen et al., 1996) an overlap in both ranges has however been demonstrated. The LO of *Unipontidinium aquaeductum* in the southern North Sea fits well with the position of the event as reported by Zevenboom (1995) in the Uaq Interval Zone of the Cessole section, N-Italy and is calibrated against the upper part of C5Bn2n.

The HO of *Systematophora placacantha* (top DN5 Zone) is interpreted by De Verteuil and Norris (1996) to mark the 'middle Serravallian'. Post DN5 Zone-occurrences are interpreted as reworked specimens. A comparable distribution pattern is recorded in NW Germany (Strauss et al., 2001). In borehole Nieder Ochtenhausen the HCO of *Systematophora placacantha*

concurs with the HO of *Unipontidinium aquaeductum*. Rare higher occurrences reach into the Late Miocene *Spiniferites pseudofurcatus* Subzone (Strauss et al., 2001). In the Dutch wells a continuous record is found at least up to the SNSM11 Zone (earliest Tortonian). *Systematophora placacantha* becomes less frequent in the SNSM 12 and 13 zones ('middle' Tortonian). In Belgian wells the taxon regularly appears in low abundances in the early Tortonian (Louwye, 2002). Zevenboom (1995) demonstrated a continuous record of *Systematophora placacantha* into his *Impagidinium strialatum* Subzone, the upper part of his *Trinovantedinium capitatum* Interval Zone at the Mazzapiedi section, N Italy. The event is estimated to mark the C4r/C4n transition. The result of the present study is congruent with the Italian record.

The HO of *Unipontidinium aquaeductum* at the Venlo Block (SE part of the Netherlands) is apparently slightly younger than that reported for the eastern Atlantic margin. The timing of the event corresponds with the calibrated HO of this taxon in N Italy. Zevenboom (1995) correlated the HO of *Unipontidinium aquaeductum* to the base of C5An (~12.4 Ma).

Achomosphaera andalousiensis has an earlier LO (SNSM10 Zone; late Serravallian) in the southern North Sea (Köthe, 2000; Strauss et al., 2001; this study) and in Italy (Zevenboom, 1995) compared to that at the eastern Atlantic margin (earliest Tortonian). The HO of *Cerebrocysta poulsenii* (top SNSM 10 Zone, this study) falls within the late Serravallian like in Germany (Strauss et al., 2001) and in Italy (Zevenboom, 1995). De Verteuil and Norris (1996) however, report sporadic appearances in the early Tortonian. The presence of *Cannosphaeropsis passio* is indicative of an age close to or at the Serravallian-Tortonian boundary. Its distribution marks the DN7 dinoflagellate cyst zone of De Verteuil and Norris (1996) at the top of the Serravallian. The results of Strauss et al. (2001) are congruent with this record. Zevenboom (1995), records *Cannosphaeropsis passio* in the Mazzapiedi section of Italy just after the significant sealevel fall at the Serravallian-Tortonian boundary (top subchron C5r). Dutch dinocyst associations from the southern North Sea confirm the HO of *Cannosphaeropsis passio* after the prominent sealevel fall, being recorded in the Trt-1 TST (top SNSM 11 Zone). This minor difference may be attributed to reworking of the older late Serravallian successions or local erosion of early Tortonian deposits.

The highest occurrence of *Palaeocystodinium golzowense* in the present study (top SNSM12 Zone) is in agreement with the records of both Zevenboom (1995) and De Verteuil and Norris (1996). The HO of *Sumatradinium soucouyantiae* (top DN 8 Zone of De Verteuil and Norris, 1996) has not been used in our study. Its last common occurrence is recorded in the SNSM11 Zone. The taxon appears infrequently in the SNSM 12 and SNSM 13 zones. The distribution of *Sumatradinium soucouyantiae* is clearly environmentally controlled, favouring (sub)tropical, nutrient-rich watermasses.

The HO of *Hystrichosphaeropsis obscura* (top DN 9 Zone of De Verteuil and Norris, 1996) in the Tortonian conficts with Early Pliocene occurrences from Dutch wells. A younger occurrence, e.g., in the latest Miocene, Messinian, was also shown by Zevenboom (1995). Lund and Heilmann-Clausen (1999) consider the HO of *Hystrichosphaeropsis obscura* (top *Amiculosphaera umbracula* Zone) in Wursterheide and Nieder Ochtenhausen to also be doubtful for the reason that the top might be truncated by the Quaternary transgression. The HO of *Labyrinthodinium truncatum*, as calibrated against the top of Chron C4n (De Verteuil and Norris, 1996) seems to fit the position in the Dutch wells. Finally, *Erymnodinium delectabile*, an index species for the top of DN10 Zone of De Verteuil and Norris (1996) has not been recognized in the studied wells from the Netherlands.

Concluding remarks

Recent drilling of the relatively well-developed Dutch marginal marine Miocene successions provided an opportunity to establish a first-ever dinocyst zonation for this region. Recognition of consistent dinocyst events between multiple boreholes allow to propose fourteen zones for the Miocene of the southern North Sea Basin, tied to the Breda Formation. By combining information from calcareous microfossils, sequence stratigraphic analysis, and previous dinocyst studies from the Mediterranean and the eastern Atlantic margin, a meaningful age-model has been developed for the Breda Formation for the first time.

This study represents but a first step; follow up investigations are currently in progress. Manuscripts focusing on the quantitative dinocyst distribution patterns, other palynomorphs, taxonomy, paleoecology, and e.g., the sequence stratigraphic framework are now being completed. With rich palynological assemblages containing besides dinocysts also e.g., abundant sporomorphs, the Neogene of the southern North Sea Basin constitutes an important sedimentary archive. Further study will allow detailed reconstruction of the response of Northern Hemisphere, mid latitude shallow marine systems to Neogene Global Change, potentially also including recognition of coeval terrestrial climate change.

Acknowledgements

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