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Dinoflagellate cyst stratigraphy and palaeoenvironment of the marginal marine Middle and Upper Miocene of the eastern Campine area, northern Belgium (southern North Sea Basin)

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A stratigraphical and palaeoenvironmental analysis with organic-walled palynomorphs of the Bolderberg and Diest formations provides new insights in the depositional history during Miocene times at the southern border of the North Sea Basin. The Neogene transgression invaded Belgium from a north–northwestern direction and fully marine sediments were deposited in the northern part of Belgium. The age and the palaeoenvironment of the deposits at the very border of the southern North Sea Basin remained till a few decades ago incomplete. The recovered dinoflagellate cysts, acritarchs and green algae from the Bolderberg Formation in the Wijshagen Borehole indicate a marginal marine depositional environment during late Burdigalian and Langhian times in the eastern Campine area, in contrast to the deeper marine conditions prevailing to the north–northwest. The relative dating of the Bolderberg Formation confirms that maximum flooding occurred during Langhian to early Serravallian times. Deposition apparently took place during the Middle Miocene Climatic Optimum, and ended when the climatic deterioration set in at around 14 Ma. A hiatus spanning *ca*. 2 Ma separates the Middle Miocene Bolderberg Formation from the Upper Miocene Diest Formation in the eastern Campine area at the border of the North Sea Basin. Copyright © 2007 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The Lower and Middle Miocene deposits of northern Belgium were deposited in a shallow marine environment at the southern edge of the southern North Sea Basin (Figure 1). The greater part of the sequence was placed into the Berchem Formation (De Meuter and Laga 1976) which occurs in the Antwerp Campine area and the western Campine area (Figures 1 and 2). Diverse sequence-stratigraphical and biostratigraphical studies during the last decade elucidated the chronostratigraphic position, shed light on the shallow marine palaeoenvironment, and allowed the reconstruction of the geometry of the sequence (Vandenberghe *et al*. 1998, 2004; Louwye *et al*. 1999, 2000, 2007; Louwye 2005).

The Bolderberg Formation occurs in the eastern part of the Campine area (Figure 1) and is regarded as a lateral succession from marine to continental sandy deposits (De Meuter and Laga 1976). Although the chronostratigraphic position of the Bolderberg Formation was never stabilized, different stratigraphic correlations with the Berchem Formation were assumed by many authors (see below), and the issue remained debated. The main reason hampering a straightforward correlation lies in the large gully which formed at the end of Middle Miocene

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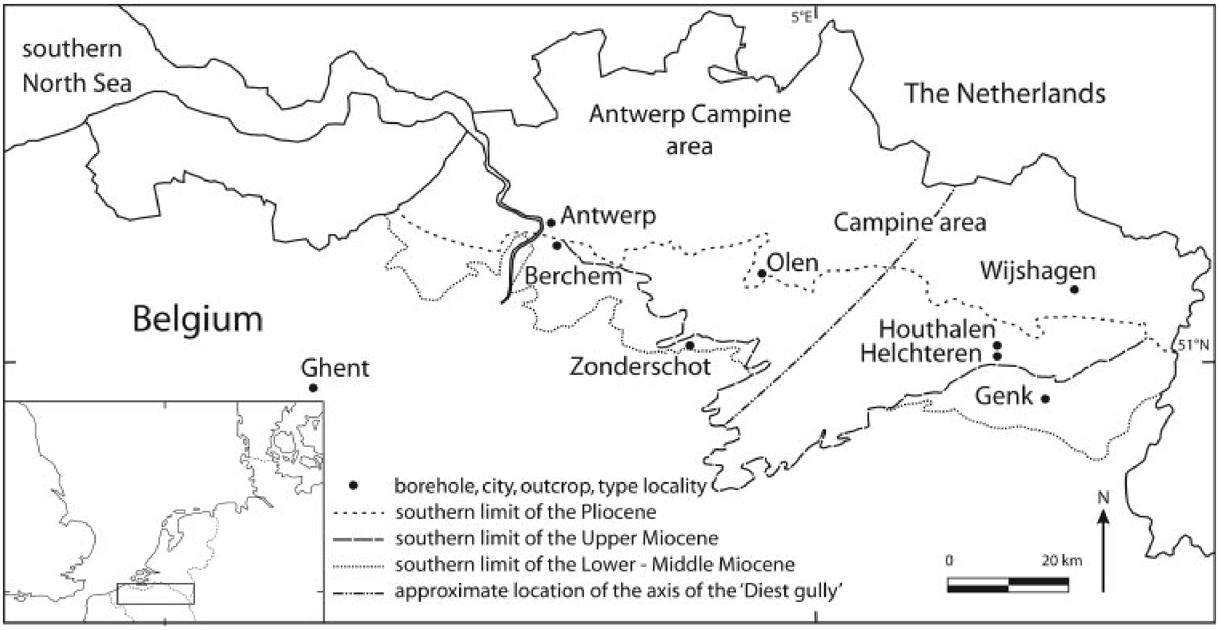

Figure 1. Location of the study area in northern Belgium.

times almost perpendicular to the strike of both of these named formations (Figure 1), and eroded both formations deeply. Eventually, the gully started to fill up during Late Miocene times with the fine- to coarse-grained sands of the overlying Diest Formation. The Diest Formation thus impedes a lateral, lithological correlation through core analyses between the Berchem and Bolderberg Formations.

Here, we report on a detailed dinoflagellate cysts analysis of the Houthalen Sands Member, the lower marine member of the Bolderberg Formation, and the Diest Formation (Figure 2). Both formations are well developed in the Wijshagen Borehole located in the eastern Campine area. The first goal of this study lies in the assessment of the chronostratigraphical position of the Houthalen Sands through a dinoflagellate cyst analysis and a stratigraphical correlation with the Berchem Formation. A second aim is the refinement of the marine palaeoenvironment in northern Belgium during Miocene times as proposed by Louwye (2005).

Series	Antwerp area	Antwerp Campine area	Campine area
Upper Miocene	Diest Fm. "Diest Sands mbr" Deurne Sands Mbr	Kasterlee Fm. Diest Fm. "Diest Sands mbr." Dessel Sands Mbr.	Kasterlee Fm. Diest Fm. "Diest Sands mbr."
Middle - Lower Miocene	Berchem Fm. Antwerpen Sands Mbr. Kiel Sands Mbr. Edegem Sands Mbr.	Berchem Fm. Zonderschot Sands Mbr. Antwerpen Sands Mbr.	Bolderberg Fm. Genk Sands Mbr. Houthalen Sands Mbr.

Figure 2. Outline of the lithostratigraphic framework of the Miocene in northern Belgium, as defined by De Meuter and Laga (1976).

2. GEOLOGICAL BACKGROUND

The North Sea constituted during Early to Middle Miocene times a semi-closed basin. To the north an open marine connection existed between the North Sea Basin and the Norwegian-Greenland Sea, while in the southwest an uplift of the Wealden-Artois axis prevented a marine connection between the southern North Sea Basin and the Channel Basins (Ziegler 1990). A marine transgression invaded Belgium from the north–northwestern direction during the Early Miocene, and the Lower and Middle Miocene deposits are thus restricted to the northern part of the country (Figure 1). The sediments consist lithologically mostly of fine- to medium-grained sand, often decalcified and with a varying but relatively high glauconite content. Layers with abundant calcareous macrofossils are often encountered. The Berchem Formation in the Antwerp area is divided into three members (Figure 2): the lower Burdigalian Edegem Sands Member, the Burdigalian Kiel Sands Member and the Antwerpen Sands Member which can be divided in a lower part (lower Burdigalian to Langhian) and an upper part (Serravallian) (Louwye 2005). The Zonderschot Sands Member (lower Burdigalian to Langhian) is a local lateral equivalent of the Antwerpen Sands Member (De Meuter and Laga 1976; Louwye 2000; Laga *et al*. 2001) (Figure 2). However, the Berchem Formation is incomplete and many hiatuses occur. The reason lies in the ongoing tectonic uplift of northern Belgium competing with a rising sea level (Vandenberghe *et al*. 1998; Louwye 2005).

De Meuter and Laga (1976) formally defined the Bolderberg Formation. The base of the formation consists of a gravel bed of rounded flint pebbles and shark teeth, followed by the marine Houthalen Sands Member consisting of dark green, medium to fine-grained sand, micaceous, glauconitic and very slightly lignitic. Molluscs are dispersed or occur in layers in the lower part of the member. These molluscs occur sometimes silicified and reworked in the basal gravel of the superjacent Diest Formation. The continental Genk Sands Member consists of whitish, fine- to coarse-grained sand with gravel intercalations. Lignite layers and glassy quartzite banks are locally present. This definition was followed during the last revision of the Neogene lithostratigraphy of northern Belgium by Laga *et al*. (2001). Based on a seismic survey on the canals and rivers of northern Belgium, De Batist and Versteeg (1999) described the seismic facies of the Bolderberg Formation as being composed of distinct, parallel and continuous internal reflections. The unit has a maximum thickness of *ca*. 180 m in NE Belgium, thins out in a western direction, and truncates locally the underlying strata.

According to Wouters and Vandenberghe (1994), the regressive character of the upper part of the Bolderberg Formation heralded a period of non-sedimentation at the boundary between the Middle and Late Miocene. During this period a large and deep gully formed (Figure 1) and eroded the underlying Miocene and Oligocene deposits. The formation of this gully was related to the combination of a tectonic uplift of the underlying Lower Palaeozoic Brabant Massif and a global lowering of the sea level during late Middle Miocene times (Vandenberghe *et al*. 1998), and to the subsiding Rhine Graben (De Myttenaere 1989). As the sea level started to rise during Late Miocene times, deposition of the Diest Formation first took place in the deeper parts of the gully and later in the greater part of the Antwerp Campine area and the Campine area. As a consequence, both the Bolderberg Formation and the Berchem Formation are disconformably overlain by the Diest Formation in the greater part of their geographical extension. The areal distribution of the Berchem Formation is thus truncated to the east by the Upper Miocene Diest Formation, and hampers a correlation with the Bolderberg Formation.

The Diest Formation was formally defined by De Meuter and Laga (1976) as a glauconitic, coarse-grained sandy unit with dispersed sandstone layers. These mostly coarse-grained sands are informally called the 'Diest Sands' and constitute the greater part of the formation. The Diest Sands are for the greater part decalcified and thus contain few or very poorly preserved calcareous macrofossils and microfossils. The Dessel Sands and the local Deurne Sands are two members found at the base of the formation. The Dessel Sands are found in the gully and in the Antwerp Campine area, while the Deurne Sands are restricted to the Antwerp area (Figure 1). Both members consist of fine-grained sand with a varying glauconite content, are rich in calcareous fossils and have a basal gravel consisting of rounded pebbles, bone fragments and shark teeth. The two basal members of the Diest Formation appear to be strongly diachronous. The depocentre was initially located in the vicinity of the gully (Figure 1) and later shifted to the area north of Antwerp during late Tortonian to Messinian times (Louwye *et al*. 1999). The Diest Formation is bounded by unconformities. The disconformity between the Berchem and Bolderberg formations, and the above-lying Diest Formation is correlated to the major sequence boundary Ser4/Tor1 of Hardenbol *et al*. (1998), while the upper boundary correlates to the major sequence boundary Me2. The Diest Formation has a maximum thickness of approximately 115 m (Wouters and Vandenberghe 1994).

3. GEOLOGICAL HISTORY

The Bolderberg Formation (formerly called 'Boldérien') was described for the first time by Dumont (1849), who considered it as the youngest Miocene stage. He recognized a twofold division: a basal gravel bed, a lower marine unit consisting of glauconitic sands followed by yellowish sands and an upper lignitic and sandy unit of fluvial origin. During the 19th century, the sequence was only exposed in scarce outcrops and a general overview was never possible. It is thus not surprising that the lithology, sedimentology and especially the stratigraphic position formed the topic of many discussions during the following decennia (see Reference De Heinzelin and Glibert (1956) for a historical overview). It was only in 1935 that Halet for the first time observed the complete sequence during the construction of a mine shaft in Houthalen, and confirmed the twofold division suggested by Dumont (1849): a lower marine unit and a superjacent non-marine or continental unit. Halet (1935) correlated the unit with the 'Anversien'. The 'Anversien' stage was at that time represented by the 'Sables d'Edeghem' and the 'Sables d'Anvers' and placed in the Middle Miocene. Nowadays, the old concept of the 'Anversien' is considered obsolete and the deposits are now termed the Edegem Sands, Kiel Sands and the Antwerpen Sands members, and are included in the Lower to Middle Miocene Berchem Formation (Figure 2). De Heinzelin and Glibert (1956) defined in the 'Lexique Stratigraphique International' formally the Bolderian stage as a twofold unit resting on a basal gravel. The lower subunit is of marine origin and consists of a lower 'Horizon de Houthalen' and an upper 'Horizon de Bolderberg', and an upper subunit of continental origin. The Bolderian stage was placed in the lower part of the Middle Miocene series.

The Diestian stage was introduced by Dumont (1839) to designate a mostly coarse-grained sandy unit in northern Belgium. The scarcity of calcareous fossils caused the chronostratigraphic position of the unit to be debated by many authors for almost a century. A detailed overview of the former stratigraphic allocations of the Diest Formation is given by Louwye *et al*. (1999). A first stratigraphic stabilization is proposed in the 'Lexique Stratigraphique International' (De Heinzelin and Glibert 1956), where the formation is placed in the Upper Miocene Series. This viewpoint was adopted by De Meuter and Laga (1976).

4. BIOSTRATIGRAPHICAL HISTORY

Micropalaeontological and biostratigraphical studies of the Bolderberg Formation are scarce, and the few studies deal with Foraminifera, Ostracoda, calcareous nannoplankton and otoliths.

One of the first biostratigraphical studies is by De Meuter (1970) who reported on a rich and characteristic foraminiferal fauna from a few selected samples of the Houthalen Sands Member in the Helchteren well (Figure 3). The Foraminifera association could easily be correlated with the fauna from the Lower to Middle Miocene Hemmoor regional stage in Germany. The high numbers of *Elphidium inflatum* and *Heterolepa dutemplei peelensis* appear typical. Although De Meuter (1970) stated that more studies are needed to clarify the relationship with the Antwerpen Sands Member in the Antwerpen type area, a cautious suggestion is made that the Antwerp Sands Member passes laterally into the Houthalen Sands Member. De Meuter (1970) assumed a Middle Miocene age for the Houthalen Sands Member (Figure 3).

De Meuter and Laga (1976) recognized the Lower Miocene *Trifarina gracilis rugulosa–Elphidium ungeri* Zone in the Houthalen Sands Member and the Edegem Sands Member from the Antwerp area. This viewpoint is repeated by De Meuter (1980), but he stressed that the Houthalen Sands Member must be placed chronologically between the Edegem Sands Member and the Antwerpen Sands Member. The lower part of the interregional benthic foraminiferal zone B7 (IGCP 124 Working Group 1988) of Early Miocene age is recognized in the Houthalen

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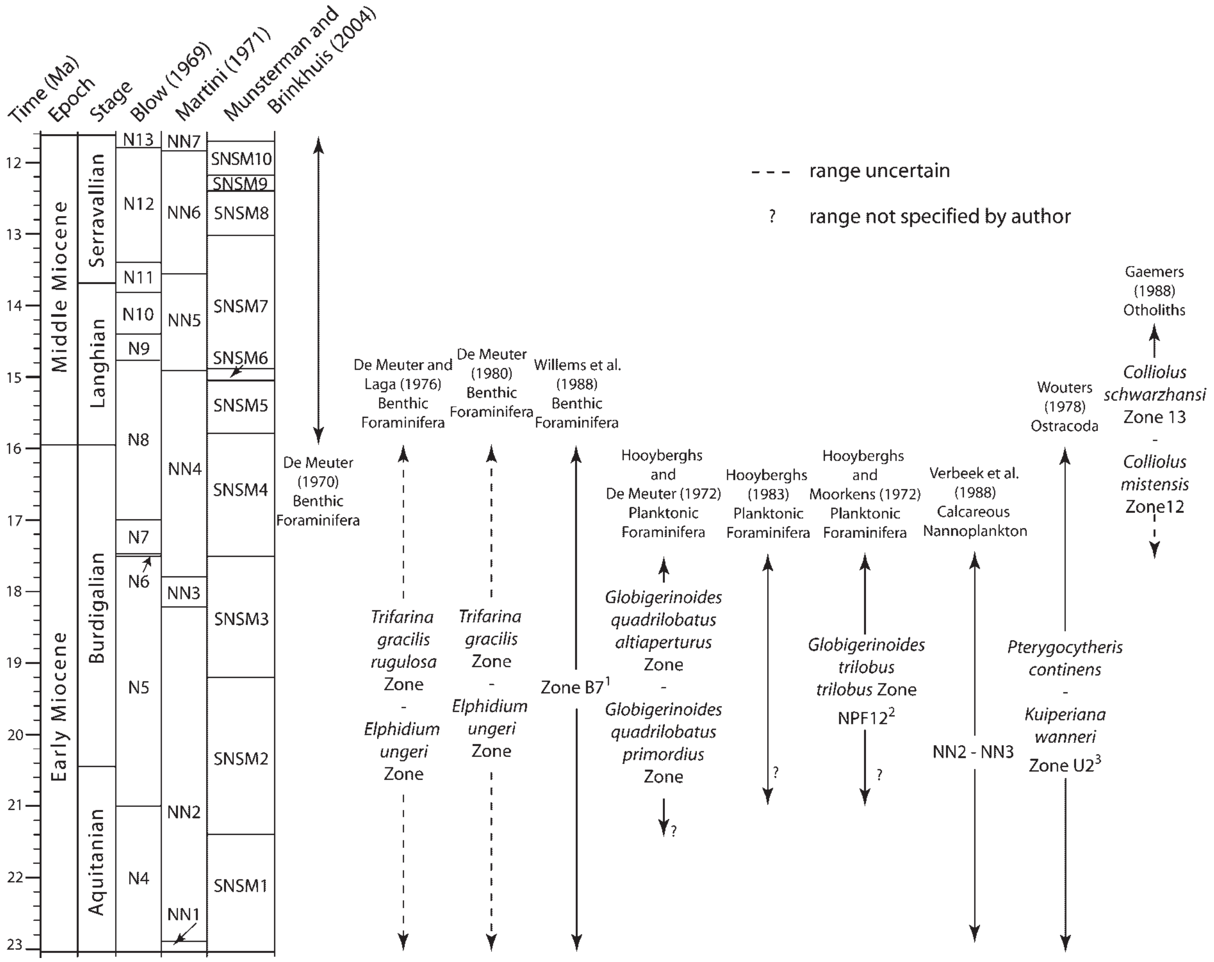

Figure 3. Stratigraphic position of the Houthalen Sands Member according to former micropalaeontological studies. Dashed lines indicate uncertain and inferred stratigraphic assessment. ^{1}Biozonation defined by IGCP 124 Working Group (1988); ^{2}biozonation defined by Spiegler *et al.* (1988); ^{3}biozonation defined by Gramann (1988). The time scale follows Lourens *et al.* (2004).

Sands Member and the Edegem Sands Member by Willems *et al.* (1988). The latter study correlated the Houthalen Sands Member thus with the Edegem Sands Member and *de facto* lowered its stratigraphic position vis-à-vis the correlation with the Antwerpen Sands Member proposed earlier by De Meuter (1970).

The planktonic Foraminifera from boreholes in the Houthalen area allowed Hooyberghs and De Meuter (1972) to place the Houthalen Sands Member in the local biostratigraphical zones *Globigerinoides quadrilobatus primordius* Zone and the above-lying *Globigerinoides quadrilobatus altiaperturus* Zone, both of Early Miocene age and correlated with the upper part of the Aquitanian Zones N4 and N5 of Blow (1969) (Figure 3). The Houthalen Sands Member is placed between the Edegem Sands Member and the Antwerpen Sands Member, but no clear correlation is given. Hooyberghs (1983) reported on a rich planktonic Foraminifera assemblage from the Houthalen Sands Member in the Helchteren well characterized by *Globigerinoides altiaperturus*, *G. primordius* and *G. quadrilobatus*. The first appearance of *Globigerinoides trilobus trilobus* in the upper part of the studied section is considered important. The Houthalen Sands Member hold the Zones N5 (?) and N6 Blow (1969), which indicates a Burdigalian age. Hooyberghs and Moorkens (1988) recognized the interregional planktonic foraminifer zone NPF12 (*Globigerinoides trilobis* Zone, middle Early Miocene, Burdigalian) of Spiegler *et al.* (1988) in the

Houthalen Sands Member and the lower part of the Antwerpen Sands Member. The Edegem Sands Member is placed in the NPF 11 Zone (*Globigerinoides primordius* Zone, earliest Miocene, Aquitanian), and thus of slightly older age than the Houthalen Sands Member. The latter authors propose a correlation with Blow's (1969) Zone N6 and probably Zone N5 at the base.

Martini and Müller (1973) described a calcareous nannoplankton assemblage dominated by *Helicopontosphaera ampliaperta* from the Houthalen Sands Member in the Wijshagen Borehole. The assemblage is strikingly similar to the one recorded in the Edegem Sands Member. Verbeek *et al*. (1988) also reported that both the Edegem Sands Member and the 'Sands of Bolderberg' (*op. cit.*) member belong to nannoplankton Zone NN2–3, while the younger Antwerpen Sands Member belongs to NN4 (Figure 3).

Wouters (1978) reported in his unpublished PhD thesis on 48 Ostracoda species from the Houthalen Sands Member. The member is placed in the *Pterygocythereis continens–Kuiperiana wanneri* Assemblage Zone of Wouters (1978), which can be correlated to the Lower Miocene U2 Zone of Gramann (1988). No bolboforma nor planktonic pteropods were recorded from the Houthalen Sands Member (Figure 3).

Gaemers (1988) reported on two silicified otoliths from the Bolderberg Formation belonging to his Otholith Zone 12 (the *Colliolus mistensis* Zone) or Otholith Zone 13 (the *Colliolus schwarzhansi* Zone). This implies an Oxlundian or Reinbeckian age (late Burdigalian to Langhian) for the Bolderberg Formation (Figure 3).

Biostratigraphical studies with calcareous microfossils or macrofossils from the Diest Formation are scarce due to their primary absence or decalcification. Only the fine-grained Deurne Sands and Dessel Sands, two members of the Diest Formation in respectively the Antwerp area and the Campine area, yielded planktonic Foraminifera and mollusc assemblages indicative of a Late Miocene age (Hinsch 1988; Hooyberghs and Moorkens 1988). Calcareous nannoplankton is extremely scarce in the Diest Formation and the few findings allow only the indication of an age younger than Early Miocene. An overview of former biostratigraphic studies with calcareous microfossils is given by Louwye *et al*. (1999), Louwye (2002) and Louwye *et al*. (2007). A dinoflagellate cyst analysis from five wells in northern Belgium attributes a Tortonian to Messinian age to the Diest Formation, and underlines the diachronous nature of the Formation (Louwye *et al*. 1999).

5. MATERIAL AND METHOD

Borehole 48W-180 was drilled in 1964 as a reconnaissance well on behalf of the Geological Survey of Belgium near the village of Wijshagen (Figure 1). The borehole reached a total depth of 215 m, and penetrated from top to bottom Quaternary deposits (6 m), the Pliocene Mol Formation (16 m), the Miocene Kasterlee Formation (28 m), the Miocene Diest Formation (44 m), the Miocene Bolderberg Formation (70 m) and terminated in the Oligocene Voort Formation (51 m) (Figure 4). The Houthalen Sands Member of the Bolderberg Formation in the borehole studied consists of fine-grained sand with occasional beds rich in petrified shells and/or micas. Fragments of wood and clayey intercalations occur sporadically. The boundary between the Bolderberg Formation and the Diest Formation is prominent and is marked by a basal layer of small sandstone pebbles, coarse-grained sand and shark teeth. Root traces and wood fragments are indicative of an emersion. The Diest Formation in the Wijshagen Borehole consists of micaceous and glauconitic medium-grained sand with clayey intercalations.

A total of 12 samples from the Bolderberg Formation, 6 samples from the Diest Formation and 1 sample from the Kasterlee Formation were macerated for palynological study (Figure 4). The preparation of the samples followed standard palynological maceration techniques. The samples were dried and two *Lycopodium clavatum* tablets were added per sample (batch no. 483216, for one tablet $X = 18\,583$). The sediment was decalcified with 30% HCl, followed by thorough rinsing until neutrality. Subsequently, the sandy sediment was treated with 40% HF for 4 h and gently stirred every 30 min. The residue was then firmly stirred, and decanted in another recipient. Approximately 50 ml of distilled water was added to the etched sand followed by decanting. This was repeated until all organic material was removed and only the etched sand fraction was left and discarded. Fluorosilicates were removed through repeated hot baths with 30% HCl. No ultrason nor oxidation techniques were applied. The residue was filtered on a 20 μm nylon screen, stained with safranin and mounted with glycerine jelly. A minimum of

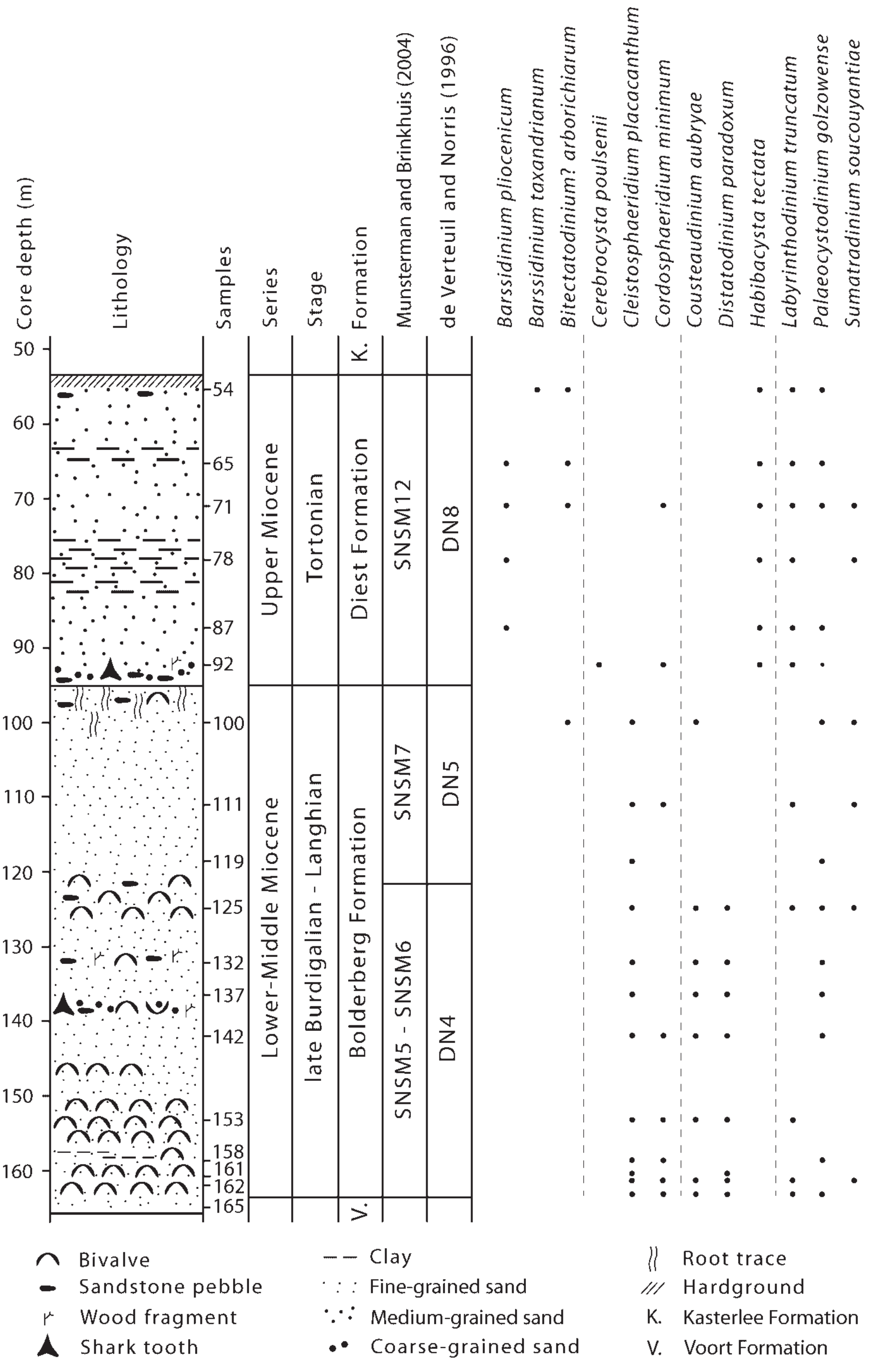

Figure 4. Lithology and stratigraphy of the section studied in the Wijshagen Borehole 48W-180 (archive of the Belgian Geological Survey), and the distribution of selected dinoflagellate cysts.

250 organic-walled palynomorphs were counted in each sample. The remainder of the slide was then scanned for rare and well-preserved specimens for photomicrography.

Nomenclature follows Fensome and Williams (2004) and Louwye *et al*. (2004). Because of their limited stratigraphic importance during Neogene times, all species from the genera *Spiniferites* and *Achomosphaera* are grouped together as *Spiniferites/Achomosphaera* spp. indet. The stratigraphically important subspecies *Achomosphaera andalousiensis andalousiensis* was not recorded in the Bolderberg Formation. The time scale of Lourens *et al*. 2004 is followed throughout.

6. THE ORGANIC-WALLED PALYNOMORPH ASSEMBLAGE

A total of 76 dinoflagellate cyst species, 6 acritarch species and 3 chlorophycean algae were encountered in the Houthalen Sands Member and the overlying Diest Formation (Table 1). Only the sample from the Kasterlee Formation was barren. Preservation of the more robust dinoflagellate cysts is moderate, while thin-walled cysts such as the acritarch *Cyclopsiella* are often torn or folded. Diversity is relatively high and species richness or concentration is poor to moderate: only three samples yielded less than 1000 dinoflagellate cysts/gram sediment (Table 1). Reworking of pre-Neogene dinoflagellate cysts is negligible. The *Spiniferites/Achomosphaera* spp. indet. group dominates the assemblage of every sample, except in the uppermost sample 54 of the Diest Formation. This sample holds very few dinoflagellate cysts, only the robust acritarch *Paralecaniella indentata* is abundant and constitutes more than 95% of the organic-walled assemblage. This sample probably underwent mild post-depositional oxidation to which only the robust palynomorphs were resistant. *Cleistosphaeridium placacanthum* is abundant in the Houthalen Sands Member and reworked in the Diest Formation. Undeterminable spherical, brown cysts with supposed protoperidinioid affinities are grouped into the 'Round Brown Cysts', which are conspicuously present in almost every sample. Other species present in considerable numbers in almost every sample are *Batiacasphaera minuta, Dapsilidinium pseudocolligerum, Lingulodinium machaerophorum machaerophorum* and *Reticulatosphaera actinocoronata*. The palaeoenvironmental meaning of the specific abundances of *Polysphaeridium zoharyi, Paralecaniella indentata, Cyclopsiella* spp. and *Pediastrum* sp. will be discussed below.

7. BIOSTRATIGRAPHICALLY SIGNIFICANT DINOFLAGELLATE CYSTS

The relative dating of the section analysed relies on a few dinoflagellate cyst species with a well-known lowest occurrence (LO) and highest occurrence (HO). Some occurrences of dinoflagellate cysts are directly calibrated against the palaeomagnetic record (Louwye *et al*. in press), others are from a comprehensive global compilation of dinoflagellate cyst LOs and HOs based on the literature (Williams *et al*. 2004). Indirect calibrated occurrences through comparison with standard nannoplankton or Foraminifera biozonations are provided by the recent Neogene biozonations (de Verteuil and Norris 1996; Munsterman and Brinkhuis 2004). The Miocene biozonation by de Verteuil and Norris (1996) was constructed in the Salisbury Embayment (Atlantic Margin, USA), a coastal plain basin bearing structural and depositional similarities to our study area. The zonation proved readily applicable to Miocene deposits from the southern North Sea Basin (Louwye *et al*. 2000, 2007; Louwye 2002, 2005). The dinoflagellate cyst biozonation by Munsterman and Brinkhuis (2004) was constructed for the subsurface Miocene of the Netherlands, and integrates regional sequence-stratigraphic and chronostratigraphic information from Mediterranean and North Atlantic dinoflagellate studies.

Following the biozonation of de Verteuil and Norris (1996) samples 165–125 m hold the DN4 *Distatodinium paradoxum* Interval Zone, a zone defined as the interval from the LO of *Labyrinthodinium truncatum* to the HO of *Distatodinium paradoxum* (Figure 4). The DN4 Zone has a late Burdigalian to early Langhian age. The above lying DN5 *Batiacasphaera sphaerica* Interval Zone is of late Langhian to possibly middle Serravallian age and defined as the interval from HO of *Distatodinium paradoxum* to the HO of *Cleistosphaeridium placacanthum*.

Table 1. Distribution of marine and terrestrial organic-walled palynomorphs in the Wijshagen Borehole

Sample	165	162	161	158	153	142	137	132	125	119	111	100	92	87	78	71	65	54
Dinoflagellate cysts																		
Apteodinium australiense		+			+		4	+			+							
Apteodinium spiridoides	8	9	1			+												
Apteodinium tectatum	4			14					+		+	12	5					
Ataxiodinium scaldemense	1	1	1		+		1		4	1					1			
Ataxiodinium zevenboomii																	1	
Barssidinium pliocenicum														+	1	+	4	
Barssidinium taxandrianum																		+
Barssidinium sp. indet.	1	+							1					+				
Batiacasphaera deheinzelinii							3	+				+						1
Batiacapshaera micropapillata														2				
Batiacapshaera minuta	5	17	4	17	11	6	3	10	1	3	6	13	5	7	5	+	3	
Batiacasphaera sp. indet.								1										
Bitectatodinium? arborichiarum												1				16	3	1
Bitectatodinium heistense	1					+		+										
Bitectatodinium raedwalldii									+			2				+		
Bitectatodinium tepikiense														+	2			
Bitectatodinium sp. indet.	2																	
Caligodinium amiculum								+R?										+
Cerebrocysta poulsenii													3					
Cleistosphaeridium placacanthum	15	43	7	25	31	59	28	30	38	8	6	14	4R	2R		1R	1R	1R
Cordosphaeridium minimum[1]	3	1		1	1						1		4			+		
Cousteaudinium aubryae	2	2			1	+	2	2	4			2						
Cribroperidinium tenuitabulatum	+																	
Cribroperidinium sp. indet.														1				
Dapsilidinium pseudocolligerum		4	3	1	2	3	4	+	1		2	3	3		2	1	+	
Dinopterygium cladoides	4	+	1		2		21	5										
Distatodinium paradoxum	1	1		1	+	2	3	8	2									
Echinidinium sp. indet.																		+
Gramocysta verricula																		2
Gramocysta sp. indet.				+														
Habibacysta tectata													2	2	4	2	7	2
Homotryblium tenuispinosum tenuispinosum				1														
Hystrichokolpoma riguadiae riguadiae				1		2			1	3			+	+				+
Hystrichosphaeropsis obscura	1	1		+		+				1	1	1	1				1	
Impagidinium patulum									2									
Impagidinium sp. indet.														1				
Labyrinthodinium truncatum modicum								+	+									
Labyrinthodinium truncatum truncatum	1	1			+				1		4		2	3	1	1	3	+
Lejeunecysta catomus														+		+		
Lejeunecysta marieae	2	+	2						1				1			1		
Lejeunecysta sp. indet.		2							1	1	2		6	1	2	2	2	+
Lingulodinium machaerophorum	7	9	6	8	3	5	3	11	18	4	6	13	12	8	3	1	6	+
Lingulodinium multivirgatum		+			+	1												
Melitasphaeridium choanophorum	1	1		5	2	6	5	1	3		5	1				2	1	+
Operculodinium? borgerholtense							1	2			3	2		1				
Operculodinium centrocarpum centrocarpum	12							9	33	16	8	2	1	4		2	3	+
Operculodinium israelianum		3	8	24	4	5	17	5			2	1	4		+		2	
Operculodinium longispinigerum								2				1						
Operculodinium piaseckii	2	1						1			3	1	1			+		
Operculodinium sp. 3 de Verteuil & Norris 1996																1		
Operculodinium sp. indet.							3							1				
Organic lining of calcareous dinoflagellate					2		1	+	1									

Raw counts are given.
For location of the samples see Figure 4.
R, reworked specimen.
[a]Species encountered after the systematic counting
[b]Species *sensu* Benedek and Sarjeant (1981)

(Continues)

Table 1. (Continued)

Sample	165	162	161	158	153	142	137	132	125	119	111	100	92	87	78	71	65	54
Palaeocystodinium golzowense	1			1		2	1	1	2	1		1	14	3		+	2	1
Pentadinium laticinctum laticinctum																3		
Polysphaeridium zoharyi zoharyi	14	2			81	1		8	19	1	1	14		+				
Pyxidinopsis brabantiana		+		1														
Quiquecuspis concreta						1		+		1			+	+	+	1		+
Round brown cyst	6	15	8	1	5	7	12	24	1	8	15	5	5		10	+	8	2
Reticulatosphaera actinocoronata	1	3	1			1	1	1	4	2	1	4	4	1	1		1	
Selenopemphix brevispinosa									+		+		1		2	+		+
Selenopemphix conspicua	+	4	1	2		+		2						1		+	+	2
Selenopemphix nephroides		3							1	1			2		1	1	+	
Selenopemphix quanta					+			+			1		1				1	
Selenopemphix sp. indet.	1	3	1					+										
Spiniferites / *Achomosphaera* spp. indet.	118	102	32	106	82	139	151	114	117	90	165	113	110	59	89	38	101	1
Sumatradinium druggii					1		+		+	2	2							
Sumatradinium hamulatum								+										
Sumatradinium soucouyantiae		2						+			1	1			+	+		
Sumatradinium sp. indet.				+														
Tectatodinium pellitum		1			+	1		+	1				3			2		+
Trinovantedinium ferugnomatum		+					1		1	1	1	1			1			
Trinovantedinium glorianum	1			1	+			+	1		1							
Trinovantedinium harpagonium																+		
Trinovantedinium sp. indet.		1							+									
Tuberculodinium vancampoae	+							+				2						
Unipontedinium aquaeductus													2					
Acritarcha																		
Cyclopsiella granosa/*elliptica* complex	5	1		25	3	1			6	42	14	19	47	7	111	56	33	+
Cyclopsiella ? *trematophora*	19	1					20	4	1	1		1				+		+
Cymatiosphaera sp. indet.			1		4						+		+					
Nannobarbophora gedlii						1		1		2	2							
Paralecaniella indentata	8	10	170	17	6	6	15	3	25	74	2	29	17	170	34	127	72	268
Small spiny acritarchs	4	4	1	1				1	2									
Chlorophyta																		
Pediastrum boryanum	1	1	2	1	13			38		1		1					+	1
Tasmanites		1		5								+		+	2			+
Pterospermella sp. indet.	+																	
Total organic-walled palynomorphs	344	316	378	319	348	302	338	329	306	346	317	291	298	328	329	299	283	329
Reworked dinoflagellate cysts	1	3	6	2	2	3	1		1	1	2		5	12	18	9	8	10
Terrestrial palynomorphs																		
Bisaccate pollen	158	109	34	245	51	146	225	36	82	152	192	120	138	46	282	84	180	35
Other pollen	9			8	2	4	4	2	2	6	7	5			17	4	5	1
Spores	9																	
Lycopodium clavatum	161	34	13	30	25	29	76	31	18	134	32	83	21	20	20	84	10	6
Number of dinocysts/gram sediment	656	3509	3070	3859	5033	4633	1945	4353	8303	636	4392	1540	5833	3351	4705	750	13667	2977

Some reservations have to be made regarding the HO of *Cleistosphaeridium placacanthum*. de Verteuil and Norris (1996) place the HO in the top of Chron C5AAr at 13.2 Ma (Figure 5) in the early Serravallian (following the time scale of Lourens *et al*. 2004). Louwye *et al*. (in press) record the highest persistent occurrence in Chron C5Ar at 13 Ma. However, this species is recorded intermittently in much younger Middle Miocene deposits in the Porcupine Basin (Louwye *et al*. in press), and it is never clear whether these occurrences relate to reworking or not.

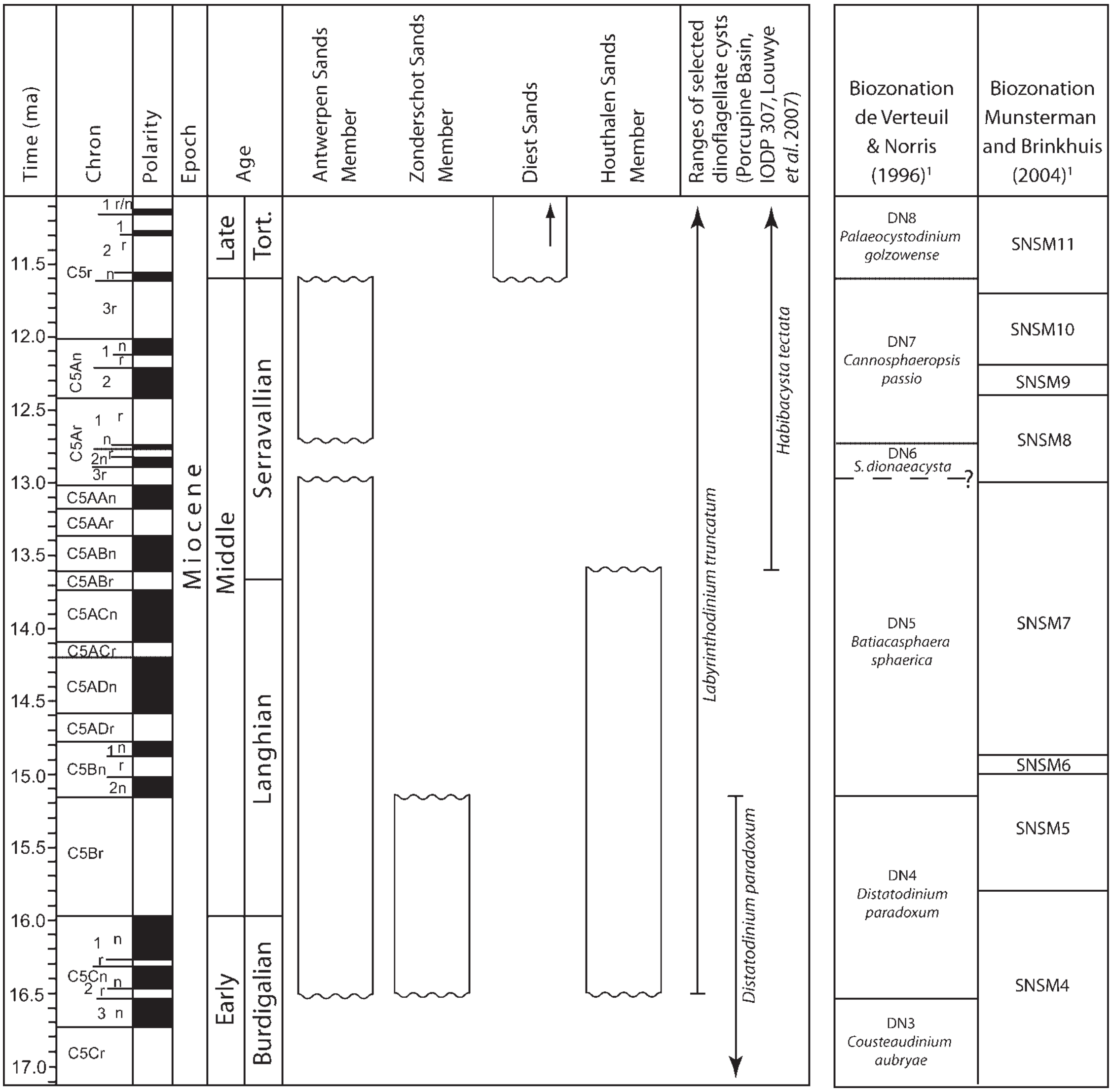

Figure 5. Stratigraphic position of the Houthalen Sands Member based on calibrated stratigraphic ranges of selected dinoflagellate cysts (Louwye *et al.* in press), and correlation with the Antwerpen Sands Member and the Zonderschot Sands Member. [1]For comparison, both the biozonation by de Verteuil and Norris (1996) and Munsterman and Brinkhuis (2004) are given. The correlation between both biozonations is discussed in detail by Munsterman and Brinkhuis (2004). The boundaries of the biozones by Munsterman and Brinkhuis (2004) and de Verteuil and Norris (1996), and also those used by Louwye *et al.* (2000) and Louwye (2005), are here recalculated for the new ATNTS (Astronomically Tuned Neogene Time Scale) by Lourens *et al.* (2004). Dashed line indicates uncertain position. Wavy line indicates disconformity. Tort. = Tortonian.

Cleistosphaeridium placacanthum is indeed a robust species and thus relatively resistant to mechanical degradation during reworking, in comparison to other fragile and more thin-walled species. As this species is present in every sample of the Houthalen Sands Member, the basal part of the DN5 Zone is thus most certainly present in samples 119–100 m, but it remains uncertain whether the upper part is present or not. Proof is given through the absence of *Habibacysta tectata* in the Houthalen Sands Member, a species with a LO within the DN5 Zone (see below). The above lying DN6 *Selenopemphix dionaeacysta* Interval Zone (interval from the HO of *Cleistosphaeridium*

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placacanthum to the LO of *Cannosphaeropsis passio*) and the DN7 *Cannosphaeropsis passio* Range Zone, both zones of middle to late Serravallian age, are missing in the Wijshagen Borehole. The section studied above the disconformity holds the DN8 *Palaeocystodinium golzowense* Interval Zone of Tortonian age. This zone is defined as the interval from the HO of *Cannosphaeropsis passio* to the HO of the eponymous species. According to de Verteuil and Norris (1996) the following species have their HO within this zone: *Cerebrocysta poulsenii*, *Cordosphaeridium minimum sensu* Benedek and Sarjeant (1981) and *Sumatradinium soucouyantiae* (Figure 4).

Samples 165–125 m hold the SNSM5 Zone (the interval from the LO of *Labyrinthodinium truncatum* to the LO of *Unipontedinium aquaeductum*) and the SNSM6 Zone (interval from the LO of *Unipontedinium aquaeductum* to the HO of *Cousteaudinium aubryae*) of Munsterman and Brinkhuis (2004). Both zones are of early Langhian age. *Unipontedinium aquaeductum* is a species with a fully marine—outer neritic to oceanic—preference and is absent in the shallow marine Houthalen Sands Member. Samples 119–100 m hold the above-lying SNSM7 Zone of late Langhian to early Serravallian age. The zone is defined as the interval from the HO of *Cousteaudinium aubryae* to the HO of *Palaeocystodinium ventricosum*. The top of the latter zone is not recognized. The LO of *Bitectatodinium*? *arborichiarum* lies within this zone. The section studied above the unconformity holds the SNSM12 Zone (interval from the HO of *Cannosphaeropsis passio* to the HO of *Palaeocystodinium golzowense*) of Tortonian age (Figure 4).

Louwye *et al*. (in press) recorded in the Porcupine Basin the LO of *Labyrinthodinium truncatum truncatum* in the base of Chron C5Cn.2r at 16.5 Ma (Figure 5). Williams *et al*. (2004) also placed the LO of this species at 16.5 Ma, based on records from de Verteuil and Norris (1996) who recorded the LO of this species in the base of Chron C5Cn. *Distatodinium paradoxum* has a HO at the upper boundary of Chron C5Br in both the Salisbury Embayment (de Verteuil and Norris 1996) and in the Porcupine Basin (Louwye *et al*. in press) at 15.2 Ma (Figure 5). As mentioned above, *Habibacysta tectata* is absent in the Houthalen Sands Member and is only recorded above the disconformity in the Diest Sands. The latter authors recorded the LO of *Habibacysta tectata* within Chron C5ABn at 13.6 Ma in Hole 1318B in the Porcupine Basin (Figure 5). Based on records from the Salisbury Embayment (de Verteuil and Norris 1996), the LO of this species was placed in the late Langhian at 14 Ma by Williams *et al*. (2004). The Wijshagen Borehole can be dated as follows: the lowest sample studied (165 m) is certainly younger than 16.5 Ma (late Burdigalian), while sample 100 m is older than 13.6 Ma. The Houthalen Sands Member has thus an inferred late Burdigalian to Langhian age. The Late Miocene age of the section studied above the disconformity is indicated by the occurrences of *Barssidinium taxandrianum* and *Barssidinium pliocenicum*. *Barssidinium taxandrianum* is recorded in the uppermost sample 54 m and its range is limited to the Upper Miocene of northern Belgium (Louwye 1999, 2002; Louwye *et al*. 2007). De Schepper *et al*. (2004) give an overview of the Late Miocene and Pliocene occurrences of *Barssidinium pliocenicum* in the North Sea Basin and the Atlantic Realm. This species is also recorded in the Upper Miocene Kasterlee Formation in northern Belgium (southern North Sea Basin) (Louwye *et al*. 2007).

8. PALAEOECOLOGICAL CONSIDERATIONS

8.1. Introduction

The organic-walled palynomorph association recovered from the Bolderberg Formation reflects a typical inner neritic or shallow marine environment as encountered in previous Miocene dinoflagellate cyst studies of the southern North Sea Basin (Louwye *et al*. 1999, 2000). Dinoflagellate cysts indicative of oceanic conditions such as *Impagidinium* or *Nematosphaeropsis* (Dale 1996) are very rare to absent in the Wijshagen Borehole (Table 1). However, a number of species with specific marginal marine or shallow marine affinities occur in relatively high numbers and are therefore discussed in detail below. Because of this, the pollen (S) versus dinoflagellate cyst (D) ratio has also been calculated for the section studied ($S/D = nS/(nS+nD)$, with n the number of specimens counted, $S =$ pollen and $D =$ dinoflagellate cysts) (Figure 6). This ratio reflects the terrestrial input into the depositional area, and can be regarded as a measure of the distance from the shoreline (Versteegh 1994). The greater part of the pollen are of the bisaccate *Pinus* type, and are blown into the study area.

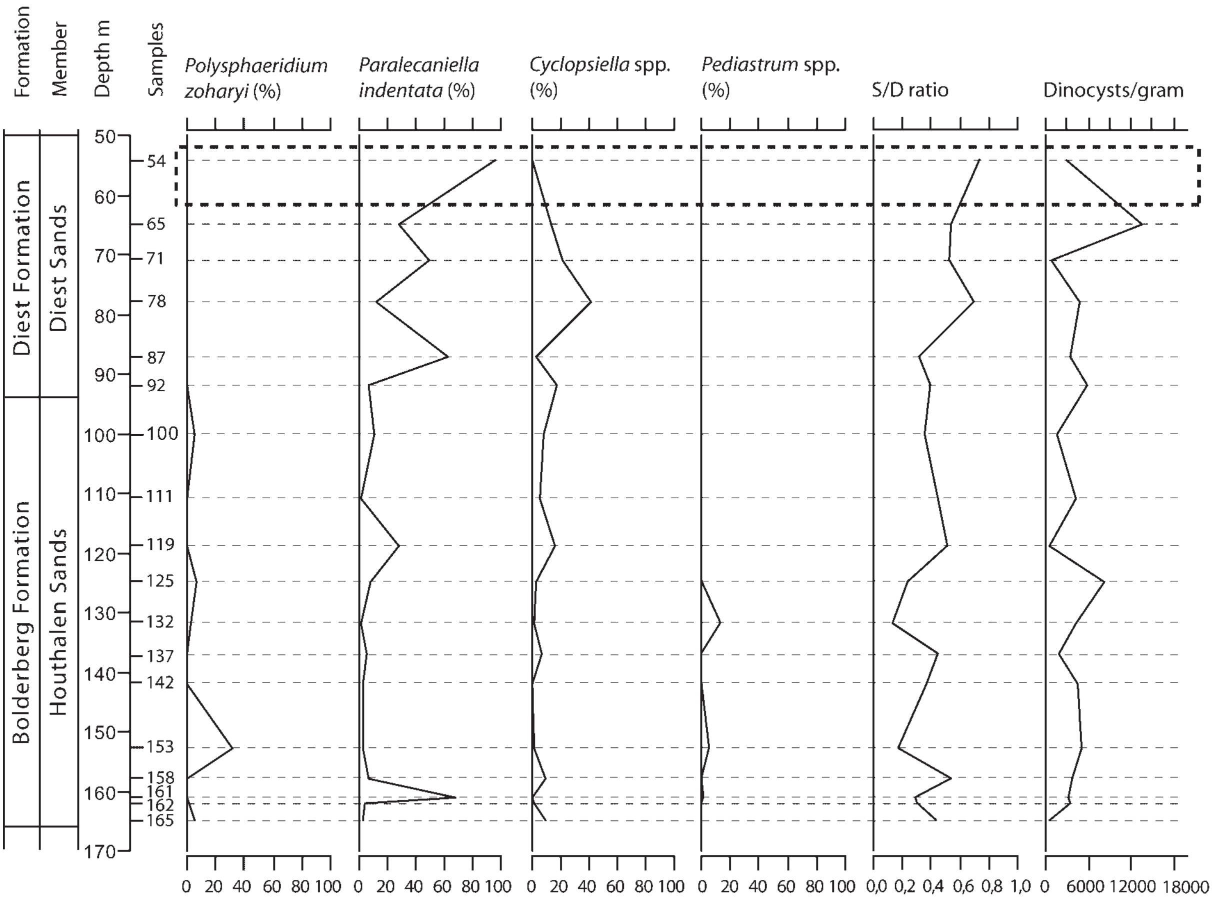

Figure 6. Relative abundance of selected organic-walled palynomorphs, pollen versus dinoflagellate cyst (S/D) ratio and number of dinocysts/g in the section studied of the Wijshagen Borehole. Dashed line frames the possible oxidized sample 54.

8.2. *Polysphaeridium zoharyi*

An extensive overview of the palaeoecological record of *Polysphaeridium zoharyi* (Figure 7) is given in Head and Westphal (1999) in their study of a Pliocene carbonate platform in the Bahamas. *Polysphaeridium zoharyi* is associated with restricted marine conditions (lowstand deposits), and thrives in normal salinity lagoons subject to periodic emergence and colonization by plants. Head and Westphal (1999) stress the present-day association of *Polysphaeridium zoharyi* and mangrove-like vegetation, but remain unsure whether this dinoflagellate cyst, in their Caribbean study area, is related to hypersaline conditions. According to Wall *et al.* (1977), *Polysphaeridium zoharyi* has a highly localized distribution. In the Caribbean it is a most abundant and often dominant species in highly saline estuaries, lagoonal areas, embayments and over carbonate platforms with a salinity ranging up to 41 psu. *Polysphaeridium zoharyi* is absent from continental shelf and slope–rise areas. Edwards and Andrle (1992) record a maximum abundance (98.4%) of *Polysphaeridium zoharyi* off Bermuda, and highest relative abundances in shallow areas (depth usually less than 22 m) with a winter sea-surface temperature above 15°C and summer sea-surface temperature above 23°C. In summary, *Polysphaeridium zoharyi* commonly occurs in tropical to subtropical environments and its distribution and abundance reflects a preference for shallow marine environments with variable but usually elevated salinities. *Polysphaeridium zoharyi* is a common species in the Burdigalian and Langhian deposits of the Porcupine Basin off southwest Ireland (Louwye *et al.* in press), and disappears from the

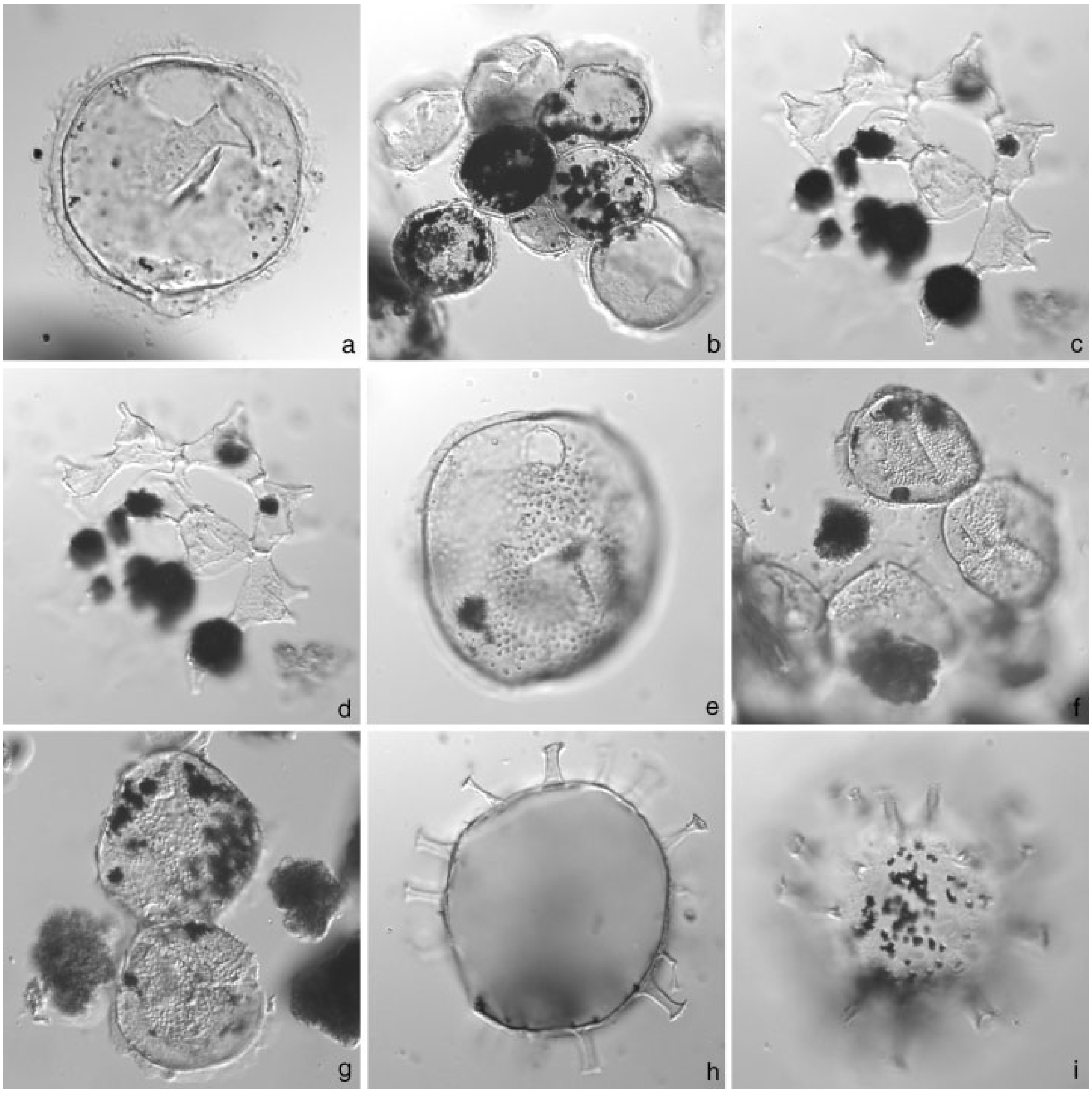

Figure 7. Selected organic-walled palynomorphs identified: a, b, e and g are acritarchs, c, d are chlorophyta, and h, i are dinoflagellate cysts. All slides are housed in the collection of the Palaeontology Research Unit, Ghent University. E.F. ref. = England Finder reference. (**a**) *Paralecaniella indentata*, sample 54 (Diest Formation), E.F. ref.: L37/2. Median focus. Maximum diameter without rim: 40 μm. (**b**) Cluster of *Paralecaniella indentata*, sample 54 (Diest Formation), E.F. ref.: P41/3. Median focus. Maximum diameter of lower left specimen: 55 μm. (**c,d**) *Pediastrum* sp., sample 132 (Bolderberg Formation), E.F. ref.: H34/1. Slightly differing high foci. Maximum diameter colony: 50 μm. (**e**) *Cyclopsiella elliptica/ granosa*, sample 78 (Diest Formation), E.F. ref.: M41/7. High focus. Maximum diameter without rim: 50 μm. (**f**) Cluster of *Cyclopsiella elliptica/ granosa*, sample 78 (Diest Formation), E.F. ref.: K32/2. High focus. Maximum diameter upper specimen: 55 μm. (**g**) Pair of *Cyclopsiella elliptica/ granosa*, sample 78 (Diest Formation), E.F. ref.: U36/4. High focus. Maximum diameter lower specimen: 45 μm. (**h**) *Polysphaeridium zoharyi*, sample 132 (Bolderberg Formation), E.F. ref.: E47/4. High focus on archeopyle. Maximum diameter without processes: 45 μm. (**i**) *Polysphaeridium zoharyi*, sample 132 (Bolderberg Formation), E.F. ref.: E47/4. Low focus on wall. Magnification same as for (8).

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record near the upper boundary of Chron C5ACr (*ca*. 14.1 Ma, late Langhian). *Polysphaeridium zoharyi* thus disappears precisely during the onset of the gradual cooling at approximately 14.1 Ma, which terminated the Middle Miocene Climatic Optimum (Miller *et al*. 1991, 1998).

The thermophilic species *Polysphaeridium zoharyi* is restricted to the Houthalen Sands Member and has a highest abundance of 31% in sample 153 and of approximately 5% in samples 165, 125 and 100. The species represents less than 1% or is absent in the other samples (Figure 6).

8.3. *Pediastrum sp.*

The green alga *Pediastrum* sp. (Figure 7) thrives in low-energy freshwater environments such as lakes and rivers, although it is also encountered in low salinity environments with a practical salinity unit lower than 1–10 such as the Baltic Sea (Weiler 1985; Brenner 2001; Head *et al*. 2005). Its presence in even shallow marine environments is indicative of nearby fluvial discharge.

Pediastrum sp. is present in the Wijshagen Borehole in eight samples in very low numbers, except in samples 153 and 132 of the Houthalen Sands Member, where a relative abundance of respectively 5 and 14.4% are recorded, and indicates an increased fluvial influence (Figure 6). This short-lived enhanced fluviatile input in the depositional area is corroborated by the presence of allochthonous, terrestrial debris (small wood fragments) at a depth of 132–133 m (Figure 4).

8.4. *Paralecaniella indentata*

Paralecaniella indentata (Figure 7) was described for the first time by Deflandre and Cookson (1955), as *Epicephalopyxis indentata*, from Paleocene to Miocene deposits of Australia, and was considered as a species of unknown biological affinity. Later Cookson and Eisenack (1970) transferred the species to the newly created genus *Paralecaniella*, and suggested affinities with the chlorophyceaen order Volvocales. Elsik (1977) emended the species and considered it as a dinoflagellate cyst. The assumption was based on a supposed cingulum found in numerous specimens from shallow marine deposits in Tertiary deposits from Alaska. Fensome *et al*. (1990) considered this species to be an acritarch.

Kurita and Matsuoka (1994) report on very low diversity dinoflagellate cyst assemblages from late Middle Eocene to early Oligocene deposits in northern Japan. *Paralecaniella indentata*, together with *Trinovantedinium boreale*, *Bellatudinium hokkaidoanum* and *Selenopemphix* spp., dominate the assemblages. Other proxies indicate that these restricted assemblages thrived in a relatively shallow embayment characterized by saline, stratified waters. High numbers of protoperidiniacean species in the Hokkaido Formation are indicative of high primary production. Kurita (2004) records high (10–30%) to very high numbers (>30%) of *Paralecaniella indentata* in the *Trinovantedinium boreale* Zone of late Eocene to Early Oligocene age in northern Japan. No palaeoenvironmental considerations are given, but the zone is typically characterized by a low dinoflagellate cyst diversity (less than five species per sample). Zaporozhets *et al*. (2006) record abundant *Paralecaniella indentata* (maximum 25% of the assemblage) in low-diversity Palaeogene assemblages of Kamchatka, where it is commonly associated with *Trinovantedinium boreale* and the acritarch *Micrhystridium*. According to the latter authors *Paralecaniella indentata* is indicative of reduced salinities and shoaling phases of depositional basins. Furthermore, they postulate that palynological residues with abundant *Paralecaniella indentata* often are enriched in amorphous organic matter of cyanobacterial origin, characteristic for deposition in a stratified oxygen-deficient depositional environment.

Brinkhuis and Schiøler (1996) describe in a high-resolution palynological analysis of the Cretaceous/Tertiary boundary from the southeast Netherlands an alternation of dinoflagellate cyst/bryophyte spore-dominated clayey layers with *Paralecaniella indentata*-dominated calcarenitic intervals. The relative importance of bryophytic spores suggests the proximity of the continent to the depositional area. The abundance of *Paralecaniella indentata* suggests marginal marine or restricted marine influence, while the dinoflagellate cyst-dominated intervals correspond to open marine conditions. The at first sight contradictory presence of bryophytic remains in the dinoflagellate cyst-dominated clay-rich intervals leads the latter authors to conclude that hydrodynamic conditions are the controlling factor: the *Paralecaniella indentata*-dominated intervals were deposited during periods of higher hydrodynamic conditions which resulted in longer suspension of clay-sized particles. Dinoflagellate cyst-dominated sediments were deposited under less energetic conditions. In a palynological study of the type Maastrichtian in The Netherlands, Schiøler *et al*. (1997) noted the relation between high numbers of *Paralecaniella* and the occurrence of numerous hardgrounds, indicating environmental change, most probably the onset of extremely marginal marine environments, most probably stressed environments.

Paralecaniella indentata is abundantly present in the Diest Formation, where in five of the six samples the species constitutes more than 10% of the organic-walled palynomorph assemblage (Figure 6). In the Houthalen Sands Member *Paralecaniella indentata* is dominant in sample 161 (68%) and abundant in sample 119 (28%). From the above, it is clear that the high numbers of *Paralecaniella indentata* indicate deposition in marginal marine or stressed environments.

8.5. Cyclopsiella spp.

The preservation of the delicate, thin-walled *Cyclopsiella* species (Figure 7) in the Wijshagen Borehole is often poor to moderate, and renders the discrimination between the morphologically similar *Cyclopsiella elliptica* and *Cyclopsiella granosa* difficult. Thus, the viewpoint of de Verteuil and Norris (1996) is followed to group *Cyclopsiella granosa* and *Cyclopsiella elliptica* together into the plexus *Cyclopsiella granosa/elliptica*. The acritarch genus *Cyclopsiella* was originally described by Drugg and Loeblichn (1967) and later emended by Head *et al*. (1989). Although *Cyclopsiella* species are often recorded in Mesozoic to Recent marine sediments, few studies deal with the palaeoecologic preferences of the genus *Cyclopsiella*. According to Matsuoka and Head (1992), the clusters or clumps are indicative of a colony-like biocoenosis, and furthermore, there is evidence for an attached or even encrusted form of life: the unornamented antapertural side, the sub-polar position of the pylome and the fact that every specimen in a clump is oriented with the apertural side face up. Smelror (personal communication, 2007) observed high abundances of solitary *Cyclopsiella* species in Jurassic deposits off Lofoten in northern Norway, and concluded that high abundances are typically recorded in prograding shoreface to intertidal environments. Acmes of *Cyclopsiella* can thus be regarded as indicative of shallow marine to nearshore high energetic environments. Furthermore, the local palynofacies is dominated by coalified plant fragments and terrestrial palynomorphs.

Cyclopsiella occurs throughout the section studied—often in clusters or clumps—but is especially abundant in the Diest Formation (Figure 6).

8.6. Gramocysta verricula

Gramocysta verricula is recorded in the highest sample analysed of the Diest Formation. This robust species is associated with coastal or restricted marine environments less favourable for other dinoflagellate cysts (Piasecki 1980; Köthe 2000; Lund and Heilmann-Clausen 2001; Strauss *et al*. 2001; Louwye *et al*. 2007).

9. DISCUSSION AND CONCLUSIONS

Although not as abundant as in the Diest Formation, *Paralecaniella indentata* is present in every sample of the Houthalen Sands Member, with two peak values of 68% and 28% in respective samples 161 and 119. This is indicative of a shallow marine environment or even—considering the peak values—a temporary stressed environment. However, there is no apparent relation between the abundance of *Paralecaniella indentata* and the distality index, that is, the relative amount of pollen versus dinoflagellate cysts does not seem to be influenced by the palaeobathymetry. The occurrence of the thermophilic species *Polysphaeridium zoharyi* in the Houthalen Sands Member confirms the assumed shallow nature of the depositional area, but is probably not indicative of an elevated salinity since the dinoflagellate assemblage points to normal salinity levels. The palaeoecological interpretation of the presence of the freshwater algae *Pediastrum* sp. in two levels of the Houthalen Sands Member is not straightforward. An analogous reasoning as above can be followed: it is unlikely that brackish conditions prevailed during these two time intervals since the dinoflagellate cyst assemblages point towards normal marine salinity levels. Thus, the short-lived pulses represent reworking of older fluvial or lacustrine deposits—possibly in combination with a relative sea-level lowering—or sporadic enhanced river discharge into the depositional area. The presence of lignite fragments at 132 m depth strengthens the first supposition.

In summary, the organic-walled palynomorph assemblage points to deposition of the Houthalen Sands Member in a shallow marine environment during late Burdigalian to Langhian times (16.5–13.6 Ma). The palynomorph assemblage does not reflect any apparent change of the palaeodepth throughout the sequence, at least at the Wijshagen locality. Deposition thus took place during the Middle Miocene Climatic Optimum and ended at the beginning of the climatic transition between 14.2 and 13.8 Ma (Zachos *et al*. 2001; Shevenell *et al*. 2004). The presence of the thermophilic species *Polysphaeridium zoharyi* and the conspicuous absence of the cool water species *Habibacysta tectata* (Head 1994, Versteegh 1994) corroborate the time frame of deposition.

According to Louwye *et al*. (2000) and Louwye (2000, 2005) the Antwerpen Sands Member holds the DN4 and DN5 Zones of de Verteuil and Norris (1996), and above a hiatus, the DN7 Zone, while the Zonderschot Sands Member, a lateral equivalent of the Antwerpen Sands Member, holds the DN4 Zone (Figures 2 and 5). The Langhian DN5 Zone has the largest geographical extent in northern Belgium, and fully marine conditions prevailed over the greater part of the Antwerp area, the Antwerp Campine area and the western part of the Campine area were flooded (Figure 1). The Houthalen Sands Member can thus be regarded as the marginal marine, lateral equivalent of the lower part of the Antwerpen Sands Member. This leads to the conclusion that during Langhian times fully marine conditions reigned during deposition of the Antwerpen Sands in the western part of the Campine area, while much shallower conditions prevailed in the eastern Campine area.

An abrupt change in the assemblage can be observed at the disconformity between the Houthalen Sands Member and the above-lying Diest Sands Member. High numbers of *Paralecaniella indentata* and *Cyclopsiella* spp. are recorded in the Diest Formation, with the latter species arising above its background levels in the Houthalen Sands Member. As described above, there are indications that *Cyclopsiella* has an encrusting mode of life in the photic zone of energetic, marine environments. This feature plus the abundance of *Paralecaniella indentata* suggests an overall shallow marine depositional environment. Furthermore, a conspicuous correlation is observed between the relative abundance of *Cyclopsiella* and the S/D ratio ($R^2 = 0.64$). Relatively, a high terrestrial input of mostly bisaccate pollen—and thus relatively lesser dinoflagellate cysts—corresponds thus with high numbers of *Cyclopsiella*. The sole record of *Gramocysta verricula* in the uppermost sample completes the image of a shallowing depositional environment, as already indicated by the afore-mentioned species. An analogous situation is observed at Olen (Figure 1) where *Cyclopsiella* spp. dominates the upper part of the Diest Formation with *Gramocysta verricula* appearing in the very top of the unit (Louwye *et al*. 2007).

According to Wouters and Vandenberghe (1994) the Diest Sands were deposited as sandbanks migrating over the erosive surface of the gully, and were influenced by coast-parallel tidal currents. This depositional environment is reminiscent of the Jurassic prograding shoreface deposits with abundant *Cyclopsiella* spp. (Smelror, personal communication, 2007), and could provide an explanation for the high numbers of *Cyclopsiella* spp. The absence of the thermophilic species *Polysphaerdium zoharyi* might be indicative of cooler conditions during late Miocene times. In summary, prolonged marginal marine conditions must have prevailed at the southern rim of the Diestian sea during Late Miocene times, in contrast to the more fully marine conditions recorded in the Antwerp Campine area and in the northern part of the Campine area during the deposition of the Diest Sands (Louwye *et al*. 1999; Louwye 2002).

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