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The Miocene–Pliocene hiatus in the southern North Sea Basin (northern Belgium) revealed by dinoflagellate cysts

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Abstract – A palynological analysis with marine palynomorphs (dinoflagellate cysts, acritarchs, green algae) and terrestrial palynomorphs (pollen and spores) of the Kasterlee and Poederlee formations provides new insights in the depositional history at the southern border of the North Sea basin (northern Belgium) around the Miocene–Pliocene transition. Dinoflagellate cyst stratigraphy constrains the age of the Kasterlee Formation in the Oud-Turnhout borehole between 7.5 and 5.32 Ma. The upper boundary of the formation can be correlated with sequence boundary Me2 at 5.73 Ma of Hardenbol and co-workers, which further constrains its age to the time interval 7.5–5.73 Ma. The palynomorph assemblages reflect a near-coast depositional environment. Where present, the Kasterlee Formation thus terminates the Miocene series in northern Belgium. The overall shallow nature of the latest Miocene deposits is related to a sea-level lowering caused by the onset of globally cooling conditions. For the first time, palynology is applied to estimate the age of the Poederlee Formation, suggesting it was deposited during the Mid-Pliocene warm period. Dinoflagellate cysts and sequence stratigraphy together constrain the age of the unit between 3.21 and 2.76 Ma, and possibly even between 3.21 and 3.15 Ma. The Poederlee Formation was deposited in neritic environments, which shoaled in the upper part of the unit as a consequence of the decreasing availability of accommodation space. We demonstrate that the magnitude of the hiatus between the Miocene and Pliocene series varies strongly at the southern boundary of the North Sea Basin, and lasts in the Antwerp area *c*. 3.2 million years and *c*. 2.52 million years in the Campine area.

Keywords: dinoflagellate cysts, palynology, Miocene, Pliocene, North Sea Basin.

1. Introduction

The understanding of the late Neogene southern North Sea Basin has advanced considerably following recent dinoflagellate cyst and sequence stratigraphic studies (Vandenberghe *et al.* 1998, 2004; Louwye, Head & De Schepper, 2004; Louwye *et al.* 2007; Louwye & Laga, 2008; De Schepper, Head & Louwye, 2009). These built further on the first Neogene chronostratigraphic framework of northern Belgium based on foraminifer research by De Meuter & Laga (1976). The recent studies made handy use of the temporary, easily accessible sections during the latest expansion phase of the Antwerp Harbour and provided new stratigraphic and palaeoenvironmental insights in the depositional history of the southern North Sea Basin during Miocene and Pliocene times. In the Campine area (Fig. 1), east of Antwerp, contemporaneous sediments were deposited in similar environments (Vandenberghe *et al.* 1998). The southern North Sea Basin was shallow at that time and hence, frequently occurring lateral facies changes render correlation based on sedimentology and geometry between units in the Campine and Antwerp areas difficult. There are also no permanent Neogene outcrops in the Campine area, making the stratigraphic studies even more complicated.

A dinoflagellate cyst study of the Kasterlee Formation at the southern edge of the North Sea Basin (Olen locality, Fig. 1a, b) revealed deposition in a near-shore environment during latest Tortonian to Messinian times (Louwye *et al.* 2007), but the character of the more northerly and possibly deeper depositional settings of this unit remained unknown. The marine Poederlee Formation occurs in the Campine area (Fig. 1a, b) and was attributed a Pliocene age based on a variably preserved mollusc content (e.g. De Meuter & Laga, 1976). A detailed age assessment and depositional history was hampered by partial decalcification of the sediments and lateral discontinuity. Nevertheless, a Piacenzian age for the Poederlee Formation and correlations with units in the Antwerp area have been proposed (Buffel *et al.* 2001; Vandenberghe *et al.* 2004).

The Kasterlee and Poederlee formations in our study site, the Oud-Turnhout borehole (Fig. 1a, b), contain well-preserved palynomorph assemblages. Comparison of the dinoflagellate cyst association from this borehole with the framework established in the Antwerp area (Louwye, Head & De Schepper, 2004; De Schepper, Head & Louwye, 2009) allows the elucidation of the current knowledge of the stratigraphy and depositional history of both formations, and enhances the current understanding of the southern North Sea Basin evolution. In this study, we intend to characterize the deeper depositional setting of the

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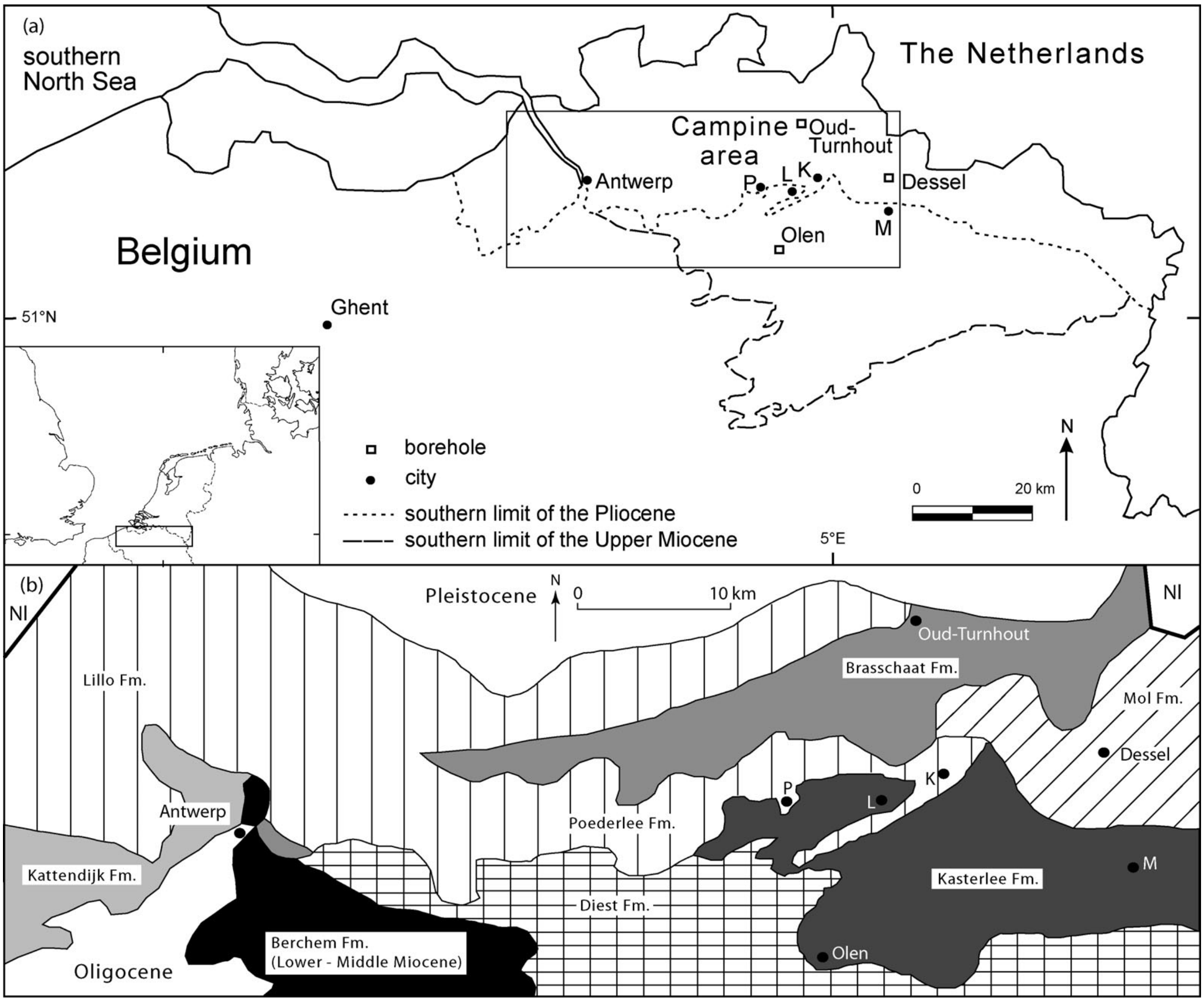


Figure 1. (a) Map of northern Belgium and southern Netherlands, and location of the study area. Inset: southern North Sea Basin. Rectangle indicates limit of (b). (b) Geological map of the study area. Explanation of abbreviations of locality names: P – Poederlee, L – Lichtaart, K – Kasterlee, M – Mol, Nl – The Netherlands. Geographic areas are printed in italics.

Miocene Kasterlee Formation; evaluate the stratigraphic position of the Poederlee Formation, estimate its age, and test and refine correlations with units in the Antwerp area; and finally, assess the magnitude of the hiatus between the Miocene and Pliocene deposits in the Campine area and the Antwerp area.

2. Geology of the Campine area

The geographic distribution of the Kasterlee Formation is limited to the Campine area (Fig. 1b). The formation is a micaceous, fine-grained sandy unit without macrofossils, slightly glauconitic and with intercalations of micaceous clay (De Meuter & Laga, 1976). The lower boundary with the Diest Formation is often inconspicuous, but a discrete basal gravel has been observed in a few localities. Louwye *et al.* (2007) proposed deposition at some time between 7.5 and 5.32 Ma (latest Tortonian to Messinian). Their palynological and geophysical study of the formation in the Dessel-2 borehole and the Olen outcrop (Fig. 1a, b) further revealed deposition in a shallow marine environment, characterized by a distinct shoaling phase in the upper part of the sequence (Louwye *et al.* 2007). It must be noted that the Olen outcrop is located near the southern boundary of Upper Miocene deposits in northern Belgium (Fig. 1a, b), and that deeper, neritic environments must have prevailed to the north. The present study area, Oud-Turnhout, is located approximately 20 km to the north of the Olen outcrop.

In parts of the Campine area, the shallow marine depositional setting of the Kasterlee Formation succeeded the distinctly transgressive, and fully marine environment of the underlying Upper Miocene Diest Formation (Louwye *et al.* 2007) (Fig. 2). The Diest Formation is a diachronous sequence genetically related to the eustatic sea-level rise following the sea-level low around the Middle–Upper Miocene boundary. Deposition started during early Tortonian times in the Campine area, and the centre of maximum deposition later shifted to the region north of Antwerp (Fig. 1) during late Tortonian to Messinian times (Louwye, De Coninck & Verniers, 1999). This shift is expressed by distinctive prograding of the sequence to the northwest. The Deurne Sands are a local and marginal marine facies of the Diest Formation in the vicinity of the city of Antwerp, and are covered by the Lower Pliocene Kattendijk Formation. The age of the

		Antwerp area	Campine area
Pliocene	Upper	Lillo Fm.	Brasschaat Fm. Poederlee Fm. Mol Fm.
	Lower	Kattendijk Fm.	
Miocene	Upper	Diest Fm.	Kasterlee Fm. Diest Fm.
	Lower - Middle	Berchem Fm.	Berchem Fm. Bolderberg Fm.

Figure 2. Stratigraphic framework of the Neogene deposits in northern Belgium (after Louwye *et al.* 2007).

Diest Formation was already established from several locations in northern Belgium by Louwye (2002), Louwye, De Coninck & Verniers (1999) and Louwye *et al.* (2007): Tortonian in the greater part of the Campine area, early to middle Tortonian in the vicinity of the city of Antwerp (Deurne Sands), and Tortonian–Messinian north of Antwerp near the border with The Netherlands.

The geographic distribution of the Poederlee Formation is restricted to the centre of the Campine area (Fig. 1b). De Meuter & Laga (1976) formally defined the Poederlee Formation as 'fine, slightly glauconitic sand with small lenses of clay in the lower part; a base gravel of rounded quartz and flint, silicified limestones (the Hukkelberg gravel); a much oxidized upper part in the type region, sometimes containing limonitic sandstones with moulds of shells'. These authors designated the iron sandstone layers on top of the hills north of the village of Poederlee as the type section, and the village of Poederlee in the southern part of the Campine area as the type locality (Fig. 1a, b). The formation has a maximum thickness of about 10 m (Schiltz, Vandenberghe & Gullentops, 1993). De Meuter & Laga (1976) broadly correlated the formation with the entire Lillo Formation from the Antwerp area (Figs 2, 3). The Poederlee Formation rests unconformably on the Kasterlee Formation throughout the study area (Buffel *et al.* 2001; Louwye *et al.* 2007) and is covered to the north by the Brasschaat Formation (Figs 1, 2), which was deposited in an estuarine environment. The absence of calcareous macrofossils, microfossils and organic-walled palynomorphs in the latter unit hampers its stratigraphic assessment.

Buffel *et al.* (2001) regarded the Poederlee Formation as a transitional facies between the fully marine Lillo Formation in the west (the Antwerp area) and the continental/estuarine Mol Formation to the east (Fig. 1b). Based on geometrical arguments and palaeontological evidence, including molluscs, these authors correlated the Poederlee Formation with parts of the shallow marine Lillo Formation (Oorderen Sands, Kruisschans Sands and lower part of Merksem Sands) from the Antwerp area (Fig. 3). They also correlated the Brasschaat Formation with the upper part of the Merksem Sands and Zandvliet Sands of the Lillo Formation in the Antwerp area. Buffel *et al.* (2001) proposed a Piacenzian age for the Poederlee Formation and a late Piacenzian age for the Brasschaat Formation, a viewpoint followed by Vandenberghe *et al.* (2004).

3. Historical background

According to Mourlon (1882), A. Dumont was the first to describe the sandy deposits in the hills around Poederlee around 1850, and the latter assumed a correlation with the Upper Miocene Diest Formation based on the ferruginous character of the deposits. Cogels & Van Ertborn (1881) were the first to coin the term 'La roche de Poederlé' after a mapping campaign. A detailed overview of the literature regarding the stratigraphy of the Poederlee Formation until 1935 was presented by Gullentops & Huyghebaert (1999).

It was only after 1950 that new insights into Neogene stratigraphy of Belgium arose, based on observations made during large excavation works for the Antwerp harbour (de Heinzelin, 1955). De Heinzelin grouped both the Diest Formation and the superjacent Kasterlee Formation in the Upper Miocene 'Diestien' stage, whereas the Kattendijk Formation, the Luchtbal and Oorderen Sands (as the Kallo Sands) were placed in the Pliocene 'Scaldisien' stage. Furthermore, a new Pleistocene stage, the 'Merksemien', was then established and consisted of the Kruisschans Sands and Merksem Sands. Based on the faunal similarity between the Merksem Sands and the Poederlee Formation (Fig. 3), de Heinzelin (1955) considered the Poederlee Formation as Lower Pleistocene, hence

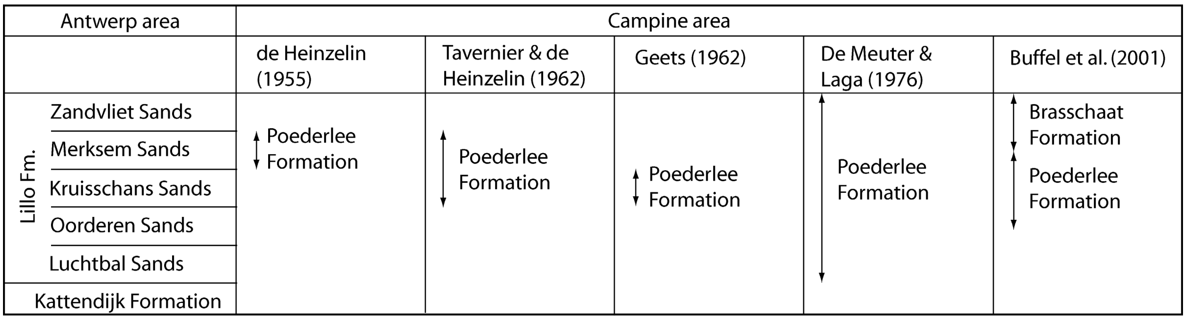


Figure 3. Previous correlations of the Poederlee Formation with members of the Lillo Formation in the Antwerp area.

excluding the presence of Pliocene deposits in the Campine area.

A heterogeneous gravel layer at the base of the Poederlee Formation was observed in the Campine area (Gulinck, 1960), and was named the Hukkelberg gravel after its locality. Geets (1962) studied mollusc moulds from the limonitic sandstone layer in the upper part of the Poederlee Formation, and suggested a correlation with the Kruisschans Sands of the 'Merksemien' stage (the present-day Lillo Formation) as defined by de Heinzelin (1955). Although the fossil content (mainly bivalves) is strongly weathered and limonitized, Tavernier & de Heinzelin (1962) identified *Cardium parkinsoni*, *Corbulomya complanata* and *Mya arenaria*, which allowed correlation with the Kruisschans Sands and Merksem Sands ('Merksemian' stage) (Fig. 3). These authors considered the Poederlee Formation as a transgressive unit of Pleistocene age in the entire the Campine area, with the Hukkelberg gravel at its base. Gulinck (1962) followed these ideas and also considered the Poederlee Formation as a lateral equivalent of the 'Merksemian' stage. Vandenberghe *et al.* (1998) agreed with Tavernier & de Heinzelin (1962) that the Poederlee Formation is the lateral equivalent of the Merksem Sands, although they suggested that sedimentological similarities rather point at an equivalence with the lower part of the Lillo Formation. They attributed a Piacenzian age to the Poederlee Formation.

Buffel *et al.* (2001) studied the Kasterlee and Poederlee formations north of the type locality in four boreholes, and one borehole, located at Oud-Turnhout, is studied herein (Fig. 1a, b). The Kasterlee Formation consists lithologically of glauconitic sands that are fining upward in the unit. The uppermost part of the formation is a zone of poorly cemented, ferruginous sandstone fragments with internal moulds of dissolved molluscs. A basal gravel of small quartz pebbles (the Hukkelberg gravel) separates the overlying Poederlee Formation from the Kasterlee Formation. The lithology of the Poederlee Formation consists of fine-grained glauconitic sands with dispersed shell debris layers. The well-sorted, fine-grained sands in the upper two metres of the Poederlee Formation are called the Heieinde facies or unit (Fig. 4). Molluscs indicate that the Poederlee Formation north of the type locality is a lateral equivalent of the Oorderen Sands Member of the Lillo Formation (Fig. 3). Also, reworked shells from the Luchtbal Sands Member occur in the Poederlee Formation, suggesting that the Luchtbal Sands were deposited in the greater part of northern Belgium, but eroded before the deposition of the Poederlee Formation in the Campine area. Based on a re-evaluation of the mollusc fauna, Buffel *et al.* (2001) refuted the biostratigraphic correlation of the iron sandstone layer at the top of the Poederlee Formation with the Kruisschans Sands proposed by Geets (1962). Buffel *et al.* (2001) rather proposed a correlation of this layer with the base of the Merksem Sands of the Lillo Formation. In summary, they correlated the Poederlee Formation with the Oorderen Sands to Merksem Sands interval in the Antwerp area. Vandenberghe *et al.* (2004) considered the Poederlee Formation equivalent to large parts of the Oorderen Sands, Kruisschans Sands and Merksem Sands, and correlated the lower boundary with sequence boundary Za2 at 4.04 Ma (Hardenbol *et al.* 1998). An exhaustive overview of the stratigraphy of the Kasterlee Formation is given in Louwye *et al.* (2007).

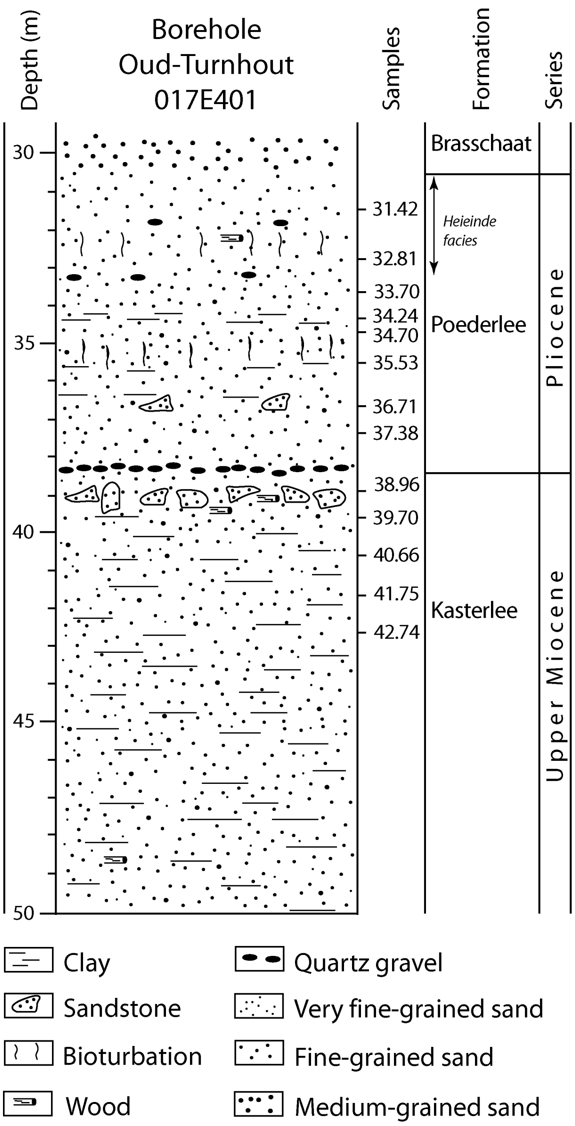


Figure 4. Lithological column and stratigraphic assignment of the units in the studied interval of the Oud-Turnhout borehole. The depths of the samples are referred to the Belgian Ordnance Datum (Tweede Algemene Waterpassing).

4. The study site

The studied borehole Oud-Turnhout (Lambert coordinates X: 192210, Y: 218431; Fig. 1a, b) was drilled in 1998 in the framework of a geological mapping project in Flanders. The borehole was entirely cored to a depth of 50 m (Fig. 4), and is now stored at the Belgian Geological Survey (archive number 017E/0399). It is located in the Campine area, north of the outcrop area of the Poederlee Formation. The lowest lithological unit (50.00 m to 38.71 m) corresponds with the Kasterlee Formation (De Meuter & Laga, 1976). It is characterized by a dominant grain size of 125–250 μm, a mica and glauconite fraction, dispersed sand concretions, and varying clay content. Loosely compacted, glauconitic sandstone fragments with internal moulds of shells occur in the top of the sequence, together with fossil wood fragments. The base of this unit was not reached in this borehole.

At the base of the overlying Poederlee Formation (38.71–30.50 m), a layer of small, discoid-shaped quartz pebbles separates this unit from the Kasterlee Formation (Fig. 4). Between 38.71 and 33.30 m, the lithology consists of fine-grained sand with an admixture of coarse glauconite grains and mica. Clayey intercalations and bioturbations are present. Between 33.30 and 30.50 m, well-sorted, fine-grained sand with dispersed pebbles, some wood fragments, and traces of bioturbation are the Heieinde facies of this formation (Buffel *et al.* 2001). An abrupt change to the glauconitic, medium-grained sand of the Brasschaat Formation occurs above the Heieinde facies at 30.50 m. A total of 19.50 m of cored sediments from the Kasterlee and Poederlee formations are thus recovered between 50.00 and 30.50 m depth.

5. Materials and methods

A total of thirteen samples were analysed from the Kasterlee and Poederlee formations (Figs 4, 5) for dinoflagellate cysts and other organic-walled palynomorphs. Test samples from the Brasschaat Formation proved to be barren. The samples were prepared following the palynological maceration technique described in Louwye, Head & De Schepper (2004), involving removal of carbonates and silicates with HCl and HF, respectively. Residues were filtered on a 20 μm nylon screen, ultrasonicated for 30 seconds, and strew mounted with glycerine jelly. All palynomorphs were analysed on a ZEISS Axioskop light microscope at 200× and 400× magnifications until a minimum of 200 dinoflagellate cysts were counted. This number was sufficient for reliable relative abundance estimates, and counting 300 specimens did not yield significant changes in relative abundances. The remainder of the slide was then scanned for rare species and well-preserved specimens for photomicroscopy. The presence and numbers of acritarchs, green algae, pollen, spores, invertebrate remains and other *incertae sedis* were noted during the systematic count of the dinoflagellate cysts. Two *Lycopodium* tablets (batch 483216, for one tablet X = 18 583; standard deviation: 1708; coefficient of variation: 9.19 %) were added for the concentration calculation of *in situ* palynomorphs following the formula of Stockmarr (1971). Photomicrographs were taken with a ZEISS MRc5 digital camera mounted on a ZEISS Axio Imager microscope. Photomicrographs of selected stratigraphic key species are given in Figures 6 and 7. Nomenclature follows De Schepper, Head & Louwye (2004), Fensome & Williams (2004), De Schepper & Head (2008*a*) and Louwye, Mertens & Vercauteren (2008). Timescale is after Lourens *et al.* (2005) and the stratigraphic subdivision of the Pliocene follows Gibbard *et al.* (2010). All slides are housed in the collection of the Research Unit Palaeontology of Ghent University.

6. Palynological analysis: results

In most samples, pollen grains are much more abundant than dinoflagellate cysts (Fig. 5). Only samples 37.38 m and 35.53 m yield more dinoflagellate cysts than pollen grains. Unfortunately, terrestrial palynomorphs are of limited biostratigraphic value in this study because of the selective loss of small specimens after sieving on a 20 μm mesh. The preservation of the marine palynomorphs is good to excellent. The presence of well-preserved protoperidinioid dinoflagellate cysts indicates that little or no post-depositional oxidation took place.

A total of 74 dinoflagellate cyst, eleven acritarch and five chlorophycean algae taxa are recorded in the Kasterlee and Poederlee formations together (Fig. 5). The assemblages in both formations are dominated by gonyaulacacean species. Highest numbers of protoperidiniacean cysts are recorded in the Kasterlee Formation (sample 41.75 m). Reworked pre-Neogene dinoflagellate cysts, pollen, spores and acritarchs are present in every sample (Fig. 5), but their numbers are relatively unimportant except in samples 34.70 m and 34.24 m, where respectively 1082 and 1443 reworked dinoflagellate cysts per gram are recorded.

A total of 47 dinoflagellate cyst taxa are recorded in the Kasterlee Formation. Undetermined specimens of the genera *Spiniferites* and *Achomosphaera* are grouped as *Spiniferites*/*Achomosphaera* spp. This group constitutes at least ∼ 50 % of the assemblage in every sample, with the highest abundance of almost 65 % in sample 40.66 m. *Lingulodinium machaerophorum* and *Operculodinium centrocarpum s.s.* are other species with high relative abundances. *Operculodinium tegillatum* is well represented in the lowest sample (42.74 m).

Fifty-three dinoflagellate cyst taxa are recorded in the Poederlee Formation. The *Spiniferites*/*Achomosphaera* spp. group is abundant to dominant in every sample. Other common species are *Achomosphaera andalousiensis suttonensis*, *Operculodinium centrocarpum sensu* Wall & Dale (1966) and *Spiniferites coniconcavus*. The taxa *Barssidinium pliocenicum*, *Bitectatodinium raedwaldii*, *Operculodinium centrocarpum s.s.*, *Operculodinium*? *eirikianum eirikianum* and *Operculodinium israelianum* have high relative abundances at the base of the unit.

Heteraulacacysta sp. A of Costa & Downie (1979) is recorded in almost every sample, and is very abundant

Lithostratigraphical unit	Kasterlee Formation					Poederlee Formation							
Sample depth (m)	42.74	41.75	40.66	39.70	38.96	37.38	36.71	35.53	34.70	34.24	33.70	32.81	31.42
Dinoflagellate cysts													
Achomosphaera andalousiensis andalousiensis	7	1	2	2	4			2		2			
Achomosphaera andalousiensis suttonensis						3	9	4	11	2	11	2	
Amiculosphaera umbraculum	+	+		1		+							1
Ataxiodinium choane							1	1					
cf. *Ataxiodinium confusum*								+					
Ataxiodinium zevenboomii		+	+	+				+					
Barssidinium graminosum					1								
Barssidinium pliocenicum	13	31	9	3	2	16	11	3	1		1	1	
cf. *Barssidinium pliocenicum*									2				
Barssidinium taxandrianum					+								
Batiacasphaera micropapillata	2		2	1	1								
Batiacasphaera minuta				+									
Bitectatodinium raedwaldii	9	8	1	1	2	22	12	1	1		2	1	
Bitectatodinium? *serratum*			1	+	+								
Capisocysta sp.								+					
Cerebrocysta poulsenii		+		+									
Corrudinium? *labradori*	1	+		3									
Cyst of calcareous dinoflagellate				1									
Cyst of *Polykrikos kofoidii* /*schwartzii*				+									
Dapsillidinium pseudocolligerum						1	+	+		1			
Desotodinium wrennii						+	+	+					
Dinoflagellate cyst sp. A													1
Dinoflagellate cyst spp. indet.							5	4	3	4	5	1	7
Echinidinium euaxum				+	+								
Gramocysta verricula		+	+	+									
Heteraulacacysta sp. A of Costa & Downie (1979)		1	2	10	50	8	4	41	7	87	8	10	48
Hystrichokolpoma rigaudiae			1		5			+					
Impagidinium patulum			1										
Impagidinium solidum								+					
Impagidinium sp. indet.						+							
Invertocysta lacrymosa	9	+	2	3	+	5	4	7	+	1	3	1	1
Invertocysta tabulata		5											
Lejeuneunecysta sp. indet.			+	1	+		1			1		1	
Lingulodinium machaerophorum	17	9	7	15	58	+		35	1			1	
Melitasphaeridinium choanophorum	3	1	+	6	1			+				+	
Nematosphaeropsis labyrinthus					1			+				+	
Operculodinium centrocarpum s. Wall & Dale (1966)	1	1		11	5	19	22	26	17	15	28	19	18
Operculodinium centrocarpum s.s.	7	20	17	24	9	13	1				2	+	1
Operculodinium? *eirikianum eirikianum*	7	8	12	7	2	6	5	5					
Operculodinium israelianum						14	9	8					
Operculodinium tegillatum	26	9	6	5	+								
Operculodinium longispinigerum	1	+											
Operculodinium sp. indet.											2		
Cyst of *Pentapharsodinium dalei*			1	1		1	+						
Pyxidinopsis braboi							1	+	3	13	6	2	
Quinquecuspis concreta	+												
Round brown cysts	9	14	8	16	3		13	6	3				1
RBC Type 1 of De Schepper, Head & Louwye (2009)							2	1					
Thick-walled round brown cysts								1					
Reticulatosphaera actinocoronota	6	5	7	1	1			+					1
Rottnestia amphicavata									1				
Scaldecysta doelensis										1		+	+
Scaldecysta sp. of Louwye, Head & De Schepper (2004)	+												
Scaldecysta sp. indet.				+									
Selenopemphix armageddonensis	2	1			1								
Selenopemphix brevispinosa	3	8	6	2	+	2	4	2	9	1	2	1	4

Figure 5. Raw counts of marine and terrestrial palynomorphs in the Oud-Turnhout borehole. A '+' indicates that a species was recorded outside the systematic count. For the Shannon-Wiener diversity index (Krebs, 1998) only the taxa encountered within the count were used.

at the top of the Kasterlee Formation (sample 38.96 m) and in sample 34.24 m of the Poederlee Formation. This species is a common element of Miocene (Louwye *et al.* 2007) and Pliocene assemblages (Head, 1993; Louwye, Head & De Schepper, 2004; De Schepper, Head & Louwye, 2009).

Lithostratigraphical unit	Kasterlee Formation					Poederlee Formation							
Sample depth (m)	42.74	41.75	40.66	39.70	38.96	37.38	36.71	35.53	34.70	34.24	33.70	32.81	31.42
Selenopemphix dionaeacysta	2	+		3		+	5						
Selenopemphix quanta	2	+	1	4	2	+	3				+	7	1
Selenopemphix nephroides	1	+		+		+		1			+		
Selenopemphix sp. indet.						+		1					
Spiniferites coniconcavus						1	1	1	15	4	40	18	3
Spiniferites falcipedius						17	22	7	2	4	2	4	2
Spiniferites membranaceus						1	1		+				+
Spiniferites mirabilis							2	1		2	+		1
Spiniferites pachydermus ?						18	23	18					
Spiniferites rubinus						+		+					
Spiniferites/ Achomosphaera Group	124	121	156	144	137	92	84	119	110	61	82	122	101
Spiniferites sp. A						8	1	5					
Tectatodinium pellitum	1	+	+	5	+	2	+	+	4	+	3	9	10
Trinovantedinium ferugnomatum	4	2	1	2									
Trinovantedinium glorianum			+		1		3						
Trinovantedinium henrietii				+									
Trinovantedinium variabile						1			+				
Trinovantedinium sp. indet.				+			1		10	1	3		
Tubercoludinium vancampoae	1					+	+						
Total in-situ dinoflagellate cysts	258	245	243	272	286	250	250	300	200	200	200	200	201
Marine algae incertae sedis													
Algal cyst type 1 of Head (1996)						1?	+	1			1		
Algae incertae sedis	1												
Acritarch sp. A						1	3						
Cyclopsiella ? *trematophora*	3	3	+	1		+	1		27	6	20	24	13
Cyclopsiella elliptica	7	4		2	+	+			7	+	12		
Lavradosphaera lucifer							+						
Lavradosphaera sp. indet.								+					
Nannobarbophora gedlii				1									
Nannobarbophora walldalei					+		3	2					
Paralecaniella indentata		+	+	+	+								
Quadrina condita			+	1									
Small acritarch spp. indet.							2						2
Green algae													
Tasmanites	1	+	2	+						1			
Pediastrum sp. indet.		1									+	1	6
Debarya glyptosperma											+		
Gelasinicysta vangeelii												1	
Prasinophyte algae									1	1		1	
Total reworked dinoflagellate cysts	4	12	3	4	1	3		8	84	28	22	31	39
Terrestrial palynomorphs													
Bisaccate pollen	994	1219	988	598	603	198	380	238	654	393	969	1124	1003
Trilete spore	8	4						3	5	2	7	8	9
Pollen sp. indet.	20	12	24	13	12	7	13	5	10	11	32	21	17
Sample data													
Dry weight (g)	60	60	60	61	60	60	60	61	62	60	60	60	60
Quantity of *Lycopodium clavatum* tablets	2	2	2	2	2	2	2	2	2	2	2	2	2
Quantity of *Lycopodium clavatum* spores counted	17	15	20	21	14	0	9	4	24	6	22	50	34
Estimated in-situ dinoflagellate cysts/g	4663	5039	3736	3959	6314	-	8563	22833	2500	10305	2803	1237	1829
Error on concentration	25	27	24	23	28	-	34	51	22	42	23	16	19
Estimated terrestrial palynomorphs/g	18472	25403	15558	8893	13578	-	13461	18723	8362	20919	14127	7130	9366
Estimated in-situ marine palynomorphs/g	4880	5182	3764	4053	6277	-	8842	23275	3009	10652	3254	1395	2006
Reworked dinocyst concentration (cysts/g)	72	247	46	58	22	-	0	609	1050	1443	308	192	355
Dinocyst:bisaccate pollen ratio [nD/(nD+nP)]	0.20	0.17	0.19	0.31	0.32	0.55	0.39	0.55	0.23	0.33	0.17	0.15	0.16
Shannon-Wiener	2.09	1.87	1.56	1.97	1.62	2.27	2.48	2.14	1.76	1.63	1.89	1.50	1.57

Figure 5. continued.

Cyclopsiella? *trematophora* (Fig. 7l) is the most common acritarch. *Impagidinium solidum* (sample 35.53 m; Fig. 7e, f) and the acritarch *Lavradosphaera lucifer* (sample 36.71 m; Fig. 7m–o) were recorded for the first time in the North Sea Basin.

Operculodinium tegillatum was defined by Head (1997) from the mid-Pliocene of eastern England. According to De Schepper & Head (2008*b*), the lowest occurrence of this species was recorded from DSDP Hole 603C in the western North Atlantic and is located

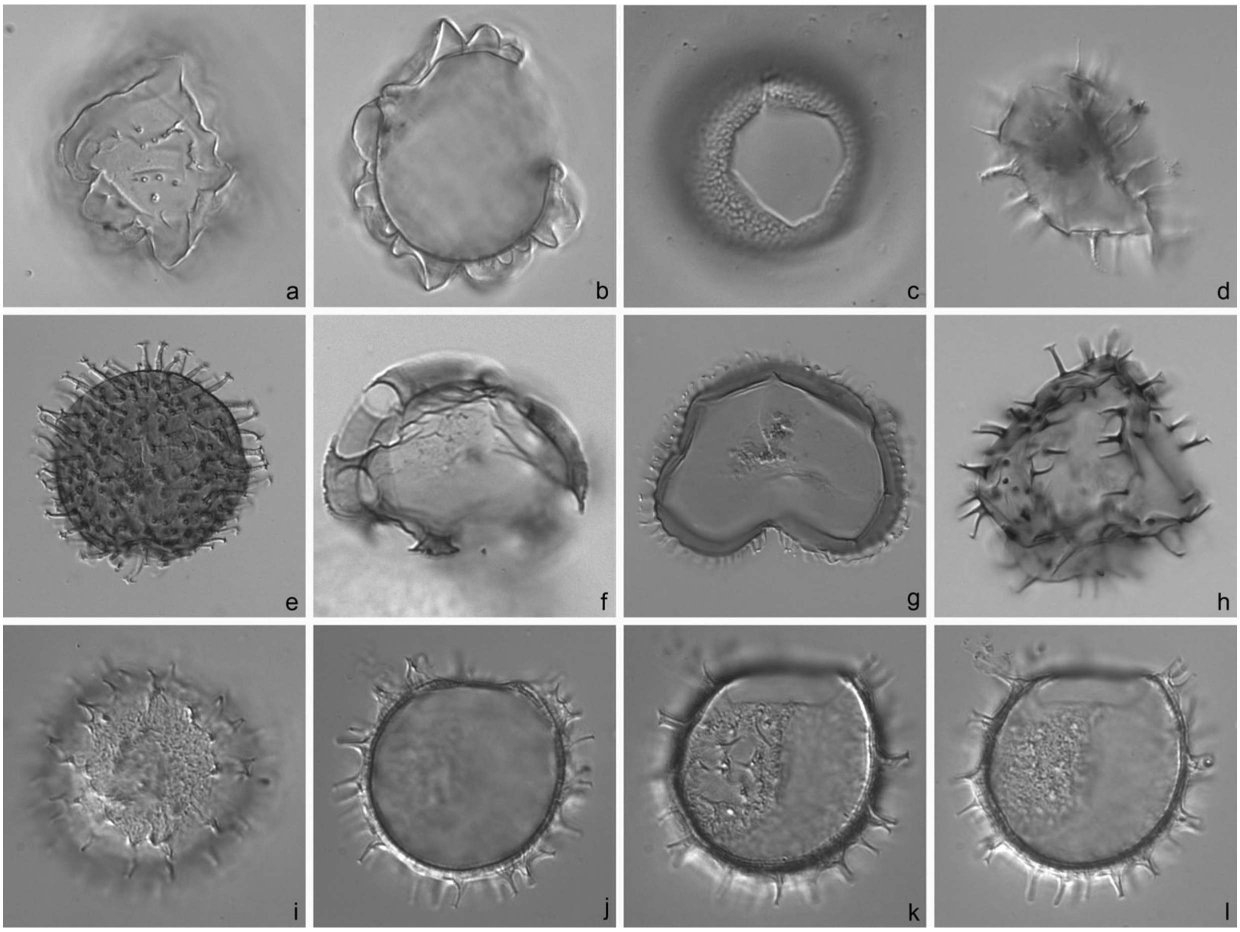


Figure 6. All photomicrographs taken in bright field. Sample number, slide number and England Finder reference are given. All specimens are from the Kasterlee Formation. (a, b) *Ataxiodinium zevenboomii* Head. High focus on left lateral surface (a) and optical section (b). Sample 39.70 m, p2, T35/3. Maximum length central body, 33 µm. (c) *Batiacasphaera minuta* (Matsuoka) Matsuoka & Head. Apical view on apical archaeopyle. Sample 39.70 m, p2, M24/4. Maximum diameter archaeopyle, 15 µm. (d) *Nannobarbophora walldalei* Head. High focus and orientation uncertain. Sample 38.96 m, p1, R19/2. Length processes approximately, 7 µm. (e) *Barssidinium pliocenicum* (Head) Head. Dorsal view on dorsal surface. Sample 40.66 m, p1, E24/1. Maximum diameter central body, 73 µm. (f) *Selenopemphix armageddonensis* de Verteuil & Norris. Dorsal view on dorsal surface. Sample 41.75, p1, V23/1. Maximum diameter central body excluding processes, 33 µm. (g) *Selenopemphix brevispinosa brevispinosa* (autonym). Dorsal view on dorsal surface. Sample 40.66 m, p1, C37/1. Maximum diameter excluding processes, 47 µm. (h) *Trinovantedinium ferugnomatum* de Verteuil & Norris. High focus on processes. Sample 42.74 m, p1, G32/3. Maximum diameter excluding processes, 38 µm; maximum length processes, 6 µm. (i–l) *Operculodinium tegillatum* Head. Antapical view of antapex (i), optical section (j), upper archaeopyle margin (k) and apex (l). Sample 38.96 m, p1, G21/1. Maximum diameter central body, 35 µm.

at 5.02 Ma (based on unpub. data of M. J. Head). The morphologically similar *Operculodinium*? *pontis* was described for the first time by Zevenboom & Santarelli *in* Zevenboom (D. Zevenboom, unpub. Ph.D. thesis, Univ. Utrecht, 1995) from the Upper Miocene and Pliocene of the Boxmeer well in the Netherlands. Louwye & Laga (1998) identified *Operculodinum*? *pontis* in the Upper Miocene Diest Formation and the Pliocene Kattendijk and Lillo formations in the Kalmthout well of northern Belgium. Louwye (1999) formally defined *Operculodinium antwerpensis* from the Upper Miocene Diest Formation, and considered *Operculodinium*? *pontis* Zevenboom & Santarelli *in* Zevenboom (D. Zevenboom, unpub. Ph.D. thesis, Univ. Utrecht, 1995) as a manuscript name and synonymous. Louwye (1999) regarded the continuous periphragm and the proximally to medially joined processes a sufficient argument to differentiate *Operculodinium antwerpensis* from *Operculodinium tegillatum*. However, new observations from the Kasterlee Formation showed both morphological criteria to be insufficient for discriminating between both species. The degree of perforation of the tegillum, and the degree of connection between processes, medially or proximally, is a variable feature within this taxon (Fig. 6i–l). Based on these observations, *Operculodinium antwerpensis* Louwye (1999) is here considered as a junior synomym of *Operculodinium tegillatum* Head (1997).

7. Biostratigraphy

7.a. Kasterlee Formation

The dinoflagellate cyst assemblage recorded from the Kasterlee Formation in the Oud-Turnhout borehole compares well to other records from the same

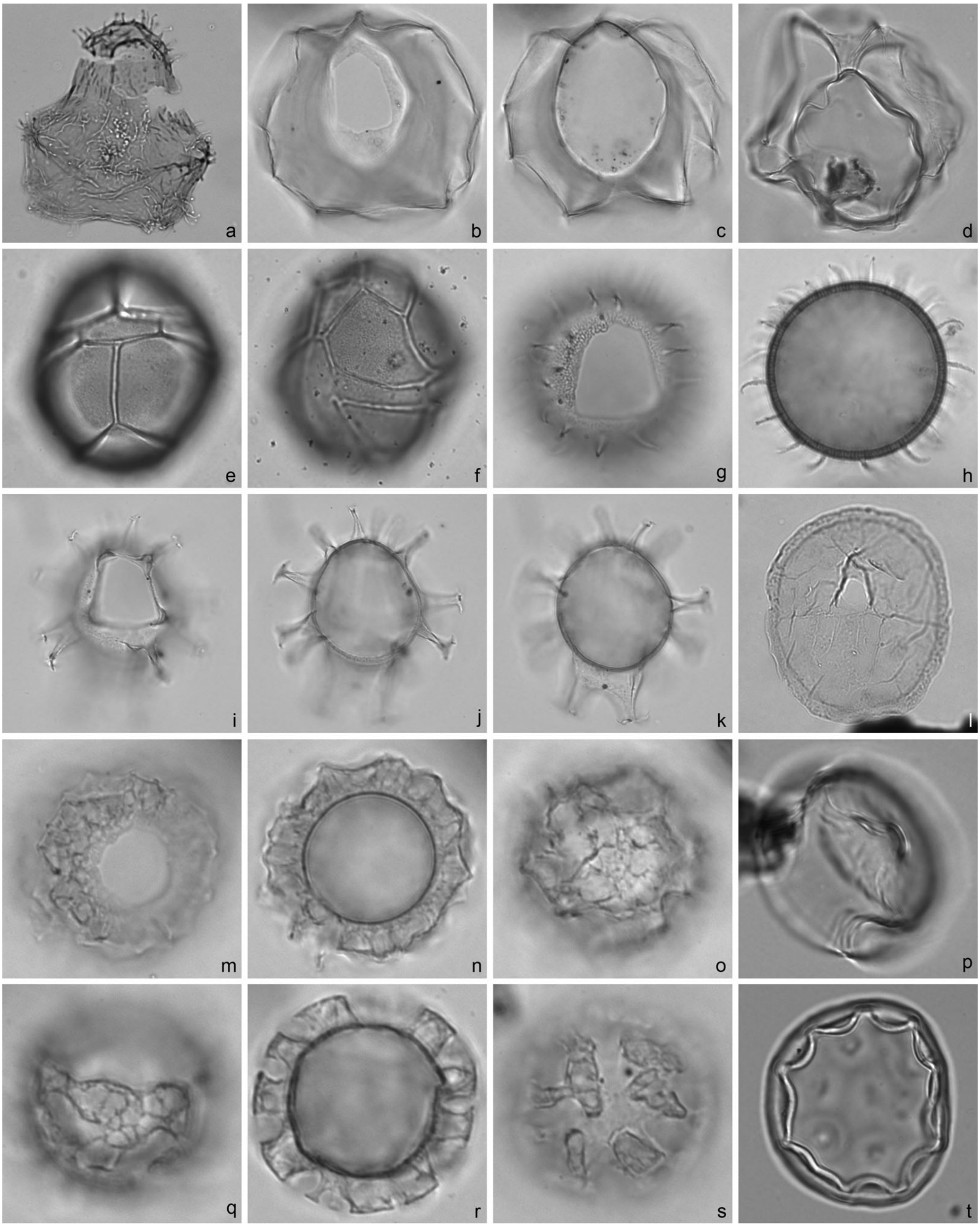


Figure 7. All photomicrographs taken in bright field. Sample number, slide number and England Finder reference are given. All specimens are from the Poederlee Formation. (a) Dinoflagellate cyst sp. A. Composite picture of various foci. Sample 31.42 m, p1, G25/0. Maximum length central body, 70 µm; maximum width central body, 64 µm. (b, c) *Invertocysta lacrymosa* Edwards. Dorsal view of (b) upper focus on dorsal surface with large archaeopyle and (c) mid-focus. Sample 36.71 m, p1, H57/3. Maximum length central body, 39 µm; maximum width central body, 29 µm. (d) *Amiculosphaera umbraculum* Harland. Ventral view on mid-focus; note funnel-shaped structure connecting apical area of periblast with endoblast. Sample 37.38 m, p1, V48/0. Maximum length central body: 36 µm; maximum width central body, 28 µm; maximum length, 50 µm; maximum width, 50 µm. (e, f) *Impagidinium solidum* Versteegh & Zevenboom in Versteegh. Oblique ventral view of (e) dorsal surface showing archaeopyle, cingulum, postcingular and antapical plates and (f) ventral surface, apical plates and cingulum. Note that cyst wall is brown coloured. Sample 35.53 m, p1, R42/1. Maximum length, 44.5 µm; maximum width, 37 µm, wall thickness, 1.2–1.5 µm. (g, h) *Operculodinium*? *eirikianum eirikianum* (autonym). Dorsal view of (g) dorsal surface with large archaeopyle, and (h) mid-focus. Sample 36.71 m, p1, R32/0. Maximum diameter cyst excluding processes, 35 µm; maximum process length, 5.8 µm; wall thickness, 1.3–1.5 µm. (i–k) *Spiniferites* sp. A.

formation in shallower environments identified in the Dessel-2 borehole and Olen outcrop (Louwye *et al.* 2007), although the relative abundance of certain species (e.g. *Gramocysta verricula*) is lower. Only four dinoflagellate cyst species encountered in the Kasterlee Formation have a biostratigraphic value and allow correlations to the timescale of Lourens *et al.* (2005).

Trinovantedinium ferugnomatum is recorded in low abundance in the Kasterlee Formation (Figs 5, 6h). *Trinovantedinium ferugnomatum* was recorded for the first time by de Verteuil & Norris (1992) in the Middle and Upper Miocene from the Maryland and Virginia Coastal Plain. The highest occurrence (HO) is placed in the dinoflagellate cyst zone DN10 of late Tortonian to Messinian age (de Verteuil & Norris, 1996) (Fig. 8). This species has also been recorded from Middle and Upper Miocene deposits of the southern North Sea Basin (Louwye, 2002; Louwye *et al.* 2007; Louwye & Laga, 2008) and the Porcupine basin (Louwye *et al.* 2008). Records from the Mogarts Beach Member of the Yorktown Formation (Upper Pliocene) by de Verteuil & Norris (1992) and the Lower Pliocene Kattendijk Formation of northern Belgium (Louwye, Head & De Schepper, 2004; De Schepper, Head & Louwye, 2009) probably represent reworking.

Selenopemphix armageddonensis is present in low abundances in three samples of the Kasterlee Formation (Figs 5, 6f). It was previously recorded in the latest Tortonian to Messinian Kasterlee Formation by Louwye *et al.* (2007). The latter authors give an extensive overview of published Miocene records of this species, and assume no *in situ* Pliocene records. According to Williams *et al.* (2004), *Selenopemphix armageddonensis* has a lowest occurrence at 9.0 Ma in equatorial areas and at 7.45 Ma in the northern hemisphere mid-latitudes. Based on data from Zevenboom (D. Zevenboom, unpub. Ph. D. thesis, Univ. Utrecht, 1995) from the Mediterranean realm, Williams *et al.* (2004) place the HO of this species at the Miocene–Pliocene boundary (5.32 Ma) in equatorial areas. Warny & Wrenn (2002) recorded *Selenopemphix armageddonensis* in the Messinian of Morocco and southern Spain, and place the HO also at the Miocene–Pliocene boundary (Fig. 8). Single records of *Selenopemphix armageddonensis* are reported in Pliocene deposits from the southern North Sea Basin (Louwye, Head & De Schepper, 2004), from the Utsira Formation in the northern Viking Graben (Piasecki, Gregersen & Johannessen, 2002) and from the Yorktown Formation in Virginia, USA (Edwards *et al.* 2005). The latter records thus most probably represent reworking, since *Selenopemphix armageddonensis* is not reported from other Lower Pliocene assemblages.

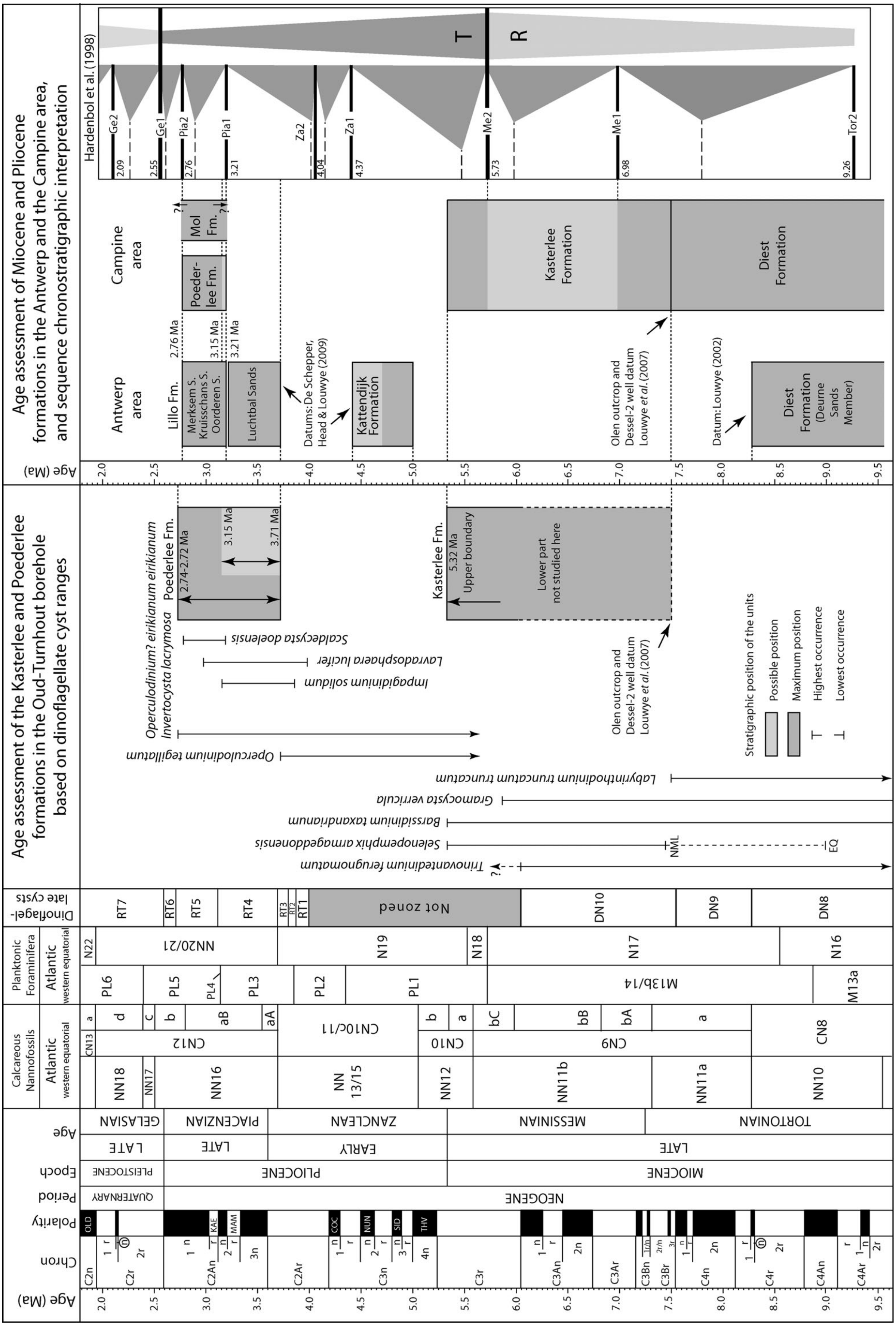
Barssidinium taxandrianum is a rare species, recorded only from the southern North Sea Basin in Upper Miocene deposits. It was recorded for the first time in the Tortonian Diest Formation from northern Belgium by Louwye (1999), and later also by Louwye *et al.* (2007) and Louwye & Laga (2008). Other records are from the early to middle Tortonian Deurne Sands Member (lower part of the Diest Formation) (Louwye, 2002), and the late Tortonian to Messinian Kasterlee Formation (Louwye *et al.* 2007). No Pliocene records are known.

A detailed overview of the stratigraphic occurrences and ranges of *Gramocysta verricula* is given by Louwye *et al.* (2007). Geographically, the species is apparently restricted to the North Sea Basin, the western North Atlantic realm and the eastern Mediterranean, and has a published HO at the base of Chron C3r (middle Messinian) in the Miocene of Morocco (Warny & Wrenn, 2002) (Fig. 8). No *in situ* Pliocene records are known. The morphology of *Gramocysta verricula* from the Kasterlee Formation is illustrated in Louwye *et al.* (2007, fig. 8h–j).

Labyrinthodinium truncatum truncatum does not occur in the Kasterlee Formation of this study, but was recorded from the very basal part of this formation in the Olen outcrop (Louwye *et al.* 2007). It is a common species in the greater part of the Tortonian Diest Formation of northern Belgium. Its HO is situated in the upper part of Chron C4n at *c.* 7.5 Ma, that is, the latest Tortonian (de Verteuil & Norris, 1996; Munsterman & Brinkhuis, 2004; see Louwye *et al.* 2007 for an overview of the stratigraphic ranges) (Fig. 8). Species with a known post-Miocene lowest occurrence (LO) are not encountered in the Kasterlee Formation.

The age of the Kasterlee Formation from the Oud-Turnhout borehole relies on the ranges of key dinoflagellate cyst species such as *Selenopemphix armageddonensis*, *Trinovantedinium ferugnomatum*, *Barssidinium taxandrianum* and *Gramocysta verricula*, and the absence of *Labyrinthodinium truncatum truncatum* and typical Pliocene species. Because only the upper part of the sequence was analysed (Fig. 4), it is obvious that an age estimate for the entire formation cannot be proposed. The formation at Oud-Turnhout is younger than 7.5 Ma and older than 5.32 Ma.

Dorsal view of (i) dorsal surface with archaeopyle, and (j, k) two slightly lower mid-foci, revealing a flange between two antapical processes. Sample 36.71 m, p1, R45/2. Maximum length central body, 35 μm; maximum width central body, 32 μm. (l) *Cyclopsiella*? *trematophora* (Cookson & Eisenack) Lentin and Williams. High focus on uncertain view. Sample 34.70 m, p1, C56/1. Maximum diameter, 27 μm. (m–o) *Lavradosphaera lucifer* De Schepper & Head. Sample 36.71m, p1, L39/4. Apical view of (m) apical surface with rounded pylome, (n) mid-focus and (o) antapical surface. Sample 36.71 m, p1, L39/4. Maximum diameter cyst excluding processes, 17 μm. (p) Zygospore of *Debarya glyptosperma* (De Bary) Wittrock. Polar view. Sample 32.81 m, p1, B36/4. Maximum diameter, 32 μm. (q–s) *Lavradosphaera* sp. Oblique apical view of (q) upper focus on pylome, (r) mid-focus, and (s) lower focus. Sample 35.53 m, p1, R51/4. Maximum diameter cyst excluding processes, 19 μm. (t) *Gelasinicysta vangeelii* Head. Polar view. Sample 32.81 m, p1, F46/0. Maximum diameter, 34 μm.


Age assessment of the Kasterlee and Poederlee formations in the Oud-Turnhout borehole based on dinoflagellate cyst ranges
Age assessment of Miocene and Pliocene formations in the Antwerp and the Campine area, and sequence chronostratigraphic interpretation
Age (Ma)
Chron
Polarity
Period
Epoch
Age
Calcareous Nannofossils
Atlantic western equatorial
Planktonic Foraminifera
Atlantic western equatorial
Dinoflagellate cysts
QUATERNARY
NEOGENE
PLEISTOCENE
PLIOCENE
MIOCENE
LATE
EARLY
GELASIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
OLD
KAE
MAM
COC
NUN
SID
THV
C2n
C2r
C2An
C2Ar
C3n
C3r
C3An
C3Ar
C3Bn
C3Br
C4n
C4r
C4An
C4Ar
NN18
NN17
NN16
NN 13/15
NN12
NN11b
NN11a
NN10
CN13
CN12
CN10c/11
CN10
CN9
CN8
a
b
c
d
aA
aB
bA
bB
bC
PL6
PL5
PL4
PL3
PL2
PL1
M13b/14
M13a
N22
NN20/21
N19
N18
N17
N16
RT7
RT6
RT5
RT4
RT3
RT2
RT1
Not zoned
DN10
DN9
DN8
Trinovantedinium ferugnomatum
Selenopemphix armageddonensis
NML
EQ
Barssidinium taxandrianum
Gramocysta verricula
Labyrinthodinium truncatum truncatum
Operculodinium tegillatum
Operculodinium? eirikianum eirikianum
Invertocysta lacrymosa
Impagidinium solidum
Lavradosphaera lucifer
Scaldecysta doelensis
Poederlee Fm.
2.74-2.72 Ma
3.15 Ma
3.71 Ma
Kasterlee Fm.
5.32 Ma
Upper boundary
Lower part not studied here
Olen outcrop and Dessel-2 well datum Louwye et al. (2007)
Stratigraphic position of the units
Possible position
Maximum position
Highest occurrence
Lowest occurrence
Antwerp area
Campine area
Lillo Fm.
Merksem S.
Kruisschans S.
Oorderen S.
Luchtbal Sands
2.76 Ma
3.15 Ma
3.21 Ma
Poederlee Fm.
Mol Fm.
Datums: De Schepper, Head & Louwye (2009)
Kattendijk Formation
Kasterlee Formation
Diest Formation
Datum: Louwye (2002)
Diest Formation (Deurne Sands Member)
Hardenbol et al. (1998)
Ge2
Ge1
Pia2
Pia1
Za2
Za1
Me2
Me1
Tor2
2.09
2.55
2.76
3.21
4.04
4.37
5.73
6.98
9.26
T
R
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5

7.b. Poederlee Formation

The presence of *Achomosphaera andalousiensis suttonensis*, *Barssidinium* spp., *Invertocysta lacrymosa*, *Operculodinium*? *eirikianum eirikianum* and *Selenopemphix brevispinosa* places the Poederlee Sands firmly within the Pliocene. Other components of the Poederlee assemblage such as *Pyxidinopsis braboi*, *Scaldecysta doelensis* and *Spiniferites coniconcavus* were first described from the Piacenzian Lillo Formation (Belgium, Antwerp Harbour area), and more precisely from the Basal Shelly Unit, Oorderen Sands Member and Kruisschans Sands Member (De Schepper, Head & Louwye, 2004). The apparent HOs of *Desotodinium wrennii* and *Operculodinium*? *eirikianum eirikianum* within the Poederlee Formation are likely environmentally controlled and do not reflect their true stratigraphic range. Nevertheless, they suggest a correlation of the Poederlee Formation with the upper part of the Lillo Formation.

The palynological assemblage of the Poederlee Sands is very comparable to the Oorderen Sands Member (Louwye, Head & De Schepper, 2004; De Schepper, Head & Louwye, 2009) and marker events are found in both units. The LO of *Scaldecysta doelensis* is halfway up the Poederlee Sands, comparable to its first record within the Oorderen Sands at the Antwerp Harbour sections. *Invertocysta lacrymosa* is recorded throughout the Poederlee Sands, comparable to the Oorderen Sands Member record in the Tunnel-Canal Dock section (De Schepper, Head & Louwye, 2009). In the Verrebroek and Deurganck docks, this species ranges to halfway up the Oorderen Sands Member (Louwye, Head & De Schepper, 2004), where its HO is likely environmentally controlled.

Reticulatosphaera actinocoronata is recorded persistently in the Kasterlee Formation but is almost completely absent from the Poederlee Formation. The two single records of *Reticulatosphaera actinocoronata* in the Poederlee Formation are attributed to reworking. This species ranges no higher than *c.* 4.7 Ma (Louwye, Head & De Schepper, 2004; De Schepper, Head & Louwye, 2009), suggesting that the Poederlee Formation is at least younger than 4.7 Ma. The maximum age of this unit can be determined more accurately from the absence of biostratigraphic markers such as *Batiacasphaera minuta*/*micropapillata* (Fig. 6c) and *Operculodinium tegillatum* (Fig. 6i–l). The absence of both species excludes a correlation with the eastern North Atlantic RT1 to RT3 zones from De Schepper & Head (2009) (Fig. 8). *Batiacasphaera minuta*/*micropapillata* has a HO at *c.* 3.83 Ma in DSDP Hole 610A (De Schepper & Head, 2008*b*) and was recorded *in situ* in the southern North Sea Basin from the Zanclean Kattendijk Sands only. *Operculodinium tegillatum* is also common in the Kattendijk Sands (5.0 to 4.7–4.4 Ma), where it has its HO in the southern North Sea (Louwye, Head & De Schepper, 2004; De Schepper, Head & Louwye, 2009). It ranges up to 3.71 Ma in the eastern North Atlantic (De Schepper & Head, 2008*b*) (Fig. 8). Thus, the Poederlee Formation is likely younger than 3.71 Ma.

The Poederlee Formation is also likely older than 2.74 Ma. This is derived from the presence of *Invertocysta lacrymosa* (Fig. 7b, c), *Operculodinium*? *eirikianum eirikianum* (Fig. 7g, h) and the acritarch Algal cyst type 1 of Head (1996), which suggests a correlation with the RT4 and RT5 zones of De Schepper & Head (2009) (Fig. 8). *Operculodinium*? *eirikianum eirikianum* has not been recorded in deposits younger than *c.* 2.0 Ma and has a HO at 2.62 Ma in the eastern North Atlantic (De Schepper & Head, 2008*b*, 2009). The highest occurrence of *Invertocysta lacrymosa* is relatively synchronous at around 2.72–2.74 Ma in the North Atlantic area (De Schepper & Head, 2008*b*). Algal cyst type 1 of Head (1996) is infrequently recorded in the Poederlee Formation. It disappears from the record in the eastern North Atlantic around 2.74 Ma, but is recorded up to 1.8 Ma in eastern England (Head, 1998) (Fig. 8).

Further hints about the age of the Poederlee Formation come from occurrences of two palynomorph taxa, previously unknown from the North Sea Basin. Their record outside the regular counts should not limit their stratigraphic value, as they are usually recorded in low abundances only in the North Atlantic (De Schepper & Head 2008*b*; SDS, pers. obs.). Firstly, a dinoflagellate cyst of the genus *Impagidinium*, thus far only reported from the Mediterranean and North Atlantic (Versteegh, 1997; De Schepper & Head, 2008*b*), suggests an even more restricted stratigraphic range for the Poederlee Sands. The brown coloured

Figure 8. Left panel: absolute and relative age, geomagnetic polarity, calcareous microfossil biozones, and Miocene dinoflagellate cyst zonation of the USA eastern coast. Time scale used is the ATNTS 2004 (Lourens *et al.* 2005), but we follow Gibbard *et al.* (2009) for the position of the Pliocene–Pleistocene boundary. Abbreviations in Polarity column are OLD – Olduvai, KAE – Kaena, MAM – Mammoth, COC – Cochiti, SID – Sidufjall, THV – Thvera. The dinoflagellate cyst zonation for the Miocene (DN zones) is from de Verteuil & Norris (1996) and for the Pliocene (RT zones) from De Schepper & Head (2009). Middle panel: stratigraphic range of selected dinoflagellate cysts used for the relative age assessment of the Kasterlee and Poederlee formations, for which a maximum and possible (minimum) age assessment is given. Right panel: combined dinoflagellate cyst and sequence stratigraphic age assessment for the Kasterlee and Poederlee formations. Their position in relation to other Neogene stratigraphic units in northern Belgium and to sequence stratigraphy of Hardenbol *et al.* (1998) is also given. Regressive (R) and transgressive (T) cycles are after Haq, Hardenbol & Vail (1987). Thin dashed horizontal lines represent correlation and age indication. Arrows indicate time ranges. HML – Northern Hemisphere Mid-latitude; EQ – Equatorial. Ranges of dinoflagellate cysts and position of the Neogene units of northern Belgium are based on this study and de Verteuil & Norris (1992, 1996), Louwye (1999, 2002), Warny & Wrenn (2002), De Schepper, Head & Louwye (2004), Louwye, Head & De Schepper (2004), Munsterman & Brinkhuis (2004), Williams *et al.* (2004), Louwye *et al.* (2007), Louwye & Laga (2008), De Schepper & Head (2008*a*,*b*), De Schepper, Head & Louwye (2009) and references therein.

Impagidinium solidum (sample 35.53 m; Fig. 7e, f) has a maximum range between 3.87 and 3.15 Ma in the eastern (DSDP Hole 610A) and western North Atlantic (603C) (De Schepper & Head, 2008*b*). Although the LO of this species may be before 3.87 Ma, this age fits well with the estimated maximum age for the Poederlee Formation. When oceanic taxa (e.g. *Impagidinium*) are recorded in shallow marine deposits, they are likely displaced from open marine environments (e.g. Dale, 1996). Nevertheless, it is likely a contemporaneous element, just like other specimens of *Impagidinium* in the Neogene units of northern Belgium (Louwye, Head & De Schepper, 2004; Louwye & Laga, 2008; De Schepper, Head & Louwye, 2009). Secondly, a rarely recorded acritarch taxon corroborates this assessment and provides further detail. In sample 36.71 m, the occurrence of acritarch *Lavradosphaera lucifer* (Fig. 7m–o) narrows down the age range for the unit. The currently known stratigraphic range in the eastern North Atlantic DSDP Hole 610A is from 3.98 to 2.97 Ma (De Schepper & Head, 2008*b*) (Fig. 8).

The range based on dinoflagellate cysts and acritarchs for this unit is thus maximally between 3.71 and 2.74–2.72 Ma, comparable to the age assessment of the Oorderen Sands (De Schepper, Head & Louwye, 2009). When considering the ranges of *Lavradosphaera lucifer* (3.98–2.97 Ma) and *Impagidinium solidum* (3.87–3.15 Ma), the Poederlee Sands could even have been deposited before 3.15 Ma, although we cannot exclude the possibility that these specimens are reworked. The dinoflagellate cyst assemblage corresponds to the eastern North Atlantic RT4 and RT5 zones, and is possibly restricted to the RT4 zone (Fig. 8).

8. Palaeoenvironmental analysis

8.a. Kasterlee Formation

The dinoflagellate cyst assemblage recorded from the Kasterlee Formation at our study site consistently reflects an inner to outer neritic marine environment. Neritic genera such as *Achomosphaera*, *Lingulodinium*, *Operculodinium* and *Spiniferites* dominate the assemblage. Dinoflagellate cyst species with an oceanic affinity are almost completely absent; only one specimen of the oceanic genus *Impagidinium* was recorded in sample 40.66 m. *Gramocysta verricula* is a dinoflagellate cyst with an affinity for shallow to shoaling marine environments (Warny & Wrenn, 2002), and is recorded in low numbers in this study. *Geonettia clineae* is characteristic for open bay environments typified by low sediment influx, and is absent in this study. Both species are, however, markedly present in the more shallow marine facies of the Kasterlee Formation identified at the Dessel-2 borehole and Olen outcrop, and occur even in very high numbers in the upper part of the sequence (Louwye *et al.* 2007). There, the study sites are closer to the palaeo-shoreline than in the Oud-Turnhout borehole of this study (Fig. 1).

Further evidence of the shallow marine environment comes from the continental palynomorphs. The dinoflagellate cysts are in every sample outnumbered by bissacate pollen, most likely blown into the depositional environment by the wind. The dinoflagellate cyst versus bisaccate pollen ratio is minimally 0.17 and maximally 0.32, which means that there are at least three pollen grains for every dinoflagellate cyst in the uppermost sample of this unit (38.96 m).

Chlorophycean palynomorphs such as *Pediastrum* are scarce. *Pediastrum* normally occurs in low-energy freshwater environments, but according to Head *et al.* (2005) can thrive also in brackish water environments with salinities lower than 5–10 psu. The occurrence of a single specimen in the Kasterlee Formation at Oud-Turnhout contrasts sharply with the large numbers of *Pediastrum boryanum* recorded in the shallow marine facies of this unit in the Dessel borehole and Olen outcrop (Louwye *et al.* 2007; Fig. 1). At the latter localities, a freshwater component was brought into the depositional environment via rivers of the palaeo-Meuse and Gete basin.

The acritarch plexus *Cyclopsiella granosa/elliptica* is present in every sample, except in sample 40.66 m. An overview of previous records and a reconstruction of the ecological preferences of the genus *Cyclopsiella* were compiled by Louwye & Laga (2008), and revealed the species to be characteristic for shallow marine to near-shore high energetic environments. Moreover, these palynomorphs most probably had an encrusting or epilithic mode of life (Matsuoka & Head, 1992), and thus lived in the photic zone.

These findings corroborate the sedimentological analysis of the Kasterlee Formation in an outcrop at Lichtaart (Fig. 1) by Gullentops & Huyghebaert (1999). Granulometric and heavy mineral analysis indicated that the upper part of the formation was deposited in a near-shore environment with long shore drift of very well-sorted fine sands rich in hornblende.

8.b. Poederlee Formation

The palynological assemblage of the Poederlee Formation is also heavily dominated by terrestrial palynomorphs, which always exceed the counted dinoflagellate cysts. In the upper three samples, for each dinoflagellate cyst counted there are about five pollen grains, mainly bisaccate pollen. This suggests a close proximity to the coast and possibly a shoaling during deposition of the upper part of the unit.

Nevertheless, dinoflagellate cysts are abundant in the record, but concentration estimates are questionable due to the limited amount of *Lycopodium clavatum* marker grains recorded. The errors on the concentrations of samples 36.71 m, 35.53 m and 34.24 m exceed 34 % and are considered questionable (Fig. 5). In the other four samples an error below 25 % on the concentration could be attained, and for these samples the concentration of 1237–2803 cysts/g compares well to the values of the Oorderen Sands (Louwye, Head & De

Schepper, 2004; De Schepper, Head & Louwye, 2009). The error could not be calculated for sample 37.38 m since no *Lycopodium* marker grains were counted.

Spiniferites/*Achomosphaera* spp. indet. dominate the record throughout, clearly indicating neritic environments. The shoaling of the environment upwards in the unit is indicated by the higher abundance of terrestrial palynomorphs and the first appearance of *Scaldecysta doelensis*. *Spiniferites coniconcavus*, a species with reduced, blunt, conical processes, becomes more abundant in the upper part of the unit. The processes of several species of *Spiniferites*/*Achomosphaera* spp. indet. are reduced in number and in shape, possibly due to a more turbulent and shallow environment. The dinoflagellate cyst diversity (Shannon-Wiener index, Fig. 5) drops in sample 34.70 m and remains low in the samples above, also likely an expression of the shoaling environment and input of fresh water. Freshwater palynomorphs such as *Gelasinicysta vangeelii*, *Debarya glyptosperma* and *Pediastrum* are recorded only in the upper part of the Poederlee Sands. Increased reworking from 35.53 m upwards points further at increased erosion of the hinterland. Reworked dinoflagellate cysts can originate from coastal erosion during maximum transgression or can be brought into the basin via rivers following erosion of deposits in the hinterland. This mechanism was proposed for the reworked Cretaceous to Miocene dinoflagellate cysts, and mostly Eocene dinoflagellate cysts recorded in the Pliocene deposits of the Antwerp Harbour area (De Schepper, Head & Louwye, 2009).

9. Discussion and conclusions

In the Oud-Turnhout area, the sediments of the Kasterlee Formation were deposited in a neritic environment as attested to by the dominant neritic dinoflagellate cyst assemblage. Terrestrial palynomorphs significantly outnumber the dinoflagellate cysts in almost every sample and are indicative of the nearby presence of the continent. The quasi-absence of freshwater algae points to a limited fluviatile input. The Kasterlee Formation in the area of Oud-Turnhout was thus deposited in deeper neritic environments compared to the Dessel-2 borehole and Olen outcrop (Fig. 1), where a shallow marine facies is recorded following deposition in a truly coastal environment, characterized by a distinct shoaling phase (Louwye *et al.* 2007). Therefore, the Kasterlee Formation shows in the Campine area a deepening of the depositional environment in a northerly direction.

The stratigraphic ranges of the dinoflagellate cysts confine the age of the Kasterlee Formation in the Oud-Turnhout borehole between 7.5 and 5.32 Ma (latest Tortonian to Messinian), comparable to the age proposed by Louwye *et al.* (2007). The unconformity at the top of the Kasterlee Formation can be correlated with the major sequence boundary Me2 of Hardenbol *et al.* (1998), which is dated at 5.73 Ma. The combination of dinoflagellate cyst stratigraphy with sequence stratigraphy narrows the time frame for deposition between 7.5 and 5.73 Ma (Fig. 8).

Messinian depositional sequences are characterized globally by regressive trends, caused by lowering sea level due to global increasing ice volume (Adams *et al.* 1977). A $\delta^{18}O$ isotope study with benthic foraminifers of a Late Miocene to Early Pliocene sequence from ODP Site 982 (North Atlantic) revealed a late Messinian glacial period between 6.26 to 5.50 Ma (Hodell *et al.* 2001). This glacial period consists of eighteen glacial–interglacial cycles, of which TG20 at 5.75 and TG12 at 5.51 Ma are the most intense. The sequence boundary Me2 at 5.73 Ma (Hardenbol *et al.* 1998), correlated to the unconformity at the top of the Kasterlee Formation, is thus likely related with glacial event TG20. According to Hodell *et al.* (2001), the magnitude of the associated sea-level drop is difficult to determine in open marine settings, but estimates range from ten metres (Aharon *et al.* 1993) to tens of metres (Braga & Martin, 1996). In summary, the regressive trends and shoaling observed in the Kasterlee Formation (Louwye *et al.* 2007) can be set against the backdrop of the onset of the late Miocene glaciation. Although the effect of a sea-level drop is first observed in coastal areas, the top of the Kasterlee Formation in the deeper (Oud-Turnhout area) and shallower facies (Dessel and Olen areas) shows no age difference. The Messinian glaciation ended with the transition from TG12 to TG11 just before 5.5 Ma, after which sea levels started to rise again.

The depositional environment of the Poederlee Formation was neritic with an open ocean influence at first, changing into more shallow waters in the proximity of the coast and fresh water influence. Deposition likely took place during a transgressive to highstand phase, under a high and possibly maximal sea level, until the accommodation space was filled. At the edge of the North Sea Basin, accommodation space is limited; hence, from halfway up the Poederlee Sands, fresh water influences are recorded together with increased pollen influx showing the proximity of the continent.

The stratigraphic range of marker dinoflagellate cyst species confine the age of the Poederlee Formation between 3.71 and 2.74–2.72 Ma. Given the stratigraphic range of *Impagidinium solidum* (3.87–3.15 Ma), the Poederlee Sands could be older than 3.15 Ma. Based on the range of marker species and the overall dinoflagellate cyst assemblage, the Poederlee Formation is correlated with the Oorderen Sands. The Oorderen Sands are placed in the sequence between the Pia1 (3.21 Ma) and Pia2 (2.76 Ma) sequence boundaries (Hardenbol *et al.* 1998; De Schepper, Head & Louwye, 2009). Therefore, also the lower boundary of the Poederlee Sands should be correlated to the Pia1 (3.21 Ma). This sequence boundary is likely related to the global glaciation event of Marine Isotope Stage M2 at around 3.30 Ma (e.g. Lisiecki & Raymo, 2005; De Schepper, Head & Groeneveld, 2009). Miller *et al.* (2005) and also Dwyer & Chandler (2009) estimate the sea-level low stand at MIS M2 at approximately

65 m below present. The Pia2 sequence boundary (Fig. 8) corresponds with the sea-level drop of about 75 m around 2.74 Ma (Miller *et al.* 2005) at the intensification of the Northern Hemisphere glaciation.

The combined evidence from dinoflagellate cysts and sequence stratigraphy suggests that the Poederlee Formation was deposited between 3.21 and 2.76 Ma, but may have even been deposited in the narrow time window between 3.21 and 3.15 Ma. Sediments from the eastern English sector of the southern North Sea Basin often have been deposited in a short amount of time, even decadal timescales (Head, 1998; Balson, 1999). Thus, deposition of the Oorderen Sands and Poederlee Formation likely took place during the Mid-Pliocene warm period or PRISM time slab (3.27–2.97 Ma), when sea level was high enough and accommodation space was adequate for sediments to be deposited. Sea level was higher by around 35 ± 18 m (Dowsett & Cronin, 1990), but more recent reconstructions suggest a sea level of 20 to 25 m higher relative to today (Miller *et al.* 2005; Dowsett, 2007; Dwyer & Chandler, 2009).

The magnitude of the hiatus between the Miocene and Pliocene series in northern Belgium varies considerably from region to region, and no continuous section exits. In the vicinity of the city of Antwerp, the hiatus between the Diest Formation (more specifically the Deurne Sands Member) and the Zanclean Kattendijk Formation can be estimated at a minimum of 3.2 million years (Fig. 8). The hiatus is at least 2.52 million years in the Campine area, where the Kasterlee Formation is covered by the Poederlee Formation. No precise estimation can be given for the areas where Miocene deposits are covered by the continental/estuarine Mol Formation for which no precise age can be proposed (Fig. 8). The major cause of this variation is the shallow depositional environment at the southernmost border of the North Sea Basin, where glacio-eustatic or local tectonically induced sea-level fluctuations determine deposition or non-deposition in marginal marine areas.

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