Geologie en Mijnbouw **78:** 31–46, 1999.

Dinoflagellate cyst stratigraphy and depositional history of Miocene and Lower Pliocene formations in northern Belgium (southern North Sea Basin)

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Received 15 September 1998; accepted in revised form 21 May 1999

Key words: biostratigraphy, Diest Formation, Neogene

Abstract

The occurrence of organic-walled dinoflagellate cysts (dinocysts) in the Diest Formation, a largely decalcified succession with a poor fossil content, and in the adjacent strata of Lower Miocene and Lower Pliocene formations, allowed a biostratigraphic evaluation of these deposits and an assessment of the hiatus between the lithostratigraphic units. The Diest Formation was deposited during Tortonian – Messinian times. Dinocyst biozones defined in the North Sea region and the U.S.A. East Coast are recognised within the Diest Formation, although environmental factors seem to have influenced the presence of some key zonal species in the shallow-marine deposits of northern Belgium. The two members of the Diest Formation studied, i.e., the Dessel Sands and the Diest Sands, appear to be strongly diachronous. The depocentre was located in the Campine area during the early Tortonian and shifted to the area north of Antwerp during late Tortonian to Messinian times. The age assessment provides a correlation of the sequence boundaries of Haq et al. (1987) at the top of the Diest Formation with SB 5.5.

Introduction

Dumont (1839) introduced the 'Diestien' stage to denominate a glauconiferous coarse-grained sand unit observable in outcrops in northern Belgium. In the literature, this deposit is commonly referred to as the 'Diest Sands' and – partly because of its very poor fossil content – its stratigraphical position has been the subject of a long debate ever since. The casts and internal moulds of molluscs in this decalcified unit do not yield sufficient biostratigraphical data to determine a precise age. The unit was first included in the Pliocene series (geological maps of 1896 and 1929) and later in the Upper Miocene (De Heinzelin 1955, Glibert & De Heinzelin 1955). Foraminiferal biostratigraphical studies by De Meuter & Laga (1970), Hooyberghs & De Meuter (1972) and Laga & De Meuter (1972) led to the formal definition of the Upper Miocene Diest Formation (De Meuter & Laga 1976).

The chronostratigraphical position of the Diest Sands Member, nevertheless, still remained poorly constrained. Recently, a well preserved flora of organic-walled microplankton from the Diest Sands was studied from the Kalmthout well (Figure 1) and, for the first time, a biostratigraphy based on dinocysts (late Tortonian – Messinian) could be proposed (Louwye & Laga 1998).

The present contribution reports on the distribution of selected, stratigraphically important dinocysts species in the Upper Miocene succession from the Kalmthout well and five other wells across northern Belgium. Correlation with biozonation schemes and dinocyst distribution of other areas (British Isles, the North Sea, the Netherlands, northern Germany, Italy and the eastern coast of the U.S.A.) is proposed, together with a relative dating of the succession and an assessment of the stratigraphic gaps between the various Neogene lithostratigraphic units.

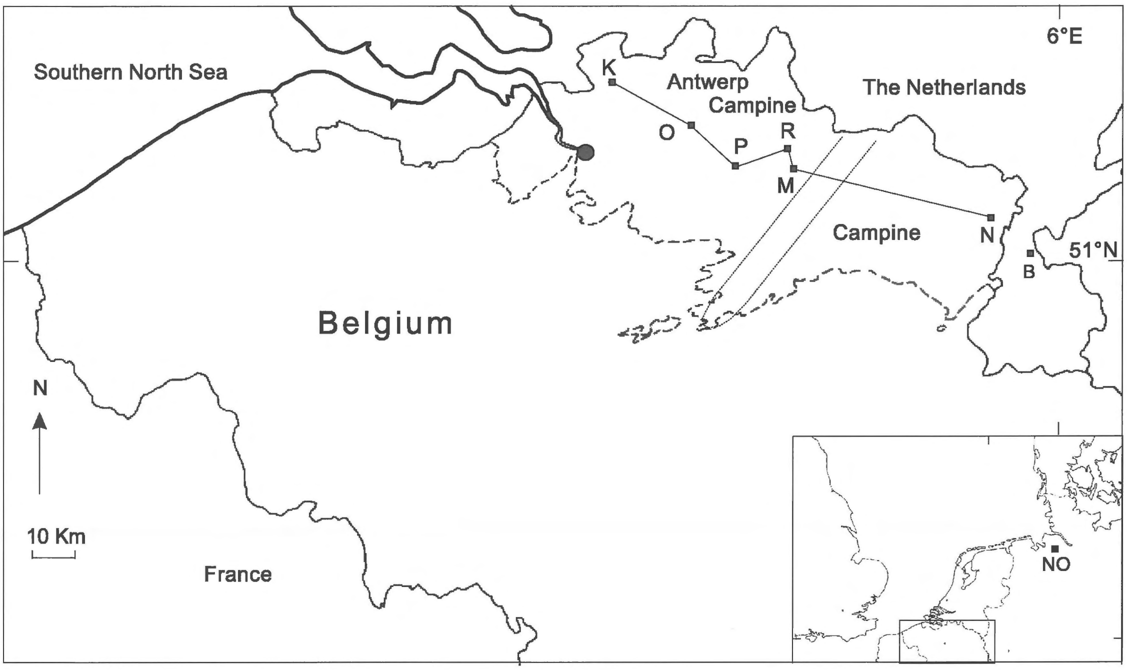

Figure 1. Location of the wells (numbers refer to the archives of the Geological Survey of Belgium). K = Kalmthout 6E110; O = Oostmalle 29E249; P = Poederlee 30W300; R = Retie 31W243; M = Mol 31W221; N = Neeroeteren 64W234; B = Broeksittard well (The Netherlands); NO = Nieder Ochtenhausen well (NW Germany). Dashed line = southern limit of Neogene deposits in northern Belgium (modified after Tavernier & De Heinzelin 1963); U-shaped dotted line = approximate position of the axis of the erosion gully.

Lithostratigraphy				Series
Antwerp	N Antwerp Campine	S	Campine	
Lillo Formation	Lillo Formation	Poederlee - Mol Formation	Mol Formation	Upper Pliocene
Kattendijk Formation	Kattendijk Formation	Kasterlee Formation	Kasterlee Formation	Lower Pliocene
Diest Formation "Diest Sands" Deurne Sands Member	Diest Formation "Diest Sands" Dessel Sands Member		Diest Formation	Upper Miocene
Berchem Formation Antwerpen Sands Mbr. Kiel Sands Member Edegem Sands Member	Berchem Formation Antwerpen Sands Member		Bolderberg Formation	Middle Miocene Lower Miocene

Figure 2. Lithostratigraphy of the Neogene of northern Belgium (partly modified after De Meuter & Laga 1976).

Lithostratigraphy

Miocene sediments in northern Belgium occur only in the Antwerp area, the Campine area and the area in between, called the Antwerp Campine (Figure 1). The Upper Miocene Diest Formation is defined as a glauconiferous coarse-grained sand, mostly barren and with occasional sandy ironstone layers. Most of the formation is informally called the 'Diest Sands' (De Meuter & Laga 1976, Figure 2). At the base, two medium- to very fine-grained sandy members can locally be distinguished within the Diest Formation. The Deurne Sands Member (Glibert & De Heinzelin 1955), in the west found only in the area just northeast of the city of Antwerp, is a glauconiferous, slightly clayey medium- to fine-grained sand, locally rich in bryozoans, brachiopods and ditrupa. The Dessel Sands Member (Laga & De Meuter 1972) consists of glauconiferous fine-grained sand, rich in foraminifers and a gravel deposit at the base. The latter member occurs in the Campine area and is defined in the Mol well (Figure 1).

The Diest Formation is bounded by unconformities. In the greater part of the study area, the formation rests unconformably on the Antwerpen Sands Member, which is the upper member of the Lower Miocene (to Middle Miocene: De Meuter & Laga 1976) Berchem Formation (Figure 2). Only in the very eastern part of the study area, in the Neeroeteren well, the Diest Formation rests unconformably on the Lower Miocene Bolderberg Formation. The Lower Pliocene Kattendijk Formation and Kasterlee Formation overlie unconformably the Berchem Formation, in the western and eastern part of the study area, respectively. To the north, a gradual transition of the Kasterlee Formation into the Kattendijk Formation is observed (De Meuter & Laga 1976). The Upper Pliocene Mol Formation overlies the Diest Formation in the Neeroeteren well unconformably.

Depositional history

After the Late Oligocene tectonic uplift, the Neogene sediments of northern Belgium were deposited in a shallow-marine environment along the southernmost border of the North Sea Basin (Vandenberghe et al. 1998). The occurrence of gravel layers in the Neogene succession indicates a discontinuous sedimentation. Sediments of Early Miocene age are represented in the Berchem Formation. The three members of this formation (the Edegem Sands, the Kiel Sands and the Antwerpen Sands) represent incomplete successions, as the result of an interplay between the continuing tectonic uplift and the rising sea level (Vandenberghe et al. 1998). A regressive phase occurred after the deposition of the Berchem Formation.

It was generally assumed that no deposition took place during Middle Miocene times; at least no sediments from that time are preserved. During this period, i.e., before the deposition of the Diest Formation, a SW–NE orientated deep gully was formed on the continental shelf (Figure 1). The gully incised locally tens of metres into the Lower Oligocene Boom Clay. According to Gullentops (1983) and Gullentops et al. (1988), the opening of the English Channel, related to a major sea-level rise, established a connection between the Atlantic and the southern North Sea via the Weald and Artois areas. During the initial stages of the transgression, the incoming strong tidal currents, parallel to the coast, further widened the gully. However, according to Wouters & Vandenberghe (1994), the magnitude of the gully itself rather indicates that the erosional base of the gully could was lowered drastically during its formation by either a sea-level drop (below the shelf margin) or by a tectonic uplift. Even during the initial stages of the transgression, erosion of the gully continued and only a coarse basal lag deposit was formed (Vandenberghe et al. 1998). Once the sea level had risen sufficiently, sedimentation started in the gully and outside the gully on the shelf to the northwest in the Antwerpen area (the fine-grained Deurne Sands). Locally, in the deeper parts of the gully, the fine-grained sand of the Dessel Sands Member is found. The sandy infilling of the gully represents sand bars displaying large-scale foresets (Gullentops 1983). Vandenberghe et al. (1998) correlate the base of the incision of the gully with sequence boundary SB10.5 (Haq et al. 1987). Deposition ended probably abruptly and only resumed again during Early Pliocene times with the deposition of the fine-grained sand of the Kattendijk and Kasterlee Formations.

Biostratigraphy

Biostratigraphical studies with macrofossils or calcareous microfossils from the Diest Sands are few, due to primary absence or to decalcification of the coarse-grained sand. Planktonic foraminiferids and benthic molluscs were studied from the fine-grained Deurne Sands Member only, whereas benthic foraminiferids

Members	Planktonic Foraminifera		Benthic Molluscs
Deurne Sands	**Hooyberghs & De Meuter (1972)** *Globigerina pachyderma* forma *dextralis* Zone	**Hooyberghs & Moorkens (1988)** *Neogloboquadrina acostaensis* Zone NPF15	**Hinsch (1988)** *Carinastarte reimersi* - *Aquilofusus semiglaber* Zone BM21A[1]

Members	Benthic Foraminifera	
Deurne and Dessel Sands	**De Meuter & Laga (1976)** *Uvigerina hosiusi deurnensis* - *Elphidium antoninum* Association Zone BFN3	**Willems et al. (1988)** B9 Range Zone[2]

Figure 3. Biozonations based on planktonic and benthic foraminiferids and benthic molluscs of the Deurne and Dessel Sands of the Diest Formation. [1] Biozone defined by Spiegler et al. (1988); [2] Biozone defined by IGCP 124 Working Group (1988).

were studied from the Dessel and Deurne Sands Members (Figure 3).

An interregional biostratigraphical correlation with biozonations defined outside the North Sea basin is severely hampered by the boreal character of the assemblages. Furthermore, the foraminiferal assemblages from the Belgian Neogene succession are ecologically controlled by the deposition in a shallow-marine environment. The Diest Formation is very poor in calcareous nannoplankton. The assemblages found in the Deurne Sands Member allow only to attribute an age younger than early Miocene (Verbeek et al. 1988). Martini & Müller (1973) propose a late Miocene age for the Deurne Sands and the Diest Sands from the Antwerpen area. Organic-walled microplankton was studied only from the Diest Sands in the Kalmthout well (Louwye & Laga 1998).

Material and methods

The study material (53 samples) comes from six wells (Figure 1). The sampling resolution in the Oostmalle and Poederlee wells is hindered by the lack of core recovery over important intervals. The lithostratigraphy of the formations under study is based on the lithological descriptions and interpretations in the archives of the Geological Survey of Belgium (Figures 4–6). The Diest Sands constitute the greater part of the Diest Formation and were found in each well, except in the Neeroeteren well where the lateral equivalent is called the 'Neeroeteren facies' of the Diest Formation (archives Geological Survey of Belgium). The fine-grained Dessel Sands Member occurs in the lowermost part of the Diest Formation in each well except in the Neeroeteren en Kalmthout wells.

The maceration of the samples followed standard palynological techniques using 40 g of sediment. A minimum of 250 and a maximum of 500 well preserved individuals were counted in each sample. The diversity and preservation of the assemblages is moderate to good, except in the Neeroeteren well where the upper four samples are strongly impoverished. Reworked pre-Neogene specimens were observed in each sample, but never constituted more than 5%.

No formal biozonation is proposed here, since the Diest Formation is bounded by unconformities and no continuous coverage of the Upper Miocene succession can be presented. Furthermore, given that large parts of the Diest Formation consist of gully infillings, deposition probably occurred rapidly and consequently represents only a small time interval, notwithstanding the thickness of the succession.

The biozonations of De Verteuil & Norris (1996), Powell (1992) and Zevenboom (1995) are applied to the formations studied. De Verteuil & Norris (1996) define a biozonation in the Miocene deposits of Maryland (Salisbury Embayment), Atlantic margin, U.S.A. The latter biozonation is indirectly correlated with the time scale of Berggren et al. (1995), the correlation being based on records of calcareous nannoplankton and planktonic foraminifers. There is a good correlation of the Maryland biozonation with the high latitude biozonations from Baffin Bay (Head et al. 1989) and the Norwegian Sea (Manum et al. 1989), defined in more open marine environments. The resolution of this biozonation is high – an average zonal duration of 1.8 Ma – and stratigraphic important dinocyst data are reviewed.

Powell (1992) proposed a Neogene biozonation for the British Isles and northwest Europe and incorporated, after evaluation, earlier published dinocyst data (by, among others, Costa & Manum 1988, Edwards 1984, Herngreen 1987, Piasecki 1980) from the NW European realm. The biozonation itself is compared against calcareous nannoplankton and planktonic foraminiferal biozones. Zevenboom (1995) defined interval biozones in the Langhian, Serravallian and Tortonian Stages in the Piedmont Basin, northwest Italy. The calibration of the biozones is mainly based

Table 1. Distribution of selected dinoflagellate cysts in the Kalmthout, Oostmalle, Poederlee and Retie wells. Well numbers are after the archives of the Geological Survey of Belgium; depths refer to TAW (Belgian ordnance datum). B: Berchem; D: Diest; Kt: Kattendijk: Ks: Kasterlee; R: reworking.

Kalmthout 6E110

Formation	Sample depth	Achomosphaera andalousiensis a.	Amiculosphaera umbracula	Operculodinium? eirikianum	Lingulodinium machaerophorum	Reticulatosphaera actinocoronata	S. brevispinosa brevispinosa	Systematophora placacantha	Habibacysta tectata	Nematosphaeropsis lemniscata	Tuberculodinium vancampoae	Impagidinium maculatum	Impagidinium strialatum	Selenopemphix armageddonensis	Apteodinium spiridoides	Cousteaudinium aubryae	Distatodinium paradoxum	Exochosphaeridium insigne	Hystrichosphaeropsis obscura	Lingulodinium multivirgatum	Operculodinium piaseckii	Palaeocystodinium golzowense	Sumatradinium druggii	Sumatradinium soucouyantae
Kt	-58	●	●	●																				
D	-60	●	●	●	●	●	●	R																
	-64	●	●	●	●	●		R	●	●	●													
	-69			●	●	●			●			●	●	●										
	-74,5			●	●	●	●		●			●												
	-83,5	●		●	●	●	●	R	●	●	●	●												
	-90	●		●	●	●	●	R	●			●												
	-92,5	●			●	●			●			●												
	-94	●		●	●	●	●					●		●										
B	-100				●	●		●			●				●	●	●	●	●	●	●	●	●	●

Oostmalle 29E249

Formation	Sample depth	Achomosphaera andalousiensis a.	Amiculosphaera umbracula	Operculodinium? eirikianum	Reticulatosphaera actinocoronata	S. brevispinosa brevispinosa	Selenopemphix armageddonensis	Habibacysta tectata	Lingulodinium machaerophorum	Trinovantedinium harpagonium	Tuberculodinium vancampoae	Operculodinium piaseckii	Hystrichosphaeropsis obscura	Impagidinium strialatum	Labyrinthodinium truncatum	Barssidinium evangelinae	Palaeocystodinium golzowense	Sumatradinium druggii	Sumatradinium soucouyantae	Unipontedinium aquaeductum	Cerebrocysta poulsenii	Nematosphaeropsis labyrinthea	Impagidinium paradoxum	Apteodinium tectatum	Cousteaudinium aubryae	Pentadinium laticinctum
Kt	-9,5	●	●	●	●	●	●																			
D	-41	●			●	●		●	●																	
	-46,5	●	●	●	●	●	●	●	●	●	●															
	-56,2	●	●	●	●	●	●	●	●		●	●														
	-66,5	●	●	●				●	●			●	●	●	●											
	-69,1	●	●			●		●							●											
	-71,2			●				●							●	●	●	●	●	R	R?	●	●			
B	-72,5				●				●				●		●		●			●	●			●	●	●

Poederlee 30W300

Formation	Sample depth	Achomosphaera andalousiensis a.	Amiculosphaera umbracula	Reticulatosphaera actinocoronata	S. brevispinosa brevispinosa	Selenopemphix armageddonensis	Trinovantedinium harpagonium	Tuberculodinium vancampoae	Habibacysta tectata	Lingulodinium machaerophorum	Operculodinium? eirikianum	Sumatradinium soucouyantae	Hystrichosphaeropsis obscura	Impagidinium maculatum	Labyrinthodinium truncatum	Operculodinium piaseckii	Nematosphaeropsis labyrinthea	Impagidinium paradoxum	Barssidinium evangelinae	Pentadinium laticinctum	Impagidinium aculeatum	Impagidinium patulum	Palaeocystodinium golzowense	Unipontedinium aquaeductum	Cerebrocysta poulsenii
K	4,7	●	●	●	●	●	●	●																	
D	2,5	●	●	●	●			●	●	●	●	R													
	-8,2	●	●	●	●				●	●	●		●	●	●	●									
	-28,2	●	●	●				●	●	●	●		●	●	●	●	●	●							
	-48,2	●	●	●	●				●	●	●				●	●	●								
	-64,2	●	●						●		●				●	●									
	-67,2	●	●						●		●		●		●	●			●	●	●				
B	-73,2	●							●		●	●			●	●						●	●	●	●

Retie 31W221

Formation	Sample depth	Achomosphaera andalousiensis a.	Amiculosphaera umbracula	Habibacysta tectata	Impagidinium maculatum	Operculodinium? eirikianum	Reticulatosphaera actinocoronata	S. brevispinosa brevispinosa	Selenopemphix armageddonensis	Hystrichosphaeropsis obscura	Lingulodinium machaerophorum	Trinovantedinium papulum	Tuberculodinium vancampoae	Labyrinthodinium truncatum	Operculodinium piaseckii	Barssidinium evangelinae	Nematosphaeropsis labyrinthea	Impagidinium aculeatum	Palaeocystodinium golzowense	Pentadinium laticinctum	Impagidinium paradoxum
D	-10,3	●	●	●	●	●	●	●	●												
	-19,8	●		●	●	●	●	●	●	●	●	●	●								
	-80,3	●		●		●	●	●		●	●		●	●	●						
	-90,3	●	●	●			●	●			●			●	●						
	-94,8	●		●		●	●	●		●	●		●	●	●						
	-105,5	●	●	●		●	●			●	●		●	●	●	●	●	●			
	-115,5	●		●		●	●			●	●		●	●	●	●			●	●	●

Table 2. Distribution of selected dinoflagellate cysts in the Mol and Neeroeteren wells. Well numbers are after the archives of the Geological Survey of Belgium; depths refer to TAW (Belgian ordnance datum). B: Berchem; Bo: Bolderberg; D: Diest.

Mol 31W243

Formation	Sample depth	Achomosphaera andalousiensis a.	Habibacysta tectata	Impagidinium maculatum	Operculodinium? eirikianum	S. brevispinosa brevispinosa	Selenopemphix armageddonensis	Lingulodinium machaerophorum	Reticulatosphaera actinocoronata	Amiculosphaera umbracula	Hystrichosphaeropsis obscura	Trinovantedinium harpagonium	Tuberculodinium vancampoae	Nematosphaeropsis labyrinthea	Labyrinthodinium truncatum	Operculodinium piaseckii	Impagidinium patulum	Sumatradinium soucouyantae	Palaeocystodinium golzowense	Apteodinium spiridoides	Apteodinium tectatum	Cousteaudinium aubryae
K	-6,5	●	●	●	●	●	●															
	-9	●		●	●	●	●	●	●													
	-25	●	●	●		●		●	●	●	●	●	●									
	-35,5	●	●		●	●	●	●	●	●	●	●		●								
	-55,5	●	●	●	●	●		●	●	●	●	●	●									
	-75	●	●		●	●		●	●		●		●		●	●						
D	-85	●	●		●	●		●	●		●		●		●	●						
	-95	●	●	●	●	●		●	●			●	●		●	●	●	●				
	-105	●	●		●	●		●	●						●	●						
	-115	●	●		●	●		●	●						●	●		●				
	-122	●	●	●	●	●		●	●			●			●				●			
B	-127							●								●			●	●	●	●

Neeroeteren 64W234

Formation	Sample depth	Lingulodinium machaerophorum	Polysphaeridium zoharyi	Tuberculodinium vancampoae	Habibacysta tectata	Nematosphaeropsis spp.	Operculodinium? eirikianum	Pentadinium laticinctum	Labyrinthodinium truncatum	Operculodinium piaseckii	Reticulatosphaera actinocoronata	S. brevispinosa brevispinosa	Selenopemphix armageddonensis	Achomosphaera andalousiensis a.	Hystrichosphaeropsis obscura	Palaeocystodinium golzowense
	37															
	34	●														
D	32,5	●	●	●												
	29	●			●	●	●	●								
	26	●	●		●	●										
	23	●		●	●	●	●		●	●	●	●	●			
B	22,5	●			●		●	●	●	●	●			●	●	●

on local magnetozones (Nakagawa et al. 1994) interpreted in terms of the global polarity timescale. A correlation of the Diest Formation with Upper Miocene formations in the Netherlands (Herngreen 1987) and northern Germany (Lund et al. 1993) is attempted. The occurrence of the dinocyst species relevant to the recognition of the biozones is given in a first downhole order in Tables 1–2. Stratigraphic important dinocysts are illustrated on Plates 1–3. The nomenclature of the dinocyst species follows Williams et al. (1998).

Dinocysts in the Neogene successions of northern Belgium: stratigraphic significance (Figures 4–5)

Berchem Formation

Louwye & Laga (1998) place the upper part of the Berchem Formation (Antwerpen Sands) from the Kalmthout well in the *Sumatradinium soucouyantae* Interval Zone DN2 of De Verteuil & Norris (1996) and the *Tuberculodinium vancampoae* Interval Biozone Tva of Powell (1992). The poorly preserved and impoverished dinocyst assemblage from the Antwerpen Sands in the Mol well allows a tentative correlation with the *Cousteaudinium aubryae* Interval Zone DN3 (De Verteuil & Norris 1996) based on the presence of the nominate species, *Apteodinium spiridoides* and the absence of the zonal markers of the DN2 and DN4 Zones, respectively, *Exochosphaeridium insigne* and *Labyrinthodinium truncatum.* A correlation of this section with the Tva Zone is proposed.

The dinocyst association found in the Berchem Formation (Antwerpen Sands) of the Oostmalle and Poederlee wells allows a correlation with the *Batiacasphaera minuta* Interval Zone DN5 (De Verteuil & Norris 1996). The occurrence of *Unipontedinium aquaeductum* is restricted to the DN5 Zone. The accompanying diagnostic species of this zone are *Cerebrocysta poulsenii, Habibacysta tectata* and *L. truncatum.* A correlation with the *Achomosphaera andalousiensis* Interval Biozone Aan (Powell 1992) can also be proposed, based on the presence of the nominate species, *C. poulsenii* and *U. aquaeductum.*

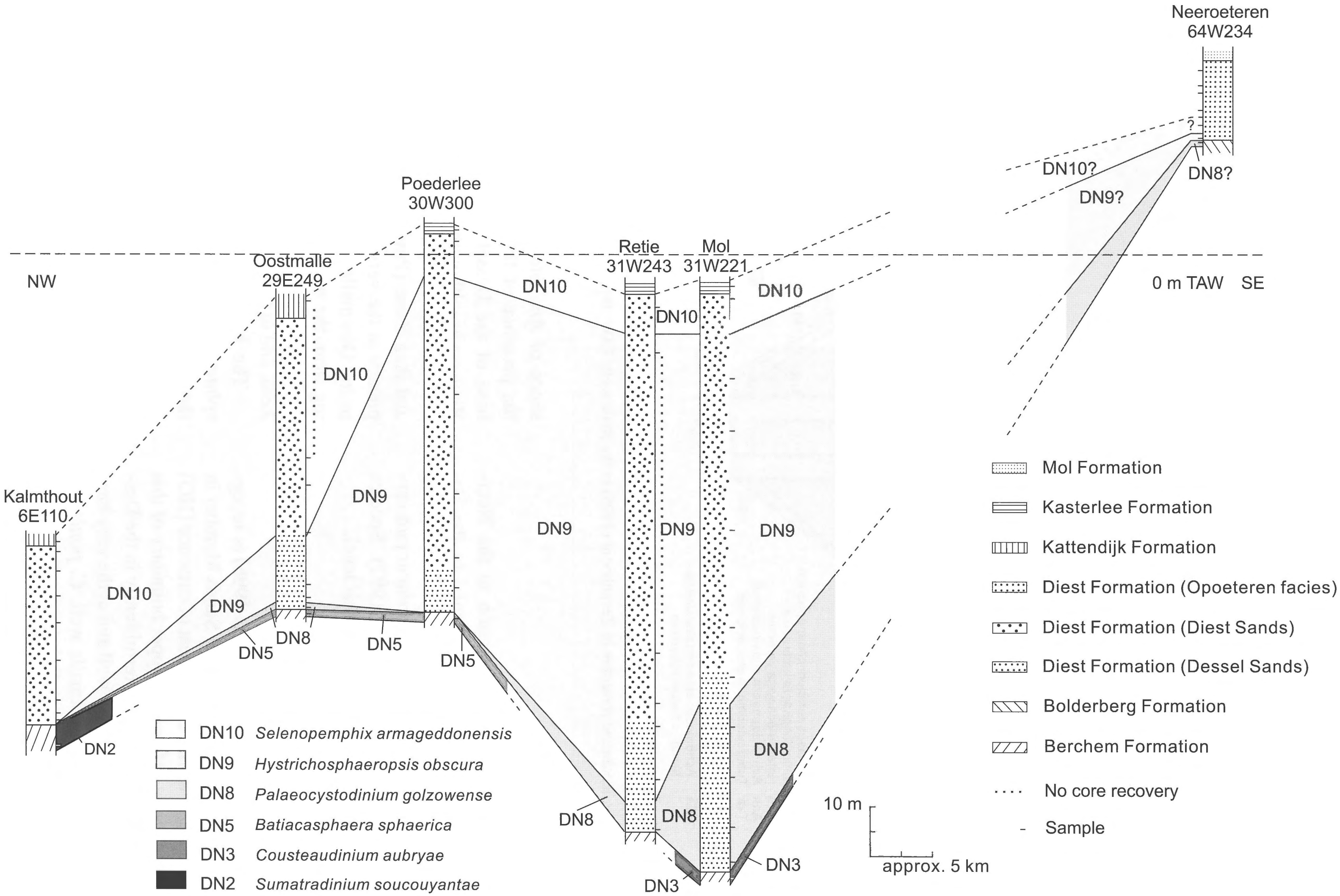

Figure 4. Correlation with the biozonation of De Verteuil & Norris (1996). The dashed line indicates an uncertain correlation or distribution of the biozone. TAW: Belgian ordnance datum.

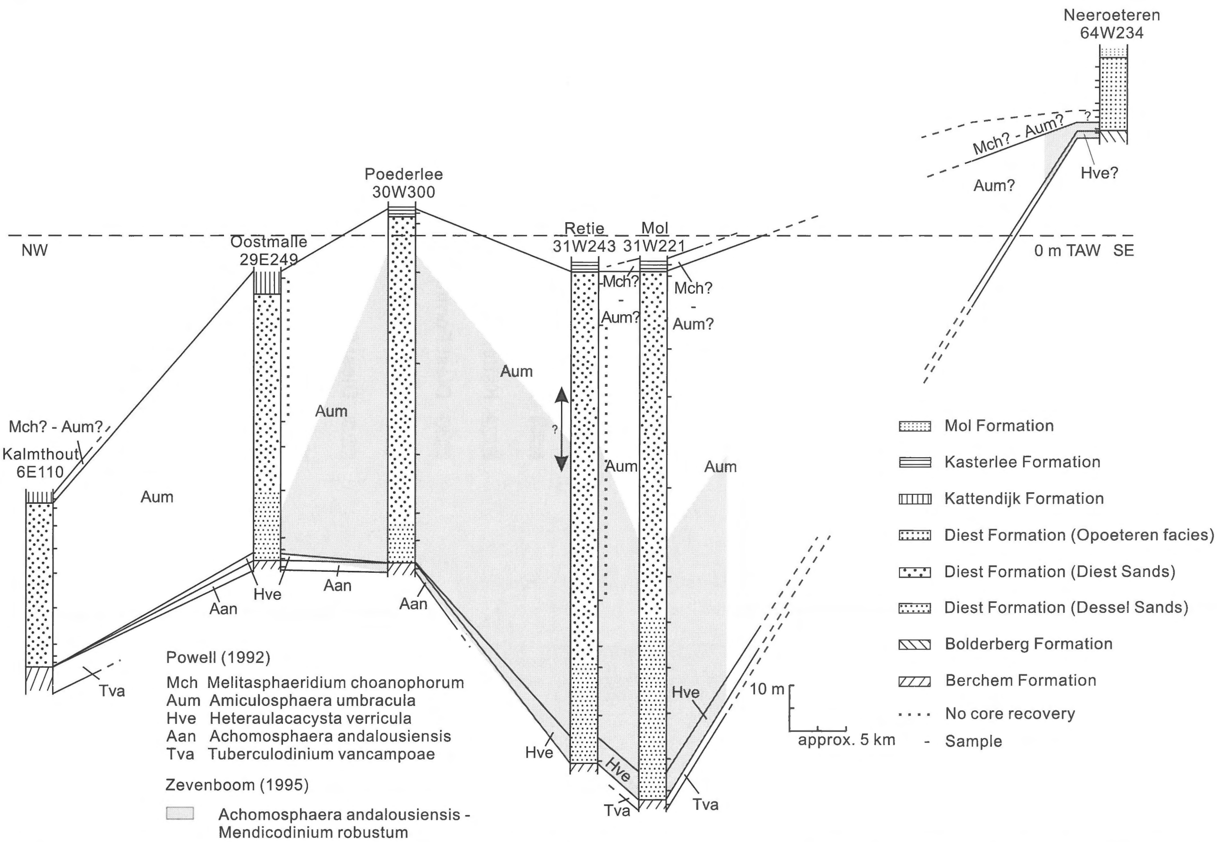

Figure 5. Correlation with the biozonations of Powell (1996) and Zevenboom (1995). The dashed line indicates an uncertain correlation or distribution of the biozone. Question marks alongside arrows indicate uncertainty of the vertical distribution of the biozones *Achomosphaera andalousiensis – Mendicodinium robustum* of Zevenboom (1995) in the Retie well. TAW: Belgian ordnance datum.

Bolderberg Formation

The top of the Bolderberg Formation in the Neeroeteren well can tentatively be assigned to the *Palaeocystodinium golzowense* Interval Zone DN8 (De Verteuil & Norris 1996) or the *Heteraulacacysta verricula* Interval Biozone Hve (Powell 1992). Species diversity and preservation are poor in this level.

Diest Formation

The DN8 Zone (De Verteuil & Norris 1996) is recognised in the lower part of the Dessel Sands Member in the Mol and Retie wells. The highest occurrence (HO) of *S. soucouyantae* defines the upper boundary of this zone; this species was found intermittently in the Dessel Sands Member of the Mol well and at the very base of the same unit in the Oostmalle well. *C. poulsenii*, *P. golzowense* and *Sumatradinium druggii* have a HO within this zone. The occurrence of *Pentadinium laticinctum laticinctum* and *P. golzowense* and the absence of *Amiculosphaera umbracula* could indicate the presence of the Hve Zone (Powell 1992) in the base of the Dessel Sands Member in the Mol and Retie wells, although the nominate species was not encountered. A DN5 Zone (De Verteuil & Norris 1996) and Aan Zone (Powell 1992) dinocyst association is present at the very base of the Dessel Sands Member in the Oostmalle well, probably the result of reworking from the underlying Antwerpen Sands. If indeed reworking occurred, then a correlation with the DN8 Zone and or the Hve Zone can be put forward.

The joined interval represented by the *Achomosphaera andalousiensis* Interval Zone (interval from the LO – lowest occurrence – of the *A. andalousiensis* to the HO of *Imperfectodinium septatum*) and the *Mendicodinium robustum* Interval Zone (interval from the HO of *Imperfectodinium septatum* to the HO of *L. truncatum*) of Zevenboom (1995) is encountered in the Dessel and Diest Sands of the Mol, Retie and Poederlee wells and in the base of the Dessel Sands Member of the Oostmalle well. The absence of *I. septatum*, the key species that separates both zones, did not allow an individual recognition of both zones.

The *Hystrichosphaeropsis obscura* Interval Zone DN9 of De Verteuil & Norris (1996) is defined as the interval from the HO of *S. soucouyantae* to the HO of *H. obscura*. Diagnostic species with their HO within DN9 are *L. truncatum* and *Operculodinium piaseckii. Barssidinium evangelinae* and *Operculodinium? eirikianum* appear for the first time within this zone. The entire Dessel Sands Member in the Poederlee well and parts of the Dessel Sands Member in the Mol, Retie and Oostmalle wells can be correlated with the DN9 Zone, as well as the greater part of the Diest Sands in the Mol, Retie and Poederlee wells. As *S. soucouyantae* was found only in the Dessel Sands Member of the Mol and Oostmalle wells, the lower boundary of this zone was not recognised explicitly in the other wells.

Almost the entire Diest Formation in the studied wells, with the exception of the Neeroeteren well, can be correlated with the *Amiculosphaera umbracula* Interval Biozone Aum (Powell 1992). The lowest occurrences (LO) of the nominate species and of *Spiniferites* cf. *pseudofurcatus* define respectively the lower and upper boundary of the zone. The HO's of *H. obscura*, *L. truncatum* and *Reticulatosphaera actinocoronata* are diagnostic events for this zone. The range of *Selenopemphix brevispinosa brevispinosa* (= *Selenopemphix* sp. A Brown & Downie 1985) is limited to this zone. *A. umbracula* is poorly represented and has an intermittent occurrence in the shallow marine Diest Formation. This can be environmentally controlled since this species has an oceanic to outer neritic preference (Head 1996). The base of the Diest Formation in the Neeroeteren well can be tentatively correlated with the DN9 Zone and the Aum Zone.

The lower boundary of the *Selenopemphix armageddonensis* Interval Zone DN10 of De Verteuil & Norris (1996) is defined by the HO of *H. obscura*. The LO of *S. armageddonensis* is located within this zone. The very upper parts of the Diest Sands in the Mol, Retie and Poederlee wells can be attributed to the DN10 Zone, as can the entire Diest Sands in the Oostmalle and Kalmthout wells. The DN10 Zone might be present in the Diest Formation in the Neeroeteren well. The upper boundary of the DN10 Zone is defined by the HO of *Erymnodinium delectabilis*, a species not found in the material studied. Consequently, the upper boundary of the DN10 Zone cannot be recognised formally.

Kattendijk Formation and Kasterlee Formation

The base of the Kattendijk and Kasterlee Formations in the Oostmalle and Poederlee wells can be placed within the Aum Zone of Powell (1992), based on the presence of *R. actinocoronata*. The absence of this species in the base of the Kattendijk Formation (Kalmthout well) and in the Kasterlee Formation (Mol well) and the presence of *Melitasphaeridium choanophorum* in both allows correlation with the very upper part of the Aum Zone or with the lower part of the *M. choanophorum* Interval Biozone Mch of Powell (1992). The assignment of this section remains open to discussion since *S.* cf. *pseudofurcatus* was not found. An analogous interpretation is given to the upper part of the Diest Sands from the Neeroeteren well.

Correlation with adjacent areas

The dinocyst distribution from the Upper Miocene Gram and Sylt Formations in the Nieder Ochtenhausen well in northern Germany (Lund et al. 1993) allows correlation with the Diest Formation (Figure 6), but the occurrence of dinocysts in both areas is not entirely analogous. The most striking feature is the lowest occurrence of *A. umbracula* in the Mol and Kalmthout wells. As already mentioned, environmental factors could have controlled this phenomenon since the Diest Formation was deposited in a marginal marine environment. Lund et al. (1993) placed the Gram and Sylt Formations within the Aum Zone of Powell (1992). The LO of *P. golzowense* allows correlation with the Miocene Breda and Inden Formations in the Broeksittard well in SE Netherlands (Herngreen 1987). The distribution of the Inden Formation, which was deposited in a coastal-lowland environment, is restricted to the Ruhr Valley Graben (Van Adrichem Boogert & Kouwe 1993).

Age

Louwye & Laga (1998) attributed a late Aquitanian – early Burdigalian age to the Berchem Formation in the Kalmthout well. A late Burdigalian age is proposed here for the upper part of the Berchem Formation in the Mol well, based on the correlation with the DN3 Zone. The upper part of the Berchem Formation in the Oostmalle and Poederlee wells are late Langhian to middle Serravallian in age, based on the correlation with the DN5 Zone. A combined correlation with the Aan Zone points more precisely to a middle Serravallian age.

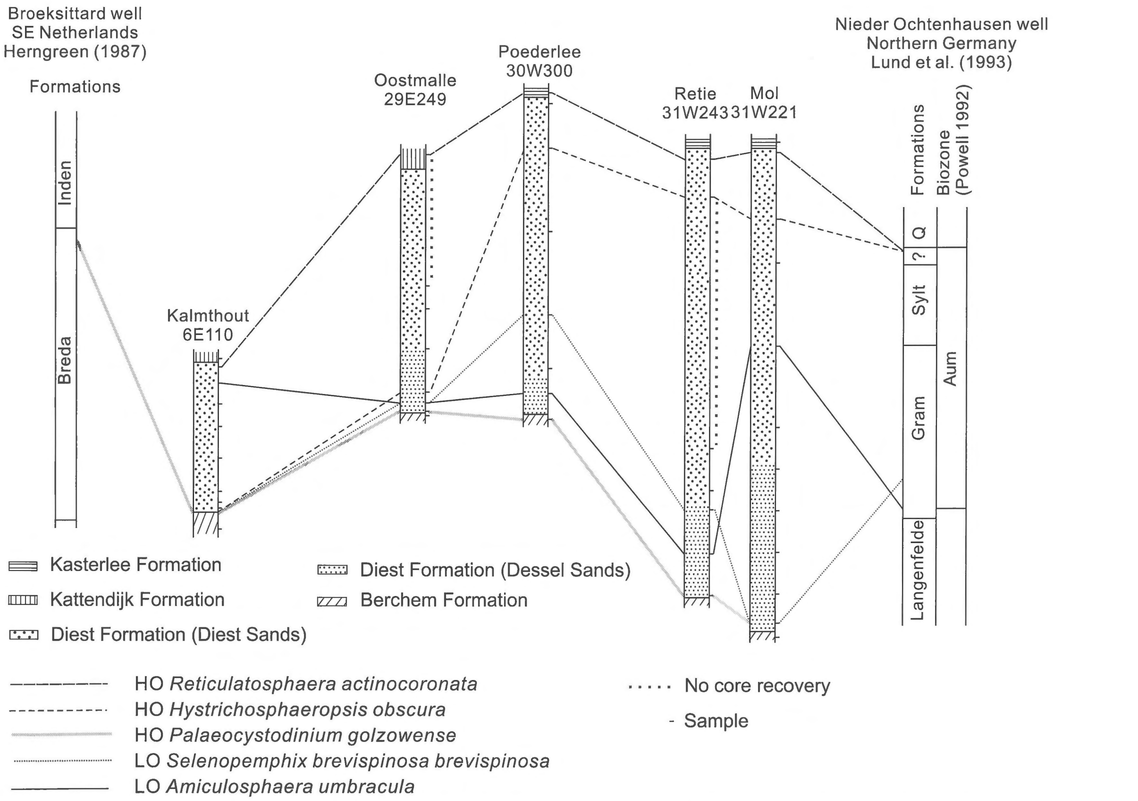

Figure 6. Correlation with the Neogene deposits in the Nieder Ochtenhausen well (northern Germany) and the Broeksittard well (southeastern Netherlands). Correlation between the wells is based on highest occurrence (HO) and lowest occurrence (LO) of selected species and indicated by various types of lines. See Figures 5 and 7 for biozonation of Powell (1992).

The chronostratigraphic position of the Dessel and Diest Sands can be inferred from Figure 7. The base of the Dessel Sands Member in the Mol, Retie and Oostmalle wells are the oldest deposits of the Diest Formation with an early – middle Tortonian or a late Serravallian – earliest Tortonian age, depending on the biozonation. The top of the Bolderberg Formation in the Neeroeteren well is perhaps of the same age, but this dating requires confirmation by further study.

Parts of the Dessel Sands Member in the Mol, Retie and Oostmalle wells, the Dessel Sands Member in the Poederlee well and the greater part of the Diest Sands in the Mol, Retie and Poederlee wells have late Tortonian age. A latest Tortonian to Messinian age is attributed to the upper parts of the Diest Sands in the Mol, Retie and Poederlee wells and to the entire Diest Sands in the Oostmalle and Kalmthout wells. The recognition of the Aum Zone confirms a Late Miocene age for the greater part of the Diest Formation. The Mch Biozone points to a Zanclean age for the Kasterlee Sands in the Mol well. The age of the Kattendijk Sands in the Kalmthout well has been discussed by Louwye & Laga (1998).

Discussion

Vandenberghe et al. (1998) advocated the hypothesis that the base of the incision of the gully can be correlated with sequence boundary 10.5 (Haq et al. 1987), corresponding with a major sea-level lowstand at the beginning of the Late Miocene. The ages of the studied upper section of the Berchem Formation give an oldest possible age for the base of the incision of the gully and do not contradict the hypothesis. The reworked dinocyst assemblage from the Middle Miocene in the very base of the Dessel Sands Member in the Oostmalle well could be indicative of a lowstand systems wedge. However, the oceanic *Impagidinium* and *Nematosphaeropsis* species are already recorded just above the very base of the Diest Formation of the Oostmalle well and throughout this formation in the Kalmthout well. These species, even in very small

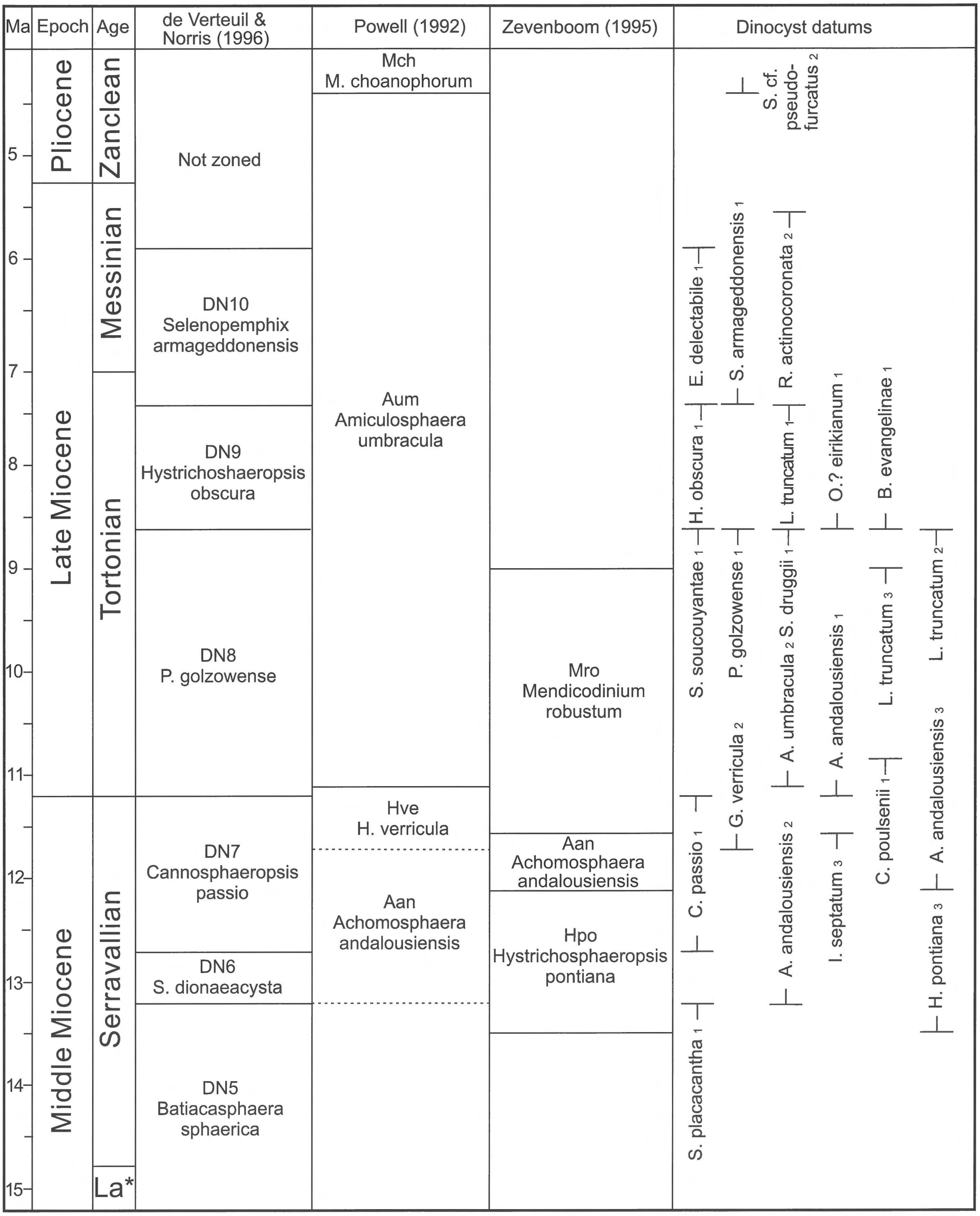

Figure 7. Chronostratigraphical position of the biozonations of De Verteuil & Norris (1996) (Atlantic Coast, U.S.A.), Powell (1992) (North Sea Basin) and Zevenboom (1995) (Mediterranean, Italy). Timescale after Berggren et al. (1995). Selected dinocyst datums (highest and lowest occurrences). [1] Occurrence according to De Verteuil & Norris (1996); [2] Occurrence according to Powell (1992); [3] Occurrence according to Zevenboom (1995). La*: Langhian. Dashed zonal boundaries indicate uncertainty. This chart does not attempt to demonstrate correlations among the biozones, but is meant only to highlight the chronostratigraphical position of each of the biozonations.

numbers, indicate the influence of oceanic waters (Dale 1996). Their presence in the nearshore deposits indicates that they have been swept in by oceanic currents.

Biostratigraphic evidence points out that the lower part of the Dessel Sands Member in the Mol, Retie and Oostmalle wells, with a probably late Serravallian or middle Tortonian age, is the oldest deposit of the Diest Formation. The Dessel Sands and the Diest Sands are diachronous; both lithological units display a marked younging towards the northwest. The general prograding aspect of the system supports the idea that the area of maximum deposition in the Mol area was located during the early Late Miocene in the vicinity of the gully. Once the sea level had risen sufficiently, the depocentre shifted to the shelf in the northwestern part of the study area during the late Tortonian – Messinian.

The occurrence of *Hystrichosphaeropsis obscura* (upper boundary of DN9) in the upper parts of the Diest Sands in the Mol, Retie and Poederlee wells can be important in this context, as De Verteuil & Norris (1996) considered it to be an important dinocyst horizon in the North Atlantic and Mediterranean realm. These authors and Powell (1992) reviewed its last appearance and situated it in the latest Tortonian around 7.4 Ma. The sequence boundary at the top of the Diest Sands could then be correlated with sequence boundary 5.5 of Haq et al. (1987).

The hypothesis that the Diest Formation was deposited during a short time span follows from the sedimentological nature of the unit: well preserved sand bars prograding towards the northeast and rapid infilling of the gully. The biostratigraphic evidence indicates, although the sampling resolution of the Diest Formation is relatively low (partly caused by an incomplete core recovery), that the Diest Formation was deposited during the time interval (approx. 6 Ma) from the early Tortonian to the Messinian. Furthermore, no evidence for a major sedimentation break was found hitherto in the dinocyst distribution within the Dessel and Diest Sands or between both units.

Conclusions

The Diest Formation contains moderate and well preserved dinocyst assemblages. Biozones defined in the North Sea Basin, along the eastern coast of the U.S.A. and in the Piedmont Basin are recognised and allow a biostratigraphical subdivision, although environmental factors must have influenced the presence of zonal key species in the marginal marine deposits of the Diest Formation. Stratigraphical diagnostic species allow to infer that the top of the underlying Berchem Formation has a Burdigalian age in the Campine area and a late Langhian to mid-Serravallian age in the Antwerp Campine area. A Tortonian to Messinian age is inferred for the Diest Formation and confirms the diachronous nature of the Diest Formation. The depocentre of the Diest Formation shifted from the Campine area towards the area north of Antwerp during Tortonian times.

Acknowledgements

P. Laga (Geological Survey of Belgium, Brussels) provided the samples for this study. His kind cooperation and the constructive discussions with him are very much appreciated. The linguistic remarks by M. Winsall (London U.K.) improved the manuscript considerably. The constructive remarks by the reviewers, G.J. Boekschoten and H. Brinkhuis, are much appreciated. The research was carried out in the framework of research project 01105098 (promotors: J. De Coninck and J. Verniers) of Gent University (Belgium).

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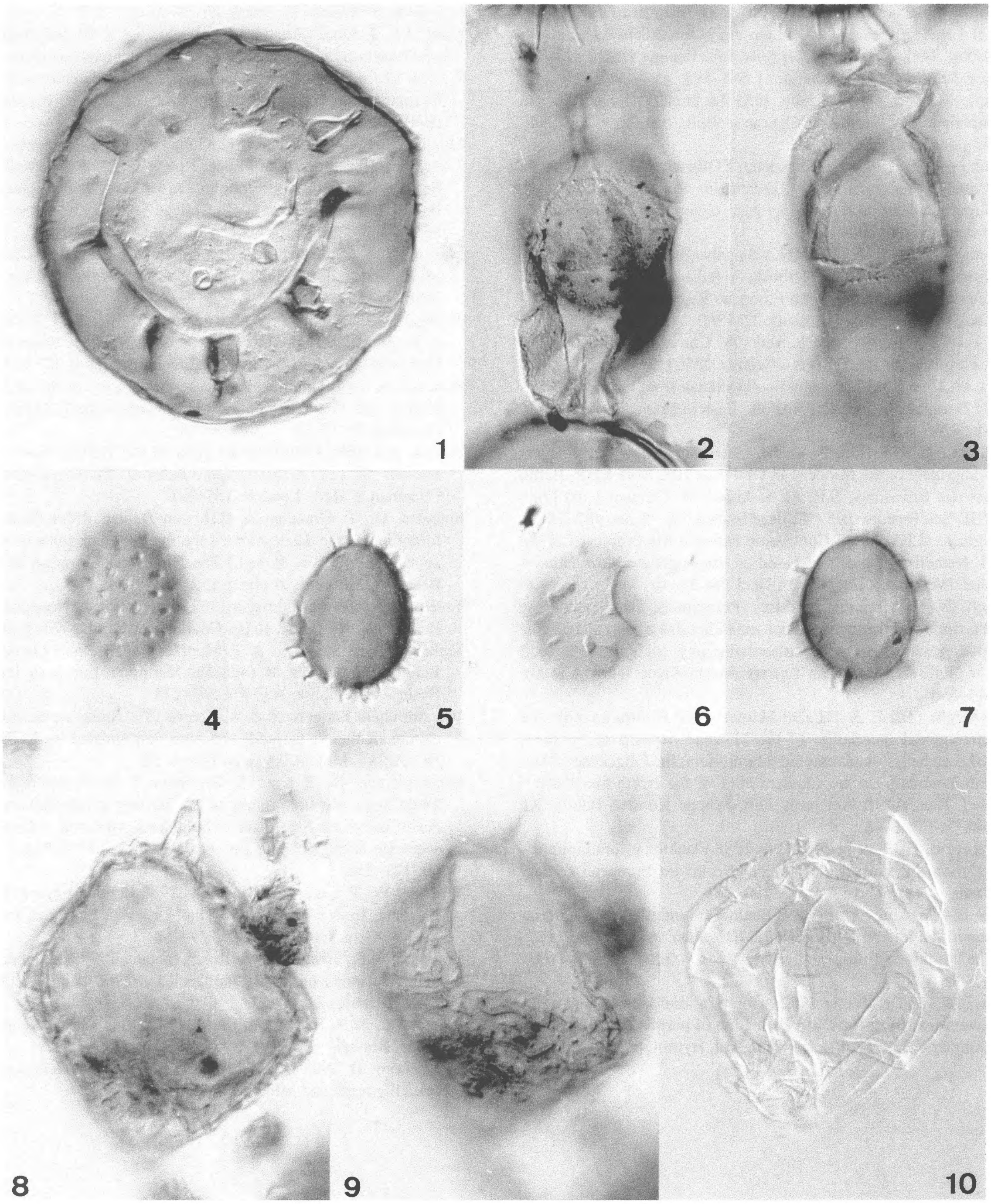

Plate 1. All magnifications × 550; various foci; well/sample/slide/England Finder coordinates. 1 (high focus): *Tuberculodinium vancampoae* (Rossignol 1962), Mol/-25/1/E40. 2 (high focus) and 3 (low focus): *Hystrichosphaeropsis obscura* Habib (1972) Mol/-25/1/C43. 4 (high focus) and 5 (medium focus): *Operculodinium piaseckii* Strauss & Lund (1992), Oostmalle/-66.5/1/D38. 6 (high focus) and 7 (medium focus): *Cerebrocysta poulsenii* De Verteuil & Norris (1996), Poederlee/-73.2/1/B51. 8 (medium focus) and 9 (high focus): *Apteodinium spiridoides* Benedek (1972), Mol/-127/P1/D40. 10 (high focus): *Amiculosphaera umbracula* Harland (1979), Poederlee/-67.2/2/F26.

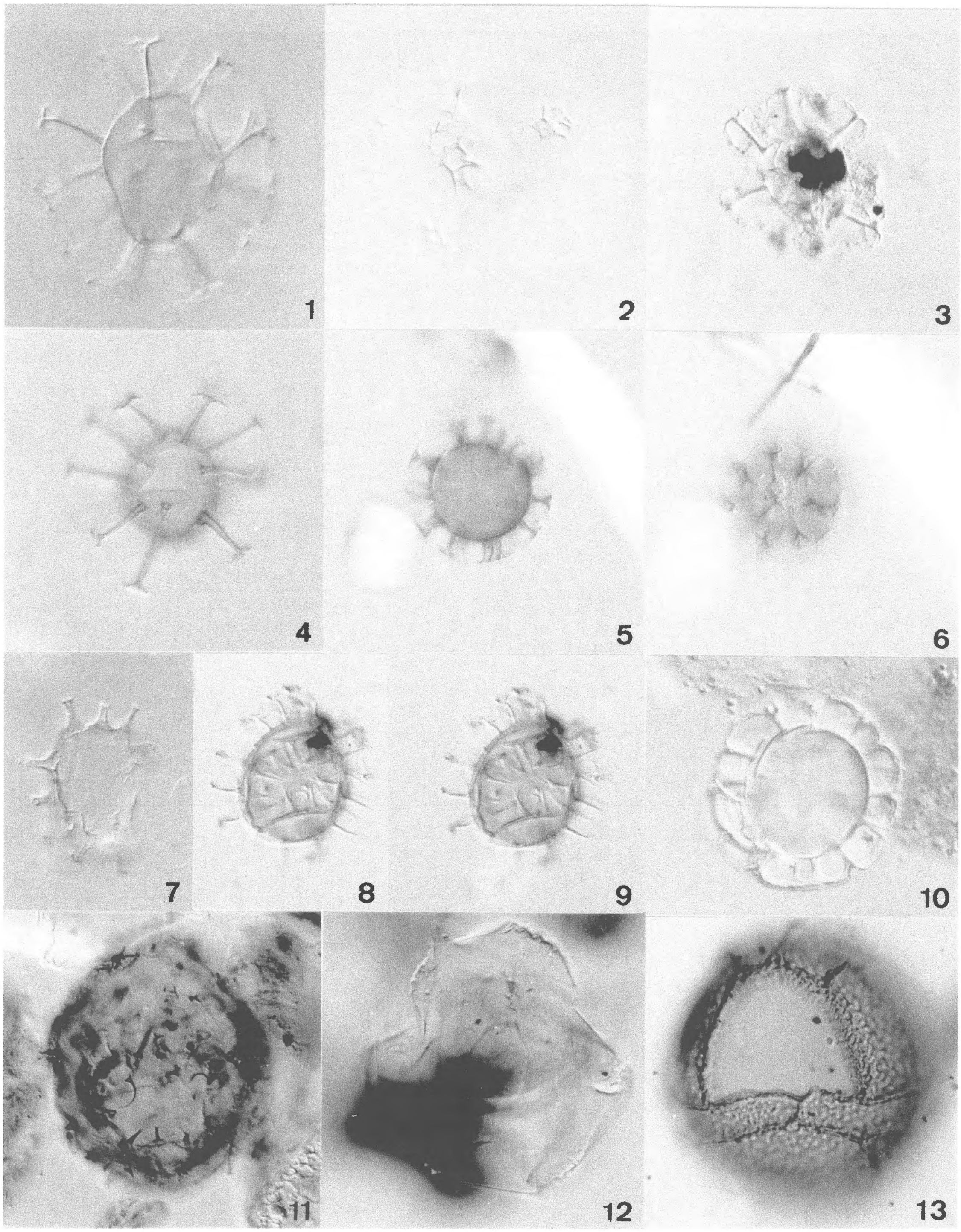

Plate 2. All magnifications × 550; various foci; well/sample/slide/England Finder coordinates. 1 (medium focus) and 2 (high focus): *Achomosphaera andalousiensis andalousiensis* Jan du Chêne (1977), Poederlee/-48.2/1/H41. 3 (high focus): *Reticulatosphaera actinocoronata* (Benedek 1972), Kalmthout/-83.5/3/K52. 4 (loew focus): *Melitasphaeridium choanophorum* (Deflandre & Cookson 1955), Poederlee/-48.2/1/G28. 5 (medium focus) and 6 (high focus): *Labyrinthodinium truncatum truncatum* Piasecki (1980), Poederlee/-48.2/1/P50. 7 (medium focus): *Polysphaeridium zoharyi* (Rossignol 1962), Neeroeteren/32.5/1/D56. 8 (medium focus) and 9 (low focus): *Operculodinium*? *eirikianum* Head et al. (1989), Kalmthout/-83.5/3/Q29. 10 (medium focus): *Unipontedinium aquaeductum* (Piasecki 1980), Oostmalle/-71.2/2/D30. 11 (medium focus): *Trinovantedinium papulum* De Verteuil & Norris (1996), Retie/-19.8/1/U31. 12 (high focus): *Cousteaudinium aubryae* De Verteuil & Norris (1996), Mol/-127/1/O47. 13 (high focus): *Impagidinium maculatum* (Cookson & Eisenack 1961), Mol/-25/1/K50.

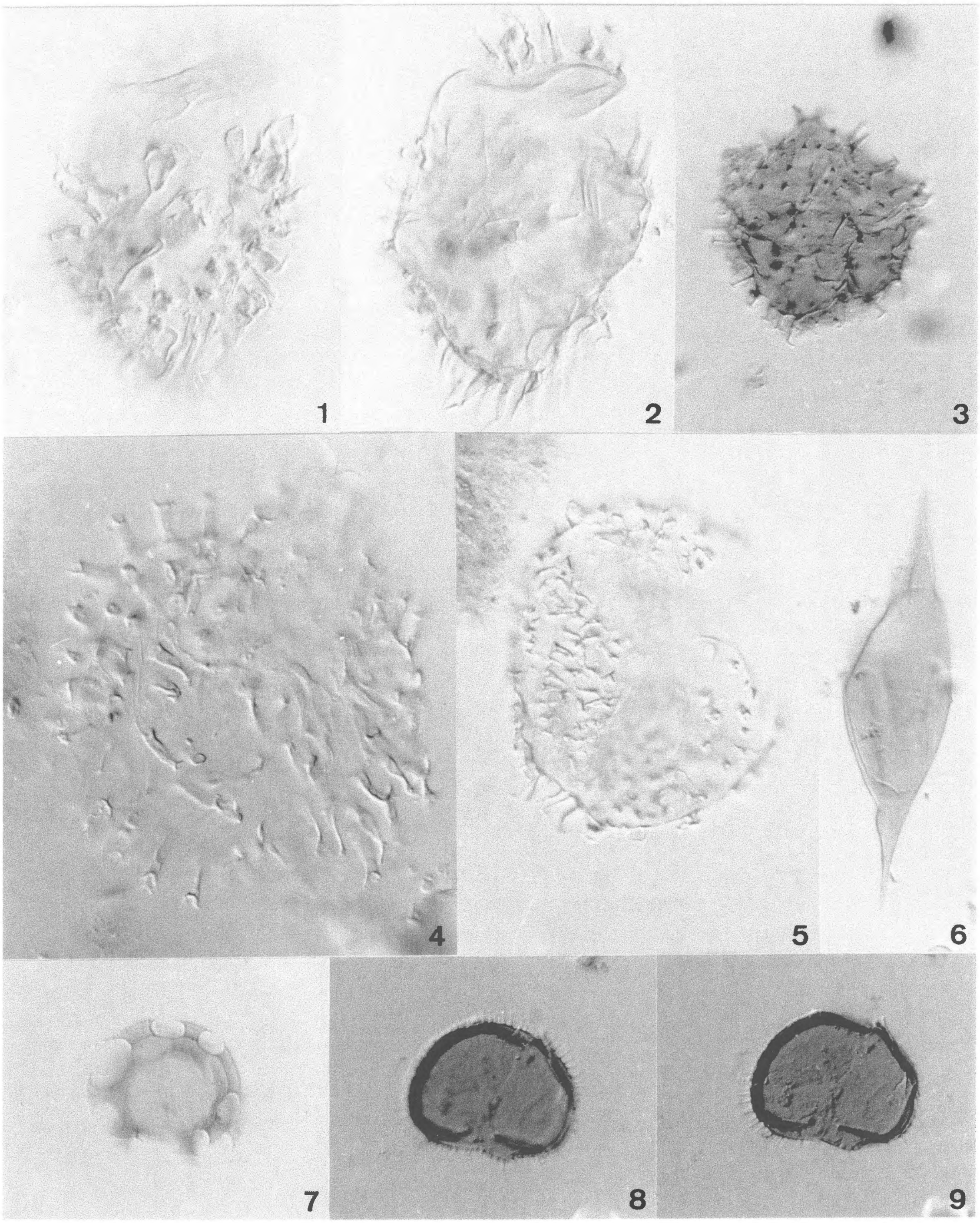

Plate 3. All magnifications × 550; various foci; well/sample/slide/England Finder coordinates. 1 (high focus) and 2 (medium focus): *Sumatradinium soucouyantae* De Verteuil & Norris (1992), Oostmalle/-71.2/2/D30. 3 (medium focus): *Trinovantedinium ferugnomatum* De Verteuil & Norris (1992), Retie/-10.3/2/S28. 4 (medium focus): *Barssidinium evangelinae* Lentin et al. (1994), Oostmalle/-71.2/2/C43. 5 (medium focus): *Sumatradinium druggii* Lentin et al. (1994), Oostmalle/-71.2/1/E46. 6 (medium focus): *Palaeocystodinium golzowense* Alberti (1961), Poederlee/-73.2/1/C41. 7 (high focus): *Selenopemphix armageddonensis* De Verteuil & Norris (1994), Retie/-10.3/1/M28. 8 (medium focus) and 9 (high focus): *Selenopemphix brevispinosa brevispinosa* Head et al. (1989), Mol/-75/1/W40.