A.A. Slupik [1] & A.C. Janse [2]
[1] Natuurhistorisch Museum Rotterdam
[2] Naturalis, Leiden

The geological record of the Breda Formation in the subsurface of the Island of Noord-Beveland (Province of Zeeland, The Netherlands) from the Colijnsplaat borehole (42G24-1): A sequence-stratigraphic approach

Slupik, A.A. & Janse, A.C., 2008 - The geological record of the Breda Formation in the subsurface of the Island of Noord-Beveland (Province of Zeeland, The Netherlands) from the Colijnsplaat borehole (42G24-1): A sequence-stratigraphic approach - DEINSEA 12: 37 - 52 [ISSN 0923-9308]. Published online 9 December 2008.

We investigate the stratigraphy of the Breda Formation of the Colijnsplaat borehole (Noord Beveland, Zeeland, The Netherlands). The formation is of Late Miocene - earliest Pliocene age. It contains two depositional sequences separated by a hiatus. The lower sequence is of the Tortonian age (Late Miocene) and the upper sequence is of Early Zanclean age (Early Pliocene). The deposits originated in the subtidal to inner neritic setting under warm temperate to subtropical conditions. The Breda Formation at Colijnsplaat is compared to the record of the Breda Formation in the south-west Netherlands (Schelphoek, Schouwen-Duiveland, Zeeland) and to the Miocene - Early Pliocene successions in the offshore at the continental platform to the north and in the Antwerp area to the south. We conclude that the record of the Breda Formation at Colijnsplaat is less complete than at Schelphoek and in the Antwerp area. The depositional sequences at Colijnsplaat correspond with middle and upper sequence of the Breda Formation at Schelphoek and with the Deurne Member and the Kattendijk Member respectively in the Antwerp area. Deposits of Middle Miocene age at Schelphoek (lowermost sequence) and in the Antwerp area (Antwerp Sands) are not present at Colijnsplaat.

Correspondence: ir A.A. Slupik*, Natuurhistorisch Museum Rotterdam, P.O. Box 23452, 3001 KL Rotterdam, The Netherlands, e-mail slupik@nmr.nl; A.C. Janse, Naturalis, P.O. Box 9517, 2300 RA Leiden, The Netherlands, e-mail acjanse@hetnet.nl. [* corresponding author]

Key words: Breda Formation, Colijnsplaat, Stratigraphy, Neogene, North Sea Basin, the Netherlands

INTRODUCTION

After a catastrophic flood in southwest Netherlands on February 1, 1953 the Dutch government launched a programme of water-control engineering works - the so-called Deltawerken to protect the coast of south-west Netherlands by means of (semi-open) storm barriers. That programme was preceded by a geological research in the scope of which hundreds of boreholes were made. The aim of the geological exploration was to establish the mechanical conditions of the subsurface of the construction locations and to investigate the hydrological conditions in the area.

The Colijnsplaat borehole (Fig. 1) is one of the boreholes executed within the framework of the Deltawerken. The succession in the Colijnsplaat borehole contains deposits from the Paleogene and later periods. Part of the record is assigned to the Breda Formation. The Breda Formation is a complex unit of

the marine Neogene deposits consisting of fine-grained to medium-grained glauconiferous sand (arenites) with calcarious, strongly sandy to moderately silty clays in some parts. The colour of the deposits is mainly green to almost black due to a high glauconite content that in some parts exceeds 50% of the sediment (Doppert *et al.* 1975; Van Adrichem Boogaert & Kouwe 1997; Weerts *et al.* 2000)

The Breda Formation is widespread in the subsurface of the Netherlands and is well represented in the south-western part of the country (Doppert *et al.* 1975; Van Adrichem Boogaert & Kouwe 1997; Weerts *et al.* 2000). However, its detailed lithostratigraphy and the stratigraphic position are rather poorly understood in the region. The Breda Formation from the Schelphoek borehole (located approximately 10 km to the north on the Island of Schouwen-Duiveland) has been recently studied by Slupik *et al.* (2007) in terms of lithostratigraphy, stratigraphic position and the depositional sequences. The position of the Colijnsplaat borehole should allow the correlation of the record of the Breda Formation between Schelphoek and Colijnsplaat and provide insight into the development of the formation in the region.

Some general geological data only concerning the deposits assigned to the Breda Formation in the borehole were reported previously by Van Rummelen (1978). He presented the lithostratigraphic data within a lithostratigraphic framework that has been drastically altered and formalized since then.

Additionally, the correlation of the stratigraphic units from the Neogene in the subsurface of the southwest Netherlands with strata from the Antwerp area to the south (Van Rummelen, 1978) added to the confusion. The units called the "Deurne Sands" and the "Kattendijk Sands" in the Antwerp area had a different stratigraphic definition in the Netherlands. The nomenclature and definition of the Belgian Neogene lithostratigraphic units has since then been improved and refined (Vandenberghe *et al.*, 1998 and references therein). Thus, their relationship with the Dutch units needs re-evaluation. The paleontological data of the borehole were so far not published. The detailed lithostratigraphic and facies description, sequence-stratigraphic and faunal accounts were also lacking.

The position of the Colijnsplaat borehole (Fig. 1) should allow a correlation between units of the Antwerp area through the delta region of southwestern Netherlands to areas located in the western Netherlands and the Dutch continental platform. The Neogene geology of the latter area has recently been investigated (Kuhlmann 2004; Kuhlmann *et al.* 2006a, 2006b), and the combination of tectonics, sea-level change and climate factors allowed the reconstruction of basin development in the North Sea since the

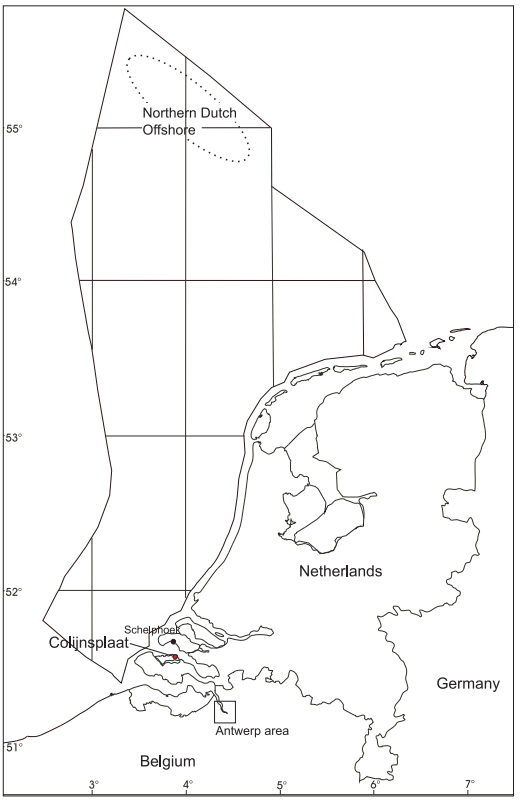

Figure 1 Location of the Colijnsplaat borehole and other areas referred to in this paper. NDO - North Dutch Offshore, study area of Kuhlmann (2004) and Kuhlmann *et al.* (2006a, 2006b). Antwerp area, study area of Vandenberghe *et al.* (1998; 2004).

Middle Miocene. Also, Miocene and Pliocene successions from the Antwerp region have recently been subject of stratigraphic studies (Vandenberghe *et al.* 1998; 2004; De Schepper 2006), drastically improving our knowledge of the ages of the various formations in that region.

The aim of this study is (1) to document the lithostratigraphy and the chronostratigraphic position of the Breda Formation in the Colijnsplaat borehole, (2) to compare the record of the Breda Formation in the Colijnsplaat borehole to the record of this formation in the Schelphoek borehole, (3) to compare the stratigraphic succession of the formation with the equivalent units in the Antwerp area to the south and those of the Dutch continental platform to the north and (4) to construct a sequence-stratigraphic framework for the deposits.

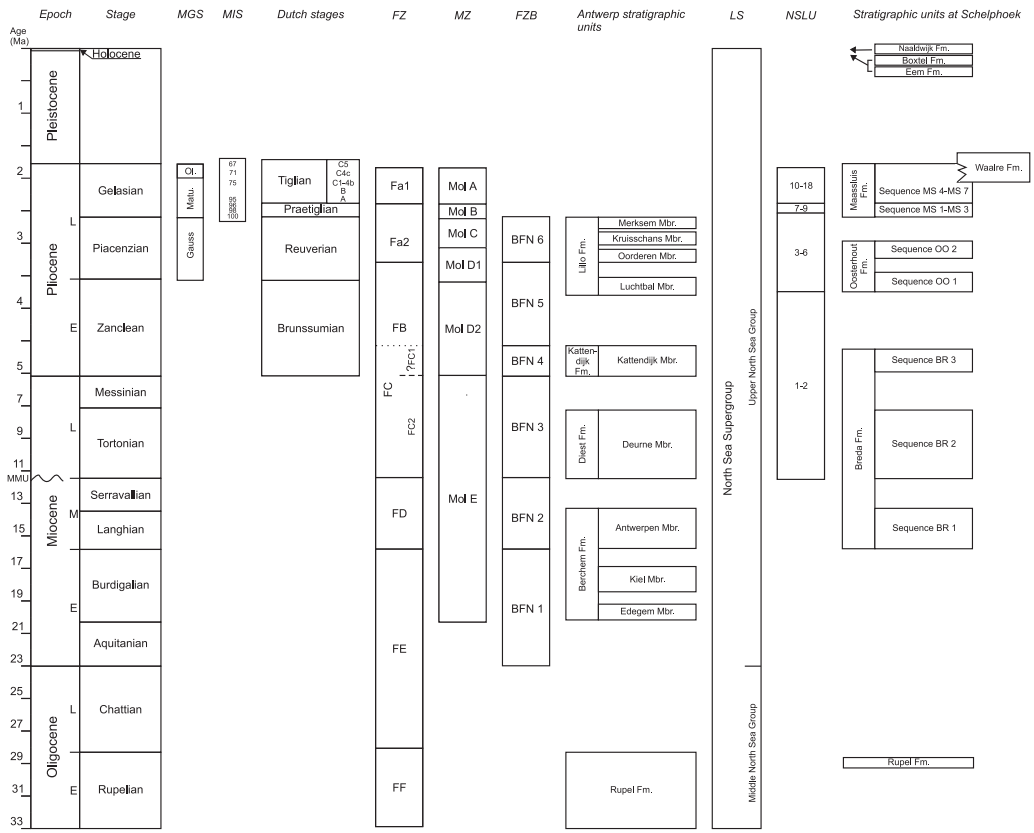

Figure 2 Stratigraphic framework for Neogene - Quaternary successions in the southern North Sea (from Slupik *et al.*, 2007). Note scale change at 5 Ma. MMU - Middle Miocene Unconformity. MGS refers to magnetostratigraphy: Ol. - Olduvai, Matu. - Matuyama. MIS refers to marine isotope stages (after Kuhlmann, 2004). Dutch stages according to Zagwijn (1985). FZ refers to benthic foraminifera zones of Doppert (1980) and Doppert & Neele (1983). MZ refers to mollusc zones from Spaink (1975). FZB refers to benthic foraminifera zones in Belgium as in Doppert *et al.* (1979). NSLU (= North Sea Logstratigraphical Units) refer to seismic units from the northern part of the Dutch North Sea (Kuhlmann, 2004; Kuhlmann *et al.,* 2006a, 2006b). The stratigraphic units of the Antwerp region have been adapted from Vandenberghe *et al.* (1998, 2004). LS (= Lithostratigraphic Subdivision) according to Van Adrichem Boogaert & Kouwe (1997). Formations names in the Colijnsplaat and Schelphoek areas follow Weerts *et al.* (2000). Stratigraphic units at Schelphoek are adopted from Slupik *et al.* (2007). Fm. = Formation; Mbr. = Member. Note the uncertain position of the sub-zone FC1 within the scheme (as mentioned in the paper).

GEOLOGICAL SETTING

The study site is located on the northern part of the Island of Noord-Beveland in the southwest Netherlands (Province of Zeeland; Fig. 1). The area is located on the southern margin of the North Sea Basin near the northern flank of the Brabant Massif, in the region where strata from the Paleogene onwards are present at shallow depth and where the Neogene is well represented. It is a transitional area between thick and complete Neogene successions to the north (e.g. Kuhlmann et al. 2006a, 2006b) and incomplete, often partly eroded successions towards the south (Vandenberghe *et al.* 1998; 2004).

During Late Cenozoic times, the North Sea Basin was part of the north-west European Basin that covered the present-day offshore and part of onshore Netherlands, Germany and Denmark. The basin was confined by landmasses in the south and east and England and Scotland to the west. Towards the northwest it was connected to the Atlantic and short-lived connections through the English Channel area occurred (Ziegler 1990).

A large delta system prograded progressively into the North Sea from the east, mostly by rivers draining the Fennoscandian Shield and the Baltic Platform (Bijlsma 1981; Overeem *et al.* 2001; Kuhlmann *et al.* 2006a, 2006b). Coeval subsidence created considerable accommodation space that was filled with these siliciclastic deposits reaching a thickness of approximately 3000 m in the depocentre (Ziegler 1990; Kuhlmann 2004).

The Neogene onwards succession in the south-west Netherlands (at Schelphoek on Schouwen-Duiveland, Zeeland) has been documented recently by Slupik *et al.* (2007). The record of the Breda Formation [North Sea Group, part of the North Sea Supergroep (Van Adrichem Boogaert & Kouwe 1997) (Fig. 2)] therein consists of siliciclastic, glauconifereous sediments and is 27,5 metres thick. It contains three depositional sequences, of Middle Miocene, Late Miocene and Early Pliocene age, separated by hiatuses (Fig. 2). The deposits in this part originated in the

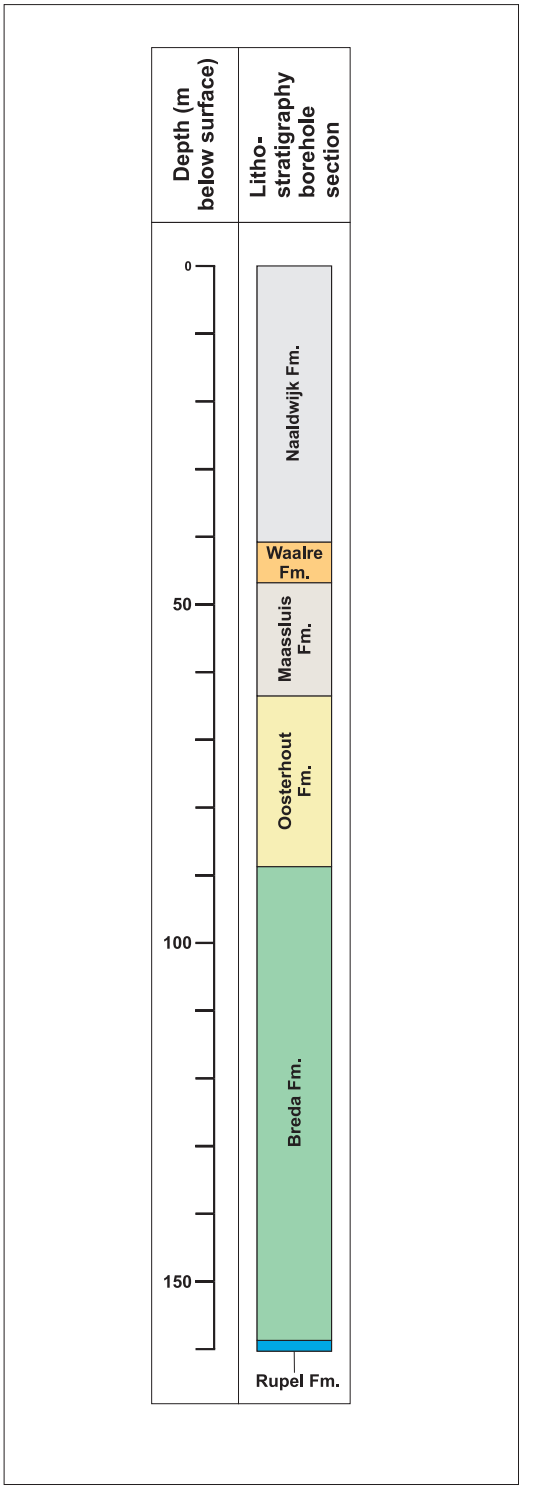

Figure 3**a** Schematic lithostratigraphy of the borehole section. Formation (Fm.) names follow Weerts *et al.* (2000).

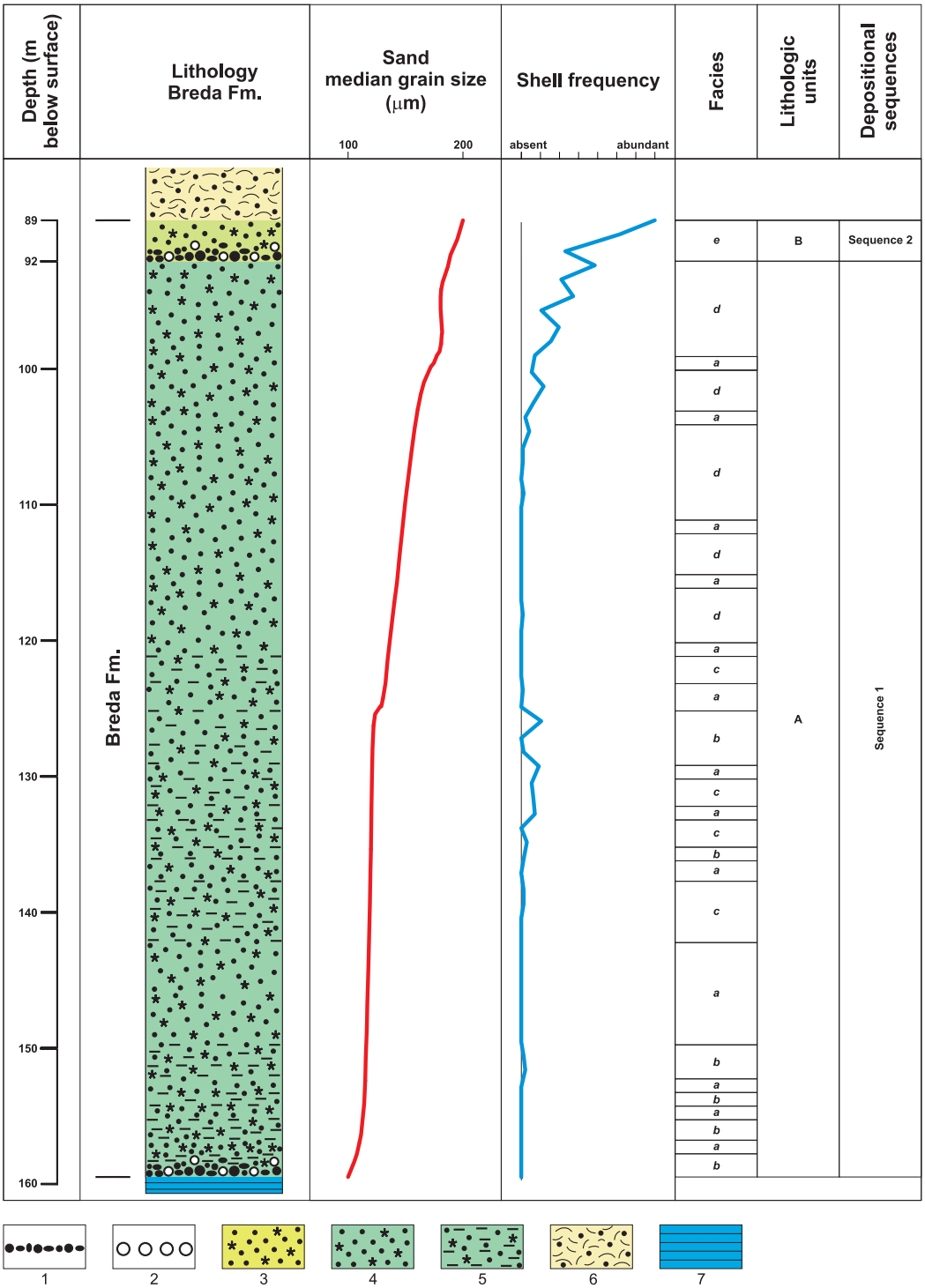

Figure 3**b** Lithostratigraphic framework of the Breda Formation in the Colijnsplaat borehole. Shell abundance estimated from sediment samples (shell fragments > 1mm, surface 40 cm^2) in eight classes (absent, 1-5 fragments/shells; 5-20, 20-50, 50-100, 100-500, more than 500 but less than 90% of the residue, more then 90% of residue). **1** - phosphorite pebbles; **2** - pebbles; **3** - sand with glauconite; **4** - glauconitic sand; **5** - silty sand; **6** - shelly sand (Oosterhout Formation); **7** - clays (Rupel Formation).

relatively shallow basin (tenths of metres), within a subtidal to inner neritic setting with prevailing warm temperate to subtropical climate conditions.

The Middle Miocene onwards successions above the Mid-Miocene Unconformity (cf. Huuse & Clausen 2001) (Fig. 2) of the Dutch sector of the North Sea have been documented lately (Kulhmann 2004; Kuhlmann *et al.* 2006a, 2006b). The Middle to Late Miocene intervals are thin (order of tens of m). The sedimentation rates increased in the Piacenzian and led to the deposition of hundreds of metres thick Late Pliocene and Early Quaternary successions overlying the Miocene deposits. Within the succession five paleo-environmental intervals were proposed by Kuhlmann *et al.* (2006b). The lowermost interval (logunits 1-5 of Kuhlmann *et al.* 2006b) covers the late Middle Miocene - Late Piacenzian (Fig. 2). The North Sea Basin was a part of a relatively deep epicontinental basin with a well mixed and ventilated water column under warm climate conditions.

Insights into the stratigraphy of Neogene successions of the Antwerp region south of the Colijnsplaat borehole (Fig. 1) have been improved in the past few years (Vandenberghe *et al.* 1998; 2004; Louwye *et al.* 2004; De Schepper 2006). The succes-

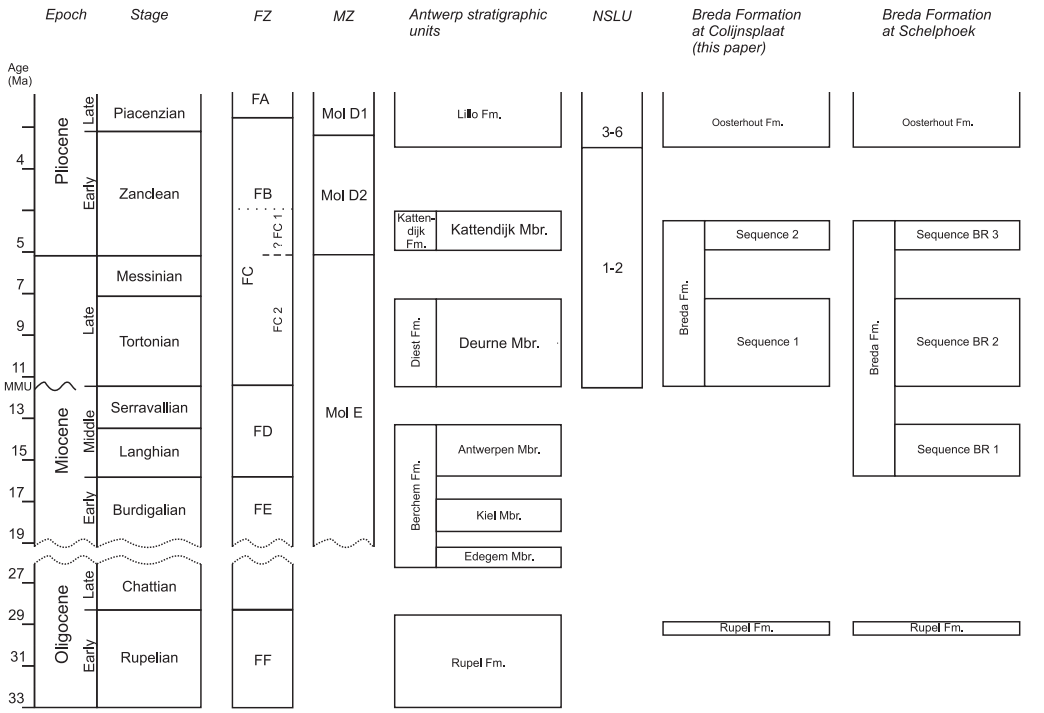

Figure 4 Position of the Breda Formation at Colijnsplaat within the stratigraphic framework for Neogene deposits in the southern North Sea. Note scale change at 5 Ma. Geologic time scale follows Gradstein *et al.* (2004); MMU – Middle Miocene Unconformity. FZ refers to benthic foraminifera zones of Doppert (1980) and Doppert & Neele (1983). MZ refers to mollusc zones from Spaink (1975). NSLU (= North Sea Logstratigraphical Units) refer to seismic units from the northern part of the Dutch North Sea (Kuhlmann, 2004; Kuhlmann *et al.*, 2006a, 2006b). The stratigraphic units of the Antwerp region have been adapted from Vandenberghe *et al.* (1998, 2004). Breda Formation at Schelphoek is adopted from Slupik *et al.* (2007). Formations names in the Colijnsplaat and Schelphoek areas follow Weerts *et al.* (2000). Fm. = Formation; Mbr. = Member. Note the uncertain position of the sub-zone FC1 within the scheme (as mentioned in the paper).

sion consists of fossiliferous fine siliciclastic intervals that presumably represent highstand snapshots and are separated by regional hiatuses (Vandenberghe *et al.* 1998, 2004). Several units have been recognised that cover the Miocene up to the Early Pliocene (Vandenberghe *et al.* 2004) (Fig. 2). The Miocene units and the Zanclean Kattendijk Formation are predominantly composed of glauconitic sands and represent deposition under warm temperate to subtropical conditions.

The improved insights into the Neogene climate and geography of the North Sea Basin were made possible by improved stratigraphic insights based on dinoflagellate cysts and magnetostratography (Vandenberghe *et al.*, 2004; De Schepper 2006; Kuhlmann 2004 for review and references) that have added significantly to the earlier pollen-based biozonation schemes of Zagwijn (1985). Planktonic foraminifera species are mostly absent in Neogene and Quaternary deposits of the southern North Sea, and most correlations were consequently based on benthic organisms (foraminifera: Doppert 1980; Doppert *et al.* 1979 and molluscs: Spaink 1975). Correlations between different areas suffer from strong environmental control over the occurrence of species (water depth, temperature). A revised stratigraphic framework for the deposits is presented in Figure 2.

MATERIAL AND METHODS

The Colijnsplaat borehole (Deltadienst 42G24-1= NITG 42G0040; coordinates RDX 47.480; RDY 401.747) was drilled in 1967 with a bailer sampler. Ground level was 1.10 m above mean sea level (NAP). The borehole reached a depth of 160.80 m below the surface. 154 samples were taken at approximately one-metre intervals, yielding 1.5-2.5 kg material each. 63 samples covering the Breda Formation have been studied. Residues are stored in the Natural History Museum Rotterdam (NMR) and at the National Museum of Natural History 'Naturalis', Leiden. All samples were visually and microscopically examined. Lithological descriptions follow procedures outlined in Bosch (1999). Grain-size ranges follow the grain-size classification scale of Wentworth (1922). Molluscs were picked from c. 1 kg wash residues (sieve mesh 1 mm). The molluscan zonation of Spaink (1975; figure 2) is followed. The original foraminifer analyses presented by Van Rummelen (1978) are included in this study. Additionally, the samples were investigated by the first author for the occurrence of foraminifer species. The foraminiferal zonation of Doppert (1980) is followed (Figs. 2 & 4). The exception is the age assignment of the zone FC1 (Miocene) of Doppert (1980) (Figs. 2 & 4). Doppert *et al.* (1979) correlate zone FC1 with the Belgian BFN4 zone that is established in the Kattendijk Formation of the Antwerp region. According to this correlation, the Kattendijk Formation should be of a Miocene age. However, an Early Pliocene age for the Kattendijk Formation is now well established (Vandenberghe *et al.*, 1998, 2004; De Schepper, 2006). Therefore, the FC1 zone of Doppert (1980) and Doppert & Neele (1983) should either be placed within or include the Early Pliovene (Figs. 2 & 4).

The lithostratigraphic definitions (formation names) follow Doppert et al. 1975; Van Adrichem Boogaert & Kouwe 1997; and Weerts *et al.* 2000). The depths are given in metres below surface (m b.s.).

RESULTS

Six formations are recognised in the record of the Colijnsplaat borehole (Fig. 3a). The scope of this paper is focused on the Breda Formation. Other formations in the borehole are briefly characterised (bottom up). Lithostratigraphic framework of the Breda Formation in the Colijnsplaat borehole is presented in Figure 3b and the position of the formation within the stratigraphic framework for Neogene deposits in the southern North Sea is presented in Figure 4.

Table 1 Sediment properties of the Breda Formation in the Colijnsplaat borehole. MGSF - Median grain size of sand fraction.

Facies	Facies properties	MGSF (µm)	Depth (m)	Interpreted environment
a	Dark green-black, very fine-grained to fine-grained, slightly silty, glauconitic arenites with a very few small shell fragments	100-140	99.00-100.00 103.00-104.00 111.00-112.00 115.00-116.00 120.00-121.00 123.00-125.00 129.00-130.00 132.00-133.00 136.00-137.50 142.00-149.50 152.00-153.00 154.00-155.00 156.50-157.50	Inner neritic, subtidal setting, very slow sediment supply from the sources within the basin, impoverished fauna
b	Dark green, very fine-grained to fine-grained strong silty glauconitic arenite	120-130	125.00-129.00 135.00-136.00 149.50-152.00 153.00-154.00 155.00-156.50 157.50-159.20	Inner neritic, subtidal setting, very quiet environment, very slow sediment supply, impoverished fauna
c	Dark brown-green, fine-grained, silty, glauconitic arenite with some shell fragments	<180	121.00-123.00 130.00-132.00 133.00-135.00 137.50-142.00	Inner neritic, subtidal setting, very slow sediment supply, impoverished fauna
d	Dark brown to green, fine-grained silty glauconitic arenites, common fine gravel, few shell fragments and phosphoritic pebbles	210-220	92.00-99.00 100.00-103.00 104.00-111.00 112.00-115.00 116.00-120.00	Subtidal offshore below storm wave base, periodic weak bottom currents, impoverished fauna
e	Grey-green, fine-grained silty glauconitic arenites with abundant very fine shell debris; rare fine gravel and phosphoritic pebbles	210-220	89.00-92.00	Subtidal offshore below storm wave base, periodic currents or winnowing, rich fauna (epi- and in-fauna)

Rupel Formation (159.20 - 160.30 m) Dark-grey to dark-green (silty) clays, with some fine-grained sand. Only the uppermost part (1.10 m) of the formation is reached in the borehole.

Breda Formation (89.00 - 159.20 m) See below.

Oosterhout Formation (63.50 - 89.00 m) Grey-yellow to grey-white, fine-grained to medium-grained arenite with some glauconite and a very high amount of shell fragments and fine shell debris (biocalcarenite) in the lower part, dark brown-grey, fine-grained to medium-grained very silty arenite with some shell fragments in the middle part and light brown-grey, fine-grained to medium-grained, silty arenite with common fine shell debris and some coarser shell fragments in the upper part.

Maassluis Formation (46.00 - 63.50 m) Brown-grey clays and sandy clays in the lower part and light-grey, fine-grained to medium-grained sands in the upper part. Shells are common to very common and are often strongly worn.

Waalre Formation (41.00 – 46.00 m) Light-grey, fine-grained to medium-grained sands and silty sands. No fossils.

Naaldwijk Formation (0.00 – 41.00 m) Light-grey, fine-grained to medium grained sands alternating with silty sands. Shell fragments present.

The record of the Breda Formation in the Colijnsplaat borehole is 70.20 m thick, from 89.00 to 159.20 m b.s. The formation is underlain by the deposits of the Rupel Formation and overlain by the deposits of the Oosterhout Formation.

The lower boundary is very sharp. The lithology changes abruptly from tough dark green-grey clays of the Rupel Formation below to the sandy glauconitic deposits of the Breda Formation above.

The upper boundary is sharp as well. The lithology changes from (dark) green sandy glauconitic deposits of the Breda Formation into the light grey-whitish, very shelly calcarenite (biocalcarenite) of the overlying Oosterhout Formation.

The deposits of the Breda Formation in the Colijnsplaat borehole consist of dark green-black to green-brown, very fine-grained to fine-grained glauconite sands with minor amounts of silty sands. Glauconite grains are usually (sub-) angular and small-sized (typical diameter is 200 – 220 μm). The deposits of the Breda Formation are heterogeneous. Five lithologic types are recognised that occur repeatedly within the succession (Table 1 & Fig. 3b). Deposits of the Breda Formation originated in the marine environment within the inner neritic, and mainly represent a subtidal, shallow setting (Van Adrichem Boogaert & Kouwe, 1997; Weerts *et al.*, 2000). In view of this varied sediment types could be referred to as the facies (Table 1).
Two distinct lithostratigraphic units are defined here identified bottom up as A and B (Fig. 3b).

Unit A

The lower unit A (92.00 - 159.20 m) is heterogeneous. In the lower part (120.00 – 159.20 m) it consists of dark green-black, very fine grained to fine grained, slightly silty glauconitic arenites (facies *a*), dark green, very fine grained to fine grained, very silty glauconitic arenites (facies *b*) and dark brown to green, fine-grained, very silty, glauconitic arenites (facies *c*). At the base, fine gravel occurs consisting of sandstones and phosphorite pebbles. In the lower part of the unit A the facies *a* and *b* alternate regularly. Facies *c* is present at 4 depth intervals from 142 m to the top of the unit. The facies are mainly 1 to 2 m thick within the unit except for the uppermost part where facies a reaches largest thickness of 7.50 m (142.00 – 149.50 m).

The upper part of the unit A (92.00 – 120.00 m) is composed of regularly alternated

Table 2 Occurrence of selected mollusc taxa in the record of the Breda Formation in the Colijnsplaat borehole. Black = present.

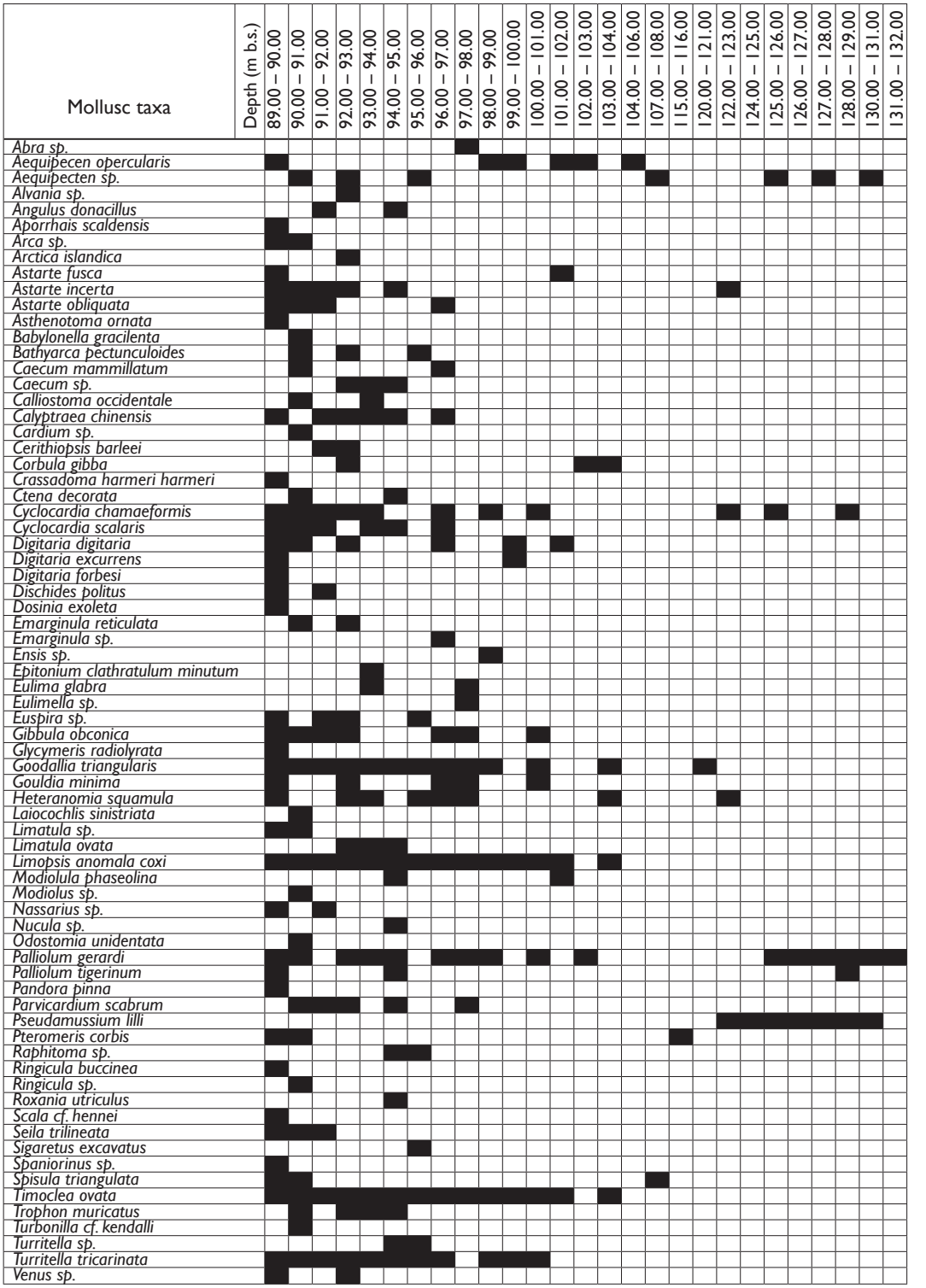

Table 3 Occurrence of selected foraminifer taxa in the record of the Breda Formation in the Colijnsplaat borehole. Black = present.

Foraminifer taxa	Depth (m b.s.) 91.00 - 92.00	92.00 - 93.00	96.00 - 97.00	123.00 - 124.00	152.00 - 153.00
Cassidulina carinata	■				■
Cassidulina laevigata		■			
Cibicides cookei				■	
Cibicides lobatulus	■	■	■	■	
Cribroelphidium arcticum	■				
Elphidium crispum	■				
Elphidium sp.	■				
Eponides umbonatus				■	
Florilus boueanus			■	■	
Globigerina bulloides			■		
Globigerina sp.	■				
Globulina paucicrassicosta	■				
Heterolepa dutemplei	■	■	■	■	■
Heterolepa pseudoungeriana			■	■	
Melonis affine				■	
Oolina cf. acubicoasta			■		
Oolina coastata	■		■		
Oolina seminula			■		
Pullenia bulloides		■		■	
Pyrgo depressa	■				
Quinqueloculima sp.		■			
Quinqueloculina seminula	■				
Siphotextularia sculpturata		■	■		■
Spiroloculina schlundbergi	■				
Textularia sagittula		■			
Textularia truncata		■			
Triloculina sp.		■			
Uvigerina hosiusi			■		■

deposits of facies *d* (dark brown to green, fine-grained silty glauconitic arenites) and facies a (dark green-black, very fine grained to fine grained, slightly silty glauconitic arenites). The thickness of facies is mainly 1 m to a few m except in the uppermost part where the facies *d* is 7 m thick.

Unit B

Upper unit B (89.00 - 92.00) is homogeneous. It consists of grey-green, fine-grained, silty, glauconitic arenites with abundant very fine shell debris. The lowermost part contains fine gravel (flints and sandstones) and fine phosphorite pebbles.

The glauconite grains within the sediments in both units are mainly sub-rounded to sub-angular, have mainly an irregular shape and seem to have a fresh nature. Grain size of the glauconite grains is usually in the range of 200 - 220 µm. These properties suggest that glauconite within the whole succession is autochthonous.

Shell content varies within the record (Fig. 3b). In the lower part some shells only and shell fragments occur. Herein the shells are mostly worn and appear to be decalcified. Within unit A small gypsum crystals are very common. The calcium ions of gypsum crystals have been probably sourced from the decalcified and dissolved shells and the sulphur has been sourced from iron - sulphur compound (pyrite) often present within the bottom sediment. In the uppermost part of the unit the shells are common. In addition to the molluscs the annelids, bryozoans and echinoid spines are very common in the uppermost part. Mollusc taxa are listed in Table 2.

Two depositional sequences could be recognised within the record of the Breda Formation (Fig. 3b & 4). Lower sequence is present from 92.00 to 159.20 m and comprises the unit A. Rounded phosporitic pebbles occur in the basal part. The abundance of fine-grained gravel (consisting of phosphorite pebbles and sandstones) in this sequence suggests shallow depositional depths and the proximity of terrestrial sources or strong winnowing water currents. The fresh nature of the glauconitic grains suggests low sedimentation rates (Reading 1996), and rules out substantial terrigenous input. The deposits originated generally in the inner neritic to subtidal environment. However the cyclical alternation of facies suggests some periodic changes of the water energy in a basin presumably due to periodic influences of the weak (tidal?) currents. A general environmental trend seen in this sequence is coarsening up. Deposits in the upper part of the unit A are slightly coarser than sediments in the lower part. The coarsening up could reflect the general trend of shallowing of the basin in this part due to regression or progradation.

A mollusc fauna is found between 92.00 and 132.00 m. The interval from 120.00 to 132.00 m (middle part of the unit A) yields following characteristic species: *Palliolum tigerinum*, *Palliolum gerardi* and

Pseudamussium lilli. In the interval from 92.00 to 120 m the mollusc association is richer than below and yields following characteristic species: *Aequipecten opercularis*, *Digitaria digitaria*, *Cyclocardia chamaeformis*, *Limopsis anomala coxi*, *Goodallia triangularis*, *Timoclea ovata*, *Palliolum gerardi* and *Turritella tricarinata*. These species prefer fine grain substratum and quiet environmental conditions. These mollusc assemblages indicate inner neritic to subtidal setting within warm temperate to subtropical temperatures.

The mollusc assemblage could be attributed to the mollusc zone Mol E of Spaink (1975) corresponding with the Late Miocene. However, it must be taken into account that the age indications using molluscs are by approximation. Most of the Cenozoic bivalve species has a large longevity and therefore are not suitable for more detailed biostratigraphy. Marquet (2004) quotes the calculated average longevity of the mollusc taxa from Doel and Kallo sites in Belgium for more than 10 Ma but some species even ranged from 10 to 20 Ma.The species *Pseudamusium lilli* could be indicative for the Late Miocene. Other species present are known from the Miocene - Pliocene and even younger deposits around the southern North Sea Basin (Marquet 2002, 2004, 2005).

Foraminifer content (Table 3; Van Rummelen 1978) including species *Uvigerina hosiusi*, *Eponides umbonatus*, *Florilus boueanus* and *Siphotextularia sculpturata* could be attributed to the zone FC (*Siphotextularia sculpturata* - *Uvigerina hosiusi* zone) of Doppert (1980). It indicates a Tortonian-Messinian (Late Miocene) age.

Upper sequence is present from 89.00 to 92.00 m and comprises the unit B. Basal fine-grained gravel (flint and sandstones) with some phosphorite pebbles marks the bottom of this sequence. A varied mollusc fauna characterised by *Astarte fusca*, *Astarte incerta*, *Astarte obliquata*, *Odostomia unidentata*, *Bathyarca pectunculoides*, *Limopsis anomala coxi*, *Cyclocardia scalaris* and *Goodallia triangularis occurs* (Table 2). These taxa are infaunal species and required fine-grained sediment and quiet environmental conditions. Mollusc assemblage could be attributed to the MOL D2 (*Palliolum gerardi* - *Astarte trigonata*) zone, that indicates Zanclean age. Foraminifer content (Table 3; Van Rummelen 1978) including species *Heterolepa dutemplei*, *Cibicides lobatulus* and *Textularia sagittula*, is characteristic of the zone FB (*Textularia decrescens* - *Bulimina aculeata* zone) (Doppert 1980), corresponding to a Zanclean - Early Piacenzian (Early Pliocene) age. The abundance of apparently autochthonous glauconite, together with common epifaunal taxa (annelids, bryozoans, echinoderms) implies the upper sequence of the Breda Formation at Colijnsplaat to have been predominantly deposited in subtidal settings in a warm temperate to subtropical climate with relatively low sedimentation rates.

The bathymetry of the depositional setting could not be assessed exactly on basis of the mollusc assemblages due to scarce data and because most of the species present (Table 2) had a large tolerance with regard to water depth and occur within a wide bathymetric range. However, some estimation could be done to get general indications of the bathymetry using molluscan species.

A lot of species in the record of the Colijnsplaat borehole are also known from the Neogene sections in the Antwerp area in Belgium (Fig. 1) (Marquet 1998, 2002, 2004, 2005). Bathymetry of various lithostratigraphic units therein had been assessed by means of molluscs (see for methodological approaches Marquet, 2004; 2005). The species *Palliolum tigerinum*, *Palliolum gerardi* and *Pseudamussium lilli* present at Colijnsplaat in the interval 120.00 - 132.00 m, occurs in the Antwerp record within two lithostratigraphic units deposited at (calculated) water depths of 50 - 70 m and 40 - 60 m. Species present at Colijnsplaat (Table 2) in the upper part of the unit A (92.00 - 120.00 m) and in the unit B (89.00 - 92.00 m) occur in the Antwerp area in units deposited at (cal-

culated) depths of 40 - 60m (Marquet 2004). By comparing the mollusc assemblages from Colijnsplaat and the Antwerp area, the suggestion can be made that the bathymetry of the depositional setting at Colijnsplaat has been in the range of 40 - 50 - 60 m, taken into account that different (litho)stratigraphic units are concerned at the Colinsplaat borehole and in the Antwerp area and indicated depth ranges are with approximation.

DISCUSSION

The lower boundary of the Breda Formation at Colijnsplaat is marked by the occurrence of a gravel layer with phosphorite pebbles. Phosphorite pebbles occur in the lowermost part of the unit B as well. Phosphorite pebble lags have been documented from large parts of the province of Zeeland in deposits we assign to the Breda Formation (Van Rummelen 1970; 1978). Van Rummelen (1970) suggests that the phosphorite records from the Island of Schouwen-Duiveland (directly to the north of the present study area) are non-conformable with respect to lithostratigraphic unit boundaries. However, the interpretations of the phosphorite layers from the subsurface of the Island of Beveland (Van Rummelen 1978) did show that the phosphorite layers are bounded to the lower boundaries of the lithostratigraphic units and are a regional feature. A recent study by Slupik *et al.* (2007) on the Neogene - Quaternary succession at Schelphoek on the Island of Schouwen-Duiveland confirms this. Therein, the sequences recognised in the Breda Formation are marked by phosphorite pebbles layer at the bottom of each sequence. The regional significance of the phosphorite layers within the basin and their presence at the bottom of the depositional sequences is also suggested by Balson (1987).

The Breda Formation at Schelphoek on the Island of Schouwen-Duiveland contains three sequences (Slupik *et al.* 2007). The sequences are of Langhian age (Middle Miocene), Tortonian age (Late Miocene) and Early Zanclean age (Early Pliocene), respectively. The lower sequence at Colijnsplaat is of Late Miocene age (contains Miocene molluscs and foraminifers of the zone FC) and therefore could be correlated with the middle sequence (BR 2) at Schelphoek. The thickness of both sequences differs significantly. At Schelphoek the sequence BR 2 has a thickness of 7 m while the sequence 1 at Colijnsplaat is 67.20 m thick. It is uncertain whether the deposits at Schelphoek are partly eroded, leaving only the lower part only of the sequence. It is impossible to state with certainty what the reason of the observed discrepancy is.

The upper sequence at Colijnsplaat is of Zanclean age (Early Pliocene) ('Early Pliocene' mollusc assemblage and foraminifers characteristic of the zone FB) and correlates with the uppermost sequence (BR 3) at Schelphoek.

Several lithostratigraphic units occur in the Antwerp area in Belgium (area south of the present study area) within the Miocene - Early Pliocene succession (Vandenberghe *et al.* 1998 & 2004). These units (Formations and members; see Fig. 2) represent depositional sequences separated by hiatuses. The latest Middle Miocene to Late Miocene is represented by the Deurne Member of the Diest Formation and the Early Pliocene is represented by the Kattendijk Member of the Kattendijk Formation. In view of this the lower sequence at Colijnsplaat with its Miocene fauna should be correlated with the Deurne Member and the upper sequence at Colijnsplaat with its undoubtedly Early Pliocene (Zanclean) fauna assemblages should be seen as an equivalent of the Kattendijk Member in Belgium.

The record of the Breda Formation at Colijnsplaat could be also 'time connected' to the succession located to the north - in the north part of the Dutch sector of the North Sea. Two sequences (sequence 1 and 2) of the Breda Formation in the borehole correspond to logunits 1 and 2 of Kuhlmann *et al.* (2006a, 2006b). At that time (late Middle Miocene - Middle Zanclean) the North Sea was a relatively deep epicontinental basin

with well mixed and ventilated waters in an overall warm climate (Kuhlmann *et al.* 2006b), with the centre of deposition in the Danish sector of the basin. The abundant glauconite in the deposits in the south-western Netherlands confirms generally low sedimentation rates in the southern part of the basin that must have been relatively unaffected by clastic input of rivers in the eastern part of the basin.

CONCLUSIONS

(1) The Breda Formation in the succession in the Colijnsplaat borehole is 70.20 m thick. The Formation is mainly of Late Miocene age; the uppermost part dates from the Zanclean (Early Pliocene).

(2) A significant hiatus does exist between the Breda Formation and underlying Rupel Formation comprising a time span of the Late Oligocene, Early and Middle Miocene.

(3) The Breda Formation contains two depositional sequences. The lower sequence is of Late Miocene age and the upper sequence is of Early Zanclean age (Early Pliocene). The sequences correlate with the succession at Schelphoek on the Island of Schouwen-Duiveland (several kilometres to the north-west of Colijnsplaat) and with the successions in the Antwerp area to the south and the central North Sea to the north.

(4) In general the depositional environment during origination of the deposits of the Breda Formation has been shallowing in the warm temperate to subtropical climate conditions.

ACKNOWLEDGEMENTS

This paper has benefited hugely from comments and suggestions made by two reviewers: prof. dr. Poppe de Boer (Faculty of Earth Sciences, Utrecht University) and Mr. Frank Wesselingh (Naturalis, Leiden). Prof. dr Jelle Reumer (Natural History Museum Rotterdam and Faculty of Earth Sciences, Utrecht University) provided helpful suggestions that improved the manuscript. Mr. Charles Barnard (Naturalis) processed the samples. Mr. Maarten van den Bosch (Winterswijk, The Netherlands) provided us with borehole documentation.

REFERENCES

Balson, P.S., 1987 - Authigenic phosphorite concretions in the Tertiary of the southern North Sea Basin: an event stratigraphy - Mededelingen Werkgroep Tertiaire en kwartaire Geologie 24(1-2): 79-94

Bijlsma, S. 1981 - Fluvial sedimentation from the Fennoscandian area into the Northwest European Basin during the Late Cenozoic - Geologie en Mijnbouw 8: 337-345

Bosch, J.H.A., 1999 - Standaard Boor Beschrijvingsmethode, versie 5 - Internal report TNO - rapport NITG 98-205-A: 88 pp.

De Schepper, S., 2006 - Plio-Pleistocene dinoflagel late cyst biostratigraphy and palaeoecology of the eastern North Atlantic and southern North Sea Basin - Unpublished PhD thesis, University of Cambridge: 403 pp.

Doppert, J.W.C., 1980 - Lithostratigraphy and biostratigraphy of marine Neogene deposits in The Netherlands - Mededelingen Rijks Geologische Dienst 32: 255-311

Doppert, J.W.C., Ruegg, G.H.J., Van Staalduinen, C.J., Zagwijn, W.H., & Zandstra, J.G., 1975 - Lithostratigrafie. Formaties van het Kwartair en Boven-Tertiair in Nederland - in: Zagwijn, W. H., & Van Staalduinen, C. J., (eds.) - Toelichting bij geologische overzichtskaarten van Nederland – pp. 11-56, Rijks Geologische Dienst, Haarlem

Doppert, J.W.C., Laga, P.G. & De Meuter, F.J., 1979 – Correlation of the biostratigraphy of marine Neogene deposits, based on benthonic foraminifera, established in Belgium and the Netherlands - Mededelingen Rijks Geologische Dienst 31-1: 1-8

Doppert, J.W.C., & Neele, N.G., 1983 - Biostratigraphy of marine Paleogene deposits in the Netherlands and adjacent areas - Mededelingen Rijks Geologische Dienst 37: 3-79

Gradstein, F.M., Ogg, J.G., & Smith, A.G., (eds.), 2004 - A geologic time scale 2004 - Cambridge University Press, Cambridge, 589 pp.

Huuse, M., & Clausen, O.R., 2001 - Morphology and origin of major Cenozoic sequence boundaries in the

eastern North Sea Basin: top Eocene, near top Oligocene and the mid-Miocene unconformity - Basin Research 13: 17-41

Kuhlmann, G., 2004 - High resolution stratigraphy and paleoenvironmental changes in the southern North Sea during the Neogene. An integrated study of Late Cenozoic marine deposits from the northern part of the Dutch offshore area - Geologica Ultraiectina, Mededelingen van de Faculteit Aardwetenshappen Universiteit Utrecht 245: 205 pp.

Kuhlmann, G., Langereis, C.G., Munsterman, D., Van Leeuwen, R-J., Verreussel, R., Meulenkamp, J.E., & Wong, Th.E., 2006a - Integrated chronostratigraphy of the Pliocene-Pleistocene interval and its relation to the regional stratigraphical stages in the southern North Sea region - Netherlands Journal of Geosciences 85: 19-35

Kuhlmann, G., Langereis, C., Munsterman, D., Van Leeuwen, R.J., Verreussel, R., Meulenkamp, J.E., & Wong, Th.E., 2006b - Chronostratigraphy of Late Neogene sediments in the southern North Sea Basin and paleoenvironmental interpretations -

Palaeogeography, Palaeoclimatology, Palaeoecology 239: 426-455

Louwye, S., Head, M.J., & de Schepper, S., 2004 - Dinoflagellate cyst stratigraphy and palaeoecology of the Pliocene in northern Belgium, southern North Sea Basin - Geological Magazine 141: 353-378

Marquet, R., 1998 - De Pliocene gastropodenfauna van Kallo (Oost-Vlaanderen, België) - Belgische Vereniging voor Paleontologie, Antwerpen, 246 pp.

Marquet, R., 2002 – The Neogene Amphineura and Bivalvia (Protobranchia and Pteriomorphia) from Kallo and Doel (Oost-Vlaanderen, Belgium) – Palaeontos 2: 1-99

Marquet, R., 2004 - Ecology and evolution of Pliocene bivalves from the Antwerp Basin - Bulletin de L' Institut Royal de Sciences Naturelles de Belgique - Sciences de la Terre 74 (supplement): 205-212

Marquet, R., 2005 – The Neogene Bivalvia (Heterodonta and Anomalodesmata) and Scaphopoda from Kallo and Doel (Oost-Vlaanderen, Belgium) – Palaeontos 6: 1-142

Overeem, L., Weltje, G.J., Bishop-Kay, C., & Kroonenberg, S.B., 2001 - The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: a climate signal in sediment supply? - Basin Research 13: 293-312

Reading, H.G., (ed.), 1996 - Sedimentary Environments: processes, facies and stratigraphy - Blackwell Scientific Publications, Oxford, 704 pp.

Spaink, G., 1975 - Zonering van het mariene Onder-Pleistoceen en Plioceen op grond van mollusken fauna's - in: Zagwijn, W. H., & Van Staalduinen, C. J., (eds.) - Toelichting bij geologische overzichts-kaarten van Nederland - pp. 118-122, Rijks Geologische Dienst, Haarlem

Slupik, A.A., Wesselingh, F.P., Janse, A.C., & Reumer, J.W.F., 2007 - The stratigraphy of the Neogene – Quaternary succession in the south-west Netherlands from the Schelphoek borehole (42G4-11/42G0022) - a sequence-stratigraphic approach – Netherlands Journal of Geosciences / Geologie en Mijnbouw 86: 317-332

Van Adrichem Boogaert, H.A., & Kouwe, W.F.P., 1997 - Stratigraphic nomenclature of the Netherlands. Revision and updates by RGD and NOGEPA - Mededelingen Rijks Geologische Dienst 50, Section I: 1-39

Vandenberghe, N., Laga, P., Steurbaut, E., Hardenbol, J., & Vail, P., 1998 - Tertiary sequence stratigraphy at the southern border of the North Sea Basin in Belgium - in: De Graciansky, P.-C., Hardenbol, J., Jacquin, T., & Vail, P.R. (eds.) - Mesozoic and Cenozoic sequence stratigraphy of European Basins – pp. 119-154, Society for Sedimentary Geology, Special Publications 60

Vandenberghe, N., Van Simaeys, S., Steurbaut, E., Jagt, J.W.M., & Felder, P.J., 2004 - Stratigraphic architecture of the Upper Cretaceous and Cenozoic along the southern border of the North Sea Basin in Belgium - Netherlands Journal of Geosciences / Geologie en Mijnbouw 83: 155-171

Van Rummelen, F.F.F.E., 1970 - Blad Schouwen-Duiveland. Toelichting bij de geologische kaart van Nederland 1:50000 - Rijks Geologische Dienst, Haarlem: 116 pp.

Van Rummelen, F.F.F.E., 1978 - Blad Beveland. Toelichting bij de geologische kaart van Nederland 1:50000 - Rijks Geologische Dienst, Haarlem: 138 pp.

Weerts, H.J.T., Cleveringa, P., Ebbing, J.H.J., De Lang, F.D., & Westerhoff, W.E., 2000 - De lithostrati grafische indeling van Nederland: Formaties uit het Tertiair en Kwartair - TNO-rapport NITG 00-95-A, TNO-NITG, Utrecht

Wentworth, C.R., 1922 - A scale of grade and class terms

for clastic sediments - Journal of Geology 30: 377-392

Zagwijn, W.H., 1985 - An outline of the Quaternary stratigraphy of the Netherlands - Geologie en Mijnbouw 64: 17-24

Ziegler, P.A., 1990 - Geological atlas of Western and Central Europe 2nd edition - Shell International Petroleum Maatschappij B.V.: 239 pp.

received 31 May 2007
accepted 31 August 2007

DEINSEA - ANNUAL OF THE NATURAL HISTORY MUSEUM ROTTERDAM
P.O.Box 23452, NL-3001 KL Rotterdam The Netherlands
www.nmr.nl