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The stratigraphy of the Neogene-Quaternary succession in the southwest Netherlands from the Schelphoek borehole (42G4-11/42G0022) – a sequence-stratigraphic approach

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Abstract

We investigate the stratigraphy of Neogene and Quaternary intervals of the Schelphoek borehole (Schouwen, Zeeland, the Netherlands). The Breda Formation (Miocene-Zanclean) contains three sequences separated by hiatuses. The Oosterhout Formation (Zanclean-Piacenzian) contains at least two sequences. This formation is overlain by seven sequences of the Gelasian Maassluis Formation that almost certainly represent glacial cycles. The three lowermost sequences are provisionally assigned to the Praetiglian (MIS 96, MIS 98 and MIS 100). A large hiatus exists between the top of the Maassluis Formation and the base of the late Middle to Late Quaternary succession. Due to extensive *in situ* reworking of older strata (including fossils) at the base of several of the formations, their exact boundaries are difficult to establish. The Neogene succession in the Schelphoek borehole is compared to the stratigraphic successions in the Antwerp area to the south and the Dutch coastal area and continental platform to the north. Finally, the stratigraphic context of the Gelasian ('Tiglian') mammal fauna dredged from the bottom of a major tidal channel in the adjacent Oosterschelde is assessed by comparison with the Schelphoek borehole.

Keywords: Schelphoek, Stratigraphy, Neogene, Quaternary, North Sea Basin, Netherlands

Introduction

As a result of the catastrophic surge that flooded the southwestern Netherlands on February 1, 1953, an ambitious programme of water control engineering works was launched (the so-called Deltawerken). These works included elevation of existing dikes as well as the erection of series of (semi-open) storm barriers. The Deltawerken were preceded by a broad geological investigation, for which hundreds of boreholes were established under the supervision of the now defunct 'Deltadienst' (a government agency that supervised these works in the 1950's to 1970's). The aim of the geological research was to establish the mechanical subsurface conditions of construction sites and to gain insight into the hydrological conditions in the area. The Schelphoek borehole (Fig. 1), one of the Deltadienst borings, is located on the margin of the North Sea Basin on the northern flank of the Brabant Massif, in a region where strata from the Paleogene onwards are present at shallow depth and where the Neogene is well represented. The region is located in a transitional area between thick and complete Neogene and Early Quaternary successions to the north (e.g. Kuhlmann et al., 2006a, 2006b) and incomplete, often eroded successions towards the south (Vandenberghe et al., 1998; 2004). Some general geological data concerning the borehole have been reported previously (Van Rummelen, 1970). In this earlier work the lithostratigraphic data were presented within a lithostratigraphic framework that has been drastically altered and formalized since then. Interpretations of the borehole were contradictory (compare figures 7, 20 and 23 in Van Rummelen, 1970). Previous correlations of stratigraphic units of the Isle of Schouwen, where the Schelphoek borehole is located, with strata from the Antwerp area to the south have added to the confusion. Van Rummelen (1978) explained that part of the deposits defined by Dutch mapping geologists as 'Deurne Sands'

Fig. 1. Location of the Schelphoek borehole and other areas referred to in this paper. North Dutch Offshore: study area of Kuhlmann (2004) and Kuhlmann et al. (2006a; 2006b). Antwerp area: study area of Vandenberghe et al. (1998; 2004). Noordwijk borehole is referred to in Jansen et al. (2004a; 2004b) and Meijer et al. (2006).

in fact comprises strata that are assigned to the Kattendijk Formation of the Antwerp region, whereas deposits assigned to the Kattendijk Sands in the Netherlands are time equivalent with the Luchtbal Sands (= Luchtbal Member of the Lillo Formation) of the Antwerp area. Furthermore, previous biozonation schemes used in correlation of units are inconsistent. For example, Doppert et al. (1979, table 2) assign a Pliocene age for the Kattendijk Formation in Belgium, which they assign to their BFN4 zone, which is correlated with the Dutch FC1 zone, which is assigned in the same table to the Miocene! The definition and stratigraphic position of the Belgian Neogene formations have since then been improved and refined (Vandenberghe et al., 1998 and references therein). Thus their relationship with the Dutch units needs re-evaluation. Only small parts of previous palaeontological and palynological data of borehole Schelphoek have been published. The part from 40.00 m to 118.00 m below surface is the designated reference section of the foraminifer zone FA (Doppert, 1980). Other fossil evidence has been reported very briefly only, without any attempt to discuss it in terms of chronostratigraphic significance (van Rummelen, 1970). The detailed facies, sequence stratigraphic and faunal account (apart from analyses of foraminifera) is lacking hitherto.

The position of the Schelphoek borehole (Fig. 1) should allow a correlation between Miocene-Piacenzian 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 and Early Quaternary 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 Middle Miocene. Also, Miocene and Pliocene successions from the Antwerp region have recently been the subject of stratigraphic studies (Vandenberghe et al., 1998; 2004; De Schepper, 2006), drastically improving insights into the ages of the various formations in that region.

The aim of this study is (1) to document the stratigraphy of the Schelphoek borehole, (2) to compare the stratigraphic succession with those from the Antwerp area in the south and those of the Dutch continental platform to the north and (3) to construct the sequence-stratigraphic framework for the deposits. The borehole is located only a few hundred metres from a classical vertebrate fossil locality, the northern tidal-channel of the Oosterschelde Estuary ('Hammen') from which important Gelasian terrestrial mammal fossils have been collected through fishing trawlers (De Vos et al., 1995, 1998; Reumer et al., 1998, 2005; Van Kolfschoten & Laban, 1995). We aim to assess the stratigraphic context of that fauna using the Schelphoek borehole.

Geological setting

The study area is located on the southern part of the Island of Schouwen-Duiveland, Province of Zeeland (Fig. 1) in the southern part of the North Sea Basin. During Late Cenozoic times, the North Sea Basin was part of the northwest 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 in the west. Towards the northwest it was connected to the Atlantic (Ziegler, 1990), and short-lived connections through the English Channel area occurred. A large clastic delta system prograded progressively into the North Sea from the east; sediments originated mostly from 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 became filled with these siliciclastic deposits reaching a thickness of approximately 3000 m in the depocentre (Ziegler, 1990; Kuhlmann, 2004). The Neogene-Quaternary successions of the Dutch sector of the North Sea have been documented lately (Kulhmann, 2004; Kuhlmann et al., 2006a, 2006b). A major horizon that is well expressed on seismic profiles throughout the North Sea Basin, the so-called Mid Miocene Unconformity (MMU) forms the base of the late Middle Miocene - Quaternary successions (Huuse & Clausen, 2001) (Fig. 2). The MMU is a very conspicuous diachronic phenomenon that is interpreted as a transgression surface characterised by sediment starvation and/or condensation. Thus the age of the MMU varies within the basin. Kuhlmann et al. (2006b) quote ages between 10.7 and 15 Ma (Fig. 2). The Middle to Late Miocene intervals are thin (order of some tens of m). Increased sedimentation rates in the Piacenzian led to the deposition of some hundreds of metres thick Late Pliocene and Early Quaternary successions in that region that have well preserved signals of climate change and basin development in the North Sea. During the Neogene, the climate in the region deteriorated from warm temperate - subtropical to the strong glacial-interglacial cycles, whose onset is estimated at ca 2.55 Ma. Both the intensification of the associated glacioeustatic sea-level dynamics, as well as changing vegetation patterns in the hinterland drastically changed, and shaped the rapid infill of the southern North Sea Basin during the late Neogene and Quaternary. Within the Miocene to Pliocene succession five paleo-environmental intervals are proposed by Kuhlmann et al. (2006b). The lowermost interval (logunits 1 - 5 of Kuhlmann et al., 2006b) covers the late Middle Miocene - Late Piacenzian. 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. Towards deposition of the top of this interval the basin shallowed and the first signals of cooling occurred. The overlying interval (logunits 6 - base of logunit 10) covering the latest Piacenzian - Early Gelasian has a transitional character from warm climatic conditions with diverse faunas and floras to cool settings and less diverse biota. The interval shows pronounced glacial-interglacial cycles that match isotope stages MIS 100 - 96 reflecting the onset of severe northern hemisphere glaciations. The third interval (logunits 10 - 12 of Kuhlmann et al., 2006b) covers the Middle Gelasian and comprises a significant change towards more restricted marine conditions in the North Sea. Cold climate conditions prevailed and the sea level dropped further from logunit 10 onward. During deposition of the fourth, Late Gelasian interval (logunits 13 - lower part of logunit 17), the North Sea had become a very shallow basin. The cold arctic climate conditions prevailed and the sea-ice cover during glacial intervals was (semi)permanent. The upper interval (logunit 17 - 18), also placed within the Late Gelasian, represents the transition of very shallow marine to fluvial and paralic conditions under cold climate settings. The westward progradation of stacked sequences preserving the Neogene history in the northern part of the Dutch North Sea is also recognised onshore in an east-west oriented transect located in the west-central Netherlands (between Apeldoorn and Den Haag) (Jansen et al., 2004a, 2004b).

Insights into the stratigraphy of Neogene successions of the Antwerp region south of the Schelphoek borehole also have been improved in the past few years (Vandenberghe et al., 1998; 2004; Louwye et al., 2004; De Schepper, 2006). The succession consists of fossiliferous siliciclastic intervals that presumably represent highstand snapshots and are separated by regional hiatuses. Nine units have now been recognised that cover the Early Miocene up to the Piacenzian-Gelasian boundary (Vandenberghe et al., 2004); fossiliferous Gelasian deposits are lacking in the Antwerp region (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 four members of the Late Zanclean to Piacenzian Lillo Formation reflect stepwise cooling of the area and decreasing maximum deposition depths. Termophile mollusc species as well as North Sea endemics show increased extinction and Pacific immigrant species adapted to cooler conditions established in the course of the Piacenzian leading to an overall drop in diversity (Marquet, 2005).

The subsurface of the delta area of the southwestern Netherlands consists of clays of the Early Oligocene Rupel Formation (Van Rummelen, 1970). A hiatus separates this formation from the Miocene-Zanclean Breda Formation that is predominantly composed of glauconitic sands reflecting deposition in shallow, warm temperate to subtropical marine conditions. The Piacenzian Oosterhout Formation and the Gelasian Maassluis en Waalre Formations reflect a general cooling of the area, with increasing glacial cyclicity, as well as a transition from predominantly marine to terrestrial conditions. To the east (Noord Brabant), the upper part of the mostly marine Maassluis Formation grades into the estuarine and fluvial lower part of the Waalre Formation (Kasse, 1998). A major hiatus, comprising most of the Pleistocene, separates these formations from the late Middle Pleistocene or Late Pleistocene-Holocene succession. This latter succession is composed of at least one warm temperate marine interval ('Eem' Formation, see discussion below about its uncertain status), a cold aeolian/fluvial interval (Boxtel Formation) and the Holocene coastal deposits of the Naaldwijk Formation (following definitions in Weerts et al., 2000). The Neogene-Quaternary successions are correlated with the Upper North Sea Group that is part of the North Sea Supergroep (Van Adrichem Boogaert & Kouwe, 1997) (Fig. 2).

The improved insights into the Neogene climate and geography of the North Sea Basin were made possible by improved stratigraphic (based on dinoflagellate cysts and magnetostratography) insights (Vandenberghe et al., 2004; De Schepper, 2006; Kuhlmann, 2004 for review and references) that have added significantly to 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 et al., 1979

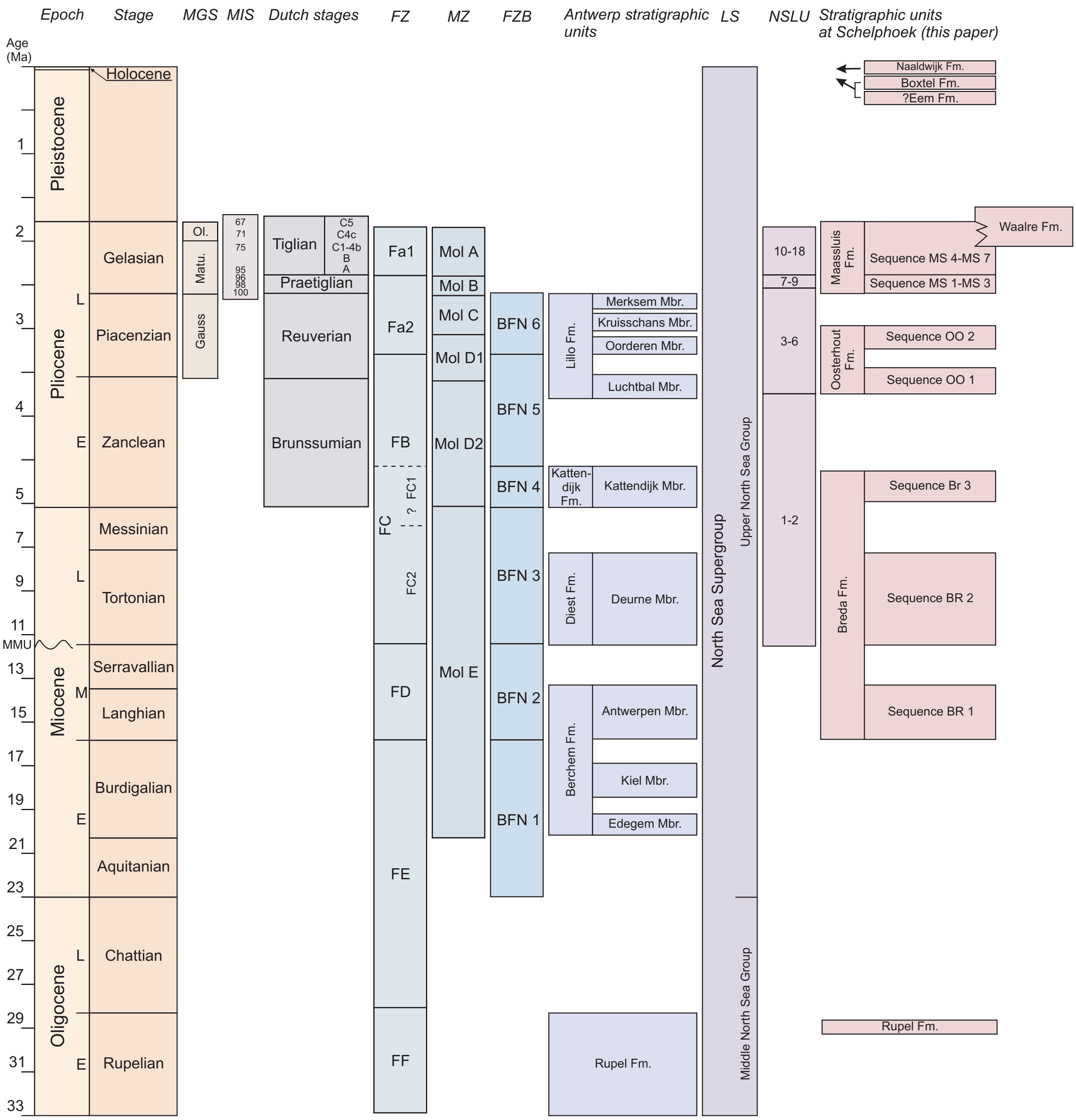


Fig. 2. Stratigraphic framework for Neogene and Quaternary deposits in the southern North Sea discussed in this paper. Note scale change at 5 Ma. MMU – Middle Miocene Unconformity. MGS refers to magnetostratigraphy: Ol. – Olduvai, Matu. – Matuyama. MIS refers to marine isotope stages (after Kuhlmann, 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 foraminifera zones in Belgium from 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); Fm. = Formation; Mbr. = Member. LS (= Lithostratigraphic Subdivision) according to Van Adrichem Boogaert & Kouwe (1997). Formations (Fm.) names in the Schelphoek area follow Weerts et al. (2000). Note the uncertain position of the sub-zone FC1 within the scheme (as mentioned in the paper).

and Doppert, 1980; molluscs: Spaink, 1975; Tables 1 and 2). These correlations suffer from strong environmental control over the occurrence of species (water depth, temperature). A revised stratigraphic framework for the deposits is presented in Fig. 2.

Well known Gelasian vertebrate faunas have been collected at a few hundreds of metres from the Schelphoek site by fishing trawlers from the floor of the Hammen tidal channel in the adjacent Oosterschelde at depths between ca 35 and 40 m since the 1950's (De Vos et al., 1995, 1998; Reumer et al., 1998, 2005; Van Kolfschoten & Laban, 1995). The fauna includes proboscidians, perissodactylids, artiodactylids and carnivores as well as small mammals (rodents and insectivores). Exact age and stratigraphic position of the fauna is uncertain. De Vos et al. (1998) concluded that the Oosterschelde fauna is comparable to the Chilhac Fauna from France on the basis of presence of *Mammuthus meridionalis* and *Anancus arvernensis* in both faunas. The Chilhac Fauna is approximately 1.9 Ma old, i.e. of Late Gelasian age. Reumer et al. (2005) studied small mammal remains trawled from the Oosterschelde floor and concluded that the Oosterschelde fauna could be best placed in the time span around the MN16B-MN17 transition confirming the Gelasian age. De Vos et al. (1998) indicated that the large-mammal fauna from the Oosterschelde has an unusual composition: fragments of proboscidian molars and postcranial bones of perissodactylids, artiodactylids and carnivores dominate suggesting selection of more residual elements. However, these authors found no clear evidence for long-distance transport of these mammal remains, and concluded that the fossils from the Oosterschelde floor originate from local sources that possibly are present in the Schelphoek borehole as well.

Material & Methods

The Schelphoek borehole (Deltadienst 42G4-11 = NITG 42G0022) was drilled in 1963 with a bailer sampler. The borehole was made at coordinates RDX 47.034; RDY 412.033. Ground level was 3.16 m above sea level. The borehole reached a depth of 164.50 m below the surface. Samples were taken at approximately one-metre intervals, yielding 1.5 - 2.5 kg material each. 169 samples were available for study. Residues are stored in the Museum of Natural History in Rotterdam (Natuurhistorisch Museum Rotterdam) 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). Grain size was partly determined by visual sample description and partly performed on a laser particle sizer Malvern Instruments Ltd., UK at the Department of Earth Sciences, University of Utrecht. Molluscs were picked from ca 1 kg wash residues (sieve mesh 1 mm), and have been tentatively identified. The molluscan zonation of Spaink (1975) (Table 1) is followed. Some down-hole contamination (caving) was observed by the occurrence of younger, stratigraphic or ecological incompatible species with different preservation styles in samples. Locally, indications of abundant (natural) reworking of older fossils in younger intervals were encountered. Both stratigraphy up reworking and down-hole contamination complicate the establishment of biozones. Molluscs suspected of having been reworked or 'caved' have been indicated during analyses. The original foraminifer analyses of Van Voorthuysen (1963), van Rummelen (1970) and Doppert (1980) were included in this study. Additional samples were investigated by the first author for the occurrence of foraminifera species. The foraminiferal zonation of Doppert (1980) and Doppert & Neele (1983) is followed (Table 2). The exception is the age assignment of Doppert's (1980) FC1 zone (Miocene) (Fig. 2). If the correlation of the FC1 zone with the Belgian BFN4 zone that is established in the Kattendijk Formation of the Antwerp region (Doppert et al., 1979) is correct, that unit 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), and the FC1 zone of Doppert (1980) and Doppert & Neele (1983) should either be located within or include the Early Pliocene as well (Fig. 2). In this paper we use the Pliocene-Pleistocene boundary as established by the International Commission on Stratigraphy (1.81 Ma: Aguirre & Pasini, 1985; see also Gradstein et al., 2004) and not the alternative boundary, commonly used in NW Europe (ca 2.6 Ma, see Gibbard et al., 2005). The lithostratigraphic definitions and formation names follow Weerts et al. (2000).

Table 1. Molluscan biozones in the Schelphoek borehole (Zonation scheme from Spaink, 1975). Note that sample 140.00 - 141.00 m. presumably is a mixture of MOL D2 and MOL F mollusc species.

Zone		Depth (m b.s.)	Age
MOL A	*Mya arenaria – Peringia ulvae*	39.00 - 61.00	Gelasian
MOL B	*Serripes groenlandicus – Yoldia lanceolata*	83.25 - 101.00	Gelasian
MOL B – MOL C / D1 Mixed		102.00 - 109.00	Piacenzian/Gelasian
MOL D1	*Hinia reticosa – Aquipecten opercularis*	110.00 - 117.00	Piacenzian
MOL D2	*Palliolum gerardi – Astarte trigonata*	117.00 - 141.00	Zanclean - Piacenzian
MOL E	Unnamed	140.00 - 157.00	Miocene

Table 2. Foraminiferan biozones in the Schelphoek borehole (Doppert, 1980; Doppert & Neele, 1983).

Zone	Subzone	Depth (m b.s.)	Age
FA1	*Ammonia – Quinqueloculina*	40.00 - 73.00	Gelasian
FA2	*Bucella – Cassidulina*	73.00 - 118.00	late Piacenzian - early Gelasian
FB	*Textularia decrescens – Bulimina aculeata*	118.00 - 141.00	Zanclean - early Piacenzian
FC	*Siphotextularia sculpturata – Uvigerina hosiusi*	141.00 - 148.00	Tortonian - Messinian
FD	*Asterigerina staeschei – Uvigerina tenuipustulata*	148.00 - 163.50	Langhian - early Serravallian
FF	*Rotaliatina bulimoides – Cibicides ungerianus*	163.50 - 163.70	late Rupelian

Results and interpretations

Seven formations are recognised in the Schelphoek borehole. Figure 3 presents the lithostratigraphic framework of the borehole. Figure 4 summarizes biostratigraphic data.

Rupel Formation (163.50 - 164.30 m)

Samples are composed of very dark-grey to dark-green (silty) clays, with some fine-grained sand. In the clays in the upper sample from this interval, some black, rounded small (3 mm) phosphorite pebbles were found that almost certainly form the basis of the overlying Breda Formation. Some fragments of calcareous nodules were found, as well as very few shell fragments (contaminated from overlying intervals). Foraminifera belong to the FF (*Rotaliatina bulimoides – Cibicides ungerianus*) zone (Fig. 2) (Van Voorthuysen, 1963), indicating a Late Rupelian age (Doppert & Neele, 1983). The clays represent middle to outer neritic marine depositional environments (Van Adrichem Boogaert & Kouwe, 1997).

Breda Formation (136.00 - 163.50 m)

The deposits consist of dark green-black to green-brown, fine-grained glauconite sands with minor amounts of sandy silts and sandy clays. Glauconite grains are usually (sub-)angular and small-sized (typical diameter is 250 µm). Shells and shell fragments are rare in the lower part and common in the uppermost part.

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

Five units (Br A to Br E) are defined (Table 3), and three sequences are identified (Fig. 3).

Sequence BR 1 (148.00 - 163.50 m) contains a phosphorite pebble lag at the base (in the 163.50-164.00 m sample that is otherwise composed of very dark-grey to dark-green clays derived from the Rupel Formation) and is directly overlain by very fine-grained to fine-grained deposits of unit BR E (Table 3) representing maximum flooding. A coarsening upward into unit BR D indicates shallowing caused by a fall of sea level or progradation. Glauconite grains are in general little worn, and appear to be largely autochthonous, indicating relatively low sedimentation rates (Reading, 1996). Between 151.00 and 157.00 m, a mollusc fauna with Miocene species is present (e.g. *Yoldia glaberrima*, *Lucinoma droueti*, *Digitaria beyschlagli*, *Venus multilamella*) (Table 4). Foraminifer species (*Uvigerina tenuipustulata*, *Bulimina elongata* and *Asterigerina staeschei*) are typical of zone FD (*Asterigerina staeschei – Uvigerina tenuipustulata* zone), indicating a Middle Miocene age.

Rounded phosporitic pebbles are found in the basal part of sequence BR 2 (141.00 - 148.00 m), indicating reworking and possibly a hiatus. The abundance of fine-grained gravel (consisting of phosphorites and sandstones) in this sequence suggests shallow depositional depths and the proximity of terrestrial sources or strong winnowing water currents. Again, the fresh nature of the glauconitic grains suggests low sedimentation rates, and rules out substantial terrigenous input. A small Miocene mollusc fauna is found between 140.00 and 143.00 m with characteristic species such as *Limopsis anomala*, *Astarte radiata* and *Venus multilamella* (Table 4). Foraminifer content (*Cassidulina carinata*, *Eponides umbonatus*, and *Florilus boueanus*) is attributed to zone FC (*Siphotextularia sculpturata – Uvigerina hosiusi* zone) indicating a Tortonian-Zanclean age.

A basal fine-grained gravel (yielding sandstone and flint pebbles) with some phosphorite pebbles marks the bottom of sequence BR 3 (136.00 - 141.00 m). Foraminifer content (*Heterolepa dutemplei, Cribrononion excavatum, Cibicides lobatulus* and *Bulimina aculeata*) is characteristic of the zone FB (*Textularia decrescens – Bulimina aculeata* zone), corresponding to a Zanclean - Early Piacenzian age. A varied mollusc fauna characterised by *Bathyarca pectunculoides, Limopsis anomala coxi, Cyclocardia scalaris* and *Goodallia triangularis* occurs (Table 4). This fauna is attributed to the MOL D2 (*Palliolum gerardi – Astarte trigonata*) zone, indicative of Zanclean age. The abundance of apparently autochthonous glauconite, together with common epifaunal taxa (annelids, bryozoans, echinoderms) implies the Breda Formation to have been predominantly deposited in subtidal settings in a warm temperate to subtropical climate with relatively low sedimentation rates.

The hiatus between the Middle Miocene sequence BR 1 and the Late Miocene sequence BR 2 in the Breda Formation might correspond with the Mid Miocene Unconformity (MMU),

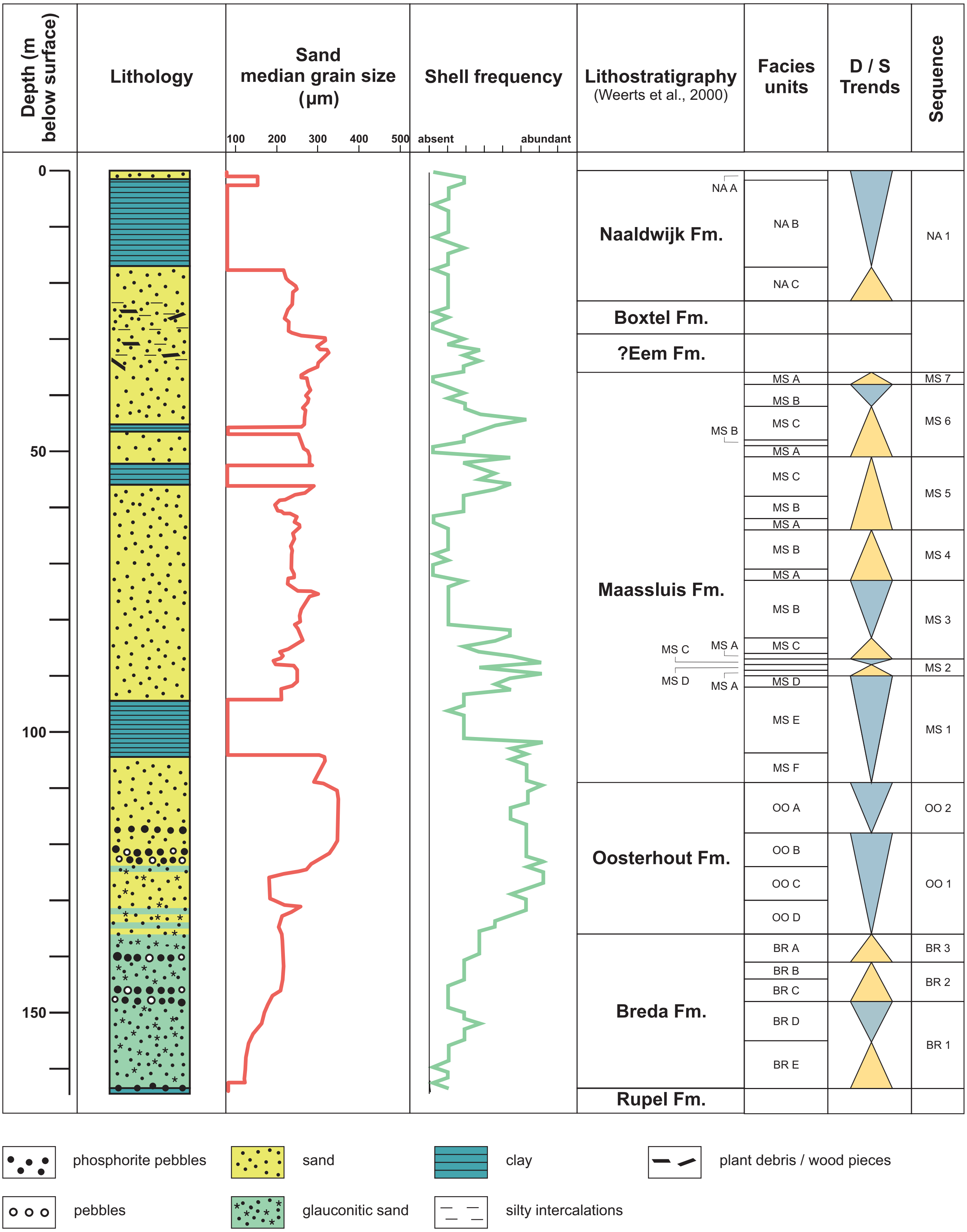


Fig. 3. Lithostratigraphic framework of the Schelphoek borehole. Shell abundance estimated from sediment samples (shell fragments >1mm, surface 40 cm^2) in eight classes (absent, 1 - 5 fragments/shells; 5 - 20, 20 - 50, 50 - 100, 100 - 500, more than 500 but less than 90% of the residue, more then 90% of residue). Units listed in Table 3. D/S refers to deepening (light/orange) and shallowing (dark/blue) trends.

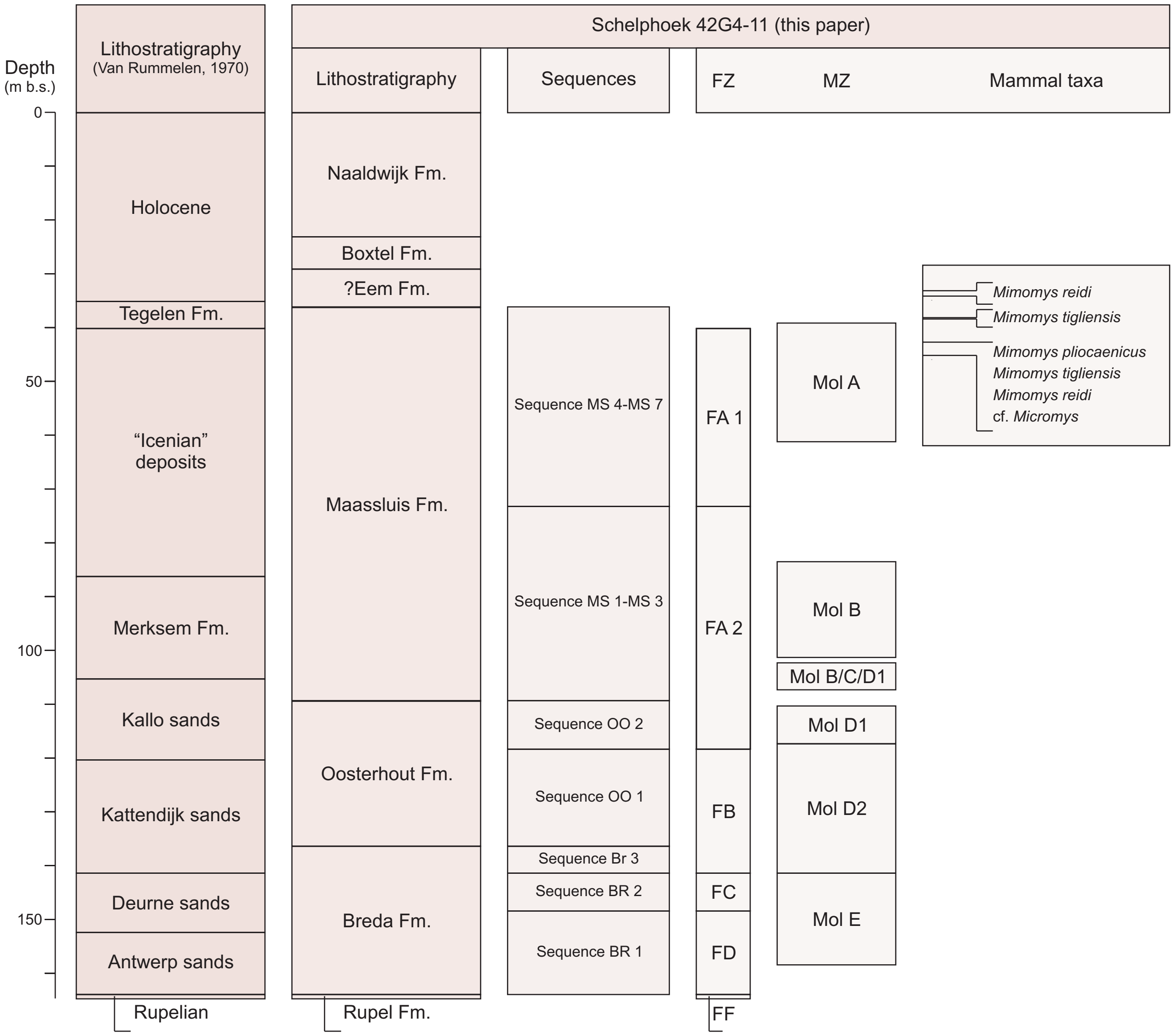


Fig. 4. Biostratigraphic framework of the Schelphoek borehole. FZ refers to benthic foraminiferan zones defined by Doppert (1980) and Doppert & Neele (1983). MZ refers to the benthic mollusc zones from Spaink (1975).

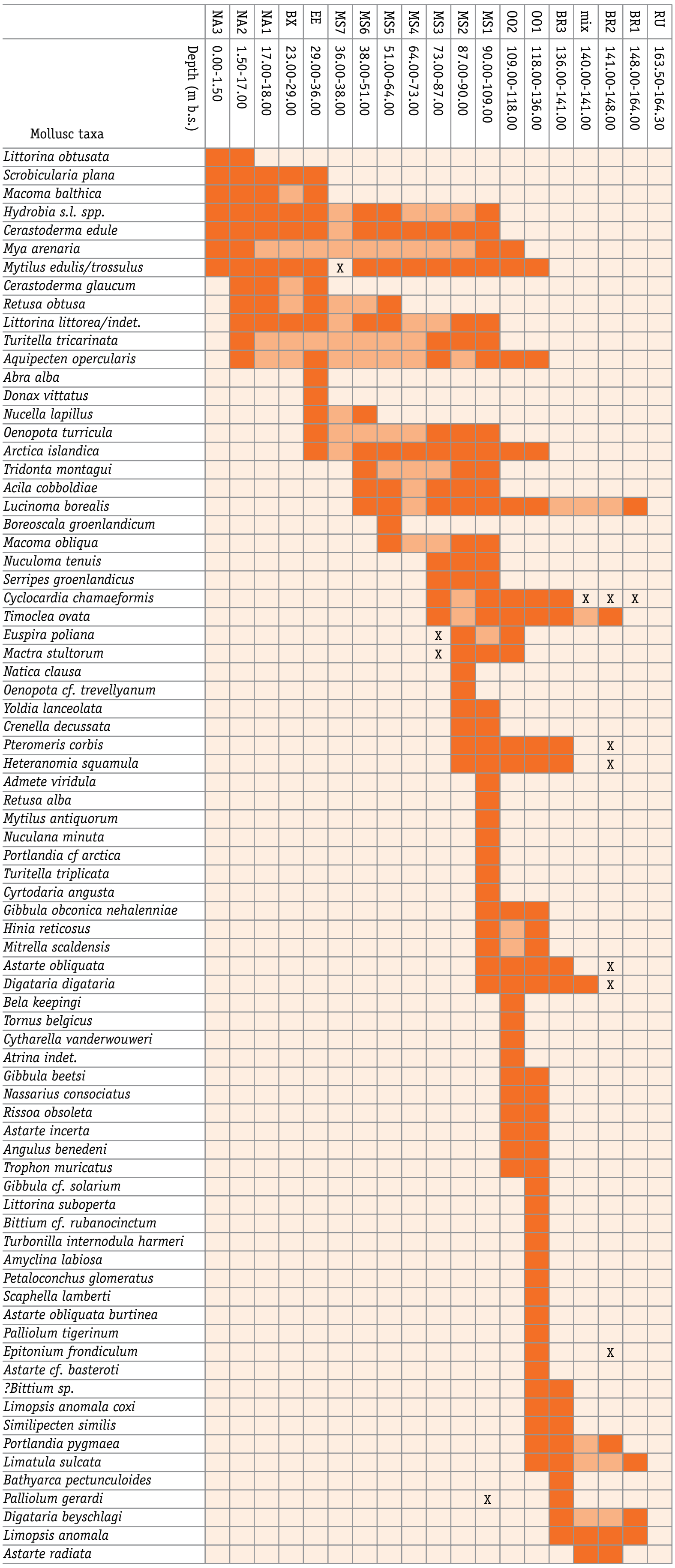
although this sueggstion is in need of further confirmation (Fig. 2). Phosphorite pebble lags have been documented from large parts of the province of Zeeland in deposits we assign to the Breda Formation (Van Rummelen, 1970; 1978). Older phosporite records from the Schouwen area (Van Rummelen, 1970) appeared to be non-conformable with respect to unit boundaries (figs 47, 48 and 49 in Van Rummelen, 1970), but later interpretations of phosphorite layers in Beveland directly to the south (Van Rummelen, 1978) did show that the lags are regional features that can be used to define 'sequences'. The exact boundaries of lithostratigraphic units as proposed by Van Rummelen (1970) for the Schouwen area are inconsistent (compare figures 7, 20 and 23 in Van Rummelen, 1970 which all include data from the Schelphoek borehole), and we therefore concur with his more recent interpretations of these phosphorite layers as regional entities (Van Rummelen, 1978).

Three sequences have been documented for Miocene deposits in the Antwerp area that are located below the MMU: the Edegem, Kiel and Antwerp sands (Vandenberghe et al., 2004) (Fig. 2). The Middle Miocene age of the lower sequence (sequence BR 1) of the Breda Formation in the Schelphoek borehole excludes a correlation of that sequence with Early Miocene Edegem (although the presence of the planctonic mollusc *Vaginella austriaca* argues for an early Middle Miocene age: A.W. Janssen, pers. comm.) and Kiel Sands, and suggests that the lower sequence of the Breda Formation in borehole Schelphoek correlates with Middle Miocene (Langhian) Antwerpen Sands. The second sequence (sequence BR 2) of the Breda Formation in the Schelphoek borehole, allegedly overlying the MMU, contains Miocene mollusc faunas and foraminiferan content characteristic of the zone FC, and should logically be correlated to the latest Middle to Late Miocene

Table 3. Units in the Schelphoek borehole. MGSF = Median grain size of sand fraction.

Formation	Units	Lithology	MGSF (µm)	Depth (m)	Interpreted environment
Naaldwijk Fm.	NA A	Brown clayey sands with abundant plant debris and some shell fragments	150	0 - 1.50	Foreshore to terrestrial with soil formation
	NA B	Light grey sandy clays with some shell fragments and plant debris	105	1.50 - 17.00	High intertidal to supratidal mudflat
	NA C	Light grey, poorly sorted, fine-grained arenite with very common shell fragments in the lower part and some shell fragments in the upper part	220 - 230	17.00 - 23.00	Subtidal to low intertidal sand flat
Maassluis Fm.	MS A	Grey (often with purple shine), well sorted, subangular to rounded, fine-grained to medium-grained arenite with very few lithic grains	210 - 270	36.00 - 38.00 49.00 - 51.00 62.00 - 64.00 71.00 - 73.00 86.00 - 87.00 89.00 - 90.00	Aeolian, partially pedogenized
	MS B	Grey-orange, moderately to well sorted fine-grained to medium-grained arenite, with limonitised clay balls, some black crusts (probably manganese oxide) and flakes, and very few, strongly abraded shell fragments	180 - 290	38.00 - 42.00 48.00 - 49.00 58.00 - 62.00 64.00 - 71.00 73.00 - 83.25	Pedogenized macrotidal (presumably channel-fill) deposits
	MS C	Grey to yellow-whitish, poorly sorted, fine-grained to medium-grained arenite, fine-grained gravel and limonite concretions rare; strongly abraded shell fragments common	190 - 256	42.00 - 48.00 51.00 - 58.00 83.25 - 86.00 87.00 - 88.00	Macrotidal deposits (probably channel fill)
	MS D	Grey, poorly to moderately sorted fine-grained, slightly silty arenite with abundant shell debris and ocassionally well preserved shells; limonite conretions very rare	240 - 250	88.00 - 89.00 90.00 - 92.00	Macrotidal deeper channel fill or foreshore
	MS E	Grey-brown, fine-grained, very silty sand to silty clay with reasonably preserved shell (fragments)	210	92.00 - 103.75	Subtidal, above storm wave base
	MS F	Poorly sorted medium-grained grey arenite and fine (shell) gravel; shells and shell fragments abundant, usually very strongly worn; mixed preservation styles, bioerosion traces common	290 - 320	103.75 - 109.00	Subtidal, below fairweather wave base?
Oosterhout Fm.	OO A	Light brown to grey, medium-grained arenite with abundant, strongly worn and rounded shell debris and shell fragments; glauconite rare; lowest sample with rounded phosporitic pebbles.	350	109.00 - 118.00	Shallow littoral
	OO B	Light brown to grey, medium-grained arenite with abundant glauconite, common phosporitic pebbles and other gravel and abundant strongly worn and rounded shell debris and sharp-edged shell fragments (partly biocalcarenite type)	280 - 350	118.00 - 124.00	Subtidal below fairweather wave base
	OO C	Light-grey to white medium fine-grained to coarse-grained arenite with abundant glauconite, shell fragments and strongly worn and rounded shell gravel (partly biocalcarenite type)	180 - 280	124.00 - 130.00	Subtidal above storm wave base
	OO D	Light grey to brownish green well-sorted fine-grained to medium-grained silty arenite with glauconite and common shell debris (partly biocalcarenite type)	200 - 260	130.00 - 136.00	Subtidal above storm wave base
Breda Fm.	BR A	Grey-green, fine-grained silty glauconitic arenites with abundant very fine shell debris; rare fine gravel and phosphorite pebbles.	210 - 220	136.00 - 141.00	Subtidal offshore below storm wave base
	BR B	Dark-brown to green, fine-grained silty glauconitic arenites with some shell fragments.	210 - 220	141.00 - 144.00	Subtidal offshore below storm wave base
	BR C	Dark brown to green, fine-grained silty glauconitic arenites, common fine gravel, few shell fragments and phosphorite pebbles	210 - 220	144.00 - 148.00	Subtidal offshore below storm wave base
	BR D	Dark brown to green, fine-grained glauconitic arenite with few shell fragments	<180	148.00 - 155.00	Subtidal offshore below storm wave base
	BR E	Dark green, very fine-grained to fine-grained silty glauconitic arenite	120 - 130	155.00 - 163.50	Subtidal offshore below storm wave base

Table 4. Occurrence of selected mollusc taxa in the Schelphoek borehole. Key: RU = Rupel Formation; BR = Breda Formation (numbers refer to sequences); mixed layer containing second and third sequence of Breda Formation; OO = Oosterhout Formation (numbers refer to sequences); MS = Maassluis Formation (numbers refer to sequences); EE = ?Eem Formation; BX = Boxtel Formation; NA = Naaldwijk Formation; orange = present; light orange = inferred due to superposition (from Mya arenaria it is known to have been absent between the Maassluis Formation and the Westland Formation); X refers to apperently caved or reworked specimens.



Deurne Sands of the Antwerp region (Vandenberghe et al., 2004). The superposition of the second sequence BR 2 in the Schelphoek borehole between Middle Miocene sequence BR 3 and Zanclean sequence BR 1 (see below) additionally supports such a correlation. The upper sequence (sequence BR 3) of the Breda Formation in the Schelphoek borehole, with its undoubtedly Zanclean mollusc faunas corresponds to the Kattendijk Formation in the Antwerp area (Fig. 3). The Breda Formation has not been subdivided in the southwest Netherlands (it is subdivided in members in the eastern part of the Netherlands) (Van Adrichem Boogaert & Kouwe, 1997), but our interpretations suggest that a further subdivision might be possible and useful. Further study (also including additional boreholes) will be needed to confirm our age estimates and proposed correlations. The upper two sequences (sequence BR 2 and BR 3) 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 southwestern 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.

Oosterhout Formation (109.00 - 136.00 m)

The deposits consist of grey-yellow to grey-white, fine-grained to medium-grained sands with abundant shell debris and shells. Rounded glauconite grains occur in variable amounts. Because of their generally rounded and polished nature we interpret them to have been reworked, presumably from Breda Formation deposits in the region.

The lower boundary is sharp. The lithology changes from grey-green, fine-grained silty glauconitic arenites with abundant very fine shell debris of the Breda Formation below into the light grey-whitish, very shelly calcarenite (biocalcarenite) of the Oosterhout Formation.

Within the Oosterhout Formation in the Schelphoek borehole four units are recognised (OO A to OO D: Table 3). Two sequences separated by a coarse lag of phosphorite pebbles are recognised in this unit in the Schelphoek borehole.

Sequence OO 1 (118.00 - 136.00 m) contains the three units (OO D to OO B). The interval is dominated by poorly sorted fine-grained to medium-grained arenites and biocalcarenites with abundant shell debris, shells, bryozoans, echinoid spines and variable amounts of rounded glauconite grains. Typical mollusc taxa include *Trophon muricatus, Limopsis anomala coxi, Cyclocardia* and *Astarte* species. The foraminifera (*Bulimina aculeata, Textularia decrescens* and *Cibicides lobatulus*) are assigned to the FB (*Textularia decrescens – Bulimina aculeata*) zone, indicating a Zanclean - Early Piacenzian age. The molluscs belong to the MOL D2 (*Palliolum gerardi – Astarte trigonata*) zone, also indicating a Zanclean to Piacenzian age.

The basal sample of sequence OO 2 (109.00 - 118.00 m) contains small (4 - 6 mm in diameter) rounded phosporite pebbles that we interpret as a basal lag. The sequence is furthermore composed of undifferentiated poorly sorted, predominantly medium-grained arenites with low amounts of rounded glauconitic grains and abundant shell gravel and worn shell fragments with mixed preservation styles. Foraminifera from sequence OO 2 (a.o. *Cribrononion excavatum, Bucella frigida,* and *Cassidulina laevigata*) are assigned to the FA 2 (*Bucella – Cassidulina*) subzone, indicating a late Piacenzian – early Gelasian age. Most common mollusc species are *Pteromeris corbis, Astarte* and *Cyclocardia taxa*, and are assigned to the Mol D1 (*Hinia reticosa – Aquipecten opercularis*) zone, indicating a Piacenzian age.

The Oosterhout Formation was deposited in shallow marine environment under warm temperate conditions. Depositional depths are in general above storm wave base.

The lower sequence (OO 1) (118.00 - 136.00 m) shares lithological similarities with the Luchtbal Member of the Antwerp region (Fig. 3): it is predominantly a yellowish calcarenite to rudstone. The age of the Luchtbal Member has recently been estimated to range between 3.2 and 3.8 Ma (latest Zanclean – Early Piacenzian: De Schepper, 2006). Similar facies are present in the Coralline Crag Formation of eastern England that is estimated to range between 3.8 and 4.4 Ma (Zanclean: De Schepper, 2006). The fauna of the upper sequence (OO 2) (109.00 - 118.00 m) resembles that of the Oorderen Member of the Antwerp area, with some possible facies related differences (such as the lack of *Tellina benedeni* that is common in the Antwerp area). The age of the Oorderen Member is estimated to range from 2.76 to 3.2 Ma (De Schepper, 2006), which would place the upper sequence of the Oosterhout Formation in the Schelphoek borehole firmly in the Piacenzian. Species characteristic for the upper marine members of the Lillo Formation in the Antwerp area (Kruisschans Member: a.o. *Cerastoderma parkinsoni* and *Yoldia heeringi*; Merksem Member: acme of *Spisula inaequilatera*) are lacking in the Oosterhout Formation interval in the Schelphoek borehole, although we have observed these in a borehole at s'Heer Abtskerke ca 30 km to the south (Fig. 1). These members represent the latest Piacenzian. If they have been present in the Schelphoek area, they must have been reworked and incorporated in the base of the Maassluis Formation (see below).

Maassluis Formation (36.00 - 109.00 m)

The deposits consist of fine-grained to medium-grained (sometimes silty) light-grey to orange sand intervals and light-grey (sometimes fine-grained sandy) silt/clay intervals. Shells, that often are strongly worn, occur in several of the intervals.

Plant debris as well as orange-brownish limonite/clay concretions occur in some of the intervals.

The lower boundary is located at the point where lithology change from light grey arenites with abundant shell debris and shell fragments (biocalcarenite) of the Oosterhout Formation below into the grey arenite with shell gravel with strongly worn shell fragments of the Maassluis Formation above.

Within the Maassluis Formation in the Schelphoek borehole six (facies) units (MS A to MS F: Table 3) are defined. Seven sequences are recognised in the Maassluis Formation (Fig. 3).

Sequence MS 1 (90.00 - 109.00 m) consists of a thick basal shelly medium-grained sand lag (103.75 - 109.00 m) (MS F) that is sharply overlain by clays (101.00 - 103.75 m) with few, well preserved mollusc fragments (MS E). The overlying interval (90.00-101.00 m) (MS E and MS D) shows a coarsening-up and contains commonly reworked flasers and worn shell fragments. The basal part of sequence MS 1 is lithologically very similar to the underlying Oosterhout Formation, but with subtle different sediment color and taphonomic properties of the fossil particles. Abundant, strongly worn and discoloured shell fragments are found that are of a Pliocene age, but whose preservation indicates reworking. Sequence MS 1 is interpreted to reflect the regressive part of a single transgressive-regressive cycle.

Sequence MS 2 (87.00 - 90.00 m) consists of a basal sample that is dominated by white-grey angular quartz arenites with a slightly purple shine, minor amounts of rounded quartz arenites, additional lithic grains and some poorly preserved shell fragments. We interpret these sands (facies MS A) as pedogenised aeolian deposits because of their good sorting and the matted grain-surfaces that typically results from collisions between grains during wind transport. The overlying interval (87.00 - 89.00 m) (MS D and MS C) represents a shallow marine setting (Table 3).

Sequence MS 3 (73.00 - 87.00 m) contains an one-metre thick layer (86.00 - 87.00 m) of fine-grained to medium-grained, well sorted aeolian sands (MS A) at the base. It is sharply overlain by fine-grained sands with numerous worn shell fragments in the lower part (83.25 - 86.00 m) (MS C) and fine-grained to medium-grained sands with very few worn shell fragments and some stony, iron-clayey nodules in the upper part (73.00-83.25 m) (MS B) that we interpret as proximal marine deposits. Sequence MS 3 is interpreted to reflect a single deepening-shallowing cycle.

Sequence MS 4 (64.00 - 73.00 m) also starts with supposedly aeolian sands (71.00 - 73.00 m) (MS A). The overlying interval (64.00 - 71.00 m) consists of well sorted fine-grained to medium-grained sands with some very small stony, iron-clayey nodules and very few worn shell fragments (MS B). These deposits represent a shallow marine setting, where the nodules are interpreted as reworked pedogenised flasers. Sequence MS 4 is interpreted to represent the transgressive part of a transgressive-regressive cycle.

Sequence MS 5 (51.00 - 64.00 m) again starts with a layer of aeolian sands (62.00 - 64.00 m) (MS A). It is overlain by proximal marine deposits. The interval from 58.00 to 62.00 m consists of fine-grained to medium-grained sands with a very few shell fragments (MS B). The overlying interval (51.00 - 58.00 m) consists of fine-grained sands with some silt (MS C). In the upper part a clay layer occurs (52.25 - 56.00 m). Shell content increases upwards in this interval from moderately low to high (MS C). Sequence MS 5 represents the transgressive part of a transgressive-regressive cycle.

Sequence 6 (38.00 - 51.00 m) also has a thin base composed of aeolian sands (49.00 - 51.00 m) (MS A). It is overlain by sands that are interpreted to reflect marginal marine depositional settings. The lowermost part (48.00 - 49.00 m) contains fine-grained to medium-grained silty sands and some shell fragments (MS B). The overlying interval (42.00 - 48.00 m) contains very silty sands and abundant shells (MS C). The shell content in the uppermost part of the sequence (38.00 - 42.00 m) (MS B) is very low, and the grain size increases and sorting decreases in the upper two metres likely reflecting a shift towards shallower and more proximal settings. Sequence MS 6 represents a single deepening-shallowing cycle. Sequence MS 7 (36.00 - 38.00 m, MS A) is composed of aeolian sands. These sands form the uppermost interval of the Maassluis Formation.

Foraminifera in the upper part of the Maassluis Formation interval in the Schelphoek borehole (*Elphidiella hannai, Ammonia beccarii* and *Cribrononion excavatum*) are assigned to the FA1 (*Ammonia – Quinqueloculina*) subzone and foraminifera in the lower part of the formation (*Buccella frigida* and *Cassidulina laevigata*) are assigned to the FA2 (*Bucella – Cassidulina*) subzone, pointing to a Gelasian age (Table 2). Molluscs are attributed to the MOL A (*Mya arenaria – Peringia ulvae*) zone (39.00 - 61.00 m) and the MOL B (*Serripes groenlandicus – Yoldia lanceolata*) zone (83.25 - 101.00 m) (Table 1). These zones also indicate a Gelasian age. In interval 102.00 - 109.00 m, the occurrence of molluscs from zones MOL B, MOL C and MOL D1 (Table 1) indicates an admixture of Piacenzian and Gelasian faunas.

Microvertebrate fossils from the top of the Maassluis Formation (sequence 7) (Table 5) are characteristic of the MN16B-MN17 zones indicating a Gelasian age. A single molar of a Gelasian vole *Mimomys tigliensis* was found in sample 38.00 - 38.25 m. More material was found in residues taken additionally to the studied metre samples from interval 40.00 - 45.00 m (Table 5). The presence of these vertebrate fossils and *Lymnaea* (in sample 37.00 - 38.00 m) indicate a terrestrial / fresh water depositional settings in the top of the Formation.

The Maassluis Formation in the Schelphoek borehole is characterised by well-developed sequences with sterile sands at the base. Today, a deep tidal channel occurs close to the study area and the Late Quaternary deposits are riddled with channel fills. Because of the terrestrial intervals, as well as the regular recurring facies successions, the Maassluis Formation

Table 5. Mammal fossils in the Schelphoek borehole. Identifications by L. van den Hoek Ostende and D. Mayhew. The 40.00-45.00 m sample is a large sediment sample that was collected in addition to the metre samples during the drilling.

Depth (m b.s.)	Mammal taxa	Molar
33.00 - 34.00	*Mimomys reidi*	M2
38.00 - 38.25	*Mimomys tigliensis*	m1 damaged
40.00 - 45.00	*Mimomys pliocaenicus*	M2
40.00 - 45.00	*Mimomys tigliensis*	M1
40.00 - 45.00	*Mimomys pliocaenicus*	m2 fragment
40.00 - 45.00	*Mimomys reidi*	M1 fragment
40.00 - 45.00	cf. *Micromys*	i1

sequences cannot be the result of stacked channel fills. Furthermore, in other boreholes in the region (unpublished data) we have found very similar, likely correlatable sequences in the Maassluis Formation, suggesting a wider regional extent of the sequences. A major surprise was the discovery of three sequences (MS 1, MS 2 and MS 3) yielding molluscs of the mollusc zone Mol B in the base of the Maassluis Formation (an interval from 73.00 to 109.00 m). The Mol B fauna presumably represents the Praetiglian, a short period in which the first three very strong glacial cycles with corresponding glacio-eustatic sea-level cycles occurred. The presence of Mol B molluscs allows for the possibility that the three sequences correspond to the three Praetiglian glacial cycles (MIS 96, MIS 98 and MIS 100) that have been recognised in boreholes from the northern Dutch continental platform (Kuhlmann, 2004; Kuhlmann et al., 2006a, 2006b) and in the eastern part of the Netherlands (Jansen et al., 2004b). However, the mollusc zonation as proposed by Spaink (1975) is in need of update, and our assignment of the three sequences to the Praetiglian is in need of further confirmation. The Praetiglian corresponds to the base of the Gelasian stage. This interval has left highly characteristic and well recognisable signatures in the central North Sea Basin (logunits 7 - 9: Kuhlmann et al., 2006a, 2006b), the western (Meijer et al., 2006) and eastern Netherlands (Jansen et al., 2004a, 2004b). All three cycles seem to be traceable as far south as the Schelphoek area. The massive reworking of Pliocene strata and faunas observed in the lower 5.25 metres of the Maassluis Formation (103.75 - 109.00 m) (the base of the lowest Maassluis sequence MS 1) should represent a drastic increased input of eroded Pliocene deposits that were outcropping in the area, presumably at the onset of the first very strong glacially induced sea-level drop around MIS 100 (2.55 Ma). The maximum depth reached in the lower four sequences in the Maassluis Formation decreases. Possibly this represents a massive increase in sedimentation in the area. It also may imply that the fourth sequence (MS 4) corresponds to the lowermost 'Tiglian' highstand (MIS 95; base of logunit 10 of Kuhlman et al., 2006a, 2006b).

Apart from the fourth Maassluis Formation sequence (MS 4), which may be the basal 'Tiglian' cycle (MIS 95), the exact age of the upper three Maassluis Formation sequences are difficult to establish, other than Gelasian. The age of mammal faunas that probably stem from the upper or second upper sequence have been estimated to be around 1.9 Ma (see below). Within the Maassluis Formation of both the onshore (Jansen et al., 2004b) and offshore parts of the Netherlands (Kuhlman et al., 2006a, 2006b), numerous stacked, prograding sequences have been documented, that have a limited regional distribution. Nevertheless, the presence of marine settings in the upper three sequences requires high base levels. Relatively high eustatic sea-levels around or before 1.9 Ma can be deduced from $\delta^{18}O$ spikes (Tiedemann et al., 1994) to have occurred during MIS 93, MIS 91, MIS 87, MIS 75, MIS 73, MIS 69 and MIS 67.

With the exception of the lowermost sequence, all Maassluis Formation sequences contain a terrestrial (aeolian) basal interval, and possible fluvial conditions have occurred during deposition of parts of sequences five (MS 5) and six (MS 6). These intervals might be assigned to the Waalre Formation (also known by its older name Tegelen Formation), which represents terrestrial to very proximal marine deposits that are partially coeval with the marine Maassluis Formation. Both formations are known to interdigitate (Van Rummelen, 1970; Weerts et al., 2000). All possibly terrestrial intervals occur within sequences dominated by assumed marine settings (with the exception of the uppermost truncated sequence). Therefore we have assigned all deposits to the Maassluis Formation.

?Eem Formation (29.00 - 36.00 m)

The deposits consist of fine-grained to medium-grained grey micaceous slightly silty arenite. Plant detritus and small wood fragments are abundant. Molluscs are common in samples 29.00 - 34.00 m. The faunas are dominated by *Cerastoderma edule* and *Macoma balthica*. Some abraded and discoloured species, apparently reworked from older deposits (*Yoldia* sp.), occur in this interval as well, as well as a single specimen of the freshwater gastropod *Lymnaea* in sample 33.00 - 34.00 m. A single molar (M2) of a vole *Mimomys reidi* was found in the same sample. This tooth is presumably derived from underlying deposits of the upper part of the Maassluis Formation. The unit was deposited in near-coastal to estuarine settings in the proximity of land and river. This interval is attributed with some hesitation to the Eem Formation. In the study area similar interglacial perimarine deposits (fine-grained to medium-grained arenites containing mollusc species: *Cerastoderma edule* and *Macoma balthica*) have been found that are of late Middle Pleistocene age and cannot be distinguished with certainty from the Eem Formation (T. Meijer, pers. comm.).

A major hiatus (of approximately 1.7 - 1.8 Ma) exists between the Maassluis Formation and the ?Eem Formation in the Schelphoek borehole. As mentioned above, we are not certain whether we deal with the Eem Formation, since similar interglacial deposits bearing warm temperate faunas of late Middle Pleistocene age have been demonstrated elsewhere in the Netherlands (Meijer, 2003). The bivalve *Corbicula fluminalis*, mentioned by Van Rummelen (1970) from the Schouwen Formation (here referred to as ?Eem Formation), is in fact a Middle Pleistocene indicator (Meijer & Preece, 2000), that is often found reworked in the base of the Eem Formation (T. Meijer, pers. comm.). The age of the ?Eem Formation is therefore uncertain in the region as yet.

Boxtel Formation (23.00 - 29.00 m)

The deposits consist of fine-grained to medium-grained grey sand with intercalations of medium-grained silty sand layers. The sands are non-calcareous. Plant debris is very common. Very rare small shell fragments include marginal marine *Hydrobia* dominated faunas which possibly have been contaminated from overlying intervals. Two units are distinguished in this interval: a medium-grained (250 - 350 µm), light grey-brown arenite with predominantly sub-angular and angular grains in interval 27.00 - 29.00 m and a slightly more silty, grey, fine-grained to medium-grained (180 - 250 µm) arenite with predominantly sub-rounded and rounded grains in interval 23.00 - 27.00 m. The Boxtel Formation represents aeolian and possibly some fluvial deposition in cold climate settings (Schokker, 2003).

Naaldwijk Formation (0.00 - 23.00 m)

The Naaldwijk Formation is composed of fine-grained light-grey arenites with common plant debris, and a middle interval of light-grey sandy clay. Shell debris and shells occur in variable amounts. Three successive units (Table 3) form a single depositional sequence. A basal unit (17.00 - 23.00 m) is dominated by fine-grained arenites with very common plant debris and marginal-marine molluscs. This interval is interpreted to reflect the basal part of a channel fill. Van Rummelen (1970, fig. 23) has shown a 30 cm thick layer of (Preboreal) peat at the base of the Holocene succession. The basal unit fines upward into a thick interval (1.50 - 17.00 m) of clays and fine-grained arenites. Rare brackish-water molluscs (including *Scrobicularia plana*) are found in interval 8.00 - 17.00 m. The overlying interval contains shallow-marine molluscs (*Peringia ulvae*, *Cerastoderma* sp.), mixed with few terrestrial snails from 5.00 m upwards. The upper 1.50 m is considered the ploughed layer and contains terrestrial as well as marginal marine molluscs. The lowermost unit represents a subtidal channel fill and the middle unit a high-intertidal to supratidal mudflat.

Discussion

Evidence for substantial reworking of older sediments and fossils into the basal parts of formations and sequences is found in the borehole. At the base of the Oosterhout Formation and in the base of the Maassluis Formation this led to a predominance of lithoclasts (and fauna elements) from older formations, to such extent that the lower interval of, e.g., the Maassluis Formation is amply recognisable based on lithology. Reworking of older sediments and fossils during transgression, in shallow agitated coastal areas or in tidal-channel floor settings is a common phenomenon in shallow basin margins such as the southern North Sea Basin. However, the extent of reworking is large. From the Schelphoek borehole data it is suspected that formation boundaries in boreholes in the southern North Sea Basin might easily be misinterpreted because of the possible occurrence of massively reworked older intervals. Purely based on lithostratigraphic arguments (very high shell content) one could argue to locate the boundary between the Oosterhout and Maassluis Formation on top of the shelly sands (103.75 - 109.00 m b.s.) in the lowermost part of the Maassluis Formation. However, we locate the lower boundary of the Maassluis Formation at the base of this layer at 109.00 m b.s. The lag (103.75 - 109.00) (unit MS F, Table 3) consists of shelly medium-grained sands that differs subtle in respect with grain-size, preservation and shape of bioclasts and more greyish colour from underlying deposits of the Oosterhout Formation (unit OO A, Table 3).

Inconsistencies exist in respect with formation boundaries and the biostratigraphical boundaries in the works of Doppert (1980) and Doppert et al. (1975 and 1979) and in this paper. In the works of Doppert (1980) and Doppert et al. (1975 and 1979) the faunal content has been taken into account for the definitions of the lithostratigraphic units. In these works the faunal boundary FA2/FA1 characterises the lithostratigraphic boundary between the Oosterhout Formation and the Maassluis Formation. In our study we use lithological features for the lithostratigraphic subdivision (following Weerts et al., 2000). The lowermost part of the Maassluis Formation at Schelphoek (sequence 1 - 3) contains foraminifers of the sub-zone FA2 and the boundary between the Oosterhout Formation and the Maassluis Formation is located within this sub-zone. According to Doppert et al. (1979) the boundary FA2/FA1 corresponds to the top of the Lillo Formation in the Antwerp area that is of the Piacenzian age. In our study this boundary is located between the sequences MS 3 and MS 4 within the Gelasian. Gelasian age is indicated by molluscs and is in accordance with the position of this biostratigraphic boundary in Kulhmann (2004).

The Schelphoek borehole is only 500 m from the localities of the Gelasian fauna at the floor of the Oosterschelde Estuary (De Vos et al., 1995, 1998; Reumer et al., 1998, 2005; Van Kolfschoten & Laban, 1995). The preservation of this Oosterschelde fauna suggests that there was no long distance transport and the fauna must therefore originate from the local sources. The concordance of the fossil molluscs (Wesselingh et al., 2003) from the same localities in the Oosterschelde with the faunas in borehole Schelphoek (both in species composition as well as taphonomic characteristics) confirm this. Structural dip of the strata in the area is very low, and therefore the vertebrate faunas from the Oosterschelde floor must correspond to those found in the top of the Maassluis Formation interval (sequence MS 6 and possibly the eroded parts of sequence MS 7) in borehole Schelphoek.

The terrestrial fauna originates from a moderately warm period (De Vos et al., 1998) within the late Gelasian and overlays marine intervals assigned to foraminiferan subzone FA1. According to Kuhlmann (2004), the uppermost part of the subzone FA1 falls within the Olduvai subchron, the onset of which is correlated with the warm period MIS 71 with an age of about 1.942 Ma, corroborating an age estimate of approximately 1.9 Ma for the mammal fauna by De Vos et al. (1998).

Conclusions

The Schelphoek borehole (42G4-11/42G0022) contains the stratigraphic record of Early Oligocene to Quaternary deposits represented by seven formations. The Miocene-Early Pliocene Breda Formation and the Late Pliocene Oosterhout and Maassluis Formations are subdivided in depositional sequences that are correlated with the successions of the Antwerp region to the south and the central North Sea Basin to the north. From our data it appears to be feasible and useful to subdivide the Breda Formation into members that are correlatable to sequences encountered in the Antwerp area to the south, and to use the Belgian terminology for these members (Antwerpen, Deurne and Kattendijk Member respectively) (Fig. 2). In general, depositional environments during the Neogene were shallowing, and a deterioration of climate from warm temperate to subtropical in the Miocene to a strong glacial-interglacial cyclicity in Gelasian intervals is recorded in the borehole. Massive reworking at the base of the Oosterhout, Maassluis and the post-Gelasian Formations has complicated the exact definition of lower boundaries of the formations. Glacial sequences with a basal aeolian facies are well developed in the Maassluis Formation of borehole Schelphoek. The Gelasian vertebrate faunas from the famous Oosterschelde localities some 500 m to the south of the borehole are attributed to the upper or second-upper sequence of the Maassluis Formation.

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