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Characterization of the Miocene successions in the Schoten borehole (southern North Sea Basin, northern Belgium) and regional correlation with the Netherlands

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Abstract

The integration of geotechnical and geophysical well logs, along with biostratigraphic and sediment analyses of borehole Schoten (northern Belgium), provides a better characterization of the glauconite-rich sandy Miocene successions near their type sections. It also provides a way to correlate the latter with more distal areas along the southern North Sea Basin. In the Schoten area, the Rupelian Boom Formation is unconformably overlain by the Lower to Middle Miocene Berchem Formation, which is in turn unconformably overlain by the Upper Miocene Diest Formation (Borsbeek Member). The Berchem Formation is formally subdivided into the Edegem, Kiel and Antwerpen members, which can be identified on the gamma-ray log of borehole Schoten. Sediment analyses show that the glauconite content and the local presence of phosphatic nodules are the main factors contributing to the fluctuating gamma-ray values. For the first time, the geophysical log signatures of the members of the Berchem Formation were correlated across large areas and major fault systems, which shows the regional significance of the boundaries between these members. Indeed, the boundary between the Edegem Member and the Kiel Member corresponds with the boundary between the Dutch Veldhoven and Groote Heide formations, known as the Early Miocene Unconformity. The overall higher gamma-ray values for the middle Miocene Antwerpen Member and equivalents in the upper part of the Dutch Groote Heide Formation are likely related to the eustatic sea level highs during the Miocene Climatic Optimum.

1. Introduction

The lower to middle Miocene Berchem Formation and upper Miocene Diest Formation in the shallow subsurface of the city of Antwerp (Fig. 1) have been described in detail in numerous temporary outcrops (e.g. De Meuter *et al.* 1976; Bosselaers *et al.* 2004; Everaert *et al.* 2020, 2024; Goolaerts *et al.* 2020). These outcrops served as stratotype sections for several stratigraphic members (De Nil & Verhaegen, 2023). The outcrop samples have been subjected to many biostratigraphical (Louwye *et al.* 2000, 2010; Everaert *et al.* 2020, 2024; Goolaerts *et al.* 2020) and sedimentological analyses (Bastin, 1966; Goolaerts *et al.* 2020; Deckers *et al.* 2023), and were correlated with cone penetration tests (CPTs) for geotechnical studies (Deckers & Everaert, 2022; Deckers & Goolaerts, 2022). The abovementioned units were not characterized on geophysical logs in the stratotype area near the city of Antwerp, so their geophysical expressions remain unknown. This is unfortunate since it would help to better characterize the stratigraphic units and their boundaries. It would also be beneficial for correlation purposes, especially towards the areas further north in the Antwerp Campine area where the Berchem and Diest formations are located deeper in the subsurface and are only known from boreholes. In the latter area, the Berchem Formation remains stratigraphically undifferentiated (Louwye *et al.* 2020). Nevertheless, in deep boreholes with wireline logs in the southernmost Netherlands (such as Goirle and Heeswijk in Fig. 1), about 50 km to the northeast of the city of Antwerp area, Munsterman *et al.* (2019) identified important stratigraphic boundaries within the lateral equivalents of the Berchem and Diest formations (Veldhoven, Groote Heide and Diessen formations), and associated them with regional unconformities. Until now, correlating these boundaries and unconformities from the Netherlands towards the city of Antwerp area remained very tentative.

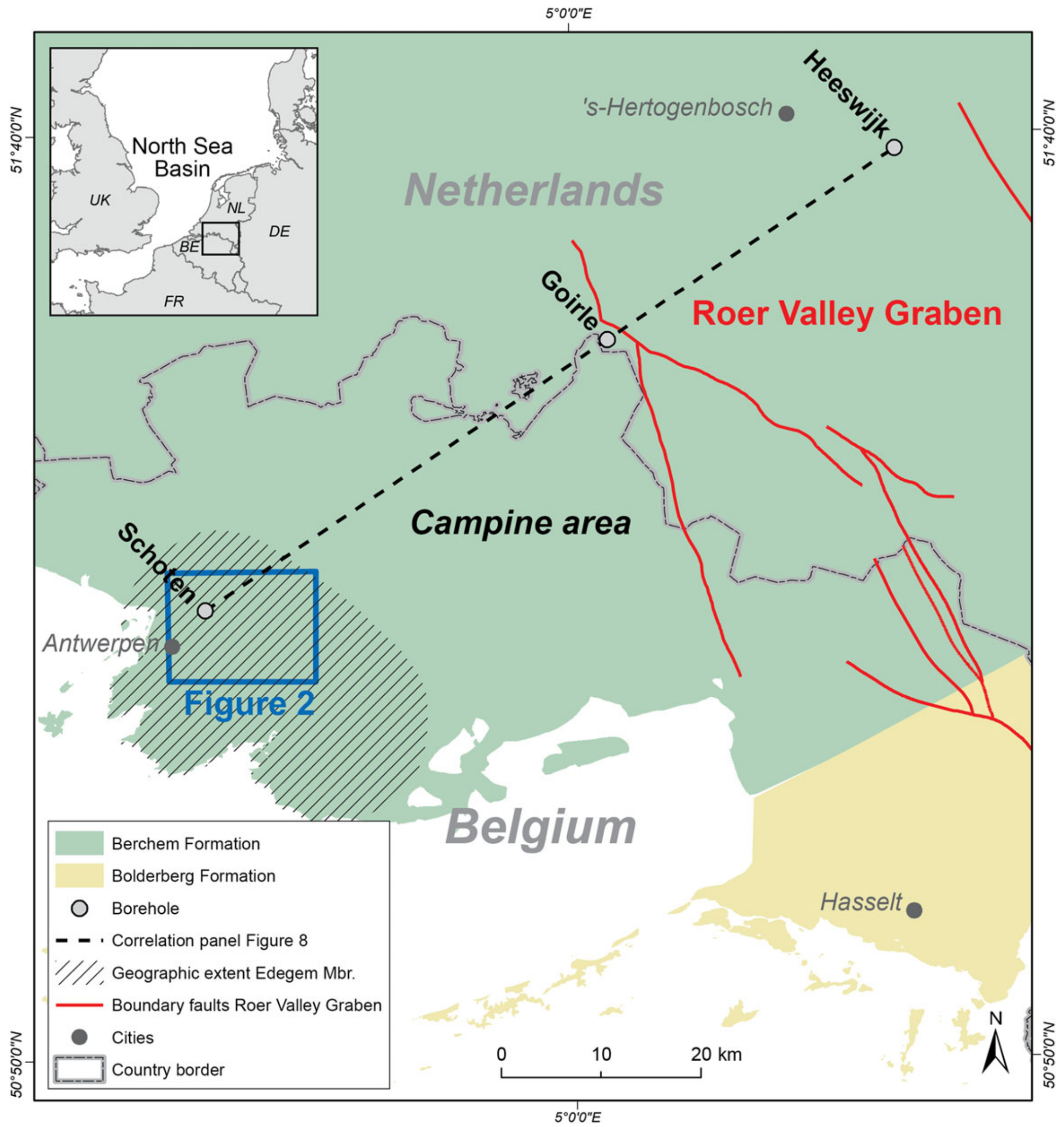

Figure 1. Map of the geographical distribution of the lower to middle Miocene stratigraphic units in the subsurface of northern Belgium (based on the G3Dv3-model, see Deckers *et al.* 2019) and the southern Netherlands. The study area (Fig. 2) around the Schoten borehole is indicated with a square. The correlation panel of Fig. 8 from the Schoten borehole towards the Goirle and Heeswijk boreholes is also indicated. The latter boreholes were analyzed by Munsterman *et al.* (2019).

To solve these issues, a research borehole was recently drilled and logged in Schoten (Figs. 1 and 2), which is located just northeast of the city of Antwerp. The location was chosen to be close to the stratotype area where the Berchem Formation is well developed and all members are present. The Berchem Formation is covered by a few metres of the Diest Formation and within the standard depth range of CPTs (< 50 m). For the first time, logging enabled the geophysical characterization of the members of the Berchem Formation near their stratotype areas. It also enables a first correlation with equivalent deposits in the southernmost Netherlands as described by Munsterman *et al.* (2019). This correlation is further supported by biostratigraphic analyses with dinoflagellate cysts (dinocysts) of samples from the Schoten core. To support the lithostratigraphic interpretations and to better interpret the geophysical expressions, also the granulometry, glauconite and carbonate content of the core samples were analysed. Just next to the Schoten borehole, an electric CPT was carried out for geotechnical characterization of the Miocene successions and correlations with the stratotype sections of the members of the Diest Formation in the east of the city of Antwerp. The integration of all newly acquired and older data, analyses and documentation will further elucidate the Lower to Upper Miocene successions within and north of the city of Antwerp. It also results in new insights on the late early Miocene to early middle Miocene relative sea-level changes in the area which are correlatable with the eustatic sea-level changes.

2. Stratigraphic background

In the Antwerp area, the glauconitic green to blackish sands of the Berchem Formation were deposited during the Burdigalian, Langhian and Serravallian (Louwye *et al.* 2000) (Fig. 3). The sands

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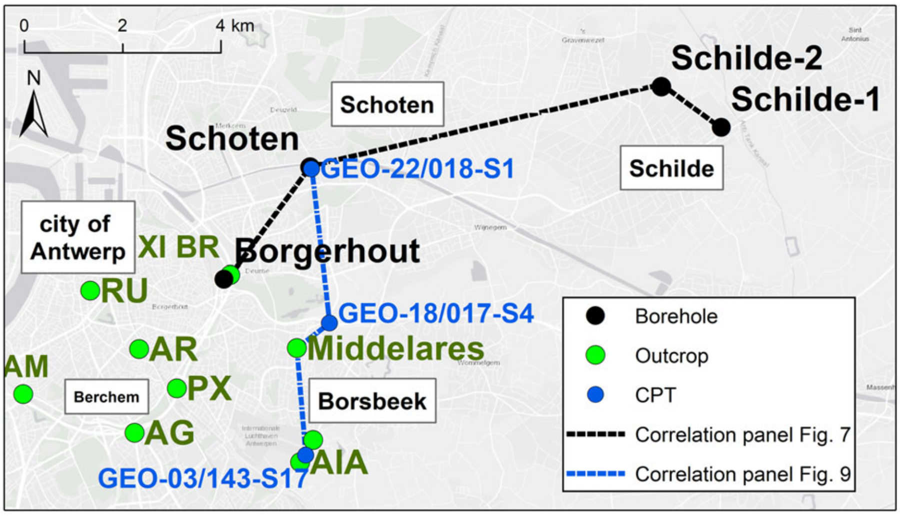

Figure 2. The study area around the Schoten borehole, with the different correlation panels between boreholes, CPTs and outcrops (Figs. 7 and 9). AG = Antwerpen Grote Steenweg; AIA= Antwerp International Airport; AM = Antwerpen Motignystraat; AR = Argenta; PX = Post X; RU= Rubenshuis; XI BR = Borgerhout; CPTs = cone penetration tests.

are fine to medium fine-grained, often slightly clayey/silty and rich in shells (De Meuter & Laga, 1976; Deckers *et al.* 2023). Horizons with sandstone pebbles and shell beds or crags are recorded throughout the formation. Antwerp is the type area of the Berchem Formation, and the Edegem, Kiel and Antwerpen members were formally described in temporary outcrops by De Meuter *et al.* (1976) and formalized by De Meuter and Laga (1976).

The Edegem Member was deposited during a major transgression in the early Burdigalian and lies unconformably on the Oligocene Boom Formation (Louwye *et al.* 2000; Louwye, 2005; Fig. 3). The Edegem Member consists of dark green, glauconiferous, clayey fine-grained sands with molluscs (De Meuter & Laga, 1976). The Edegem Member passes generally without a basal gravel layer (De Meuter & Laga, 1976; Gaemers & De Ceuster, 1978) upwards into the Kiel Member. The Kiel Member forms a particular unit of the Berchem Formation, as it often lacks fossils in the southern part of the city of Antwerp area (De Meuter & Laga, 1976; Gaemers & De Ceuster, 1978). Recent studies have, however, shown that the Kiel Member contains some fragile shell beds, dominated by *Glycymeris obovata baldii*, further north in the city (De Schutter & Everaert, 2020; Everaert *et al.* 2020; Everaert *et al.* 2024). Compared to the Edegem Member, the Kiel Member is much richer in glauconite and less silty and clayey (on average 3% silt and <1% clay in outcrops according to Deckers *et al.* 2023). The Kiel Member also frequently contains sandstones (De Meuter *et al.* 1976; Herman & Marquet, 2007; Everaert *et al.* 2020), and has a middle to late Burdigalian age (Louwye *et al.* 2000, 2020; Fig. 3). The Kiel Member is covered by the Antwerpen Member in the central and northern Antwerp city area. The Antwerpen Member is very fossiliferous with numerous well-developed shell beds (De Meuter *et al.* 1976) that can be correlated across the entire city of Antwerp, as shown by Deckers & Everaert (2022). Besides the presence of shells and shell beds, the lower part of the Antwerpen Member is also generally siltier than the Kiel Member (16% silt fraction in outcrops according to Deckers *et al.* 2023), which is expressed as a distinct colour difference in dry outcrops, as the dark green to blackish Antwerpen Member contrasts with the more greyish Kiel Member (Everaert *et al.* 2020). Dinocyst analyses by Louwye *et al.* (2000) showed that the main body of the Antwerpen Member has a Langhian age, and only the topmost section reached into the Serravallian (Louwye *et al.* 2020; Fig. 3). Compared to the Kiel Member, sedimentation rates in the Antwerpen Member were more than halved (Deckers & Everaert, 2022).

After a late Serravallian sea level lowering corresponding to the Mid-Miocene Unconformity, (Munsterman *et al.* 2019), northern Belgium was flooded again and covered by the shallow marine, grey-green to brownish, glauconiferous, mostly coarse-grained sand with sandstones of the Diest Formation (Houthuys *et al.* 2020; Fig. 3). The Diest Formation in the Antwerp area is differentiated into a lower Borsbeek Member and upper Deurne Member, the first being more enriched in the <128 μm fraction and having less glauconite compared to the latter (Goolaerts *et al.* 2020). Deckers and Goolaerts (2022) characterized the Borsbeek and Deurne members on CPTs at the stratotype of the Borsbeek Member near the Antwerp International Airport. The CPT correlations showed – in support of the outcrop sections – that the Borsbeek Member incised into the Antwerpen Member, whereas the Deurne Member in its turn incised the Borsbeek Member and locally completely removed it. The Borsbeek and Deurne members have a middle Tortonian age (Fig. 3), which is approximately time-equivalent to the lower half of the Dessel Member in the subsurface of the Campine area (Goolaerts *et al.* 2020).

After the latest Miocene sea-level fall and associated hiatus (the Late Miocene Unconformity; Munsterman *et al.* 2019), the Diest Formation was unconformably overlain in the Antwerp area by the Lower Pliocene glauconite and shell-bearing fine-grained sand of the Kattendijk Formation (De Meuter *et al.* 1976; Fig. 3). Correlation of CPTs north of the City of Antwerp indicates that the Kattendijk Formation progressively truncates the subjacent units in western direction (Deckers & Louwye, 2020).

3. Dataset and methods

3.a. Schoten borehole and CPT

The Schoten borehole (DOV 1411-GEO-22/019-B1) was drilled in 2022 by order of the Department of Mobility and Public Works of the Flemish Government. The gamma-ray and resistivity logs were ordered by the Planning Bureau for the Environment and Spatial Development (Department of Environment) of the Flemish Government. The borehole reached a total depth of 50 m (Fig. 4). Sonic drilling with cores of 3 m length was applied. Cores were cut into 1 m lengths and stored in the Geotheek of the Flemish Government at Vilvoorde. In August 2022, the cores of the borehole were lithologically described and lithostratigraphically interpreted by the authors of this study.

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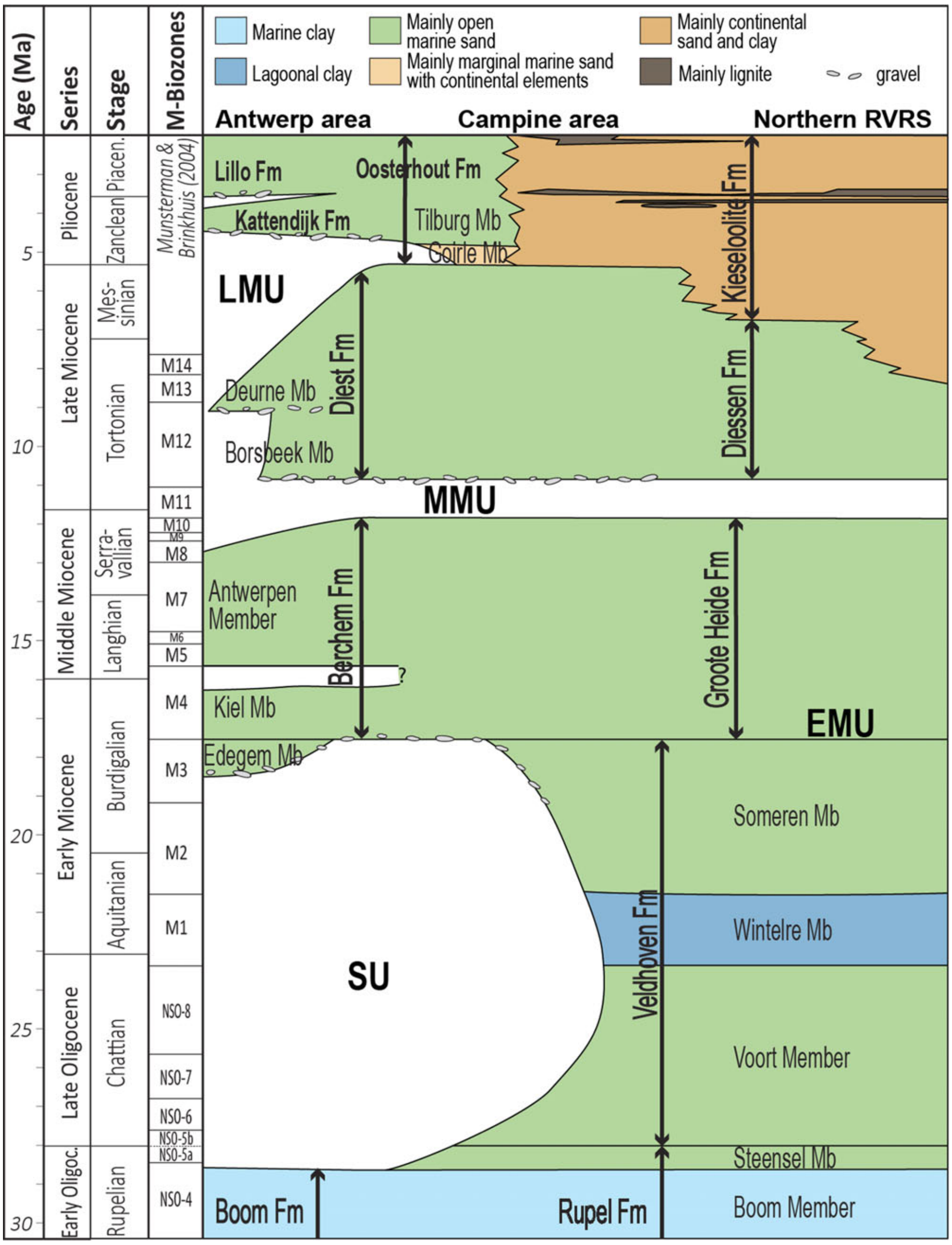

Figure 3. Overview of the Miocene litho- and biostratigraphy from the city of Antwerp (Belgium) in the west towards the northern Roer Valley Rift System (Netherlands) in the northeast. This figure is updated from Munsterman *et al.* (2019). EMU = Early Miocene Unconformity; LMU = Late Miocene Unconformity; MMU = Middle Miocene Unconformity; SU = Savian Unconformity.

An electric CPT (DOV GEO-22/018-S1) was carried out at a distance of 17 m from the borehole location and reached a depth of 50.5 m. The CPT data comprise cone resistance (qc), sleeve friction (fs) and the friction ratio (R_f) logs (Fig. 4).

The abovementioned data as well as other datapoints in Flanders (northern Belgium) mentioned in this study are available at https://www.dov.vlaanderen.be/data/opdracht/2024-042359

3.b. Core sample analyses

A total of 21 samples were taken from the cores of borehole Schoten for further analyses (Fig. 5). Eighteen of these samples were taken from the Berchem Formation and three from the superjacent Diest Formation. All samples were subjected to granulometric (using laser diffraction), glauconite (using Frantz Isodynamic Magnetic Separator) and carbonate content analyses (Supplementary Table 1). In addition, five samples were subjected to X-ray diffraction (XRD) analyses.

Ten samples were chemically macerated for a palynological analysis: nine from the Berchem Formation and one from the superjacent Diest Formation (Fig. 5). The carbonates and silicates of thirty grams of sediments were removed through acid treatment with HCl and HF, respectively. The remaining organic residue was filtered on a nylon screen with a 10 µm mesh size and mounted with glycerine jelly. The slides were scanned in non-overlapping traverses under a 200x magnification on a transmitted light microscope until 250 palynomorphs were counted. The rest of the slide was then scanned for rare specimens for photomicrography. The dinocyst biozonations of Dybkjær and Piasecki (2010), Munsterman and Brinkhuis (2004) and de Verteuil and Norris (1996) are applied and

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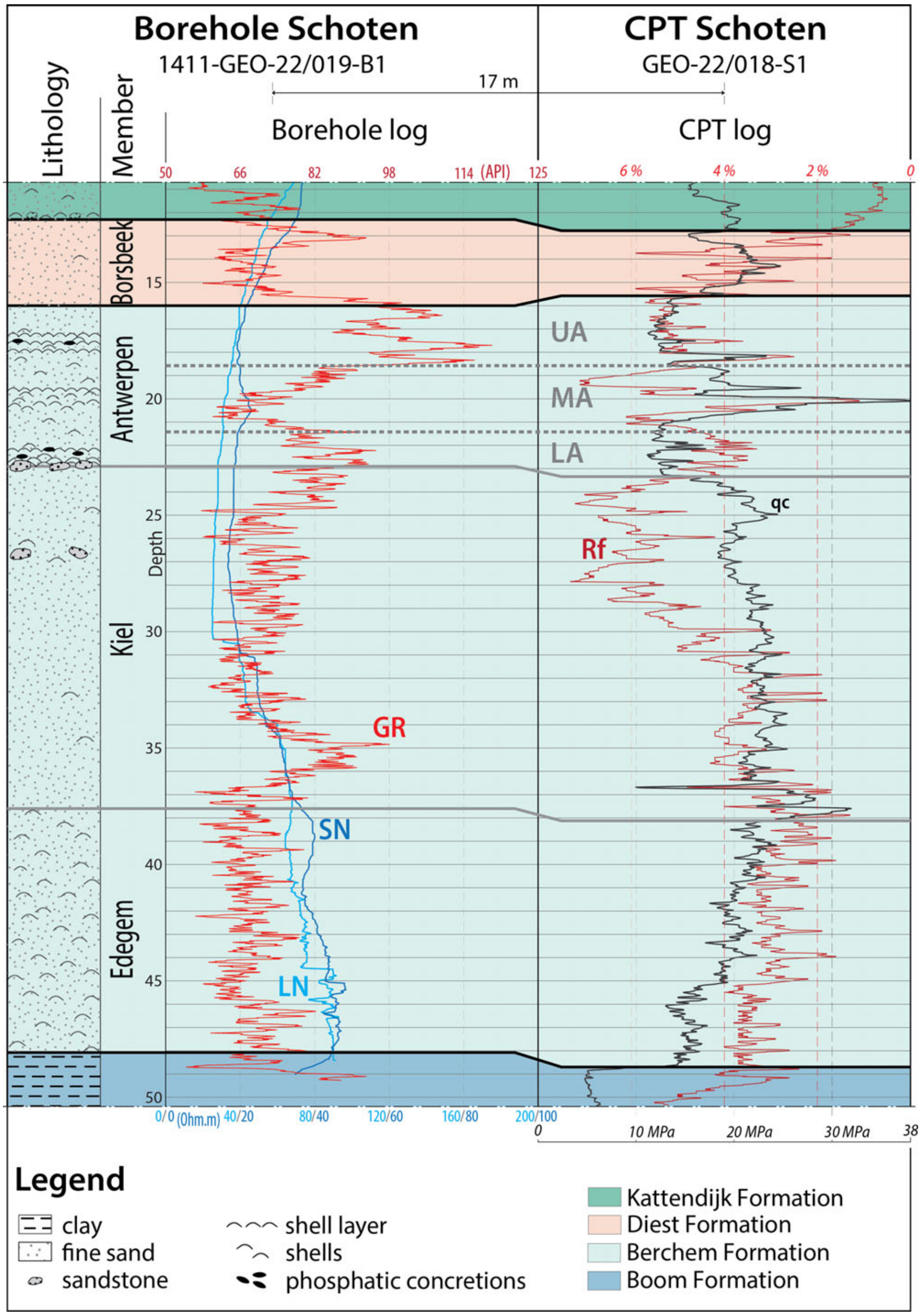

Figure 4. Logs of the cores and cone penetration test of Schoten with the lithological column and lithostratigraphic interpretations. LA, MA and UA represent the informal lower, middle and upper units of the Antwerpen Member.

discussed, as these have been used during the last decades for analyses in the southern North Sea Basin (Fig. 6).

4. Interpretation of the core and CPT of Schoten

4.a. Edegem Member – Berchem Formation

The Schoten core comprises between 48 m and 37.6 m depth olive grey, glauconite-rich, silty, fine-grained sands. Molluscs are dispersed in the matrix or as shell grit, rather than as shell beds (Fig. 4). Compared to the shells of the Antwerpen Member, which is characterized by plenty of large *Glycymeris obovata baldii*, the shells in the Edegem Member are smaller. Fragments of typical Edegem Member molluscs were identified at 41.4–42 m depth, including *Glossus lunulatus* spp. and *Ennucula haesendoncki hanseata*. The Edegem Member rests upon the clay and silt of the Rupelian Boom Formation (between 50 m and 48 m depth). The upper boundary of the Edegem Member with the Kiel Member is placed at a level where the fine shell fragments disappear and carbonate content is reduced to almost zero (Fig. 5). The glauconite content also increases upwards at this boundary, which is expressed by a change in sediment colour from greenish grey to greyish green. The Edegem Member is characterized by relatively uniform gamma-ray and

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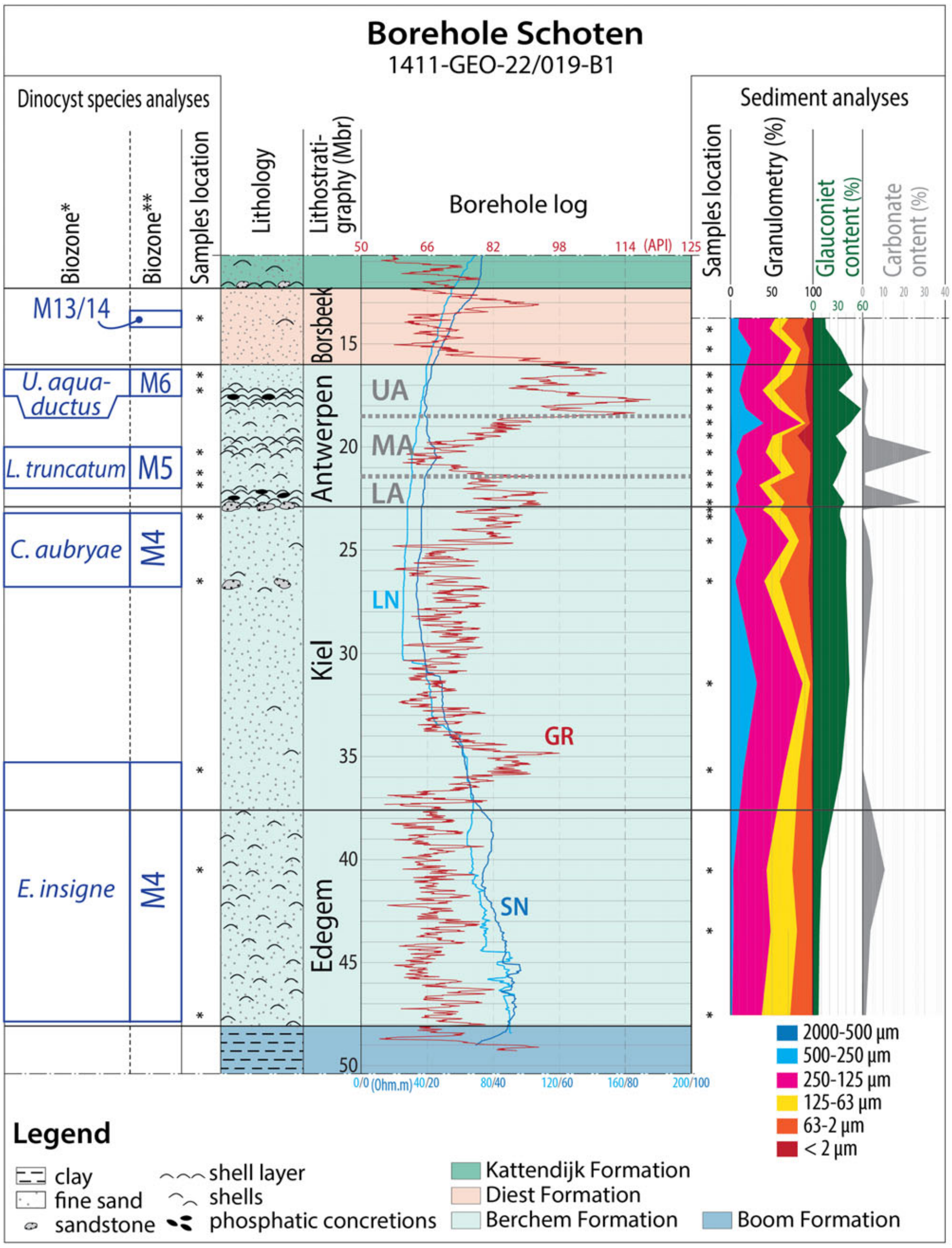

Figure 5. The borehole core of Schoten with results of the biostratigraphic and sediment analyses. For details on sediment analyses, see Supplementary Table 1. Biozone schemes * and ** are after Dybkjær and Piasecki (2010) and Munsterman and Brinkhuis (2004), respectively. For details on the biostratigraphic analyses, see Supplementary Table 3. LA, MA and UA represent the informal lower, middle and upper units of the Antwerpen Member.

SN resistivity values (Fig. 4), which is consistent with the relatively uniform < 63 µm fraction and glauconite content in the samples of this unit, ranging between 19.5% and 27.8% and between 6.6 and 10%, respectively (Fig. 5). The glauconite values are much lower than the averages in the superjacent Kiel and Antwerpen members (see below), which explains the relatively low gamma-ray and Rf values for the Edegem Member. The qc values show an increase from 14 MPa at the bottom towards 24 MPa just below the top. This probably corresponds to an upward increase in grain size, but the three granulometric analyses of this member show that local variations are present on top of this trend.

4.b. Kiel Member – Berchem Formation

Dark green-grey to olive-grey, glauconite-rich, silty, fine-grained sand is present between 37.6 m and 23 m depth (Fig. 4). Molluscs are rare and, if present, they are heavily weathered due to corrosion and partial dissolution (*Glycymeris obovata baldii* observed at 34.5–35 m; 26.53–26.56 m and 24.55–25 m depth). The carbonate content in the samples of the Kiel Member is overall low (<4%) and sometimes 0% (Supplementary Table 1). The upper boundary with the Antwerpen Member is placed where the number of molluscs and overall carbonate content sharply increases upwards (Fig. 5). This level is located on top of a 15 cm thick interval comprising small sandstone nodules (Fig. 4), which may (partly) represent lithified *Ophiomorpha* that are often observed in the top section of the Kiel Member (Everaert *et al.* 2020). At 3.5 m below the top of the Kiel Member, a layer (7 cm) with carbonate cemented sandstone and some remains of *Glycymeris obovata baldii* is present (Fig. 4). The glauconite content of the Kiel Member ranges between 32.5% and 44.5% (Fig. 5).

The gamma-ray and qc patterns of the Kiel Member show several cycles of upward-increasing and upward-decreasing values,

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which, in accordance with the granulometric analyses, seem indicative of coarsening and fining upward trends (Fig. 5). However, the vertical granulometric sampling resolution is too low for detailed analyses. In any case, the typical relatively coarse facies of the Kiel Member (3% of < 63 µm fraction) as described and granulometrically analysed in several outcrops in the city of Antwerp (Everaert *et al.* 2020; Deckers *et al.* 2023) is only observed between 34 and 31 m depth, which indeed holds the coarsest sample of the Kiel Member of the Schoten core (at 31.4–31.5 m depth).

4.c. Antwerpen Member – Berchem formation

Between 23 and 16 m depth, dark to black-green, fine-grained glauconite-rich, silty sand is present. The molluscs, either dispersed or concentrated in distinct shell beds, are dominated by stacked *Glycymeris obovata baldii* (Fig. 4). Two levels with some phosphatic concretions are observed (at 22.2–22.55 m and 17.5–17.75 m depth). Phosphatic concretions are composed of apatite, which explains the presence of 6.6% of apatite in the sample at 22.65–22.7 m according to XRD analyses. The upper boundary with the Diest Formation coincides with an upward colour transition from very dark green-grey towards very dark grey-green sand.

Compared to the Kiel Member, the Antwerpen Member shows overall higher gamma-ray values. Glauconite analyses show that the highest gamma-ray values (> 100 API) correspond to the sample with the highest glauconite content (58.2% at 18.1–18.2 m). Glauconite content alone, however, doesn't explain the gamma-ray pattern: the samples at 22.65–22.7 m and 20.15–20.35 m have similar glauconite content, but the latter has higher gamma-ray values compared to the first (Fig. 5). This can be explained by the presence of apatite only in the latter sample. Apatite typically contains uranium and could therefore explain the relatively elevated gamma-ray values despite similar glauconite contents.

The gamma-ray and resistivity patterns, but also the geotechnical qc values, show a threefold subdivision within the Antwerpen Member with a lower and upper section with (very) high gamma-ray and low SN resistivity/qc levels and a middle section with lower gamma-ray and higher SN resistivity/qc values (Fig. 4). This subdivision is hereafter informally referred to as lower, middle and upper units of the Antwerpen Member (LA, MA and UA on Figs. 4 and 5). The differences in gamma-ray values are thus related to differences in glauconite and/or apatite content. The changes in resistivity and qc values are related to the granulometric changes. Indeed, the finest samples with about 50% of < 63 µm fraction are in the lower and upper units of the Antwerpen Member (at 17.2–17.3 m and 21.8–21.9 m, respectively), whereas the coarsest sample with only 9% of < 63 µm fraction is located in the middle unit of the Antwerpen Member (at 18.8–18.9 m; Fig. 5).

The lower and upper units of the Antwerpen Member appear consistently relatively enriched in clay and silt content with low resistivity and qc values, but the middle unit of the Antwerpen Member shows very strong variations in grain size and qc trends. On top of the background values, several spikes in the qc values are present (Fig. 4). Deckers and Everaert (2022) noted a very similar pattern of qc spikes in the Antwerpen Member in the northern part of the city of Antwerp, which they correlated largely with shell beds. Also for the Schoten CPT, several of the qc spikes are correlative with shell beds in the Antwerpen Member. The most pronounced qc spike for the Antwerpen Member was correlated by Deckers and Everaert (2022) with an often compact interval composed mainly of *Glycymeris* beds, the so-called *S3 – Glycymeris crag*. At the estimated level of this *S3 – Glycymeris crag* in the Schoten core (ca. 19.9 m to 20.75 m based on the nearby CPT), however, no thick shell accumulation was observed. Unfortunately, core samples at this level have a lower preservation and are heavily disturbed, which could be caused by the removal of the shells during drilling. Indeed, the shell fragments observed at the level of the *S3-Glycyermis crag* were all crushed (<1 cm), which is not the case in temporary outcrops. The sample taken from this interval does have a high carbonate content of 33% and this is the highest value of all samples of the Schoten core.

The correlation between CPTs near the type sections of the Kiel and Antwerpen members in the city of Antwerp area by Deckers and Everaert (2022) showed that the transition between these members typically coincides with an abrupt upward decrease in qc values. This was recently confirmed at the Rubenshuis outcrop (Fig. 2) by Everaert *et al.* (2024). An identical transition is observed at 23.3 m depth in the Schoten CPT, near the boundary between the Kiel and Antwerpen members in the Schoten borehole (Fig. 4).

4.d. Borsbeek Member (Diest Formation)

A homogeneous succession is present between 16 m and 12.3 m and consists of glauconite-bearing (14.7 to 33.4 %; Supplementary Table 1), very dark grey-green, fine-grained sand with almost no shell fragments and a carbonate content of less than 1% (Figs. 4 and 5). Isolated dark green nests of clay/silt were observed. The boundary with the Berchem Formation is indicated only by an upward change in colour from very dark green-grey to very dark grey-green and a decrease of the silt content. The boundary with the superjacent Kattendijk Formation is marked by a layer containing light grey sandstone pebbles with a diameter of 3 cm, the presence of molluscs and a change in colour from grey-green to grey. Also in the nearby Borgerhout temporary outcrops, sandstone pebbles were described at the base of the Kattendijk Formation by De Meuter *et al.* (1976). In most outcrops, the Kattendijk Formation indeed contains a well-developed basal gravel (Janssen, 1974; Deckers & Louwye, 2020; Everaert *et al.* 2024). Some of the more typical Pliocene molluscs, such as *Laevastarte omalii* and *Pygocardia rustica*, were encountered within the Kattendijk Formation of the Schoten core.

The Diest Formation shows markedly lower gamma-ray values compared to the underlying upper unit of the Antwerpen Member. This corresponds to differences in glauconite content. The R_f values show a general trend of upward decrease within the Diest Formation, which corresponds to an upward decrease in glauconite content (Fig. 5).

In the Antwerp area, the Diest Formation is subdivided into two units, namely the Borsbeek and Deurne members. Besides the lithological description, also the granulometry, glauconite content and CPT expression of the interval between 16 and 12.3 m depth in Schoten core are in line with those described in the stratotype section of the Borsbeek Member by Goolaerts *et al.* (2020) and Deckers and Goolaerts (2022). Granulometric analyses of the Borsbeek Member by Goolaerts *et al.* (2020) indicated an upward decrease in fine fraction (< 64 µm), which corresponds to the upward increase in resistivity values in the unit in the Schoten core.

5. Dinoflagellate cyst biostratigraphy of the Schoten core

The samples of the Berchem Formation hold a poor to moderate preserved dinocyst assemblage. Many dinocysts are torn or broken

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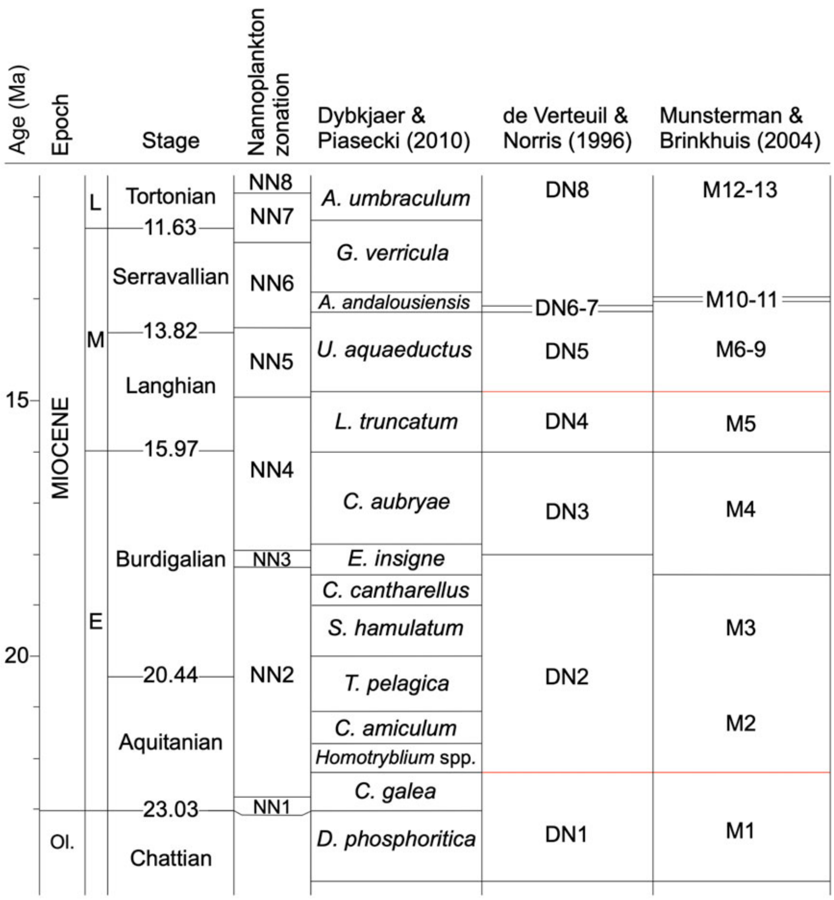

Figure 6. Comparison of the dinoflagellate cysts biozonations by Dybkjær and Piasecki (2010), Munsterman and Brinkhuis (2004) and de Verteuil and Norris (1996), after Dybkjær and Piasecki (2010). Red lines are firm correlations (after Fig. 3 of Everaert *et al.* 2020).

and their morphology is often obscured by amorphous organic debris. Significant is the rare presence of the cysts of heterotrophic dinoflagellate, which are prone to destruction by oxidation. This implies that the dinocyst assemblages in samples of the Berchem Formation underwent significant mechanical and chemical degradation.

The two samples in the Edegem Member (at 47.50–47.60 m and 40.45–40.55 m) and the lowermost in the Kiel Member (35.60–35.70 m) hold *Exochosphaeridium insigne*, a key species which highest occurrence (HO) in the US Atlantic Coastal Plain (de Verteuil & Norris, 1997) defines the upper boundary of the DN2c Subzone. The lower boundary of this subzone is defined by the HO of *Cordosphaeridium cantharellus*, a species not recorded in the three samples. The DN2c Subzone dates from the middle Burdigalian (Fig. 6). A comparison with the southern North Sea Basin dinoflagellate cyst biozonation by Munsterman and Brinkhuis (2004) places the three samples in the SNSM4 Zone, a 'gap' zone between the HO of *C. cantharellus* and the lowest occurrence (LO) of *Labyrinthodinium truncatum*. Both key species were not recorded in these samples. The SNSM4 Zone has a slightly younger age (late Burdigalian to early Langhian). As *E. insigne* is present in all three samples, a correlation with the *E. insigne* Zone of Dybkjær and Piasecki (2010) can be advanced. The latter zone is defined from the HO of *C. cantharellus* to the LO of *C. aubryae*. The occurrence of *E. insigne* is restricted to this zone. Dybkjær and Piasecki (2010) parallel their *E. insigne* zone with the upper part of the DN2 zone of de Verteuil and Norris (1996). The age of the *E. insigne* Zone is 18.4 Ma to 17 Ma (Dybkjær & Piasecki 2010).

The superjacent two samples in the Kiel Member (26.47–26.54 m and 23.30–23.40 m) are slightly better preserved and hold less amorphous debris. The samples can be correlated to the DN3 Zone of de Verteuil and Norris (1996) which is a 'gap' zone defined as the interval between the HO of *E. insigne* and the LO of *Labyrinthodinium truncatum*. Both species are not recorded in both samples. The DN3 Zone has a mid- to late Burdigalian age (Fig. 6). Both samples can also be allocated to the SNSM4 Zone of Munsterman and Brinkhuis (2004) given the absence of *C. cantharellus* and *L. truncatum* (see above). Given the absence of *E. insigne* and *L. truncatum* in both samples, a correlation with the *Cousteaudinium aubryae* Zone by Dybkjær and Piasecki (2010) can be postulated (17.8 Ma to 15.97 Ma). The latter authors suggest a correlation of their zone with the upper part of the DN3 Zone of de Verteuil and Norris (1996).

The samples in the lower and middle units of the Antwerpen Member (21.20–21.30 m and 20.15–20.35 m) hold *Labyrinthodinium truncatum*. The LO of this species marks the lower boundary of the Langhian DN4 Zone by de Verteuil and Norris (1996), the Langhian Zone M5 by Munsterman and Brinkhuis (2004) and the *L. truncatum* Zone (age 15.97 Ma and 14.8 Ma) by Dybkjær and Piasecki (2010). The upper boundary of both latter zones is defined by the LO of *Unipontedinium aquaeductus*, a species that is absent in both samples. The upper boundary of the DN4 Zone (de Verteuil & Norris, 1996) is defined by the HO of *Distatodinium paradoxum*; a bio-event that coincides in the US Atlantic Coastal Plain with the LO occurrence of *U. aquaductus*. Dybkjær and Piasecki (2010) correlate their

L. truncatum zone with the DN4 Zone of de Verteuil and Norris (1996) and the M5 Zone by Munsterman and Brinkhuis (2004). The two samples can thus be placed within the three zones.

In the above-lying samples in the upper unit of the Antwerpen Member (17.2–17.3 m and 16–17 m), the dinocyst species *U. aquaeductus* is recorded, which marks the *U. aquaeductus* Zone of Dybkjær and Piasecki (2010). The zone equals the range of the eponymous species and has an age between 14.8 Ma and 13.2 Ma (late Langhian to early Serravallian; Fig. 6). The latter authors parallel their zone with the DN5 Zone of de Verteuil and Norris (1996) and partly with the SNSM6 Zone of Munsterman and Brinkhuis (2004). *Achomosphaera andalousiensis* and *Gramocysta verricula*, key species of the superjacent Middle Miocene biozones of Dybkjær and Piasecki (2010), were not recorded in the samples. The key species *Selenopemphix dionaceacysta* and *Cannosphaeropsis passio* of the superjacent Middle Miocene biozones of de Verteuil and Norris (1996) are also absent.

The allocation of the sample in the Diest Formation (13.5–14 m) to the biozones of de Verteuil and Norris (1996) proves difficult because of the absence of marker species. The absence of the above-mentioned species in the sample and the presence of *Palaeocystodinium golzowense* are indicative of a Tortonian age recorded in the sample. It can be tentatively placed within the SNSM12 to SNSM13 biozones of Munsterman and Brinkhuis (2004). Noteworthy is the presence of *Bitectatodinium*? *arborichiarum*, which is recorded in the Upper Miocene Diest Formation (Louwye, 1999, 2002).

6. Correlations

6.a. Correlation of the Berchem Formation with contiguous areas (Fig. 7)

The correlation panel of Fig. 7 was created for a better understanding of the continuity of the geophysical signatures and dinocyst biozones within the Berchem Formation from the Schoten borehole towards the proximal areas further south and northeast. The panel includes an outcrop in Borgerhout and four boreholes: Borgerhout, Schoten, Schilde-1 and Schilde-2 (Fig. 7). The Borgerhout-Rivierenhof outcrop (XI B.R.; GSB 028e0499; DOV kb15d28e-B580; for location see Fig. 2) is one of the type sections of the Antwerpen Member (Berchem Formation) that was described and interpreted by De Meuter *et al.* (1976) and biostratigraphically analyzed with dinocysts (Louwye *et al.* 2000). It is located at only 150 m from borehole Borgerhout (GSB 028e0725; DOV kb15d28e-B733; for location see Fig. 2), which has low-quality samples, but is provided with a wireline log. The cores of borehole Schilde-1 (GSB 029w0283; DOV kb16d29w-B290; for location see Fig. 2) were biostratigraphically analysed with dinocysts and subjected to granulometric analyses (Verhaegen, 2019; Supplementary Table 2). In contrast, borehole Schilde-2 (GSB 029w0499; DOV B/1-1107; for location see Fig. 2) has low-quality samples, but wireline logs are useful for correlation purposes. A revision of the biostratigraphic analysis with dinocysts of the uppermost two samples of the Schilde-1 borehole demonstrates that both samples belong to the *Cousteaudinium aubryae* Zone of Dybkjær and Piasecki (2010). This interpretation is consistent with the lithostratigraphic interpretation of both samples as belonging to the Kiel Member, which is known to hold the *C. aubryae* Zone (see Louwye *et al.* 2000, 2020).

6.b. Geophysical log correlations with the southern Netherlands (Fig. 8)

The panel of Fig. 8 was created for correlation of the geophysical signatures and dinocyst biozones from the Schoten borehole towards boreholes Goirle (dinoloket: B50H0373; for location see Fig. 1) and Heeswijk (nlog: HSW-01; for location see Fig. 1) in the southeastern Netherlands. Borehole Goirle is located at the eastern edge of the Campine area, while borehole Heeswijk is located in the northern Roer Valley Graben, which experienced differential subsidence during the Miocene. The Goirle and Heeswijk boreholes have rather concise borehole descriptions, so correlation with the Schoten core was mainly based on the gamma-ray signature. Both Dutch boreholes were biostratigraphically analysed and lithostratigraphically interpreted according to the Dutch stratigraphy by Munsterman *et al.* (2019). The latter authors recognized the Miocene dinoflagellate cyst biozones of Munsterman and Brinkhuis (2004) at specific depth intervals. A sample gap of about 10 m between biozones SNMS3 and SNM5/6 in the Goirle borehole is now bridged by the analysis of four extra samples in the interval 282–289 m (for methodology, see above). The analyses showed that all four samples hold the SNM4 biozone, based on the HO of *Exochosphaeridium insigne* and the LO of *Sumatradinium druggii.* Chronostratigraphic important dinoflagellate cysts are *Distatodinium paradoxum, Apteodinium tectatum, Apteodinium spiridoides, Hystrichosphaeropsis obscura,* and *Sumatradinium soucouyantiae. Cordosphaeridium cantharellus* (one specimen counted in sample 286–287 m) is considered as reworking. Additional reworking in low percentages (1–2 %) is recorded in sample 286–287 m (*Pareodinia* spp.) and in sample 288–289 m (*Enneadocysta pectiniformis*, *Glaphyrocysta* spp., and *Wetzeliella* spp.).

6.c. Geotechnical correlations with the type area of the Borsbeek and Deurne members (*Fig. 9*)

The panel of Fig. 9 was created to compare the geotechnical CPT expression of the Borsbeek Member (Diest Formation) in the Schoten CPT to that at the stratotype area of the Borsbeek and Deurne members (Diest Formation) as shown by Deckers and Goolaerts (2022). The Antwerp International Airport and Middelares Hospital outcrops represent the stratotype areas for the Borsbeek and Deurne members, respectively (Goolaerts *et al.* 2020). The panel of Fig. 9 correlates the Schoten CPT to an interpreted, representative CPT at the Antwerp International Airport outcrop (DOV GEO-03/143-S17; Deckers & Goolaerts, 2022) and the Middelares Hospital outcrop interpretation. About 800 m northeast of the Middelares Hospital temporary outcrop, Deckers and Goolaerts (2022) identified the Borsbeek Member in CPT GEO-18/017-S4 along the E313 highway (for location see Fig. 2), which is in the direction of the Schoten CPT and is therefore also included in the correlation panel.

7. Discussion

7.a. Lower Miocene Edegem member – Berchem formation

The Edegem Member has characteristically low gamma-ray values in the boreholes Borgerhout, Schoten and Schilde-2. These low gamma-ray values are related to the low amounts of clay (< 2%) and glauconite (10% or less based on magnetic separation; Fig. 5). According to Vandenberghe *et al.* (1998), the unit comprises a transgressive pebble layer (Burcht Gravel;

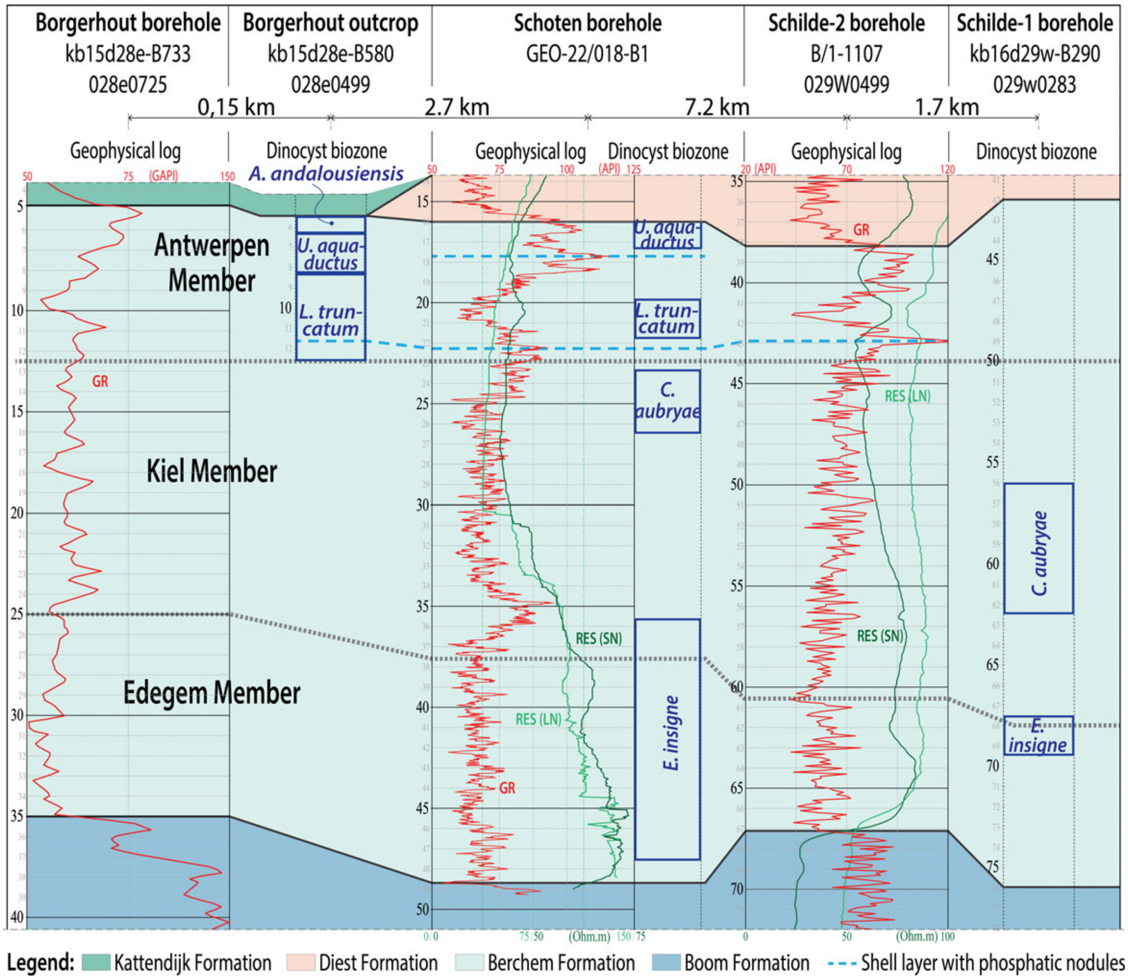

Figure 7. Correlations of borehole Schoten with borehole Borgerhout and temporary outcrop Borgerhout further southwest, and boreholes Schilde-1 and -2 further northeast. The lithostratigraphic interpretation and dinocyst biozonation of the Borgerhout outcrop are taken from De Meuter *et al.* (1976) and Louwye *et al.* (2000). The lithostratigraphic interpretations of boreholes Schilde are performed by this study. The interpretation of the Edegem Member in the Schilde-1 borehole is consistent with the interpretations by Laga (1977). The dinocyst biozonation of the Schilde-1 borehole is modified after Verhaegen (2019). The panel is horizontally aligned at the level of the base Antwerpen Member. For location see Fig. 2.

Louwye *et al.* 2020) overlain by a coarsening upward sequence (Bastin, 1966), suggesting a highstand system tract. In the Schoten core, no transgressive pebble layer was encountered, but the CPT values support a general coarsening upward trend.

Based on the regional geological model, the Edegem Member pinches out north of the Schilde boreholes (Deckers *et al.* 2019; Fig. 1). The correlation panel of Fig. 8 shows that further northeast in the Goirle and Heeswijk boreholes in the southern Netherlands, the low gamma-ray facies of the Edegem Member reappears and is lithostratigraphically interpreted as the upper part of the Dutch Veldhoven Formation by Munsterman *et al.* (2019; Fig. 7). The latter authors showed that this low gamma-ray facies holds the NSM3 biozone of Munsterman and Brinkhuis (2004). The analyses of numerous outcrop samples in the southern part of the city of Antwerp showed that the Edegem Member holds the same biostratigraphic age (*C. cantharellus* biozone of Dybkjær & Piasecki, 2010 according to Louwye *et al.* 2020). Surprisingly, in the Schoten core, the Edegem Member holds the younger *E. insigne* biozone of Dybkjær and Piasecki (2010) or the NSM4 biozone of Munsterman and Brinkhuis (2004). The distinction between the NSM3 and NSM4 biozones is mainly based on the presence of dinocyst *Cordosphaeridium cantharellus*. This dinocyst species is often present in low numbers and can be locally absent within samples of the Edegem Member, such as in the two central samples of the Antwerpen–Montignystraat outcrop in the city of Antwerp (for location see Fig. 2) according to Louwye *et al.* (2000). It is likely that the same occurred for the two samples of the Edegem Member in the Schoten core, which are therefore interpreted as holding the *E. insigne* biozone rather than the *C. cantharellus* biozone. This example shows that it is difficult to distinguish both biozones in the Berchem Formation based on a low number of samples.

At the borehole of Goirle in the southeastern Netherlands, the Edegem Member equivalent shows low gamma-ray values that increase downwards towards a zone where the lowermost Miocene or Aquitanian (biozone NSM2) was identified by Munsterman *et al.* (2019; Fig. 7). This geophysical facies and age have not been identified in the Schoten core. Indeed, in the Schoten and larger Antwerpen area, the earliest Miocene represents a hiatus (Louwye, 2005; Louwye *et al.* 2020).

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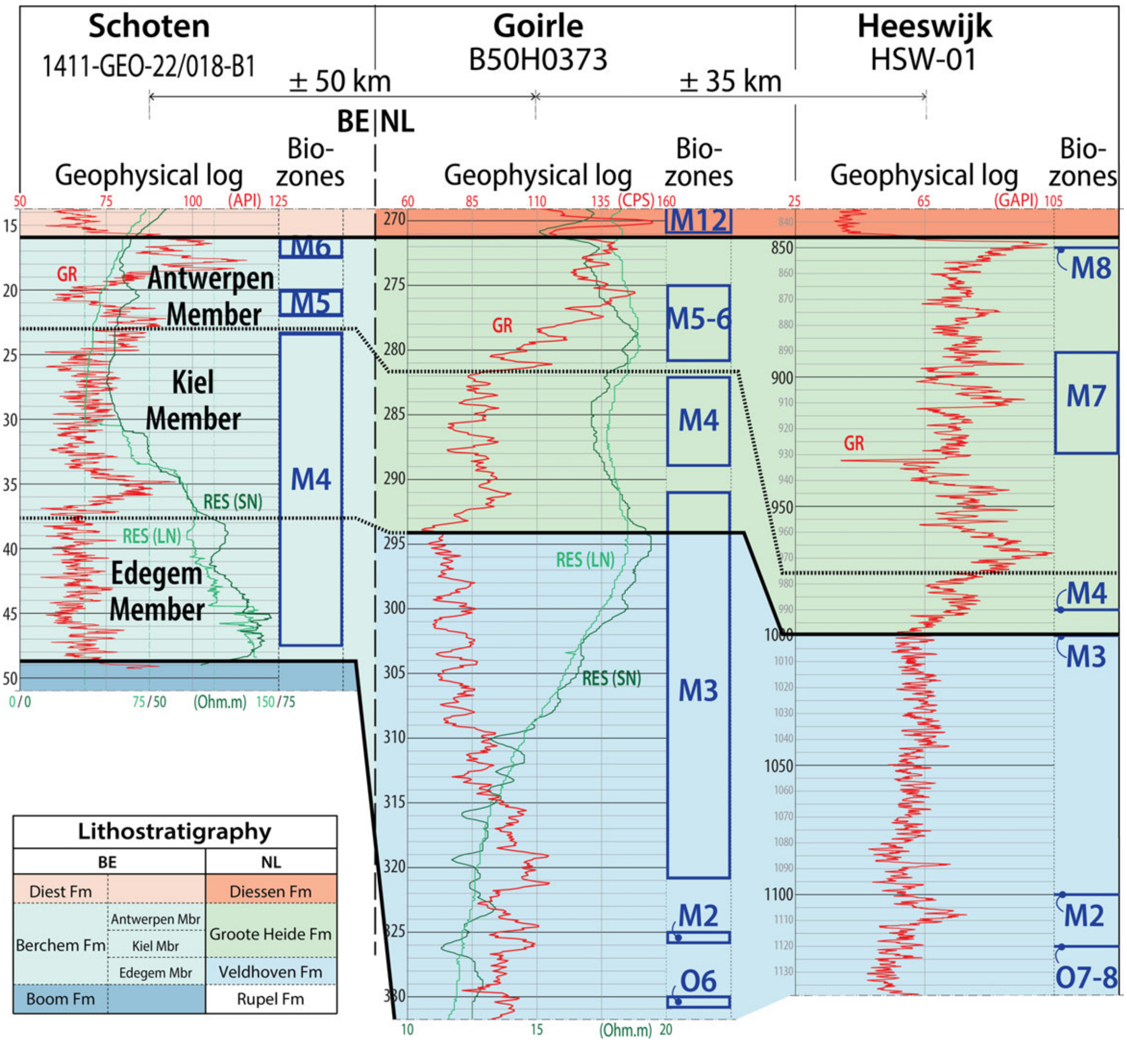

Figure 8. Well log correlations between the Belgian borehole Schoten (with Belgian lithostratigraphy) and the Dutch boreholes Goirle and Heeswijk (with Dutch lithostratigraphy). The litho- and biostratigraphic interpretations of the latter two boreholes are taken from Munsterman *et al.* (2019). The new dinocyst analyses of borehole Goirle for this study, i.e. the NSM4 biozone, are also added. Note that the Heeswijk borehole has a different scale than the Goirle and Schoten boreholes. Compared to the latter, the Miocene in the Heewijk Borehole is much thicker developed due to syn-sedimentary differential subsidence in the Roer Valley Graben. The panel is horizontally aligned at the level of the base Diest/Diessen Formation. For location see Fig. 1.

7.b. Lower Miocene Kiel member – Berchem formation

Compared to the Edegem Member, the Kiel Member shows a much lower carbonate content and higher glauconite content, the latter being reflected by overall higher gamma-ray values in the boreholes Borgerhout, Schoten and Schilde-2 (Fig. 5). The gamma-ray values and granulometry indicate several fining and coarsening upward trends within the Kiel Member. These trends are not always correlatable, as evidenced by the presence of a coarsening upward sequence in the lower part of the Kiel Member in the Schilde-1 borehole (Supplementary Table 2) which seems absent based on the log-signature of the nearby (1.7 km) Schilde-2 borehole. Sedimentological facies changes from sand to silty sand within the Kiel Member across distances of a few kilometres are also sporadically noted in boreholes and temporary outcrops in and around the city of Antwerp (Deckers *et al.* 2023; Everaert *et al.* 2024). The presence of the *E. insigne* and *C. aubryae* biozones of Dybkjær and Piasecki (2010) in the Kiel Member of the Schoten borehole is consistent with literature on the Kiel Member (Louwye *et al.* 2020; Fig. 7).

Similar to the facies (see above), also the thickness of the *C. aubryae* biozone shows strong changes across short distances within the Kiel Member: from less than 1 m in the Argenta, Post X and Rubenshuis temporary outcrops (east and centre of Antwerp city; Everaert *et al.* 2020, 2024) towards 6 m in the Berchem Grote Steenweg temporary outcrop (southeast city of Antwerp; Louwye *et al.* 2000) and an estimated 12 m in the Schilde-1 borehole (for locations see Fig. 2).

The Kiel Member in the Borgerhout, Schoten and Schilde-2 boreholes shows gamma-ray values in between the relatively low values of the Edegem Member and high values of the Antwerpen Member (Fig. 7). Correlations with the Dutch Goirle and Heeswijk boreholes indicate that this intermediate gamma-ray interval corresponds to the basal part of the Dutch Groote Heide Formation (Fig. 8). In the Goirle and Heeswijk boreholes, this interval furthermore holds the NSM4 in consistency with the Kiel Member in the Schoten core. In the Goirle borehole, the lower few metres of this interval still hold the NSM3 biozone. Munsterman *et al.* (2019) situated the Early Miocene

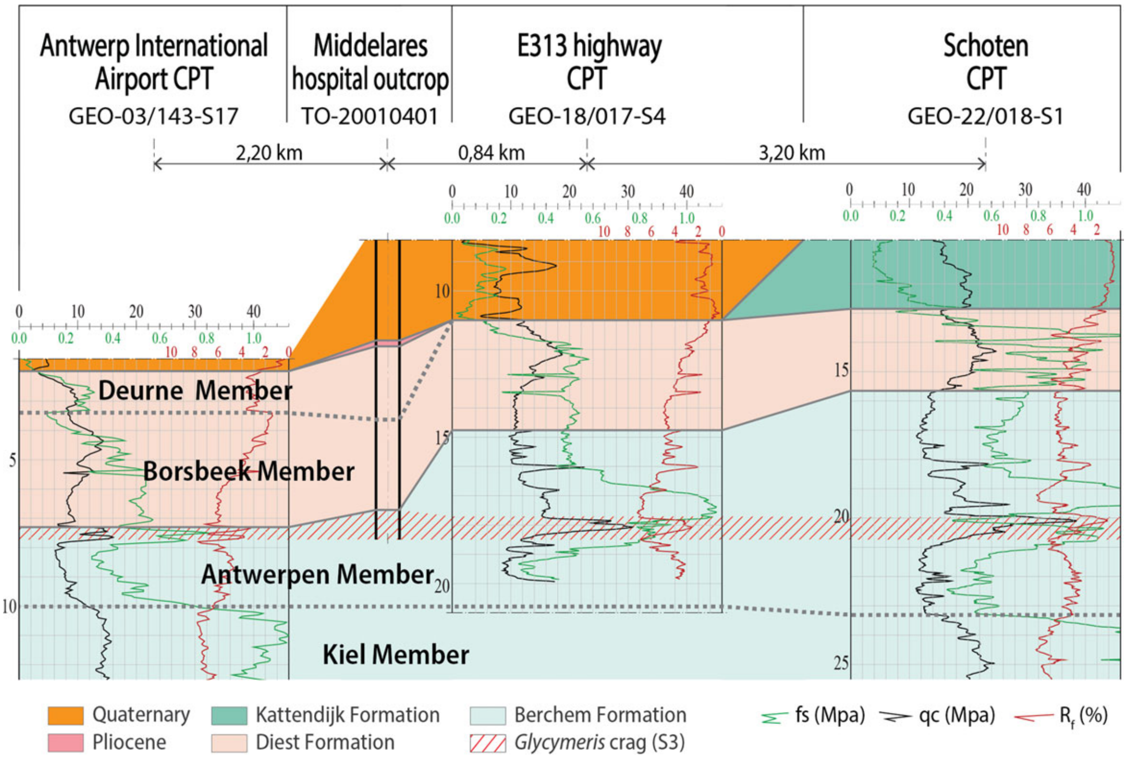

Figure 9. Correlation panel between cone penetration tests for the members of the Diest Formation from Antwerp International Airport (left) towards Schoten (right). Antwerp International Airport represents the stratotype area for the Borsbeek Member, while the Middelares Hospital outcrop is the stratotype of the Deurne Member (Goolaerts *et al.* 2020). The panel is horizontally aligned at the level of the base *Glycymeris* crag (S3). For location see Fig. 2.

Unconformity or EMU at the NSM3/NSM4 biozone boundary in the Goirle and Groote Heide boreholes, now correlated based on log-signature to roughly the base or basal part of the Kiel Member, on top of the Edegem Member. Considering the absence of a biostratigraphic hiatus or basal gravel between the Edegem and Kiel members, the EMU represents a major facies change within the study area, but a much less pronounced unconformity than the younger Middle Miocene Unconformity or MMU. Before, Everaert *et al.* (2020) erroneously positioned the EMU between the Kiel and Antwerpen members, by comparing the dinocyst biostratigraphy with borehole Goirle in which the NSM4 biozone was then not yet recognized. The boundary between the Kiel and Antwerpen members is now considered an important, yet unnamed unconformity situated between the EMU (base Kiel Member) and MMU (top Antwerpen Member). The hiatus associated with this Kiel-Antwerpen unconformity most likely corresponds to the late Burdigalian eustatic sea-level fall (Fig. 10).

In several temporary outcrops of the Kiel Member in the east of the city of Antwerp, Everaert *et al.* (2020) recognized the NSM3 biozone in the major part of the Kiel Member due to sporadic occurrences of the dinocyst *C. cantharellus*. Given the younger datings of the Kiel Member by Louwye *et al.* (2000) in nearby temporary outcrops (NSM4 biozone) and the overall shallow facies of the Kiel Member, the specimens of *C. cantharellus* found by Everaert *et al.* (2020) in the Kiel Member may have been reworked, implying that the entire Kiel Member in the city of Antwerp should be interpreted as belonging to the NSM4 biozone. The age determinations and correlations of this study reinforce this reinterpretation.

7.c. Middle Miocene Antwerpen member – Berchem formation

Geophysically, the transition from the Kiel Member towards the Antwerpen Member is very subtle in boreholes Borgerhout and Schoten (Fig. 7). This is consistent with limited granulometric changes between both units as measured from samples of the Schoten cores (Fig. 5). Nevertheless, the typical upward reduction in qc values from the Kiel Member towards the basal Antwerpen Member, as observed elsewhere (Deckers & Everaert, 2022), was also recognized at Schoten. The latter authors interpreted the base of the Antwerpen Member as a basal transgressive surface marking the start of the Middle Miocene. Indeed, in the Dutch Goirle and Heeswijk boreholes, the base of the Middle Miocene corresponds to a strong increase in gamma-ray values which is typical for transgression (Fig. 8). In the latter boreholes, the gamma-ray values remain on average highest throughout the middle Miocene interval or upper part of the Groote Heide Formation, which is consistent with the geophysical expression of the Antwerpen Member in the Borgerhout, Schoten and Schilde-2 boreholes (Fig. 7). The log correlation panels of Figs. 7 and 8 show that the Antwerpen Member and its Dutch equivalents attain rather uniform thicknesses of around 6–7 m in the boreholes in the Antwerp Campine area. This is consistent with the rather uniform thickness of middle Miocene biozones in other boreholes in the Antwerp Campine area, as reported by Louwye (2005). In the Heeswijk borehole in the northern Roer Valley Graben, the middle Miocene is over 100 m or anomalously thick (Fig. 8), which can be related to the differential subsidence of this tectonic structure compared to the flanking Antwerp Campine area.

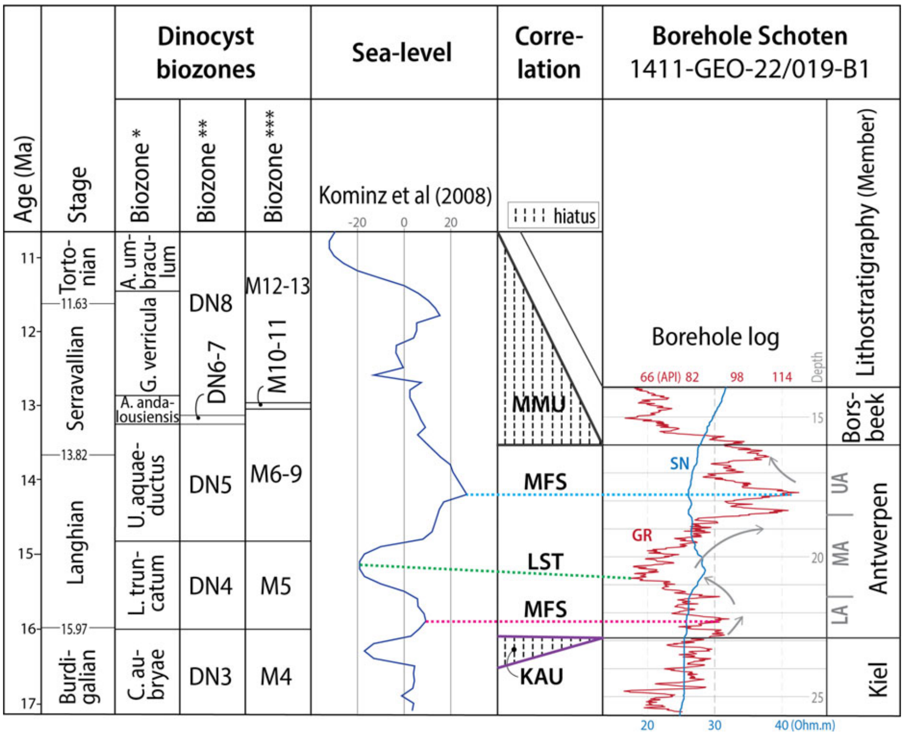

Figure 10. Correlation of relative sea-level trends based on the gamma-ray and resistivity log signature and inferred hiatuses in the Schoten core to the inferred eustatic sea-level changes (middle estimate with inferred lowstands) for the New Jersey margin by Kominz *et al.* (2008) modified by John *et al.* (2011). The age estimates for the Schoten core sediments are based on the dinoflagellate cysts biozonations and their absolute ages as given in Dybkjær and Piasecki (2010). KAU = Kiel-Antwerpen unconformity; LST = Lowstand System Tract; MFS = Maximum Flooding Surface; MMU = Mid-Miocene Unconformity. LA, MA and UA represent the informal lower, middle and upper units of the Antwerpen Member.

In the Schoten core, the high gamma-ray values for the Antwerpen Member reflect a high glauconite and/or apatite content. Glauconite contents of the Antwerpen Member variate between 23.8% and 58.2%. Apatite was only present in one of the four samples of the Antwerpen Member that was subjected to XRD analyses. The apatite is believed to originate from the phosphate nodules that are encountered at specific levels in the Antwerpen Member. Indeed, the sample with measured content of 6.6% apatite lies just a few decimetres below the lower phosphatic horizon of the Antwerpen Member in the Schoten core. In the Dutch province of Zeeland, horizons with large concentrations of phosphatic nodules were noted in deposits equivalent to the Berchem Formation, which contained significant amounts of uranium and were therefore reflected as major gamma-ray spikes (Harsveldt, 1973). In borehole Schilde-2, the correlative level to a phosphatic horizon of the Schoten core indeed shows a very pronounced gamma-ray spike (dashed blue line on Fig. 7).

The geophysical facies of the Antwerpen Member in the Borgerhout, Schoten and Schilde boreholes are very particular with a lower and upper unit with high gamma-ray and low resistivity values, separated by a middle unit with lower gamma-ray and higher resistivity values (Fig. 5). The Schoten CPT shows that the threefold subdivision is also geotechnically distinct (Fig. 4). Based on this differentiation, we informally subdivided the Antwerpen Member into a lower, middle and upper unit. The profile of Janssen (1987) of an outcrop in Borgerhout, south of the Schoten core, shows a similar threefold subdivision in the Antwerpen Member, with a lower and upper unit comprising medium fine-grained to medium coarse-grained sands separated by a central unit comprising medium coarse-grained sands with some oblique bedding. In the Schoten core, shell beds with phosphatic nodules were encountered near the central parts of the lower and upper units of the Antwerpen Member (around 22.3 m and 17.6 m; Fig. 5). The lower bed was correlated across the Antwerp area by Deckers and Everaert (2022). This horizon was informally called "*Haustator eryna* phosphatic horizon" by Everaert *et al.* (2020) and *S2 shell bed* by Deckers and Everaert (2022). Due to taxonomic modifications, this level is more recently referred to as *Ptychidia eryna* phosphatic horizon (Everaert *et al.* 2024). In borehole Schilde-2, the correlative level to the *Ptychidia eryna* phosphatic horizon corresponds to a very pronounced gamma-ray spike at the transition from upward decreasing to upward increasing resistivity values (blue dashed line Fig. 7). Also on CPTs in the Antwerp area, the *Ptychidia eryna* phosphatic horizon correlates with the transition from upward decreasing towards upward increasing qc values, which could indicate maximum fining (Deckers & Everaert, 2022). This, together with the presence of phosphorite nodules and phosphatic shell casts that typically accumulate in quiet water with decomposing bones and a reduced supply of sediment to the shelf, indicates that the *Ptychidia eryna* phosphatic horizon developed under high sea level conditions. Maximum flooding in our study area during the early Langhian (*L. truncatum* Biozone of Dybkjær & Piasecki, 2010) is consistent with the eustatic sea level high during this period (Fig. 10). Subsequently, the relative sea level fell resulting in the overall coarser and less glauconite-rich (lower gamma-ray values) middle Antwerpen Member (Fig. 5). The transition towards the overlying *U. aquaeductus* Zone of Dybkjær and Piasecki (2010) could mark

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the start of a next relative sea level rise with a fining upward sequence (decrease in qc and resistivity values and increase in gamma-ray values) towards the next sea level high (lowest resistivity values; Fig. 5) at the upper shell bed that contains phosphatic nodules in the Schoten core. A transgression during the late Langhian to early Serravallian *U. aquaeductus* Zone of Dybkjær and Piasecki (2010), which corresponds to the NSM6 to NSM8 biozones of Munsterman and Brinkhuis (2004), can be correlated with a eustatic sea-level high (Fig. 10) which also caused marine ingression of the Roer Valley Graben/Lower Rhine Graben (Deckers & Munsterman, 2020).

The Serravallian section of the Antwerpen Member is very thinly developed or condensed at Schoten and other boreholes in the Antwerp Campine area (see Louwye, 2005). The uppermost two metres of the Antwerpen Member in the Schoten core indicate shallowing upwards (gradually increasing resistivity and qc values) towards the superjacent Diest Formation (Figs. 4 and 5). This shallowing upwards is probably reflecting the Middle Miocene Climatic Transition after the maximum sea-levels associated with the Miocene Climatic Optimum (Fig. 10). The middle and late Serravallian *A. andalousiensis* Zone of Dybkjær and Piasecki (2010) is absent in the Schoten core (Fig. 7). However, it was identified before in the uppermost section of the Antwerpen Member in the Borgerhout-Rivierenhof outcrop by Louwye *et al.* (2000). Also in some other boreholes in the Campine area, this biozone is missing (Louwye, 2005), probably by the combination of thin deposition and erosion by the Diest Formation. In the Schoten core, the uppermost metre of the Antwerpen Member is completely devoid of shells and carbonate content is near 0% which could be due to dissolution processes taking place during the hiatus in between the Antwerpen Member and Diest Formation. This hiatus is associated with the MMU (Munsterman *et al.* 2019; Fig. 10).

Although the threefold subdivision of the Antwerpen Member is observable in the larger Antwerp area, it is not clearly expressed in the Middle Miocene of the Dutch Goirle borehole further to the northeast. Instead, the gamma-rays remain at a high level in the latter borehole, indicating the absence of the equivalents of the (herein referred) middle unit of the Antwerpen Member. The absence of this relatively shallow depositional sequence might be due to the more distal location of the Goirle borehole to the contemporaneous shoreline.

7.d. Upper Miocene Borsbeek member (Diest formation)

Based on the lithology and sedimentological analyses of three samples, the Borsbeek Member of the Diest Formation was identified on top of the Berchem Formation in the Schoten borehole. Biostratigraphic analyses from a sample of this unit indicate a Tortonian age (NSM12 to −13 biozones of Munsterman & Brinkhuis, 2004), which is also consistent with the age established in the stratotype area by Goolaerts *et al.* (2020). The correlation panel of Fig. 9 furthermore shows that the geotechnical CPT facies of the Borsbeek Member in Schoten is similar to that established by Deckers and Goolaerts (2022) further south in the stratotype area of the Borsbeek Member.

Goolaerts *et al.* (2020) first described the Borsbeek Member to the east of Antwerp. The recognition of the Borsbeek Member in the Schoten core indicates that this unit extends up to the northeast of the city of Antwerp (Fig. 2), thereby proving its relevance outside the stratotype area. Figure 9 shows that compared to the areas further south around the type sections, the Borsbeek Member at Schoten has incised several meters less deep into the Antwerpen Member.

In the Schoten core, the transition from the Antwerpen Member towards the Diest Formation corresponds to a strong decrease in gamma-ray values and an increase in resistivity values, related to an upward decrease in glauconite-content and increase in grain size (Fig. 5). The boundary between these units has a similar log expression in the Antwerp Campine area (Houthuys *et al.* 2020). In the latter area, however, the Diest Formation or the Dutch equivalent Diessen Formation is much thicker developed, reaching over 100 m in the Goirle borehole (Munsterman *et al.* 2019).

8. Conclusions

The integration of geotechnical and geophysical well logs, along with biostratigraphic and sediment analyses of borehole Schoten (northern Belgium), provides a better characterization of the glauconitic sands of the Edegem, Kiel and Antwerpen members of the Berchem Formation. The middle Burdigalian Edegem Member unconformably overlies the Rupelian Boom Formation in the area. As it holds a relatively low amount of glauconite, the Edegem Member and age equivalents in the southern Netherlands (upper part of Veldhoven Formation) are characterized by relatively low gamma-ray values. An increase in gamma-ray values, related to an increase in glauconite content, marks the transition from the Edegem Member towards the carbonate-poor middle to upper Burdigalian Kiel Member. Based on correlations with existing and new analyses of boreholes in the southern Netherlands, we identified the Early Miocene Unconformity at the boundary between the Edegem and Kiel members. In the Netherlands, this unconformity marks the boundary between the Veldhoven and Groote Heide Formations. Boreholes and existing outcrop descriptions reveal that the Kiel Member shows sedimentological facies changes across short distances. The top of the Kiel Member represents a hiatus related to the latest Burdigalian sea-level fall. Under Langhian sea-level rise, the Kiel Member was transgressed and covered by the shell-rich Antwerpen Member. This transgression is expressed by subtle to strong increases in gamma-ray values related to an increase in glauconite content. Throughout the region, the gamma-ray values remain the highest for the middle Miocene sediments which is most likely related to a eustatic sea level high during the Miocene Climatic Optimum. Local gamma-ray spikes in the middle Miocene interval can also be related to levels enriched in phosphatic nodules. Two of such levels were identified in the Schoten core and are interpreted as periods of maximum sea-level. These are correlative to known eustatic sea-level maxima in the Langhian. The sea-level fall at the end of the Serravallian and beginning of the Tortonian, associated with the Mid-Miocene Unconformity, marks the end of deposition of the Antwerpen Member or Berchem Formation. During the middle Tortonian transgression, the Borsbeek Member of the Diest Formation unconformably covered the Antwerpen Member at the location of the Schoten core. The recognition of the Borsbeek Member in the Schoten core indicates that this unit extends up to the northeast of the city of Antwerp, thereby proving its relevance outside the stratotype area.

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