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Deep channel incisions in the Rupelian clays filled with the middle Burdigalian sands (northern Belgium and southern Netherlands)

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Abstract

This study provides evidence for the presence of channel incisions at the base of Lower Miocene glauconitic sands deposited in the southern North Sea Basin. A cross-boundary correlation panel between boreholes in Belgium and the Netherlands shows that the glauconitic sands of the Lower to Middle Miocene Berchem Formation strongly vary in thickness from less than 15 m to almost 70 m. The palynological analyses of borehole samples show that the main thickness change can be attributed to the presence/absence of the middle Burdigalian sands (dinocyst biozone NSM3) in the basal section of the Berchem Formation. These sands can be interpreted as infill of channels cut in the Rupelian clays of the Boom Formation. Indeed, also along a seismic line nearby, individual channels incised up to 45 m deep into the Boom Formation can be observed at the base of the Berchem Formation. The results of this study raise the question of whether other local middle Burdigalian sediment bodies in the region may also represent channel infills. Because the base of the Berchem Formation coincides with a major hiatus spanning the late Oligocene to the earliest Miocene, the channel incisions at this base could be related to the eustatic sea-level fall that occurred at the Oligocene–Miocene transition. During a middle Burdigalian sea-level rise, the sea transgressed into the channels, widening and filling them with sediments. Compared to other transgressed paleo-valley systems, which generally comprise at least in part fluvial or estuarine sediments, those in the base of the Berchem Formation are entirely composed of shallow marine, glauconite-rich sediments. By late Burdigalian times, the channels were filled, and sediment thicknesses became much more uniform across the region.

Introduction

During the Early to Middle Miocene, the glauconitic sands of the Berchem Formation were deposited along the southern margin of the North Sea Basin, which currently comprises northern Belgium and the southern Netherlands (Figure 1). In the Antwerp Campine area, these sands are now buried below more than a hundred metres of younger sediments, hence mainly studied in boreholes. Although the Berchem Formation can be subdivided in different stratigraphic units in outcrops within the city of Antwerp stratotype area (for location, see Figure 1), this has remained difficult for boreholes in the Antwerp Campine area (Louwye et al., 2020; Figure 2). Due to the lack of internal lithostratigraphic subdivisions, all the knowledge on internal thickness variations within the Berchem Formation has been derived from palynological analyses of borehole samples carried out by Louwye (2005) in northern Belgium. He showed a more than 12 m thick middle Burdigalian succession in the borehole Kalmthout (for location, see Figure 1), which was absent in other boreholes in the Antwerp Campine area, such as, for example, Rijkevorsel (for location, see Figure 1). The spacing between the boreholes analysed by Louwye (2005) is unfortunately very large – generally over 10 km. This, of course, hinders to draw comprehensive conclusions on the reasons for the observed differences in internal thickness and biostratigraphic age. Recently, however, as part of the cross-boundary project H3O-De Voorkempen (Vernes et al. 2023), palynological analyses of several boreholes in the southernmost Netherlands (Bergen op Zoom-1, Schijf-1 and -2 in Figure 1), northwest and northeast of the borehole Kalmthout, were carried out. In addition, the nearby cored boreholes ON-Essen-1 (Figure 1) and Bergen op Zoom-2 (Figure 1) were analysed in this study. Also recently, low-resolution seismic lines were acquired near the study area and interpreted for the H3O-De Voorkempen project (Vernes et al., 2023).

The existing palynological analyses by Louwye (2005) with new palynological analyses of nearby boreholes are integrated in this paper. These analyses are shown on a borehole correlation panel to better understand the thickness variations within the Berchem

Formation. A seismic line that covers the western part of the borehole correlation panel (for location, see Figure 1) was used to support the obtained findings. This provides new information on the Early Miocene palaeogeography of the study area and the influence that eustatic sea-level changes exerted upon it. Our results show a rare example of a paleo-valley system that is completely infilled with marine, glauconite-rich sediments.

Geological background

A schematic overview of the stratigraphic successions in the subsurface of the study area across the border between Belgium and the Netherlands is provided (Figure 2). Both countries have a different lithostratigraphic nomenclature. However, the present study focuses on the Belgian lithostratigraphy. The glauconitic sands of the Berchem Formation were deposited during the Early to Middle Miocene in a shallow marine depositional environment of the southern North Sea Basin (Louwye et al., 2020). These sands unconformably overlie the clay and silt of the Rupelian Boom Formation, hence the hiatus spanning the Chattian to Aquitanian. The extent of this hiatus decreases towards the east (Munsterman & Deckers, 2020, 2022). As the result of their high glauconite content, the sands of the Berchem Formation are mostly dark green to black. They are fine- to medium-grained, often slightly clayey and rich in shells (De Meuter & Laga, 1976).

In the area of the city of Antwerp, where the stratotype of the Berchem Formation is located, three of its members were described in temporary outcrops by De Meuter et al. (1976) and formalised by De Meuter and Laga (1976). North of Antwerp, in the Antwerp Campine area, it has not yet been

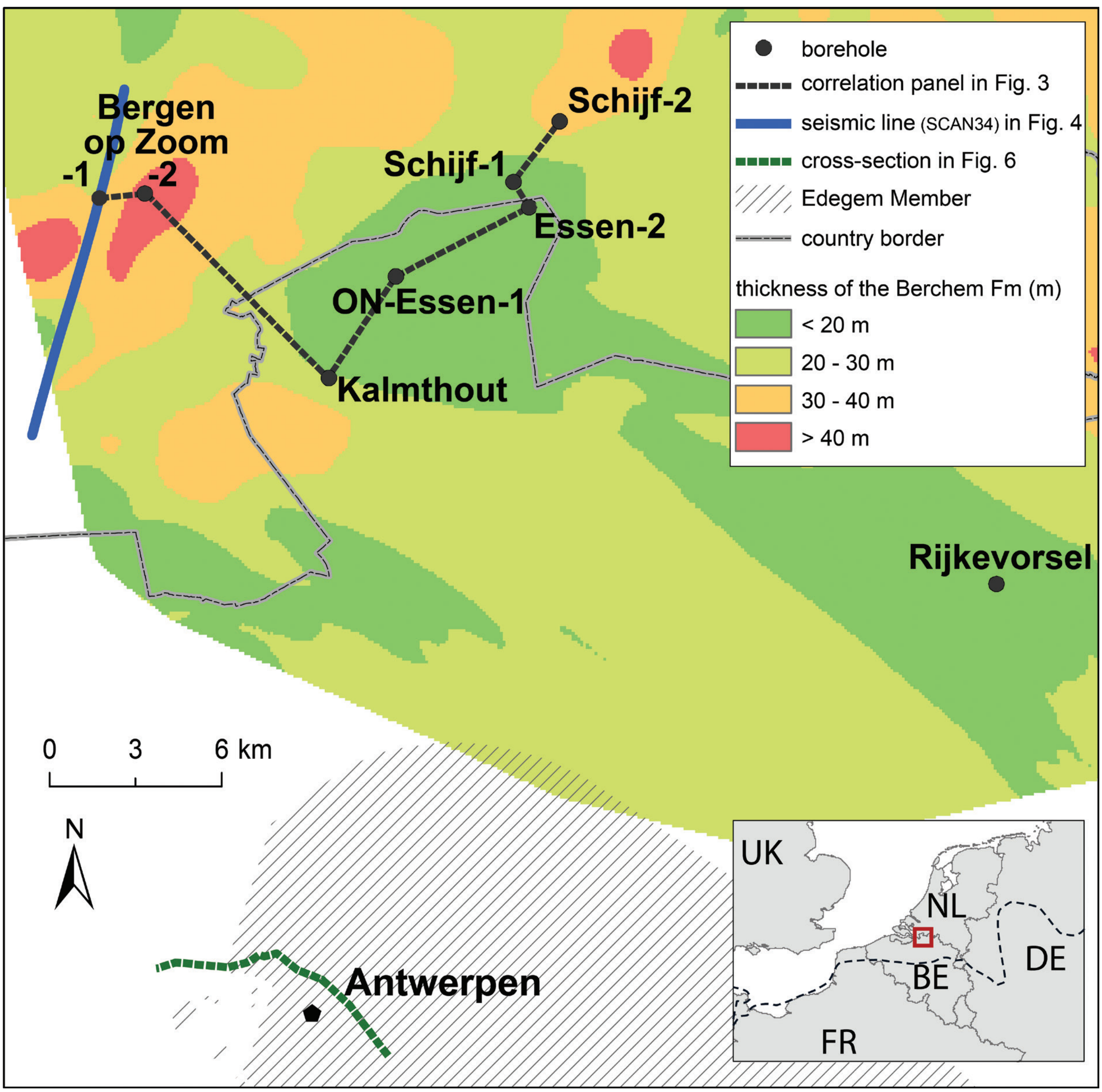

Figure 1. Location map of the study area with the key boreholes, the borehole correlation panel and the seismic line SCAN34. The thickness map of the Berchem Formation, based on borehole data, showing its relatively strong thickness variation (modified after Vernes et al., 2023). The geographic extent of the Edegem Member is modified after Deckers et al. (2019).

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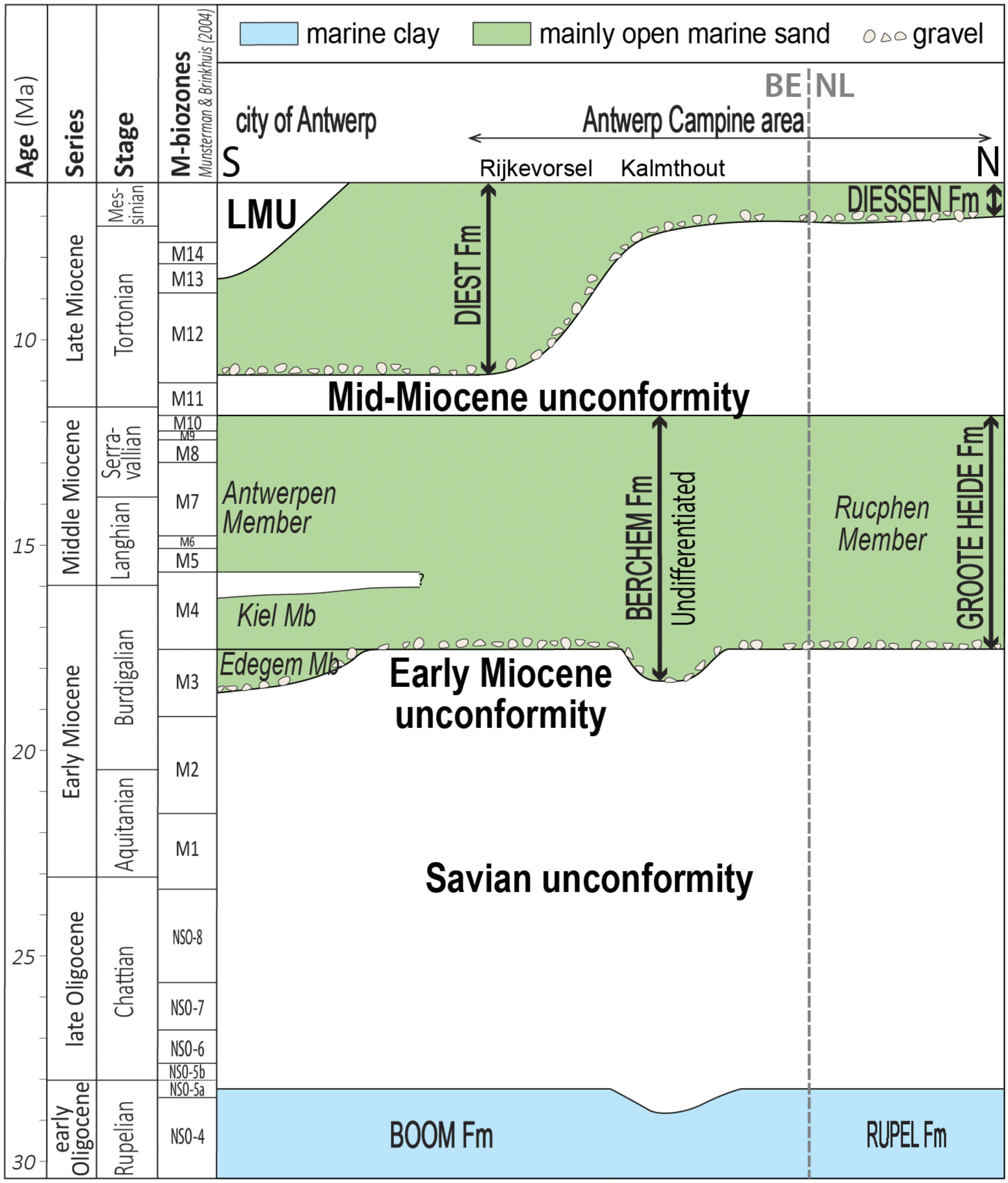

Figure 2. Schematic lithostratigraphy of the study area with chrono- and biostratigraphic zonation (modified after Munsterman et al., 2019). LMU, Late Miocene Unconformity.

possible to distinguish these members within the Berchem Formation (Louwye et al., 2020). However, Louwye (2005) correlated dinocyst biozones of the Berchem Formation between several boreholes there. He noted the presence of the middle Burdigalian biozone DN2b of De Verteuil and Norris (1996), corresponding to biozone M3 of Munsterman and Brinkhuis (2004), only in the borehole Kalmthout (for location, see Figure 1). In the other boreholes further to the southeast (Oostmalle, Poederlee, Retie and Rijkevorsel; for location of the latter, see Figure 1), at the base of the Berchem Formation, there is the younger middle Burdigalian DN2c biozone, which is overlain by the biozone DN3 of De Verteuil and Norris (1996), both corresponding to biozone M4 of Munsterman and Brinkhuis (2004). The overlying Middle Miocene is poorly developed in this area (Louwye, 2005), which may indicate sediment starvation (Deckers & Louwye, 2019). Deposition of the Berchem Formation continued in this region until the end of the Middle Miocene – Serravallian (Louwye et al., 2020).

In the Antwerp Campine area, the Berchem Formation is covered by the shallow marine, grey green to brownish, glauconiferous, mostly coarse-grained sands with sandstone layers of the Diest Formation (Houthuys et al., 2020). The Diest Formation is of Tortonian to Messinian age (Louwye et al., 1999).

North of Belgium (i.e. in the Netherlands), the Berchem Formation refers to the Rucphen Member of the Groote Heide Formation (Figure 2). The village of the same name (i.e. Rucphen) is located just north of the border with Belgium in the area of the current study. The Belgian Boom and Diest formations, situated above and below the Berchem Formation, correspond to the Dutch Rupel and

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Diessen formations, respectively (Figure 2; Munsterman et al., 2019).

Dataset and methodology

Borehole interpretations and wireline logs

The boreholes located in Belgium were obtained from the public databases of DOV (https://www.dov.vlaanderen.be) and GSB (https://collections.naturalsciences.be/ssh-geology-archives/arch). The boreholes located in the Netherlands come from the public database of Dinoloket (https://www.dinoloket.nl/ondergrondgegevens). However, the subject of this study are six boreholes – from west to east, they are: Bergen op Zoom-1 (Dinoloket: B46E1437), Bergen op Zoom-2 (Dinoloket: B49E1446), Kalmthout (GSB 006E0110; DOV kb7d6e-B136), ON-Essen-1 (GSB 001E0071; DOV B/1-1092), Essen-2 (GSB 001E0042; DOV kb1d1e-B59), Schijf-1 (Dinoloket B49F0431) and Schijf-2 (Dinoloket B49F0436; for location see Figure 1).

In the current study, existing lithostratigraphic interpretations and borehole descriptions were used to determine the boundaries of the Berchem Formation in the boreholes. Five of them (Bergen op Zoom-1 and -2, ON-Essen-1, Schijf-1 and -2) are equipped with wireline logs (gamma-ray and resistivity logs), which are helpful in lithostratigraphic interpretations and correlations. For the Kalmthout and Essen-2 boreholes, no wireline log data are available; therefore, the existing lithostratigraphic interpretations of Gullinck (1969) and Laga (1975) were adopted. The borehole ON-Essen-1 was cored from 145 m downwards. Originally, the Belgian upper Oligocene Voort Member and Lower to Middle Miocene Berchem Formation were interpreted in the ON-Essen-1 borehole between 142–153 m and 125–142 m by Laga (2006). However, he stated that the presence of the Voort Formation was hypothetical. Based on the log-signature, the Berchem Formation was reinterpreted in the 142–153 m interval in this paper, whilst the 125–142 m interval is considered as the base of the Diest Formation. Indeed, the latter interval is described as medium- to coarse-grained, grey, grey green to dark green, sometimes badly sorted sands, which are typical of the Diest Formation.

Biostratigraphic analyses of borehole samples

All boreholes considered contain biostratigraphic data. From these, boreholes Kalmthout and Essen-2 have already been biostratigraphically studied using dinocyst species analysis by Louwye and Laga (1998) and Louwye (2005). The boreholes Bergen op Zoom-1, Schijf-1 and -2 were recently biostratigraphically analysed in the same way for the cross-boundary H3O-De Voorkempen project (Vernes et al., 2023). These results have never been published and will therefore be discussed in detail in the next section. The boreholes Bergen op Zoom-2 and ON-Essen-1 were biostratigraphically analysed specifically for this study. All samples from the borehole Bergen op Zoom-2 were taken from the lower part of the Berchem Formation, whilst those from the borehole ON-Essen-1 were collected from a cored interval of the Berchem Formation at a depth of 145 to 153.5 m.

Sample preparation for the boreholes Bergen op Zoom-1 and -2, ON-Essen-1 and Schijf-1, -2 was executed on selected (air-lifted) cores. Standard palynological techniques were used to process the selected samples. Hydrochloric acid (HCL) and hydrogen fluoride (HF) digestion followed by 15-micron sieving was carried out according to Janssen and Dammers (2008). The slides were mounted in glycerine jelly. Both dinocysts and sporomorphs were counted under light microscope at 500x magnification until a minimum of 200 specimens (if present) were found. Rare species were identified during a final scan of the microscope slide. The dinocyst taxonomy follows that given in the Lentin and Williams Index (Fensome et al., 2019). Other fossils (including *Pediastrum*, *Botryococcus*) were also counted, but they were excluded from the total of 200 specimens.

The Miocene dinoflagellate cyst (dinocyst) zonation was made after Munsterman and Brinkhuis (2004), recalibrated to the Geological Time Scale of Ogg et al. (2016) by Munsterman et al. (2019). This zonation is based on consistent dinocyst occurrences (mainly the last one) in available peer-reviewed palynological contributions from NW Europe (see Munsterman et al., 2024). It also includes the application of a global compilation calibrated to palaeomagnetic, calcareous plankton and/or foraminifera/Bolboforma (De Verteuil & Norris, 1996; Van Leeuwen, 2000; Zevenboom, 1995; and other references therein). Finally, the Oligocene zones are based on the zonation of Van Simaeys et al. (2005).

Seismic data

For the recent SCAN project (https://scanaardwarmte.nl), which focusses on geothermal exploration, a series of long seismic lines were acquired throughout the Netherlands. One of these lines (i.e. SCAN34) runs in a SW–NE direction along the borehole Bergen op Zoom-1 and just west of the borehole Bergen op Zoom-2 of the correlation panel of this study (for location, see Figure 1). In the Cenozoic section of this line, several horizons were interpreted for the project H3O-De Voorkempen by Vernes et al. (2023), amongst which the near base Boom Formation (top Belsele-Waas Member) and base Diest Formation. These interpretations were used in this study to interpret the base Boom Formation and base Berchem Formation horizons on the SCAN34 line.

Results

New biostratigraphic results (age assessment)

In the paragraphs later, we list the results of the palynological analyses performed by this study for each borehole, in accordance with the biozonation scheme of Munsterman and Brinkhuis (2004).

Biostratigraphic analyses and age interpretation of the borehole Bergen op Zoom-1 (Dinoloket: B46E1437):

- 120–121 m: late Tortonian biozone SNMS 14. Based on Last Occurrence Datum (LOD) *Labyrinthodinium truncatum*, LOD *Impagidinium densiverrucosum*, First Occurrence Datum (FOD) *Ataxiodinium choane*.

- 126–127 m: late Tortonian biozone SNMS 13 or older. Based on LOD *Systematophora placacantha*. However, the relatively high number of this taxon may likely indicate that the mid-Miocene has been reached.
- 134–135 m: early to middle Langhian biozone SNMS 5–6. Based on LOD *Apteodinium spiridoides* and LOD *Cousteaudinium aubryae*.
- 145 m: late Burdigalian biozone SNMS 4. Based on LOD *Exochosphaeridium insigne.*
- 172 m: middle Burdigalian, upper part biozone SNMS 3. Based on LOD of *Cordosphaeridium cantharellus* and the FOD of *Exochosphaeridium insigne*.
- 177–178: late Rupelian biozone NSO4b. Based on LOD *Achilleodinium biformoides*, LOD *Membranophoridium connectum* and LOD *Membranophoridium intermedium*.

Biostratigraphic analyses and age interpretation of the borehole Bergen op Zoom-2 (Dinoloket B49E1446):

- 160–174 m: mid-Burdigalian biozone SNMS 3. Based on the Last Occurrence Datum (LOD) of *Cordosphaeridium cantharellus* and on the First Occurrence Datum (FOD) of *Sumatradinium druggii* at 160–161 m depth. *Exochosphaeridium insigne* is present in the microflora of all samples. Other significant chronostratigraphic bioevents are as follows: FODs of *Cousteaudinium aubryae, Hystrichosphaeropsis obscura* and *Sumatradinium soucouyantiae. Deflandrea phosphoritica* is considered as reworking.

Biostratigraphic analyses and age interpretation of the borehole ON-Essen-1 (GSB 001E0071):

- 145–152 m: late Burdigalian–earliest Langhian biozone SNMS 4. Based on the LOD of *Exochosphaeridium insigne* (145.2–145.5 m) and based on the FOD of *Sumatradinium druggii* at (152.0–152.7 m)*. Exochosphaeridium insigne* is present in the associations of all samples. *Membranophoridium aspinatum* (1 specimen in the core sample from a depth of 145.3–145.5 m) is considered as reworking from the Oligocene (- earliest Miocene). Additional reworking in low percentages (1–2%) is recorded in the sample from a depth of 149.6–150.3 m (*Dingodinium spinosum*) and in the sample from a depth of 152.0–152.7 m (*Hystrichodinium pulchrum*). Both taxa occur in the late Jurassic-earliest Cretaceous.

Biostratigraphic analyses and age interpretation of the borehole Schijf-1 (Dinoloket B49F0431):

- 129–171 m: latest Tortonian–early Zanclean. Based on the LOD of *Reticulatosphaera actinocoronata* and the FOD of *Selenopemphix armageddonensis* (129–130 m). The dinoflagellate cysts *Invertocysta lacrymosa, Invertocysta tabulata* and *Melitasphaeridium choanophorum* fit chronostratigraphically. Incidental occurrences, like *Eatonicysta ursulae* (129–130 m)*, Areoligera semicirculata, Cleistosphaeridium placacanthum* (149–150 m) and *Areosphaeridium dictyoplokum* (170–171 m) indicate reworking from the Palaeogene. Common occurrences of *Paralecaniella* (34% of the total marine specimens) at a depth of 170–171 m point to near-coastal environment.
- 180–181 m: late Langhian–early Serravallian biozone SNMS 7. Based on the LOD of *Apteodinium spiridoides* and *Unipontidinium aquaductum.* The genera C*ordosphaeridium* and *Deflandrea* are considered as reworking.
- 188–189 m: late Rupelian biozone NSO-5 or older. Based on the LOD's of *Achilleodinium biformoides* and *Rhombodinium draco*. The presence of *Areoligera semicirculata, Deflandrea phosphoritica, Hystrichokolpoma cinctum* and *Wetzeliella symmetrica* confirm the early Oligocene age of the sediments.

Biostratigraphic analyses and age interpretation of the borehole Schijf-2 (Dinoloket B49F0436):

- 179–189 m: early Zanclean or older. Based on the LOD of *Reticulatosphaera actinocoronata*.
- 200–201 m: mid-Langhian biozone SNMS 6. Based on the LOD of *Distatodinium paradoxum, Apteodinium spiridoides, Apteodinium tectatum* and *Sumatradinium hamulatum*.
- 211–212 m: late Burdigalian–earliest Langhian biozone SNMS 4. Based on the LOD of *Exochosphaeridium insigne.*
- 221–229 m: mid-Burdigalian biozone SNMS 3. Based on the LOD of *Cordosphaeridium cantharellus* and the FOD of *Sumatradinium soucouyantae* at (221–222 m depth). Individual occurrences of *Chiropteridium* spp., *Deflandrea phosphoritica, Wetzeliella symmetrica* (221–222 m), and *Chiropteridium galea*, *Wetzeliella gochtii* (228–229 m) are considered as reworking from older lithostratigraphic units, for example from the (completely eroded) Voort Member and the Rupel Formation.

Integration of existing biostratigraphic interpretations

Louwye and Laga (1998) first biostratigraphically analysed the borehole Kalmthout based on dinocyst species. Later, their interpretations were revised by Louwye (2005), who in addition analysed the nearby borehole Essen-2. Louwye (2005) used the biozonation scheme of De Verteuil and Norris (1996). More recently, Louwye et al. (2020) applied the biozonation scheme of Dybkjær and Piasecki (2010) to existing results for the borehole Kalmthout. For consistency with the other analyses in this study, the biozonation scheme of Munsterman and Brinkhuis (2004) was applied to existing analyses of the boreholes Kalmthout and Essen-2 by Louwye and Laga (1998) and Louwye (2005), respectively.

Biozonation of borehole Essen-2 based on Figure 4 of Louwye (2005):

- 177.7 m: late Langhian to early Serravallian biozones SNMS 7–8. Based on the LOD *Unipontedinium aquaeductum. Distatodinium paradoxum* and *Cousteaudinium aubryae* are absent.
- 180.3 m: early Langhian biozone SNMS 5. Based on the FOD of *Labyrinthodinium truncatum*, LODs of *Distatodinium paradoxum* and *Cousteaudinium aubryae. Unipontedinium aquaeductum* is missing.

Biozonation of the borehole Kalmthout (GSB 006E0110) based on Louwye and Laga (1998, their Table 1):

- 112 m: late Serravallian or younger biozone SNMS 10. Based on the FOD of *Achomosphaera andalousiensis*.
- 113 m: mid-Langhian biozone SNMS 6. Based on the LOD of *Cousteaudinium aubryae* and the FOD of *Unipontedinium aquaeductum*.
- 117 m: early Langhian biozone SNMS 5. Based on the FOD of *Labyrinthodinium truncatum modicum*. *Unipontedinium aquaeductum* is missing.
- 118–120 m: late Burdigalian–earliest Langhian biozone SNMS 4. Based on the LOD of *Exochosphaeridium insigne*.
- 124–136.6 m: mid-Burdigalian biozone SNMS 3. Based on the LOD of *Tityrosphaeridium cantharellus (Cordosphaeridium cantharellus)*.

Results borehole correlations

The geological map of Figure 1 (taken from Vernes et al., 2023) shows the presence of the Berchem Formation across the study area. In all boreholes, the Berchem Formation is encountered above the Boom Formation and below the Diest Formation (Figure 3). As it comprises plastic clays, the Boom Formation can be easily distinguished from the sands of the overlying Berchem Formation. On wireline logs, this transition corresponds to a strong upwards increase in resistivity values. The gamma-ray log is a less useful tool to distinguish between the clays and glauconitic sands, since both lithologies share a relatively enhanced natural

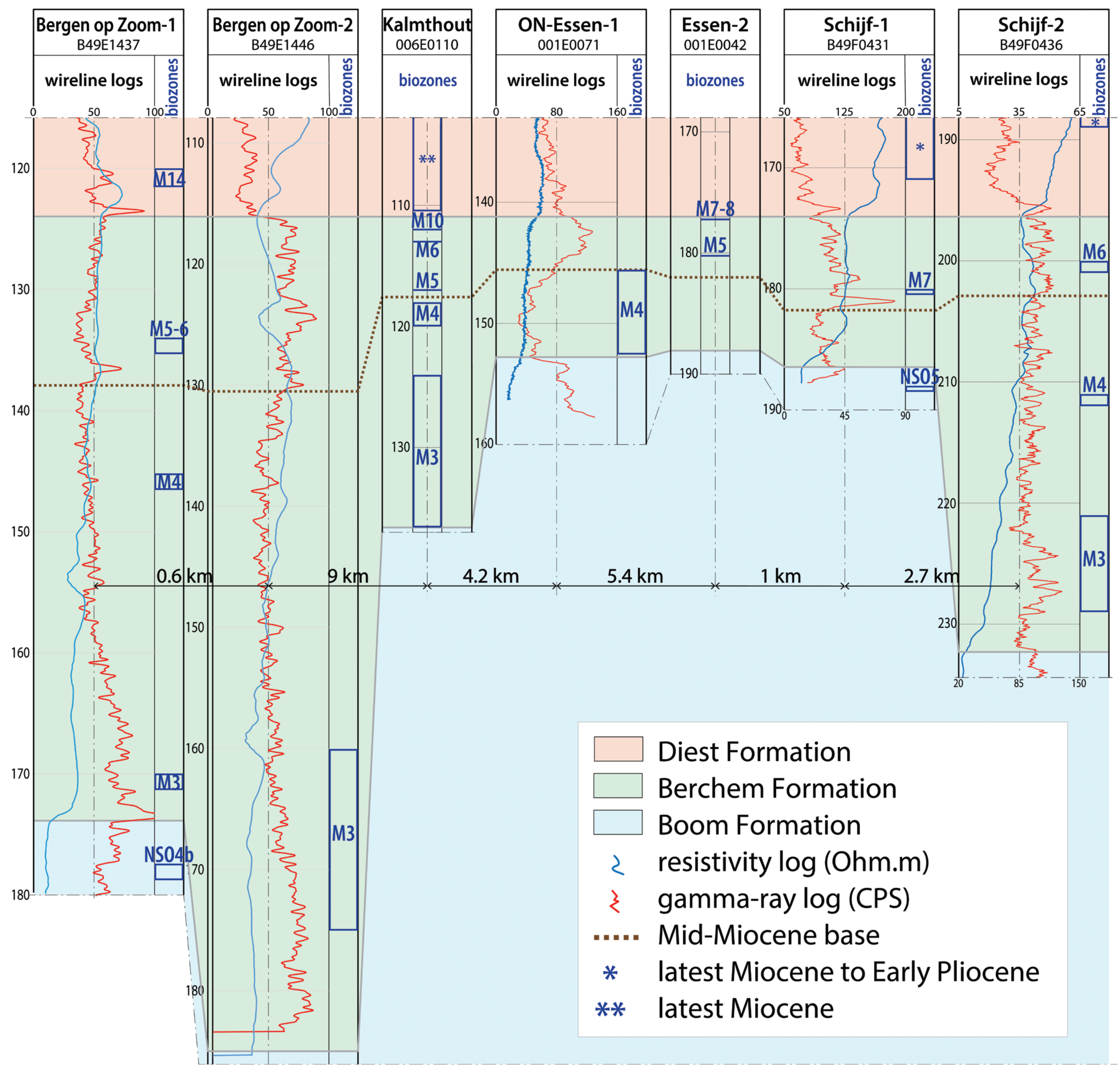

Figure 3. Borehole correlation panel for the Berchem Formation in the study area with the interpreted palynological biozones as defined by Munsterman and Brinkhuis (2004). The panel is horizontally aligned or flattened at the top of the Berchem Formation. The palynologic interpretation of boreholes Kalmthout and Essen-2 is based on the analyses by Louwye and Laga (1998) and Louwye (2005). The boreholes Bergen op Zoom-1, Schijf-1 and Schijf-2 were recently biostratigraphically analysed by means of dinocyst species for the cross-boundary H3O-De Voorkempen project (Vernes et al., 2023). The boreholes Bergen op Zoom-2 and ON-Essen-1 were biostratigraphically analysed in this study. The dashed brown line represents the estimated Early/Middle Miocene boundary based on the wireline log expressions and/or biostratigraphic data. For location, see Figure 1.

radioactivity. The distinction between the glauconitic sands of the Berchem and Diest formations is more difficult to make. In general, however, the Diest Formation is more coarse-grained, carbonate poor and less glauconite-rich compared to the Berchem Formation. On the wireline logs, the increase in grain size is generally expressed by an upwards increase in resistivity values, whilst the decrease in glauconite content is expressed by an upwards decrease in gamma-ray values.

The biostratigraphic analyses show that the biozones range from M3 at the base up to M10 at the top of the Berchem Formation. Not all biozones were detected in all boreholes, which can — in part – be related to the non-continuous sampling. In the boreholes Bergen op Zoom-1 and Schijf-1, samples from the top of the Boom Formation were also analyzed, which hold the Rupelian biozones NSO4a and NSO5. The Diest Formation was sampled in the boreholes Bergen op Zoom-1 Kalmthout and Schijf-1 and -2, where sediments/biozones of Late Miocene age were found.

The correlations carried out show relatively great thickness changes for the Berchem Formation: from 12 to 15 m in the boreholes ON-Essen-1, Essen-2 and Schijf-1, 25 m in the borehole Kalmthout, 35 m in the borehole Schijf-2, 50 m in Bergen op Zoom-1 with a maximum of 69 m in the borehole Bergen op Zoom-2. A part of this thickness variation appears to be related to the absence/presence of the biozone M3: this biozone is present in the lower part of the Berchem Formation in the boreholes Bergen op Zoom-1 and -2, Kalmthout and Schijf-2, where the Berchem Formation is thickest, whilst the same biozone is absent in the borehole Essen-1 where the Berchem Formation is thinnest. Biozone M3 encompasses a 12.6 m thick interval in the borehole Kalmthout and at least 14 m and 8 m thick intervals in the boreholes Bergen op Zoom-2 and Schijf-2, respectively.

Based on the wireline logs, the uppermost part of the Berchem Formation is of Mid-Miocene age (biozones M5–M11) and shows consistently higher gamma-ray values than the upper part of the Lower Miocene (biozone M4). This is consistent with the wireline log correlations between biostratigraphically analysed boreholes located further south (northeast of city of Antwerp) and east (northern part of the Roer Valley Graben) of the study area conducted by Deckers et al. (2025a). This supports the latter's conclusion that the gamma-ray log is a useful tool for identifying the early to middle Miocene boundary in the Berchem Formation. In addition, the correlations performed in this study show that the Middle Miocene is relatively thin, which is consistent with the biostratigraphic analyses of boreholes across the Antwerp Campine area by Louwye (2005). Downwards from the relatively low gamma-ray values of biozone M4 in the boreholes Bergen op Zoom and Schijf-2, the gamma-ray values increase towards high to very high values at the stratigraphic level of the biozone M3. According to the borehole descriptions, these high gamma-ray values can be related to the high glauconite content. Also in the borehole Kalmthout, the biozone M3 sediments are described as dark green to black, which is typical for high glauconite content.

Results seismic interpretations

The Boom Formation typically has very weakly reflective facies on seismic data because it is a relatively thick and homogeneous clay/silt unit. The underlying lower Rupelian and the overlying Neogene successions show stronger internal reflections. In the north and south, the reflection from the Boom Formation top runs subparallel to the reflection from the Boom Formation base. In the centre of the line, the Boom Formation top reflector shows two depressions, each about 50 milliseconds deep in two-way traveltime (Figure 4). The northern depression is about 1.5 km wide, whilst the size of the southern one is uncertain due to distortion of the seismic image. The northern depression shows two concave downwards high amplitude reflections. They are overlain by medium amplitude reflections that run subparallel to the Boom Formation base reflection. Given this geometry, these depressions can be interpreted as channels in the Boom Formation top or Berchem Formation base. Considering an acoustic interval velocity of 1800 and 50 milliseconds two-way traveltime, the channel depth can be estimated at 45 m. The two individual channels are part of a larger channel system in the Boom Formation top (Figure 4). Borehole Bergen op Zoom-1 is in the shallow part of the channel system, whereas borehole Bergen op Zoom-2 projects in a deep channel in the north of the channel system (Figure 4). Finally, based on the interpretation of surrounding, older and lower quality seismic lines, the channel system can be traced in the northern part of the research area having an east-northeast direction (Figure 5).

Discussion and conclusions

Channels in the base of the Berchem Formation

Louwye (2005) in a palynological analysis of the Berchem Formation in several boreholes in the Antwerp Campine area recorded only the middle Burdigalian biozone DN2b of De Verteuil and Norris (1996) or the biozone M3 of Munsterman and Brinkhuis (2004) in the borehole Kalmthout (for location, see Figure 1; Figure 2). In the other investigated boreholes, the base of the Berchem Formation comprised the younger, upper Burdigalian biozone DN2c of De Verteuil and Norris (1996) or lower part of the biozone M4 of Munsterman and Brinkhuis (2004; Louwye, 2005). This may indicate that a middle Burdigalian (biozone M3) marine transgression took place in northern Belgium from a north–northwestern direction (Louwye, 2005). Indeed, the same biozone M3 was encountered again in the boreholes Bergen op Zoom-1 and -2 (northwest of the borehole Kalmthout) and in the borehole Schijf-2 (northeast of the borehole Kalmthout; see Figure 3). However, in the borehole ON-Essen-1, located between the boreholes Kalmthout and Schijf-2, the biozone M3 is lacking. This shows that the deposits holding biozone M3 have an irregular occurrence in the area, in between depositional surface elevations on top of which the biozone sediments are lacking. The absence of biozone M3 sediments could be either due to non-deposition or post-depositional erosion on the depositional surface elevations.

The seismic line (SCAN34; for location, see Figure 1) that runs in the west of the study area provides an important clue on the most likely reason for the locality of the deposits holding the biozone M3. The interpreted section of this seismic line indicates a channel system at the base of the Berchem Formation with two deeper individual channels that are cut to a depth of about 45 m into the top of the Boom Formation (Figure 4). The interpretation of the surrounding seismic lines

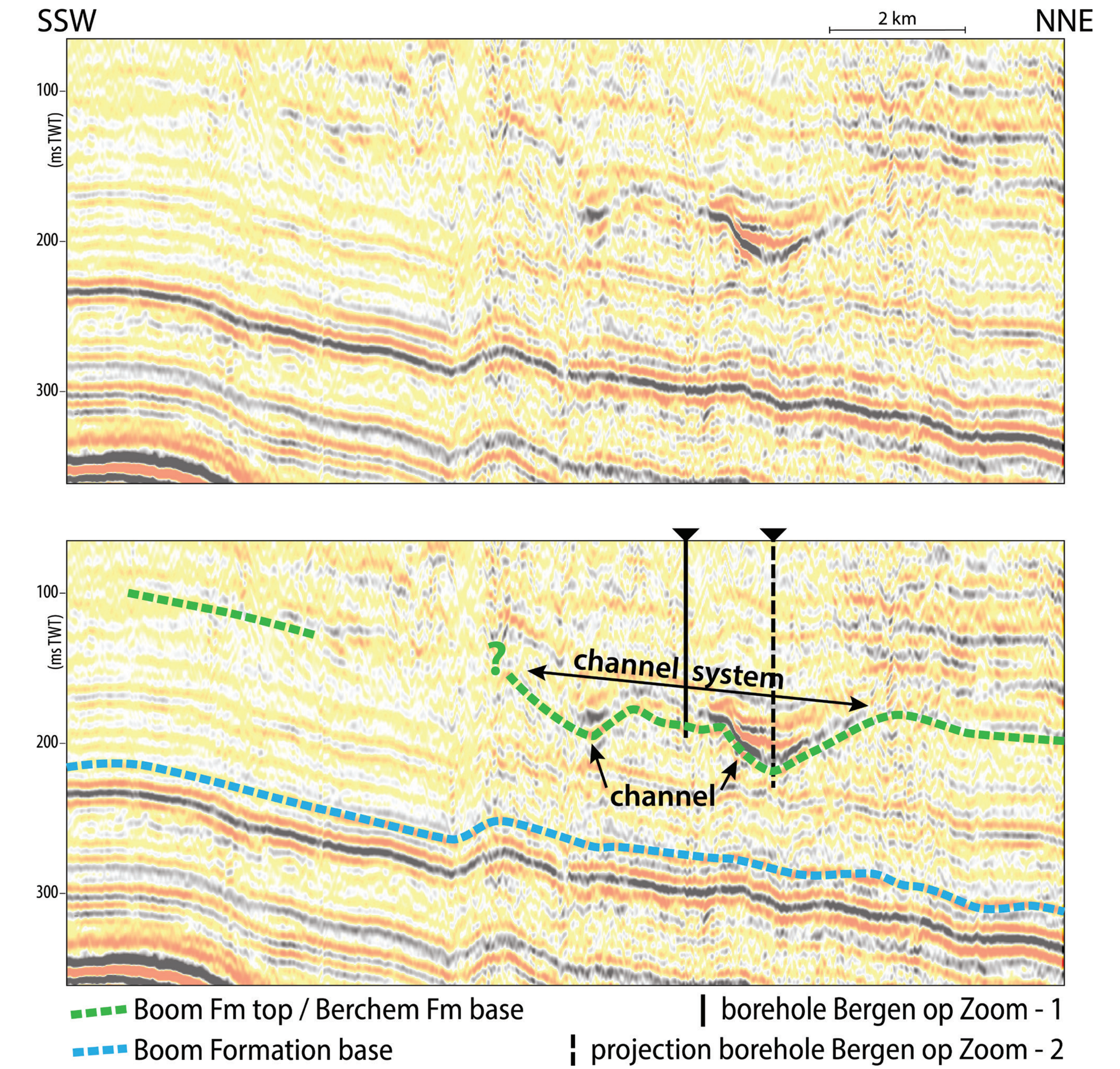

Figure 4. Seismic line SCAN34 uninterpreted (above) and interpreted for the relevant lithostratigraphic units of this study (below). Note the channel incisions in the top of the Boom Formation. The seismic line runs along borehole Bergen op Zoom-1 and just west of borehole Bergen op Zoom-2 (Figure 1). Red and black shading represent hard- and soft-kicks, respectively. For location of the seismic line and the Bergen op Zoom boreholes, see Figures 1 and 5.

shows that the channel system has a west-southwest–east-northeast orientation (Figure 5). The orientation of individual channels within the channel system remains uncertain. The boreholes Bergen op Zoom-1 and -2 are located along and nearby the seismic line SCAN34 and are both within the channel system (cf. Figures 4 and 5). Their location in the channel system visible on the seismic data explains the anomalous thickness of the Berchem Formation in these boreholes (50 m and 69 m) relative to the boreholes Essen and Schijf-1 east in the area (less than 15 m; Figure 3). As the channel system is located at the base of the Berchem Formation, it was initially filled with the oldest sediments of the Berchem Formation, which hold the biozone M3 in the boreholes Bergen op Zoom. The presence of channels at the base of the Berchem Formation filled with deposits holding biozone M3 explains why this biozone occurs only locally and is highly variable in thickness. Based on analogy with the Bergen op Zoom boreholes, it is assumed that channel incisions in the Boom Formation also explain the thick development of the Berchem Formation (with the biozone M3 in its basal section) at other locations, such as at borehole Kalmthout or Schijf-2. However, compared to the borehole Bergen op Zoom-2, where the Berchem Formation reaches its maximum thickness, the other boreholes penetrated channel systems that more shallowly incised into the Boom Formation. The presence of Oligocene dinocysts in the Burdigalian biozone M3 in the

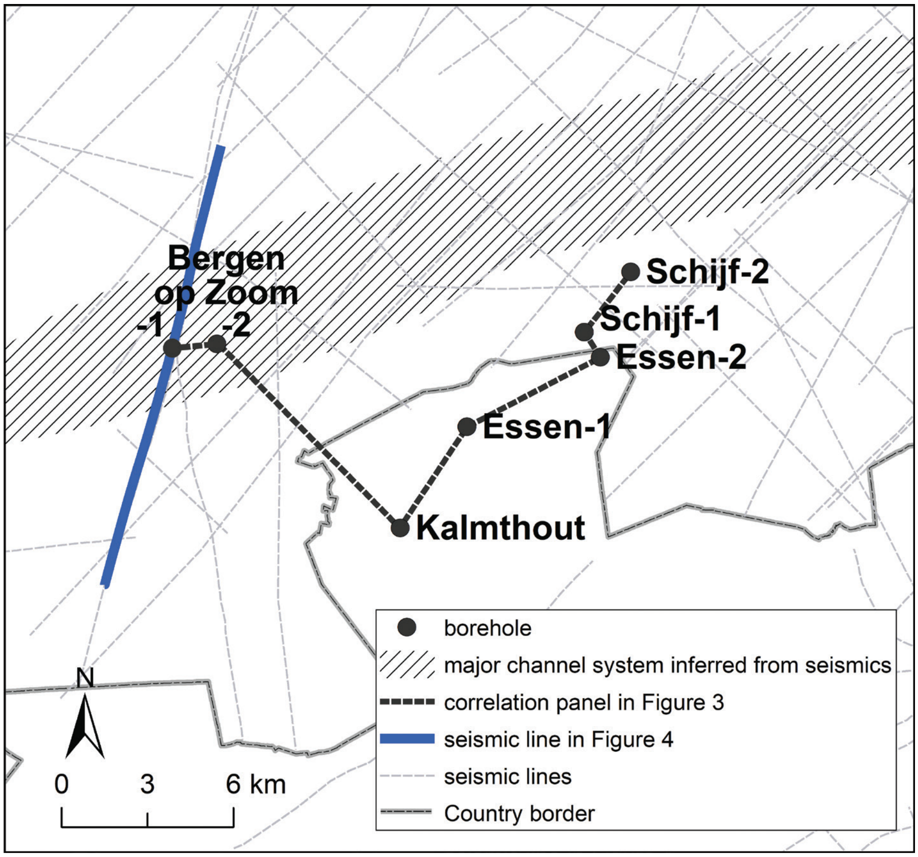

Figure 5. Map of the extent of the channel system which comprises deep channels at the base of the Berchem Formation that are observable on the seismic lines. Other channels at the base of the Berchem Formation, such as those at the borehole Schijf-2, might be missed on the seismic lines due to poor imaging or because they are shallower incised.

boreholes Kalmthout and Schijf-2 is consistent with their redeposition into the incised channel.

Taking into account the above-presented results, the question can be raised whether other sediment bodies holding the biozone M3 on the western flank of the (differentially subsiding) Roer Valley Graben also represent a channel infill? For example, the Edegem Member of the Berchem Formation (see Figure 2), which typically holds this biozone (*Cordosphaeridium cantharellus* zone of Dybkjær & Piasecki, 2010; Louwye et al., 2020), occurs only locally in the vicinity of the city of Antwerp (for geographic extent, see Figure 1). The arguments in favour of deposition of this lithostratigraphic unit in a wide channel system are few. In the recent model of the shallow subsurface of Antwerp, Van Haren et al. (2023) did notice the absence of the Edegem Member on the relatively elevated Boom Formation just northwest of Antwerp (Figure 6). However, more data on the geometry of the Edegem Member are needed to confirm the hypothesis that it was deposited in a wide channel system.

Channel formation and infill

The process of formation of the channels in the top of the Rupelian Boom Formation is yet unknown. The most common form of incised-valley system develops during a lowering in base level associated with a fall in relative sea level (Zaitlin et al., 1994). Because the hiatus between the Boom Formation and Berchem Formation spans a long period of time, that is Chattian to early Burdigalian, several individual or a combination of eustatic sea-level falls could have caused the channel incisions. The sea-level fall associated with the Oligocene-Miocene transition corresponds with this hiatus and was estimated to be about 50 m by Beddow et al. (2016), which is close to the 45 m of erosion (incision) observed on the seismic line by this research. In the stronger subsiding Roer Valley Graben to the east of the study area, no base Miocene channel systems were observed on seismic data (Deckers, 2016; Siebels et al., 2024; Verbeek et al., 2002) but instead the same sea-level lowering resulted in a transition from shallow to open marine sands of the upper Oligocene Voort Member towards the restricted/lagoonal clays of the latest Oligocene to earliest Miocene Wintelre Member (Munsterman & Deckers, 2022). The sea-level fall at the Oligocene-Miocene boundary thus resulted in a retreat of the sea towards the strongest subsiding areas, that is the Roer Valley Graben, whilst exposing the higher Antwerp Campine study area to sub-aerial erosion with river incisions. During middle Burdigalian sea-level rise, the river incisions were transgressed, widened and infilled with sands of the lower Berchem Formation. The same process was repeated during later episodes of major sea-level changes in the southern North Sea Basin: after major sea-level falls at the Middle/Upper Miocene boundary, Mio-Pliocene boundary and Pliocene/Quaternary boundary, the sands of the Diest Formation, Kattendijk Formation and Merksplas Formation were deposited in >10 m deep incised channel systems, in the Hageland, Antwerp and northern Antwerp Campine areas, respectively (Deckers & Louwye, 2020;

https://doi.org/10.70712/NJG.v104.12070

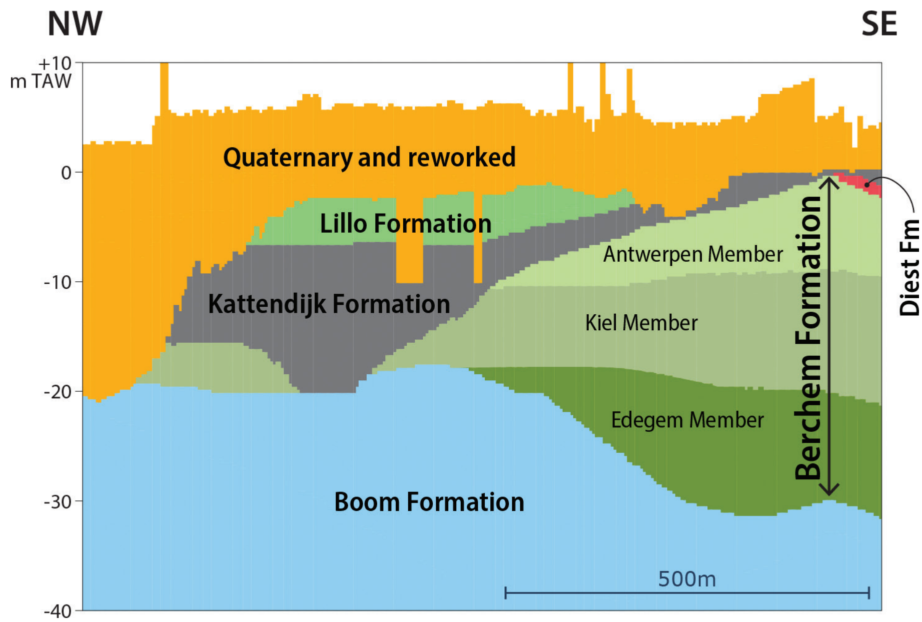

Figure 6. Section across the geological model of the shallow subsurface of Antwerp, modified after Van Haren et al. (2023). Notice how the Edegem Member is almost 10 m thick in the southeast and pinches out towards a sedimentary high in the top Boom Formation in the northwest. In analogy with the hypothesis put forward by this study, the Edegem Member (biozone M3) could have filled a wide channel system incised in the Boom Formation top. For location of this section, see Figure 1.

Deckers et al., 2025b; Houthuys et al., 2020). The orientation of the channel system in the base of the Upper Miocene Diest Formation is WSW-ENE, similar to that in the base of the Berchem Formation in the study area. This channel system direction is probably related to the consistent tilt of the basin floor in ENE direction from the relative high Brabant Massif in the west towards the differentially subsiding Roer Valley Graben in the east during the Miocene (c.f. Vandenberghe et al., 2004).

Although the abovementioned type of incised-valley systems is characterised by fluvial erosion (Zaitlin et al., 1994), no indications were found for fluvial deposits in the middle Burdigalian channel infill of the Berchem Formation in the boreholes. Instead, the dinocysts indicate a shallow to marginal marine depositional environment in the channels. The abundant presence of glauconite is also consistent with a marine depositional environment (Amorosi, 1997; Odin & Fullagar, 1988). Likewise in the younger channel-filling units of the Diest, Kattendijk and Merksplas formations, fluvial deposits are also lacking. Earlier fluvial deposits could have been removed during the marine transgression of the channels, similar to the transgression of paleo-valleys along the French Atlantic coast (c.f. Estournès et al., 2012; Féniès & Lericolais, 2005). Channels in the base of the lower Pliocene Kattendijk Formation – as observed by Deckers and Louwye (2020) northwest of Antwerp (for location, see Figure 1) – also comprise marine, glauconite-bearing sands (Gaemers, 1975; Janssen, 1974; Marquet, 2004). Based on faunal content, the depositional depths of the Kattendijk Formation in the channels system are estimated around 50 m below sea-level (Gaemers, 1975; Marquet, 2004). Detailed paleo-bathymetric studies have not been performed on the middle Burdigalian sands in the region, but otolith-based assemblages studied near the stratotype of the middle Burdigalian Edegem Member south of the study area (Nolf & Smith 1983) may roughly indicate a depth of 20–50 m (pers. comm. K. Hoedemakers), which is rather similar to the Kattendijk Formation. This would require a fast middle Burdigalian sea-level rise.

For the lower Pliocene Kattendijk Formation, the channel infill lithology cannot be distinguished from the overlying, more widely deposited sequences (Deckers & Louwye, 2020), which is similar as for the Burdigalian sands in the study area. Given the lack of fluvial facies or other distinct lithological characteristics, this type of channel system with purely marine infill can easily be overlooked when boreholes are more widely spaced or lack supporting geophysical (seismic) data.

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