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Corresponding author:
Dirk Munsterman
Email: dirk.munsterman@tno.nl

Enhancing mutual stratigraphic resolution in Belgium and the Netherlands by cross-border study of mid Eocene successions in the southernmost North Sea Basin

Dirk Munsterman[1]* and Jef Deckers[2]

[1]TNO-Geological Survey of the Netherlands (GSN), Utrecht, The Netherlands; [2]VITO, Flemish Institute for Technological Research, Mol, Belgium

Abstract

The lack of age-indicative calcareous nannoplankton has rendered the mid Eocene stratigraphic framework of the southern North Sea Basin uncertain. Palynological analyses by this study succeed in bridging this gap. A series of wells in the border region between Belgium and the Netherlands was biostratigraphically analysed, based on dinocyst species. The Belgian middle to late Eocene lithostratigraphic framework, comprising the Maldegem and Zelzate formations and their respective members, was applied to interpret the wells, which strongly increased the existing stratigraphic detail for the Dutch wells. A well-log correlation panel shows consistent biostratigraphic ages for the different middle to late Eocene units. It shows that the Zomergem and Buisputten members of the Maldegem Formation are still of Lutetian age, whereas the Onderdijke Member of the same formation is completely of Bartonian age. Palynological assemblages indicate an intra-Bartonian sea-level fall at the boundary between the Maldegem and Zelzate formations. The lowermost few metres of the Zelzate Formation consistently comprise Bartonian dinocyst species, which had been previously interpreted as reworked, but are now considered in situ, placing the Bartonian/Priabonian transition in the basal Zelzate Formation. The newly established Bartonian/Priabonian boundary corresponds to the start of a new sea-level rise, indicated by an increase in gamma-ray values, in a nummulite level attributed to calcareous nannoplankton NP18 biozone. Hence, the previously established hiatus between the Belgian Maldegem and Zelzate formations now falls within the (upper part of the) Bartonian.

Introduction

During the middle-upper Eocene, northern Belgium and the Netherlands were situated along the southern North Sea Basin where deposition consisted of sands and clays (Figure 1). Currently, these Eocene strata are located in the shallow subsurface of northwestern Belgium and the southern Netherlands (Figure 2). The middle-upper Eocene stratigraphic succession is still poorly understood in the Netherlands. This is largely because of the absence of detailed stratigraphy for this interval as only one lithostratigraphic unit, being the Asse Member, is assigned to the entire middle Lutetian to Bartonian interval (TNO-GDN, 2025). The Belgian lateral equivalent, the middle Lutetian to Bartonian Maldegem Formation, is much more detailed as it comprises seven members (Figure 3), which can be correlated across northwestern Belgium based on their typical log-signatures (Vandenberghe et al., 1998). Deckers et al. (2016, 2024) show how these units can also be correlated with the southwestern part of the Netherlands. In Belgium, the chronostratigraphic framework of the middle-upper Eocene is mainly based on biostratigraphic analyses based on the calcareous nannoplankton. These analyses on the key well Kallo in northwestern Belgium (see Figure 2 for location) showed a middle Lutetian age (NP15/16) for the basal units of the Maldegem Formation (Wemmel, Asse and Ursel) (Steurbaut, 1986). The middle and upper members of the unit (Onderdale, Zomergem, Buisputten and Onderdijke) were barren of calcareous nannoplankton. Dinocyst species analyses on the same well indicate the Bartonian age (De Coninck, 1995). The latter author makes detailed correlations between these middle and upper members of the Maldegem Formation in the Kallo well and the Barton Beds in the Hampshire Basin of southern England (for location, see Figure 1). The lower parts of the Barton Clay Formation, however, have been attributed more recently to the upper Lutetian (Hooker & King, 2019), which puts doubt on the Bartonian age of the lateral

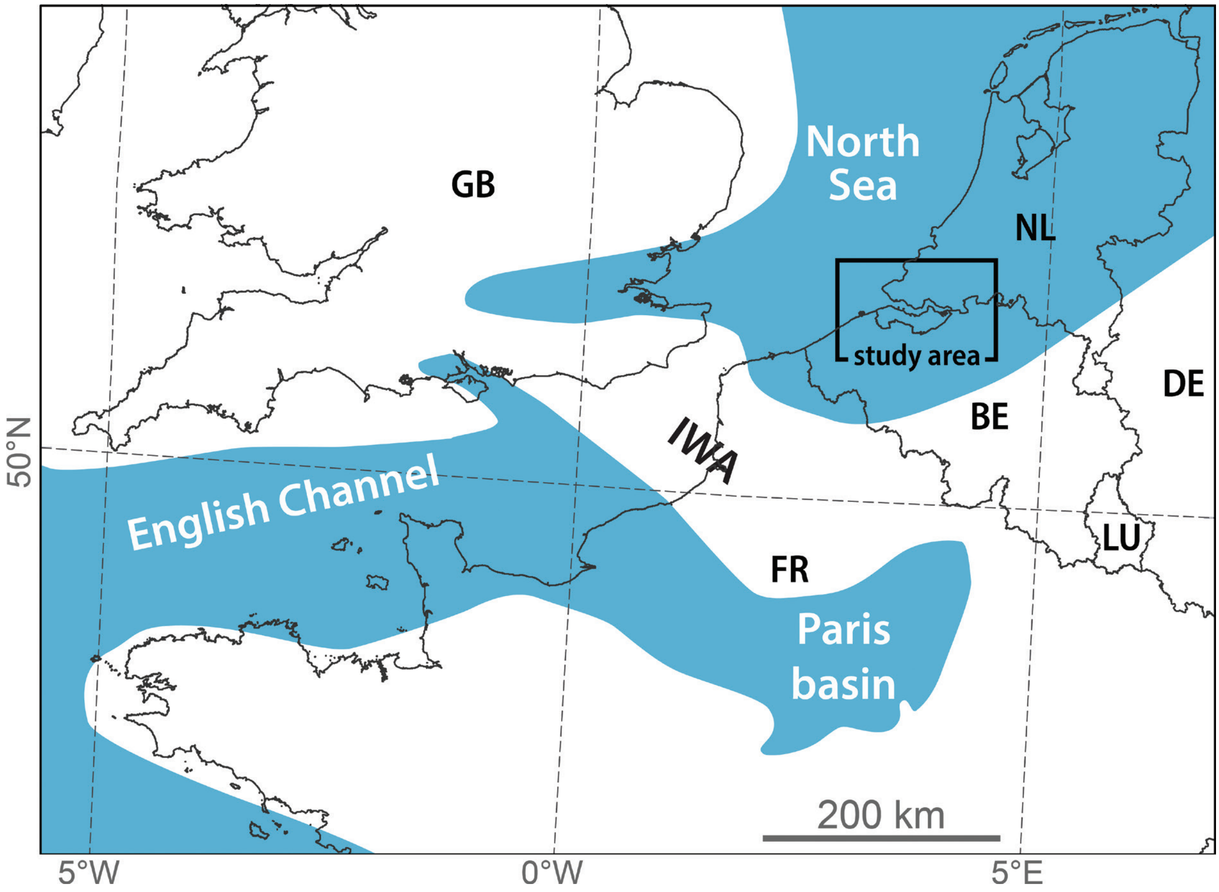

Figure 1. Paleogeography in western Europe during the middle Eocene (Bartonian), based on figure 1 of Brachert et al. (2022). IWA= Isthmus of Weald-Artois. The study area of Figure 2 is indicated by a grey rectangle.

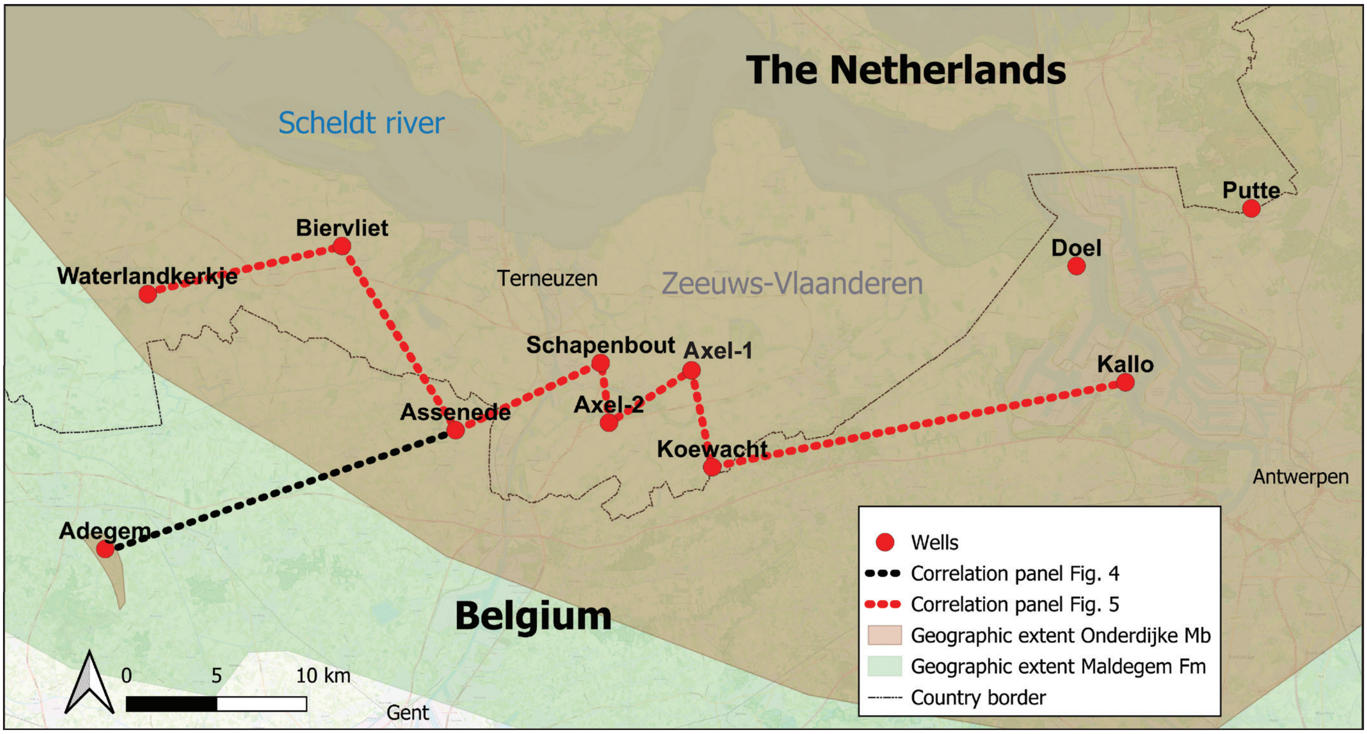

Figure 2. Overview of the study area with the main wells and correlation panels between them. The geographic extent of the Maldegem Formation and its uppermost Onderdijke Member based on the G3Dv3 model (Deckers et al., 2019) is also shown. For location see Figure 1.

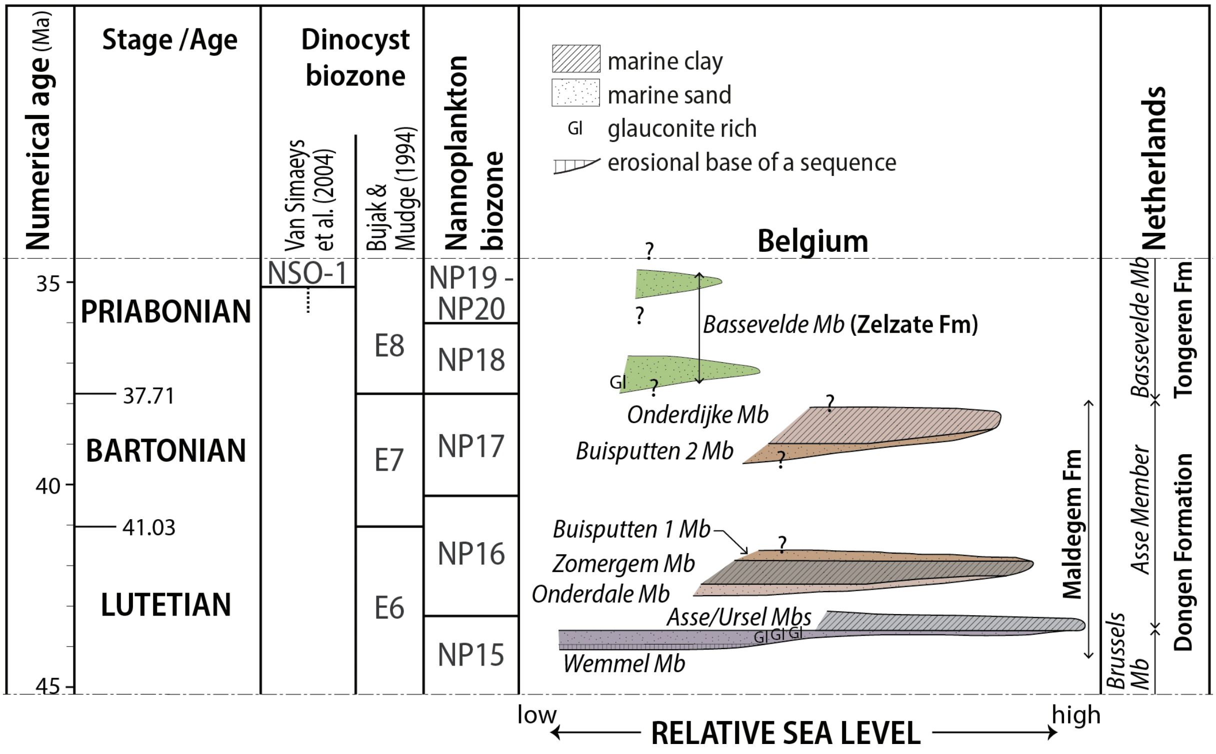

Figure 3. Middle Eocene to lower Oligocene sediment sequences at the southern border of the North Sea area and their relative sea level at the time of deposition after Vandenberghe et al. (2004) and Deckers et al. (2016). Dinocyst biozones are based on Bujak and Mudge (1994).

equivalent members of the Maldegem Formation. Consequently, the sequence stratigraphic framework of the middle Lutetian to Bartonian for the southern North Sea region, as constructed by Vandenberghe et al. (2004), remains rather uncertain (see question marks on Figure 3). Just northwest of Belgium, in Zeeuws-Vlaanderen in the southwestern Netherlands, numerous wells have been subjected to palynological analyses for the Lutetian to Rupelian interval which can help clarify the above-mentioned uncertainties (indicated on Figure 2). These analyses were, however, written down in internal TNO-GSN reports by Munsterman (2003, 2004a, 2004b, 2005a, 2005b), but never published. In this study, we present these palynological analyses to improve our knowledge on the mid-Eocene stratigraphic interval in the region. We therefore first interpreted these wells according to the detailed Belgian lithostratigraphy and correlated them based on their gamma-ray log signatures. We then compare the analyses and insights in the southwestern Netherlands with an updated version of the dinocyst species analyses of De Coninck (1995) for the Kallo well in northwestern Belgium. This will provide a more rigid bio- and chronostratigraphic and therefore also sequence stratigraphic framework for the upper Lutetian and Bartonian in the region.

Geological background

In the Netherlands, the middle Lutetian to Bartonian interval comprises the Asse Member of the Dongen Formation, which is overlain by the Priabonian to lower Rupelian Tongeren Formation (Figure 3; TNO-GDN, 2025). In Belgium, the Maldegem and Zelzate Formations represent the equivalent to the Dutch Asse Member and Tongeren Formation, respectively. The Maldegem Formation comprises alterations of sandy and clayey units that make up its members, namely Wemmel, Asse, Ursel, Onderdale, Zomergem, Buisputten and Onderdijke (Figure 3). Based on sediment analyses, Jacobs et al. (1990) provided a sequence stratigraphic framework for the different units of the Maldegem Formation that was later slightly modified by Vandenberghe et al. (2004). The sandy units are thereby interpreted as representing the initial transgressive system tract and late highstand system tract (highstand prograding wedges), whereas the clayey units representing the late transgressive to early highstand system tracts (Figure 3).

The lower members of the Maldegem Formation, that are Wemmel, Asse and Ursel, comprise calcareous nannoplankton that allow the interpretation in biostratigraphic zones. Based on calcareous nannoplankton in the Kallo well in northwestern Belgium (for location, see Figure 2), Steurbaut (1986) noted that the Wemmel and Asse members correspond to the middle Lutetian NP15 biozone, while the Ursel Member holds the upper Lutetian–lower Bartonian NP16 biozone. In the Mol well in northeastern Belgium, the NP16 biozone was also recognised in the Onderdale Member (Vandenberghe et al., 1998). No calcareous nannoplankton biozones were established for the overlying Zomergem, Buisputten and Onderdale members of the Maldegem Formation. Based on dinocyst species analyses of the Kallo well by De Coninck (1995), the Onderdale, Zomergem, Buisputten and Onderdijke members of the Maldegem Formation were interpreted as Bartonian. In the north of the Kallo well, the Doel-2b well was drilled up to the Onderdijke Member in the top of the Maldegem Formation (for location, see Figure 2). Dinocyst species analyses in the top of the Onderdijke Member again revealed Bartonian dinocyst species (Vandenberghe et al., 2003). In the Doel-2b well, the Onderdijke Member of the Maldegem Formation is overlain by the Bassevelde

Member of the Zelzate Formation which corresponds to the Priabonian NP18–NP20 biozones as well as mainly Priabonian dinocysts, like *Melitasphaeridium pseudorecurvatum* and *Reticulatosphaera actinocoronata*, in its lower and middle sections (Vandenberghe et al., 2003; Figure 3). The latter authors discuss that Bartonian dinocysts, like *Rhombodinium porosum*, in the basal parts of the Bassevelde Member are probably reworked.

Dataset and methodology

Eight wells form the focus of this study, from west to east: Waterlandkerkje (B54A0088), Biervliet (B54B0085), Assenede (025E0123), Schapenbout (B54E0335), Axel-1 (B54F0093), Axel-2 (B54F0097), Koewacht (B54H0021) and Kallo (027e0148; for location, see Figure 2). The Axel-1 and -2, Schapenbout, Biervliet, Koewacht and Waterlandkerkje wells are located in the southwestern Netherlands and the Assenede and Kallo wells in northwestern Belgium. The Assenede and Dutch wells are provided with wireline loggings: Axel-2, Biervliet, Koewacht, Schapenbout and Waterlandkerkje with only a gamma-ray log and Assenede and Axel-1 in addition have a resistivity log.

The Kallo well is cored and was lithostratigraphically interpreted in the interval of the Maldegem and Zelzate formations by Steurbaut (1986) who provides an updated lithostratigraphic nomenclature as proposed by Gulinck (1969) based on the more recent work by Jacobs (1978). The Assenede well is cored and lithostratigraphically interpreted for the same formations by Laga (1990). The latter mentioned that there is a vertical shift of 1.5 m between the well cores and wireline log. Therefore, we shifted the depth of the sampling 1.5 m upwards to match the wireline log on Figure 5.

The Dutch wells had been lithostratigraphically interpreted according to the Dutch lithostratigraphy on https://www.dinoloket.nl/ondergrondgegevens; but since this is not very detailed, we reinterpreted them according to the Belgian lithostratigraphy. This lithostratigraphic reinterpretation was based on the available well descriptions and wireline logs in accordance with those shown by Vandenberghe et al. (1998), Deckers et al. (2016) and Deckers et al. (2024) and by correlation with the Belgian Assenede well.

The Adegem well in northwestern Belgium was proposed as the stratotype for most of the members of the Maldegem Formation (excluding the Wemmel Member) by Geets (2000). It is located on the top of the Meetjesland cuesta and was interpreted by Jacobs (1978). It is not provided with wireline logs, but numerous electric Cone Penetration Tests (CPTs) were performed along the flanks and crest of the Meetjesland cuesta southeast of the Adegem well. As a result, we were able to geotechnically characterise the Maldegem Formation near the Adegem well for cone resistance and friction ratio. In Figure 4, this CPT signature is correlated with the wireline logs of the Assenede and Axel-2 wells further north for further support of the correct interpretations of the members of the Maldegem Formation in the wells under investigation by this study. Figure 5 shows the correlation of all the wells that are subjected to biostratigraphic analyses by this study.

Biostratigraphic analyses were performed on the Kallo well by Martini (1969), Steurbaut (1986) and De Coninck (1995). The latters dinocyst nomenclature was updated by Fensome et al. (2019). Chronostratigraphic ranges of dinocyst taxa were also updated to recent key references (see below).

The palynological analyses of 141 core and airlift (semi-core) samples from the Dutch wells Axel-1, Axel-2, Biervliet, Waterlandkerkje, and the wells Koewacht and Schapenbout were reported by Munsterman (2003, 2004a, 2004b, 2005a, 2005b). Ten core samples of the Belgian Assenede well are additionally analysed by this study.

The well samples were subjected to palynological preparation. Standard palynological techniques, including HCl and HF digestion and 15 µm sieving, were applied following Janssen and Dammers (2008). No oxidation was used. The slides were mounted in glycerin jelly. One microscope slide per sample was counted as the TNO standard until an initial minimum of 200 palynomorphs (spores, pollen and dinoflagellate cysts) had been identified (when present). The remainder of the slides were scanned (at least an additional minimum of 200 specimens) for rare taxa. Miscellaneous fossils (e.g. fresh water *Pediastrum*, and fresh to brackish water *Botryococcus*) were also quantitatively (and relatively to the total palynomorph sum) counted, but standardly kept outside the total sum of 200 specimens (of dinocysts, spores and pollen). Together a total average number of approximately 200–250 microfossils is reached, statistically sufficient for indicating the dominant dinocyst species fluctuations (Brinkhuis et al., 2003).

Since the 1970s, in particular from Brinkhuis (1994), numerous studies have contributed to the current understanding of the palaeoecology of Paleogene dinoflagellate cysts. For some dinoflagellate cysts, the palaeoecology is now well known. For the present study, the palaeoecological affinities of dominant Eocene dinocyst, genera and species are applied cf. the monograph of Dybkjaer (2004) and the compilation of Frieling and Sluijs (2018). The present paper does not foresee in an overall palaeoecological study, facial condition details are only described in order to confirm interpreted sequences (see Discussion).

The age interpretation is based on the Last Occurrence Datum (LOD) and also First Occurrence Datum (FOD) of dinoflagellate cysts. For the dinoflagellate cyst taxonomy, the so-called “Lentin and Williams” Index is followed (Fensome et al., 2019). The palynological interpretation is based on key references related to the Eocene-Oligocene strata from the North Sea Basin s.l., like Bujak (1980), Powell (1992), Bujak and Mudge (1994), Eldrett et al. (2004), Heilmann-Clausen and Van Simaeys (2005), Van Simaeys et al. (2005), Thomsen et al. (2012) and Iakovleva (2024). If these papers show slightly different ages for stratigraphic ranges of dinoflagellate cysts (Bijl, 2024), the nearest topographic source for the southern North Sea Basin is chosen; unless the succession of dinocyst events from the nearest source is out of harmony with that from the present study, the next nearest source is considered. Outdated data are discussed below (see Discussion).

The dinocyst biozonation of Bujak and Mudge (1994) is followed. For the Assenede and Kallo wells, besides the dinocyst biozonation, the calcareous nannoplankton biozones are also indicated based on Steurbaut (1986). The Geologic Time Scale 2020 is applied (Gradstein et al., 2020).

Well interpretations and correlations

On the CPTs near the Adegem well, the clayey units of the Maldegem Formation, i.e. Ursel, Zomergem and Onderdijke members, correspond to very low cone resistance values of 1 to 4 MPa and high friction ratio values of 4 to 7% (Figure 4). As the Asse Member is also clayey, but relatively glauconite-rich, it displays relatively low friction ratio values of around 2%. In contrast to the clayey units, the sandy units of the Maldegem Formation, the Wemmel, Onderdale and Buisputten members, are generally expressed by higher cone resistance of 5 to 14 MPa and lower friction ratio values of 1 to 2% (Figure 4). The lower part of the Buisputten Member is described as relatively silty in the Adegem well, which explains why its cone resistance values are still relatively low (2 to 4 MPa) in comparison with its sandy top.

Correlation of the Adegem CPTs towards the Assenede well shows that the cone resistance and friction ratio show similar relative trends as the resistivity and gamma-ray logs, respectively, for the members of the Maldegem Formation (Figure 4). The top of the Onderdijke Member as well as the overlying Zelzate Formation are missing in the Adegem well due to the Quaternary erosion. In the Assenede well, the boundary between the Onderdijke Member and Bassevelde Member of the Zelzate Formation is expressed by a truncation surface according to the lithological descriptions of cores of

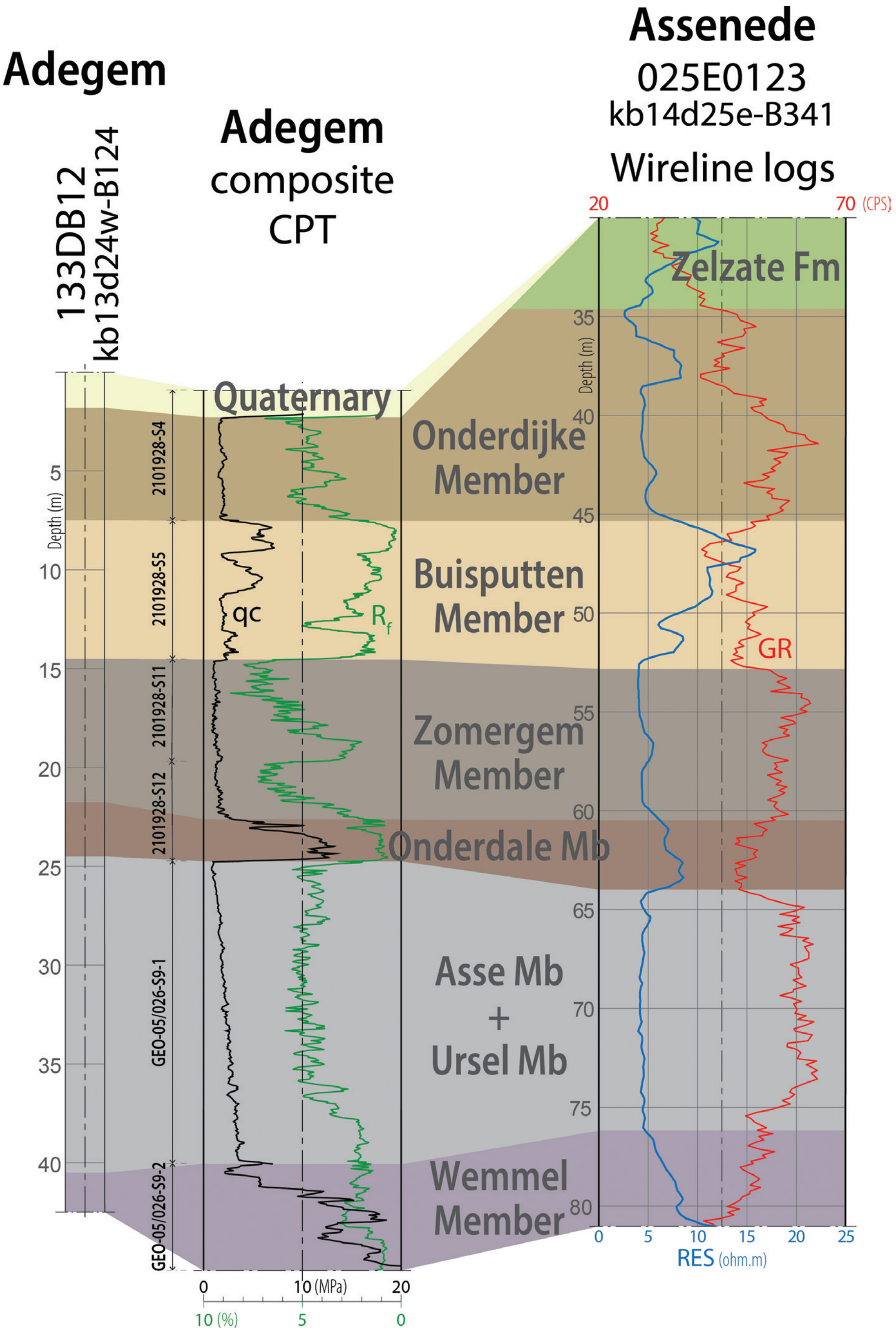

Figure 4. The Adegem stratotype well of the Maldegem Formation correlated to nearby Cone Penetration Tests. The latter are correlated with the Assenede well further north. The panel was horizontally aligned at the base of the Onderdijke Member. For location of the panel see Figure 2.

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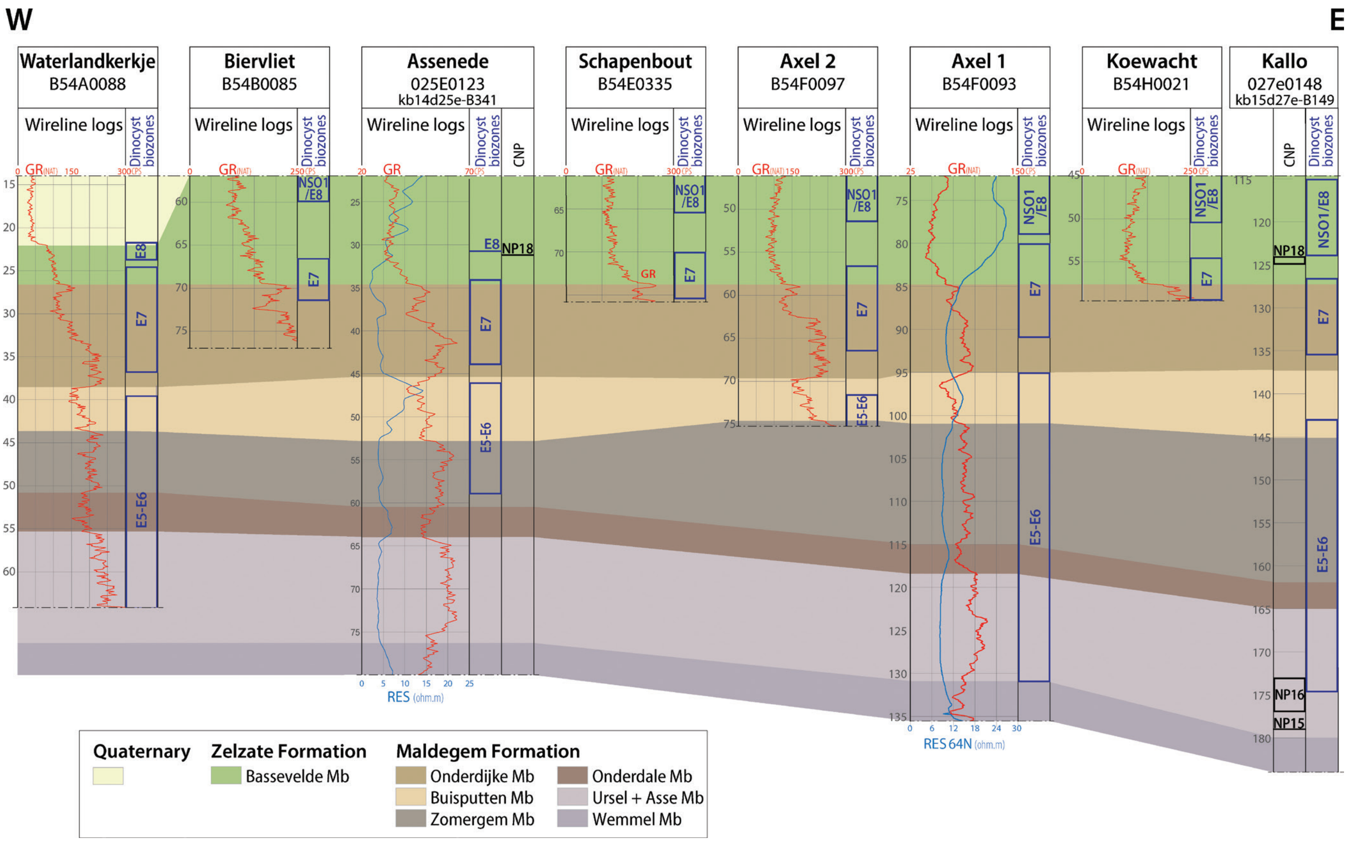

Figure 5. Correlation between palynologically analyzed wells for this study. Dinocyst biozones are based on Bujak and Mudge (1994). When available, the wireline logs are indicated. The palynological analyses of the Kallo well is a revision of De Coninck (1995). The revised calcareous nannoplankton biozones of Steurbaut (1986) by Steurbaut (pers. comm.) are shown. The panel was horizontally aligned at the top of the Onderdijke Member. The location of this panel is shown in Figure 2.

this well by Laga (1990). On the wireline logs, it corresponds to a decrease in gamma-ray values and increase in resistivity values (Figure 4), which is consistent with the log characterisation of this boundary in Vandenberghe et al. (1998). In the Dutch wells north of Assenede, the members of the Maldegem and Zelzate formations show a near identical wireline log pattern and thickness as the first (Figure 5). The Bassevelde Member shows a gamma-ray decrease towards a minimum in its basal part, then increases upwards towards a maximum in the centre before declining again towards the upper part of the unit. In the lower minimum gamma-ray level of the Assenede well, a high number of nummulites is present according to descriptions by Laga (1990). In the Kallo well, a nummulite-rich level is also present a few metres above the base of the Zelzate Formation (Gulinck, 1969). Both levels hold calcareous nannoplankton initially interpreted as a part of the NP20 biozone by Steurbaut (1986), and later on revised as the NP18 biozone (E. Steurbaut, pers. comm.), thus confirming the correlations of this level between the Assenede and Kallo wells (Figure 5).

Biostratigraphic results

Waterlandkerkje well (Figure 6)

Interval 21.65–23.50 m is dated Priabonian, Zone E8, based on the LODs of *Areosphaeridium dictyoplokum*, *Areosphaeridium michoudii*, *Cordosphaeridium funiculatum*, *Melitasphaeridium pseudorecurvatum* and the FOD of *Reticulatosphaera actinocoronata.*

Interval 24.50–36.85 m is interpreted as Bartonian, Zone E7, based on the LODs of *Rhombodinium porosum* and *Rottnestia borussica. Rhombodinium draco* has a FOD at 30.95 m.

Interval 39.50–65.30 m points to the Lutetian, zones E5–E6. The age is based on the LOD of *Petalodinium rhomboideum* (was *Rhombodinium rhomboideum*) at 39.50 m. Deeper in the succession *Areosphaeridium ebdonii*, *Diphyes pseudoficusoides* and *Phthanoperidinium regalis* have their LODs. Taxa with a FOD in the Lutetian are *Cordosphaeridium cantharellus*, *Corrudinium incompositum*, *Heteraulacacysta porosa* and *Glaphyrocysta semitecta*.

Biervliet well (Figure 7)

The assemblage of interval 33.50–60 m is interpreted as Late Eocene-earliest Oligocene, Priabonian-earliest Rupelian, Zone NSO1/E8, based on the LOD of *Areosphaeridium diktyoplokum.* The Priabonian is evidently reached at depth 34 m, based on the LODs of *Melitasphaeridium pseudorecurvatum* and *Areosphaeridium michoudii.* Furthermore, the FODs of *Reticulatosphaera actinocoronata* and *Thalassiphora reticulata* are recognised.

Interval 66.50–71.50 m is dated as Bartonian, Zone E7, based on the LODs of *Rhombodinium porosum*, and *Rottnestia borussica.*

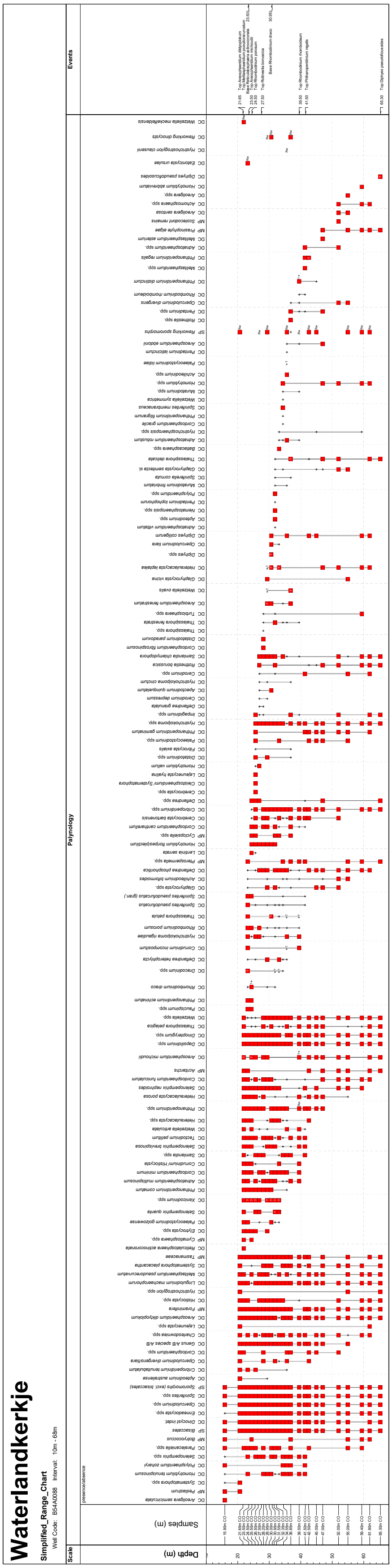

Figure 6. Palynological distribution chart of borehole Waterlandkerkje, interval 15.90-65.30 m. DC: Dinocysts; MP: Miscellaneous Palynomorphs; SP: Sporomorphs.

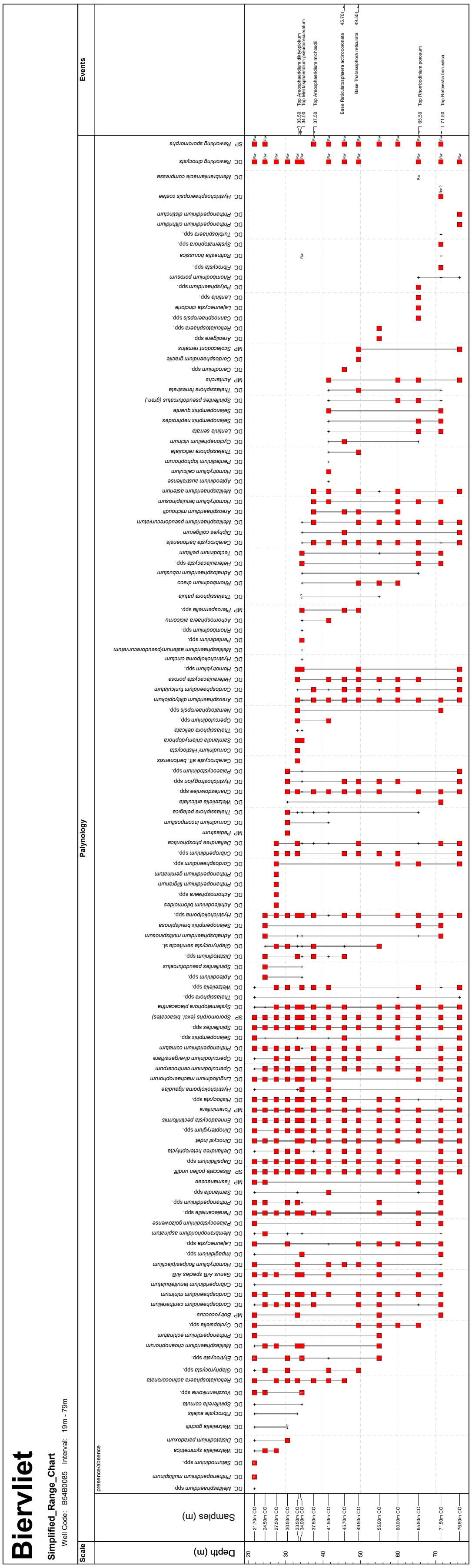

Figure 7. Palynological distribution chart of borehole Biervliet, interval 21.70-76.50 m. DC: Dinocysts; MP: Miscellaneous Palynomorphs; SP: Sporomorphs.

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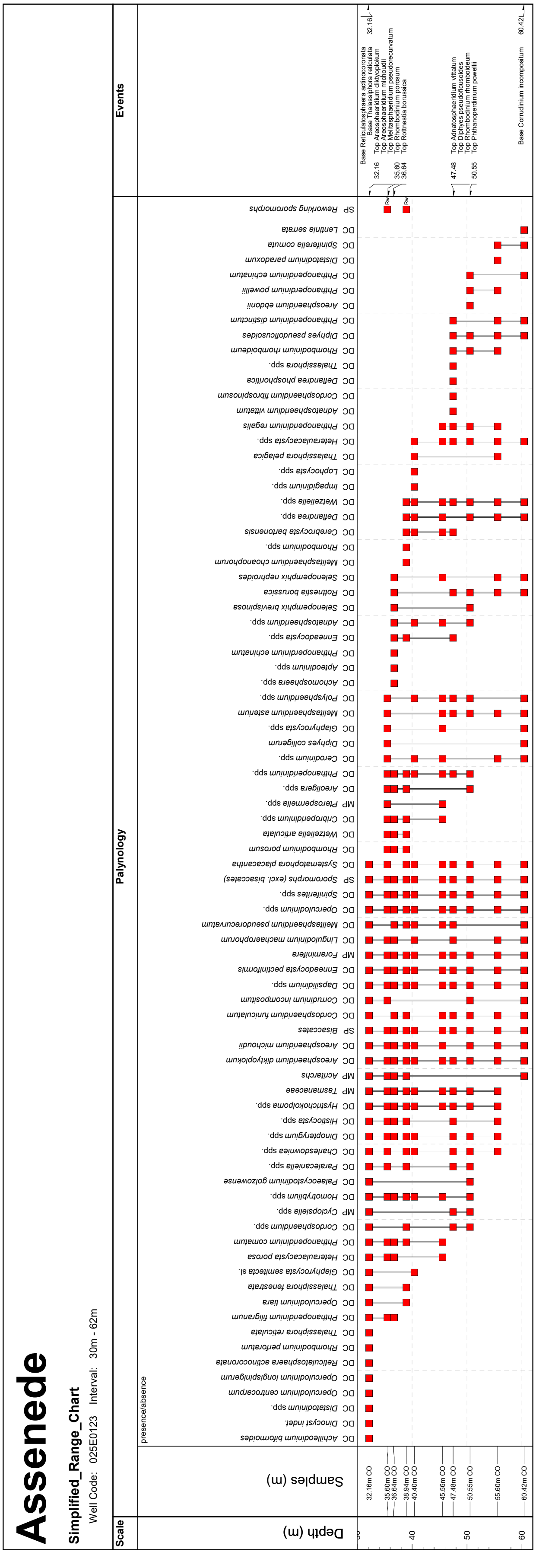

Figure 8. Palynological distribution chart of borehole Assenede, interval 32.16-60.42 m. DC: Dinocysts; MP: Miscellaneous Palynomorphs; SP: Sporomorphs.

Assenede well (Figure 8)

The uppermost sample at 32.16 m is dated as Priabonian, Zone E8, based on the LODs of *Areosphaeridium diktyoplokum, Melitasphaeridium pseudorecurvatum* and *Areosphaeridium michoudii.* The FODs of *Reticulatosphaera actinocoronata* and *Thalassiphora reticulata* are also noted.

Interval 35.6–45.56 m is interpreted as Bartonian, Zone E7, based on the LODs of *Rhombodinium porosum,* and *Rottnestia borussica.*

The age of interval 47.48–60.42 m is dated as Lutetian, zones E5–E6. The dating is based on the LODs of *Adnatosphaeridium vittatum, Diphyes pseudoficusoides, Phthanoperidinium powelli, Petalodinium rhomboideum. Corrudinium incompositum* has its FOD here.

Schapenbout well (Figure 9)

The age of interval 37.5–65.5 m is assessed as Late Eocene-earliest Oligocene, Priabonian-earliest Rupelian, Zone NSO1/E8, based on the LOD of *Areosphaeridium diktyoplokum.* At depth 45.5 m, the Priabonian is reliably interpreted based on the LOD of *Melitasphaeridium pseudorecurvatum.* In addition, the FOD of *Reticulatosphaera actinocoronata* is recorded.

At interval 70.5–75 m the Bartonian, Zone E7, is reached, based on the LODs of *Rhombodinium porosum* and *Rottnestia borussica.*

Axel-1 well (Figure 10)

Interval 48–79 m is interpreted as Zone NSO1/E8. The upper part of the interval 48–55 m is earliest Rupelian and at depth 56–57 m the Priabonian is reached. The former is based on the LOD of *Areosphaeridium dictyoplokum.* The latter is based on the LOD of *Melitasphaeridium pseudorecurvatum.* Furthermore, the FODs of *Reticulatosphaera actinocoronata* and *Rhombodinium perforatum* are recognised. The occurrences of *Thalassiphora fenestrata* and *Thalassiphora reticulata* fit with the chronostratigraphic interpretation.

Interval 80–91 m holds the Bartonian Zone E7 based on the LOD of *Rhombodinium porosum.*

For the interval 95–131 m, the Lutetian, Zones E5–E6 are interpreted based on the LOD of *Phthanoperidinium powellii.* Other chronostratigraphic important taxa with a LOD in the Lutetian are: *Areosphaeridium ebdonii, Diphyes pseudoficusoides, Glaphyrocysta vicina* and *Phthanoperidinium regalis.*

Axel-2 well (Figure 11)

Interval 26.50–51.51 m is interpreted as Zone NSO1/E8. The upper part of the interval 26.50–31.51 m is earliest Rupelian and at depth 36.5 m the Priabonian is reached. The top of the Zone NSO1/E8 is based on the LOD of *Areosphaeridium dictyoplokum.* This taxon has a latest occurrence in the earliest Rupelian. At depth 36.50–36.51 m the LOD of *Melitasphaeridium pseudorecurvatum* indicates that the Priabonian is reached. In addition the FODs of *Reticulatosphaera actinocoronata, Rhombodinium perforatum* and *Thalassiphora reticulata* are recorded here.

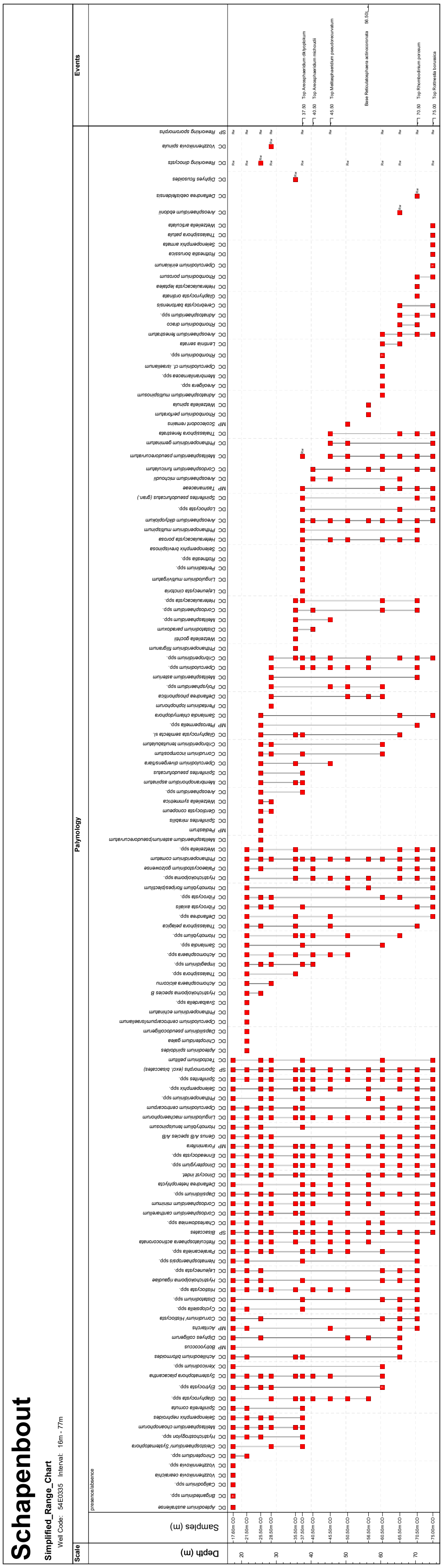

Figure 9. Palynological distribution chart of borehole Schapenbout, interval 17.60-75.00 m. DC: Dinocysts; MP: Miscellaneous Palynomorphs; SP: Sporomorphs.

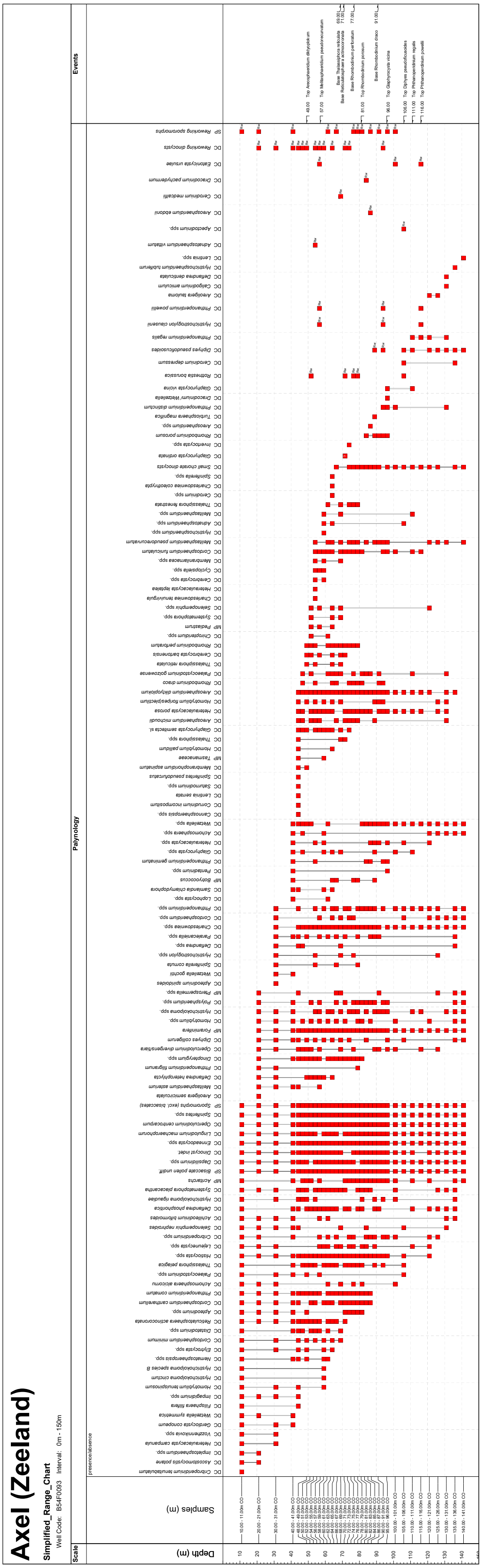

Figure 10. Palynological distribution chart of borehole Axel 1, interval 10.00-141.00 m. DC: Dinocysts; MP: Miscellaneous Palynomorphs; SP: Sporomorphs.

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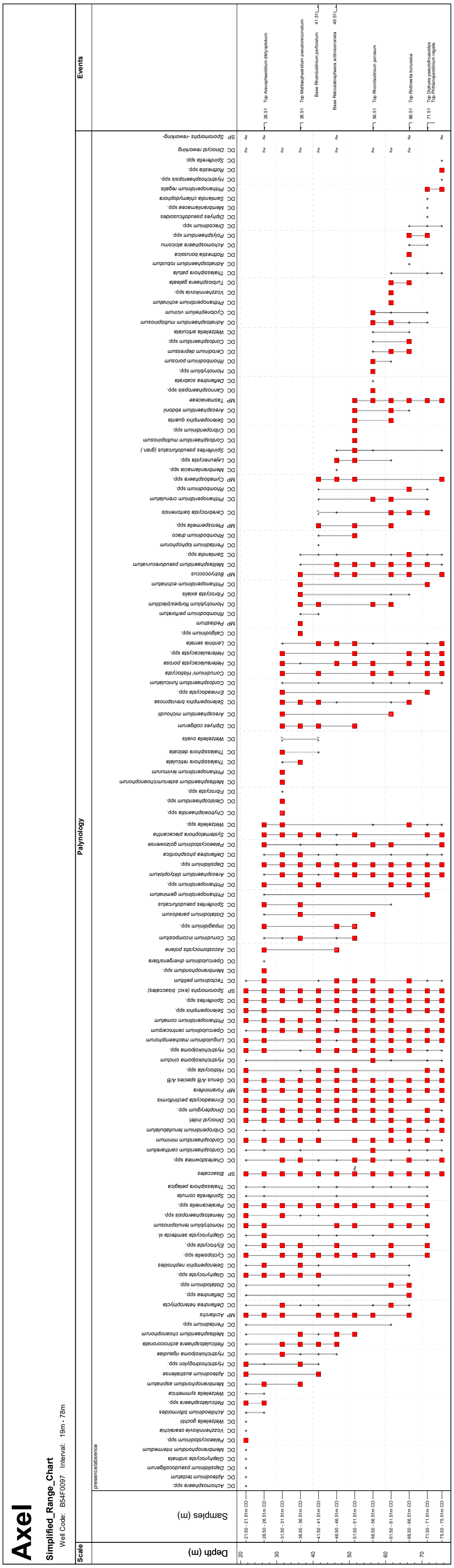

Figure 11. Palynological distribution chart of borehole Axel 2, interval 21.50-75.51 m. DC: Dinocysts; MP: Miscellaneous Palynomorphs; SP: Sporomorphs.

Interval 56.5–66.51 holds the Bartonian Zone E7. The dating is based on the LODs of *Rhombodinium porosum* and *Rottnestia borussica*.

Interval 71.5–75.51 m is dated as Lutetian, zones E5–E6. The dating is based on the LODs of *Diphyes pseudoficusoides*, and *Phthanoperidinium regalis*.

Koewacht well (*Figure 12*)

Interval 25.50–50.50 m is dated as Late Eocene-earliest Oligocene, Priabonian-earliest Rupelian, Zone NSO1-Zone E8. The interpretation is based on the LOD of *Areosphaeridium dictyoplokum*. The Priabonian is reached at 30.40 m, based on the LODs of *Melitasphaeridium pseudorecurvatum* and *Areosphaeridium michoudii*. Within the Priabonian, several taxa have a FOD, like *Reticulatosphaera actinocoronata*, and *Rhombodinium perforatum*.

The Bartonian, Zone E7, is dated for interval 54.50–59.50 m, based on the LOD of *Rhombodinium porosum.*

Biostratigraphic re-interpretation of well Kallo

The analysis of 16 cores samples from interval 91–187 m by De Coninck (1995) was re-interpreted. The Priabonian dating of the association from sample depth 115 m is confirmed and corresponds to NSO1/E8 Zone. The assessment of the zone is based on the LOD of *Areosphaeridium dictyoplokum* and the FOD of *Rhombodinium perforatum*.

One sample higher than earlier interpreted by De Coninck (1995), that is at depth 124 m instead of 126.5 m, the Bartonian, Zone E7, is already reached by the recording of the LOD of *Rhombodinium porosum* and the FOD of *Membranophoridium aspinatum*. Based on superposition, the entire interval of 124–135.5 m belongs to Zone E7. *Petalodinium rhomboideum* has its LOD in the Lutetian and is here at depth 124 m. The calcareous nannoplankton association of the Kallo well at 124–125 m depth, studied by Martini (1969), was however, interpreted as Priabonian NP19/NP20 biozone by Cavelier (1979), so much younger than Lutetian. Martini (1969) reported reworked species of the upper Eocene in this interval. We consider it therefore likely that also the record of *Petalodinium rhomboideum* by De Coninck (1995) was the result of reworking of this upper Eocene dinocyst species. Indeed, the taxon is absent in the associations of the two samples below, confirming the interpretation of reworking by an isolated, not continuous, occurrence.

Deeper however, at 143 m, the occurrence of the LOD of *Petalodinium rhomboideum* is considered as in-situ present. Hence the interpretation of the top of the Lutetian, Zone E6 or older, in this study is shifted three samples upwards from depth 169 to 143 m. The FODs of *Cordosphaeridium cantharellus* (174.5 m), *Corrudinium incompositum* (174.5 m), *Glaphyrocysta semitecta* (165 m), and *Heteraulacacysta porosa* (169 m) fit within the Lutetian age.

Discussion

Age assessment of stratigraphic units and sequence stratigraphic framework

Calcareous nannoplankton analyses have shown that the Wemmel and Asse members correspond to the NP15 biozone

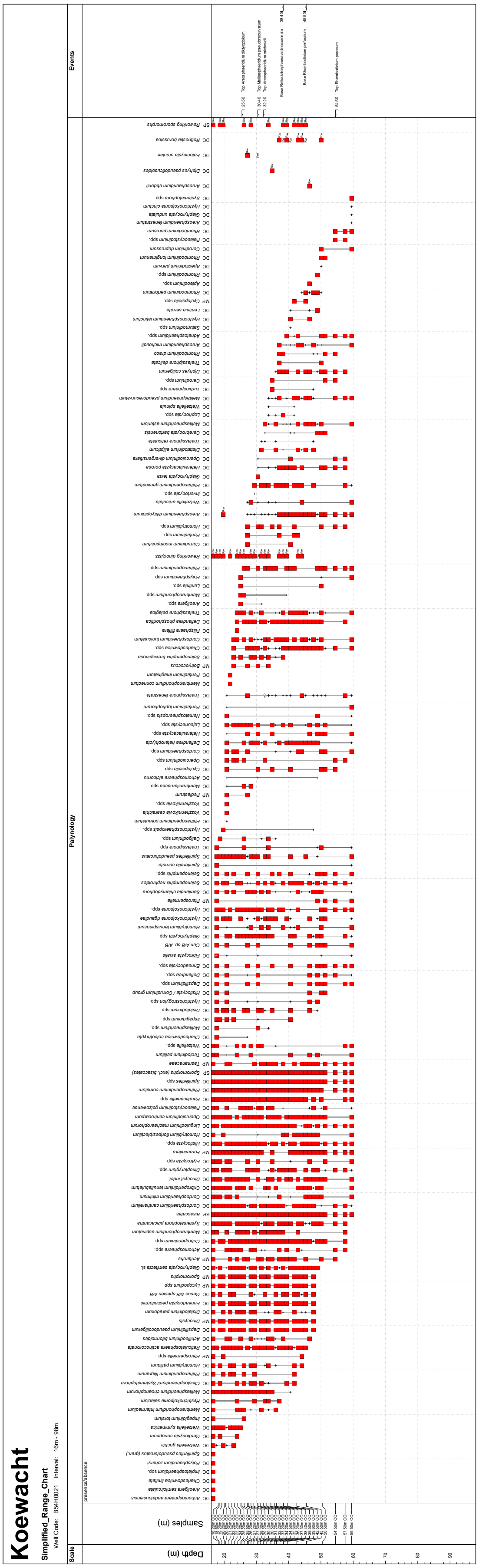

Figure 12. Palynological distribution chart of borehole Koewacht, interval 18.20-59.50 m. DC: Dinocysts; MP: Miscellaneous Palynomorphs; SP: Sporomorphs.

while the Ursel and Onderdale members hold the NP16 biozone (Vandenberghe et al., 1998). The overlying Zomergem and Buisputten members of the Maldegem Formation do not contain useful calcareous nannoplankton and were therefore thus far of unknown age. Our palynological analyses of samples from the Waterlandkerkje, Assenede, Axel-1 and -2 wells and the re-analyses of the Kallo well now consistently show that the interval of the Zomergem Member up to the Buisputten Member holds the Lutetian E5–E6 biozones as suggested by Bujak and Mudge (1994) which correspond to the range of the upper NP15 to lower NP16 biozones. The previously established NP16 biozone for the Onderdale Member (see above), located underneath the Zomergem Member, therefore makes it evident that the interval of the Zomergem Member up to the Buisputten Member also corresponds to the upper Lutetian NP16 biozone. The sequence stratigraphic model by Vandenberghe et al. (2004) also estimated a Lutetian age for the Zomergem Member and lower half of the Buisputten Member (Buisputten 1), but they considered the upper part of the Buisputten Member (Buisputten 2) as Bartonian. The samples of the Axel-1 and Assenede wells in the upper part of the Buisputten Member (Buisputten 2) of this study, however, suggest a Lutetian age for the entire Buisputten Member.

The dinocyst species analyses of the eight wells here studied consistently show that the Onderdijke Member holds the Bartonian E7 biozone reported by Bujak and Mudge (1994). In other wells in the area, such as Doel-2b, Kallo and Woensdrecht, dinocyst species analyses support a Bartonian age for the top of the Onderdijke Member (De Coninck, 1995; Vandenberghe et al., 2003). We therefore situate the Lutetian-Bartonian boundary in the base of the Onderdijke Member. The wireline log signature shows that the Onderdijke Member is composed of two sequences (Figure 13). The high gamma-ray values and low resistivity values in the lower part represent the highstand system tract following the transgression of the Buisputte 2 sequence. The high gamma-ray and low resistivity values are upwards delimited by a spike in resistivity values and abrupt decrease in gamma ray values that mark a shallowing or the base of the second sequence of the Onderdijke Member (Figure 5). This sequence shows a fining upwards trend (decrease in resistivity and increase in gamma-ray values) towards the top of the Onderdijke Member. The contact with the sandy Bassevelde Member represents a sharp boundary that is interpreted as a sequence boundary (Figure 13).

All eight wells examined in this study show a consistent presence of Tasmanaceae in the heavy clays of the Onderdijke Member as well as in the subjacent members of the Maldegem Formation. Tasmanaceae are Prasinophyte algae, a class of unicellular green algae in the division of *Chlorophyta*. The development of a marine embayment, the supply of clastic material and freshwater (surface-water stratification), and specific ecological conditions in the water column (light intensity, nutrient supply and temperature) are expected to favour the growth and accumulation of Tasmanaceae. High abundances of *Tasmanites* occur when reactive nitrogen and phosphorous become freely available in the photic zone (Van de Schootbrugge et al., 2007, 2013). High concentrations indicate stagnation of ventilation, and an- or dysoxic (marginal) marine conditions. These depositional setting could possibly be related to the closing of the marine gateway

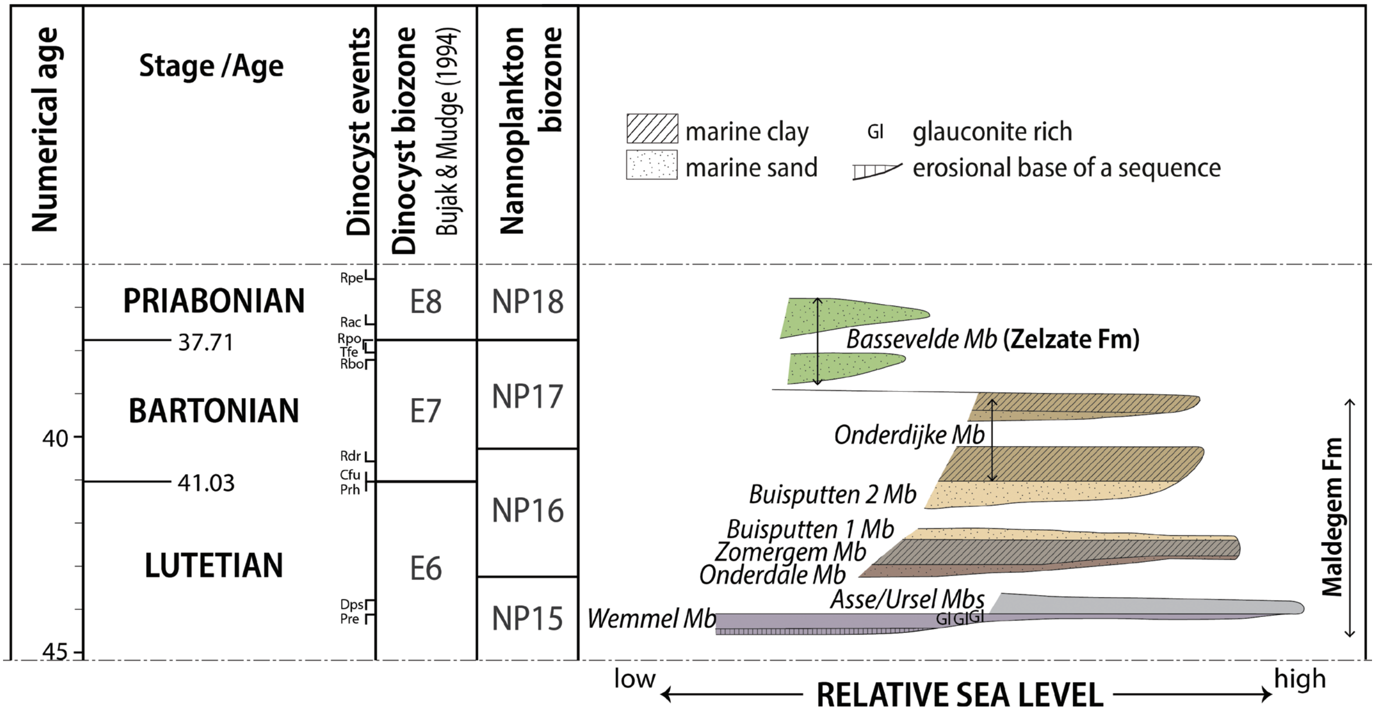

Figure 13. Updated figure on the Middle to Upper Eocene sediment sequences and their relative sea level based on the results of this study. In addition the stratigraphic position of key dinoflagellate cyst events and the biozonation (Bujak & Mudge (1994) used in this study is shown. Compare with Figure 3 of this study. Modified after Vandenberghe et al. (2004) and Deckers et al. (2016). Abbreviations used are: Rpe (*Rhombodinium perforatum*), Rac (*Reticulatosphaera actinocoronata*), Rpo (*Rhombodinium porosum*), Tfe (*Thalassiphora fenestrata*), Rbo (*Rottnestia borussica*), Rdr (*Rhombodinium draco*), Cfu (*Cordosphaeridium funiculatum*), Prh *Petalodinium rhomboideum* (was *Rhombodinium rhomboideum*), Dps (*Diphyes pseudoficusoides*), Pre (*Phthanoperidinium regalis*).

connecting the northeast Atlantic to the North Sea by the late Lutetian through uplift of the Isthmus of Weald-Artois (see Brachert et al., 2022; Figure 1).

The basal few metres of the Zelzate Formation show upwards decreasing gamma-ray and increasing resistivity values, indicative of coarsening upwards. After reaching a gamma-ray low, values increase back upwards again, which is indicative for fining upwards. The dinocyst species analysis of the seven wells of this study shows a Bartonian E7 biozone for the coarsening upwards sequence, while the younger fining upwards sequence corresponds to the Priabonian E8 biozone. The results of this study thereby for the first time indicate that the Bartonian/Priabonian boundary is located in the basal part of the Zelzate Formation, and therefore that the lowermost part of the Zelzate Formation is still Bartonian. Vandenberghe et al. (2003) also found Bartonian dinocysts in the basal part of the Zelzate Formation in the Doel-2b well but considered them as reworked. Reworking of Bartonian dinocysts (like *Rhombodinium porosum*) is indeed evident at the level of 168.75 m of the Doel-2b well since *Reticulatosphaera actinocoronata* (FOD in Priabonian) is also present there. Below this level, however, Priabonian marker species are absent and the Bartonian could be considered in situ for the basal part of the Zelzate Formation, similar to the result of this study. In the Assenede well, the lowest gamma-ray level or maximum coarsening consists of a nummulite-rich interval, which was first interpreted as NP20 by Steurbaut (1986), but later revised as NP18 (E. Steurbaut, pers. comm.). Also based on the reported dinocysts of the Doel-2b and Kallo wells by De Coninck (1995) and Vandenberghe et al. (2003), the Bartonian/Priabonian boundary is situated at the nummulite level corresponding to the NP18 biozone.

Approximately at the boundary between the Onderdijke and Bassevelde members, in wells Waterlandkerkje (27.5 m: 12% of the total dinocyst sum), Assenede (36.64 m: 19%), Schapenbout (75 m: 13%), Axel-1 (84–85 m: 32%) and Koewacht (57.5 m: 21%) the number of genus *Homotryblium* reaches a peak, which indicates an increase in restricted-marine influence. This signal fits with the high S/B ratio of continental spores/bisaccate pollen at this level. In marine environments, the average deposition of spores shows a relatively proximal position (nearshore deposition) as compared to bisaccates which are recorded in more distal depositions to the coast. Bisaccate pollen have a high buoyancy in both air and water and may be transported over larger distances than spores. The palynological indication for restricted marine conditions around the boundary between the Onderdijke and Bassevelde members seems to fit with the environment of peaty layers in the top of the Onderdijke Member as noted for the Kallo well by Gulinck (1969).

The Bartonian/Priabonian boundary (biozone E7/E8) is situated near low values on the gamma-ray logs (Figure 5). The increase in gamma-ray values in the basal Priabonian is indicative of a development towards sea-level rise. The Tasmanaceae disappeared from the palynospectrum. In agreement with this sea-level rise is the change in the S/B ratio, showing an increase in relative numbers of (bisaccate pollen have a higher buoyancy, hence showing a more distal position from the coast), while the percentages spores decrease within the sporomorph category.

An increase in reworking is recorded in all wells at the basal part of the Bassevelde Member. Most of these reworked dinoflagellate cysts have an origin in the (early) Middle Eocene. Redeposition from the Dongen (Brussels Sand) and Maldegem formations seems to have occurred. This reworking may be triggered by the Pyrenean tectonic phase that affected basins around the study area during the Priabonian (Vandenberghe et al., 2004; Deckers et al., 2016, 2024). The latter authors noted similar reworking in the Priabonian in wells Putte and Zegge northeast of the study area.

Dinoflagellate cyst zonation for the North Sea Basin

Following the North Sea Dinocyst zonation of Bujak and Mudge (1994) for the mid Lutetian-Priabonian, zones E5–E8, in this study, most relevant dinocyst events recorded were verified in the Belgium-Dutch border area. The top occurrence (LOD) of *Heteraulacacysta porosa* at the top of the Bartonian (Zone E7b) however, does not remain standing, because the present taxon shows a younger Priabonian age (top Zone E8b) in all wells. Furthermore the LOD of *Phthanoperidium distinctum* was given in the Lutetian, Zone E6b (Bujak & Mudge, 1994). This taxon was however already recorded in the Bartonian, mid Zone E7b by Heilmann-Clausen and Van Simaeys (2005) in the central Danish Basin. Iakovleva (2024) confirms a top occurrence for this taxon in NE Italy in the Bartonian, Zone NP16, mid-Chron C18n.1n. Our study also shows a younger LOD in the Bartonian. Not mentioned by Bujak and Mudge (1994) is the LOD of *Melitasphaeridium pseudorecurvatum*. This taxon has a consistent youngest occurrence in the Priabonian, Zone NP19-20 (Heilmann-Clausen & Van Simaeys, 2005; Vandenberghe et al., 2003, and this study).

Unfortunately Bujak & Mudge (1994) take into account only last occurrences (extinctions) of taxa. Several consistent first occurrences are however known from the North Sea Basin literature (e.g. compilation in Speijer et al., 2020) and confirmed by this study. A useful selection of consistent base occurrences of taxa in the Priabonian are: *Thalassiphora reticulata* (c. 34.9 Ma), *Rhombodinium perforatum* (c. 36.3 Ma), and *Reticulatosphaera actinocoronata* (c. 37.4 Ma). Although several authors (e.g. Powell, 1992, Speijer et al., 2020) show a first occurrence for *Thalassiphora fenestrata* in the Priabonian, the taxon may already be present in the late Bartonian (c. 38 Ma; Heilmann-Clausen & Van Simaeys, 2005, Iakovleva, 2024, and this study). A very consistent first occurrence of *Rhombodinium draco* is recorded in the Bartonian (c. 40.5 Ma; Powell, 1992, Speijer et al., 2020, and this study).

Conclusions

The sandy and clayey members of the Belgian Maldegem Formation can be correlated from the stratotype Adegem well in northern Belgium towards wells in Zeeuws-Vlaanderen in the southern Netherlands. The members of the Maldegem Formation are formally not distinguished in the Dutch Stratigraphic Nomenclature, but all grouped into the Asse Member of the Dongen Formation (https://www.dinoloket.nl/stratigrafische-nomenclator). Correlating the members of the Maldegem Formation to the southern part of the Netherlands has, however, shown to strongly increase the stratigraphic resolution and understanding of successions in the Dutch wells. Hence in this study we propose to include the different members of the Maldegem Formation also as separate units in the Dutch Stratigraphic Nomenclature (for application in the southwestern Netherlands).

The palynological analysis of samples from the upper Maldegem Formation and lowermost Zelzate Formation in the wells in northwestern Belgium and the southwestern Netherlands has provided new insights into age assessment and sequences of the stratigraphic units. It shows that the Lutetian/Bartonian boundary corresponds to the boundary between the Buisputten and Onderdijke members of the Maldegem Formation. The Onderdijke Member is completely of Bartonian age. An intra-Bartonian sea-level fall is indicated by the presence of marginal-marine palynomorph assemblages at the top of the Onderdijke Member, where also peat layers have previously been noted. The Maldegem Formation shows the consistent presence of Tasmanaceae, indicative of stagnation of ventilation, and an- or dysoxic (marginal) marine conditions. Such depositional conditions could be related to the closing of the marine gateway connecting the northeast Atlantic to the North Sea.

The lowermost few metres of the Zelzate Formation continue to comprise Bartonian dinocyst species, which had been previously considered as reworked, but are now considered in situ. While former studies positioned the Bartonian/Priabonian boundary at the contact between the Maldegem and Zelzate Formation, this study shows it to be located higher, within the basal part of the Bassevelde Member of the Zelzate Formation. The base of the Priabonian corresponds to a nummulite level holding the calcareous nannoplankton NP18 biozone. The Priabonian marks the start of the new sea-level rise as indicated by an increase in gamma-ray values and a change in palynomorph assemblages.

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