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A proposal for an updated and revised stratigraphical framework of the Miocene in the Achterhoek (eastern Netherlands)

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Abstract

The comprehensive overview of Neogene lithostratigraphy in the eastern Netherlands dates back to the mid-1970s. In the present study, continuous gamma-ray logs and *in situ* sediment core samples from six boreholes in the area allowed palynological and mollusc analyses and wireline log-based correlation. These investigations were aimed at updating and revising the existing Neogene lithostratigraphy within the Stratigraphic Nomenclature of the Netherlands by integrating litho-, bio-, and sequence-stratigraphic approaches. The analytical results yielded the establishment of new holo- and lectostratotype sections, together with cross-border interregional correlation. The lithostratigraphic revision resulted in the modified definition of the Aalten, Eibergen and Delden members and the definition of two new proposed members: the Dale and Doetinchem members. The Ticheloven bed, removed in earlier studies, is proposed to be reinstated, and the Stemerdink Bed is upgraded in its hierarchical status to the Stemerdink member. All lithostratigraphic units are included in the present Miocene subdivision of the Groote Heide and Diessen formations, which include three recognisable unconformities: the Early-Miocene Unconformity (EMU), Mid-Miocene Unconformity (MMU) and Late-Miocene Unconformity (LMU). The new, revised, reintroduced and existing local lithostratigraphic units and sequences are discussed with their counterparts in the south and southeast of the Netherlands, in Germany and Belgium, and from this a regionally consistent framework has emerged of the regional Neogene lithostratigraphy.

Introduction

The stratigraphic insights into the Neogene successions of the southern Netherlands (the Brabant and Limburg provinces) have been further developed in recent years following several H3O (Deckers et al., 2014; Vernes et al., 2018; Vernes et al., 2023) and related internal TNO projects. These projects are led by TNO – Geological Survey of the Netherlands in cooperation with institutions of neighbouring countries, the Flemish Institute for Technical Research (VITO, Belgium), the Royal Institute of Natural Sciences (RINS, Belgium) and the Federal Institute for Geosciences and Natural Resources (BGR, Germany). These projects are designed to establish cross-border harmonisation of hydrological/geological units, through mapping and the construction of hydrogeological models. The results of these studies have led to significant improvement in the development and correlation of Cenozoic successions. In these studies, a new semi sequence-stratigraphic approach was applied, integrating several disciplines, including lithological description, log correlation, biostratigraphic and seismic survey. This has resulted in an update and revision of definitions of lithostratigraphic units (individual description of lithostratigraphic units are the official building blocks of the Stratigraphic Nomenclature that the Dutch Geological Survey publishes in the Dinoloket.nl website). For example, the Miocene Breda Formation has been upgraded to the Breda Subgroup and split into the new Groote Heide and Diessen formations (Munsterman et al., 2019). The newly identified lithostratigraphic units are also based on regional discontinuities such as the Early-, Mid- and Late-Miocene Unconformities (EMU, MMU and LMU). Persistent problems with lithostratigraphic transitions (Veldhoven/Breda and Breda/Oosterhout) in the southern Netherlands and with correlations of these units and lateral equivalents in neighbouring countries were thus overcome for the southern part of Netherlands. A regionally consistent framework has emerged.

Problem statement

In the southern part of the Netherlands, the Geological Survey of the Netherlands has defined an accurate lithostratigraphic framework for the Paleogene–Neogene successions (Stratigraphic

Commission, resolution 12-03-2024). This contrasts with the eastern Netherlands where such a framework is lacking, and which relies upon the chronostratigraphic 'floating' classification of local lithostratigraphic units by Van den Bosch et al. (1975). The Breda Formation (Miocene) was locally distinguished by four different members in the Achterhoek (Table 1). Here, the holostratotype sections were based on poor-quality borehole techniques, whereas samples of the type locality are only partially available.

The holostratotype borehole sections were drilled (by co-author Maarten van den Bosch) using poorly executed straight-flush drillings, including a small diameter drill. This method is limited by a lack accurate depth control and, hence, important lithological details are not available. Over the past 40 years, advances in understanding and experience have brought improved drilling techniques that increase sample resolution (Van den Bosch, 2015), which allow a revision of the original lithostratigraphic scheme.

The way forward

In the present study, the geological interpretation of Miocene strata in the eastern region is improved, following the example of the methodology used in the southern Netherlands. Previous palynological analyses on the proposed borehole sections are expanded. These results are correlated on the basis of sediment log characteristics, via type-section boreholes, to the updated and revised lithostratigraphic framework in the southern part of the country (i.e. the Venlo and Roer Valley grabens) so that they align with the current sequence stratigraphic framework for the region. The local lithostratigraphy in the Achterhoek district has been updated and revised where necessary. The current study provides new lectostratotype sections in boreholes in the Gaanderen (B40F1874) and De Haart (B41G0024) boreholes in regard to the existing Miocene Zenderen Member (Fig. 1). New (Dale member and Doetinchem member), amended (Aalten, Stemerdink, Eibergen and Delden members) and reintroduced (Ticheloven bed) lithostratigraphic units are described here (see also Addendum, below). From the perspective of stratigraphic coherence, this development is not only necessary but also a logical intermediate step towards a northwards correlation of successions into the offshore subsurface of the Netherlands' North Sea sector.

Study area and methods

Study area

The Achterhoek (in the Low-Saxon language 'Achterhook' is a remote area) is a region in the province of Gelderland in the eastern part of the country. This region is also called 'De Graafschap' (in English: 'County'), after the old county of Zutphen, which in the broadest sense covers an area bordered by the regions of Salland and Twente (in Overijssel province) in the north, to the German border in the east and southeast, and the river IJssel in the southwest (Fig. 1).

The geology and stratigraphy, in particular from the Mesozoic, of the Achterhoek has been described in detail by Waterschoot van der Gracht (1918), Gerth (1955), Pannekoek (1956), Harsveldt (1963), Stapert (1974), Herngreen & de Boer (1974), Van den Bosch (1994; 1996; 1999; 2022), Van den Bosch et al. (1975), Van Adrichem Boogaert and Kouwe (1993-1997), Herngreen et al. (1983; 1994; 2000), Janssen (1984), Peletier & Kolstee (1986), Geluk (1998), Van den Berg et al. (2000), Van den Bosch & Kleijer (2003) and Van den Bosch & Brouwer (2009), among others. The Neogene strata of the Achterhoek have yielded exceptionally rich and internationally important vertebrate and invertebrate faunal assemblages that have been subject of extensive studies (e.g. Janssen, 1984; Bor et al., 2012; Schwarzhans, 2010). They have also provided important insights into regional ecosystem and biotic development during the Miocene.

Table 1. Holostratotype sections of Miocene members in the Achterhoek (Van den Bosch et al., 1975).

Member	Borehole	Co-ordinates (X, Y in RD)	Interval (m below surface)
Aalten	B41E0211	240935, 437975	8–20.80
Eibergen	B34G1371	243100, 451360	0–8.50
Zenderen	B28G0172	245520, 481740	16.50–23.46
Delden	B28G0201	244610, 478790	1.40–7.50

Figure 2 shows an overview of the important structural units, fault zones and salt structures in the geological development of the eastern part of the Netherlands. During the Paleogene and Neogene, the Achterhoek area was part of a marine, southern North Sea basin. The contours of this basin during the Langhian Stage (Middle Miocene Subseries) are reflected in the palaeogeographic map (Fig. 3). The cumulation of several Mesozoic tectonic phases provoked a predominantly directed NW-SE structural trend in the area (Geluk, 1998). Here, the Paleogene and Neogene were marked by the most pronounced subsidence in the western part of the area. Starting in the latest Neogene, uplift in the east of the district (Achterhoek High) resulted in erosion of the Paleogene and Neogene deposits. This uplift continues today. Consequently, the Neogene strata are now located in the shallow subsurface in the east at Miste and dip towards larger depths (Fig. 1).

Borehole and gamma-ray log data

To establish holo- and additional lectostratotype sections, boreholes encountering high-quality *in situ* sediment were selected, based on the analyses including continuous (gamma-ray) wireline logs, in order to enable interregional correlations. The boreholes currently examined from the Achterhoek and the Miocene reference drill holes on the Venlo and Campine Blocks are listed in Table 2.

For all boreholes, standardised lithological descriptions (SBB5.1, Bosch, 2000 and NEN 5104, Munsterman & Van den Bosch, 2021) and gamma-ray logs are available from the NLOG (https://www.nlog.nl/welkom-bij-nlog) or DINO booth (https://www.dinoloket.nl/) portals.

Palynological analysis

Samples from the borings studied were selected for palynological analysis. In air-lift drilling operations samples were taken every 1 to 3 m intervals. Recently however, using novel drilling technique, a maximum sample resolution of four samples per metre could even be reached (Van den Bosch, 2015).

In order to support the correlation of lithology- and gamma-ray logs, organic-walled dinoflagellate cysts (dinocysts) analysis (Fensome & Munsterman, 2020) was undertaken. This type of analysis has led to significant improvements in age-dating of Neogene successions in NW Europe and beyond, and in understanding their palaeoenvironmental setting (e.g. Powell, 1986, 1992; Head et al., 1989; Zevenboom, 1995; De Verteuil and Norris, 1996; Dybkjaer & Rasmussen, 2000; Louwye, 2002; Louwye

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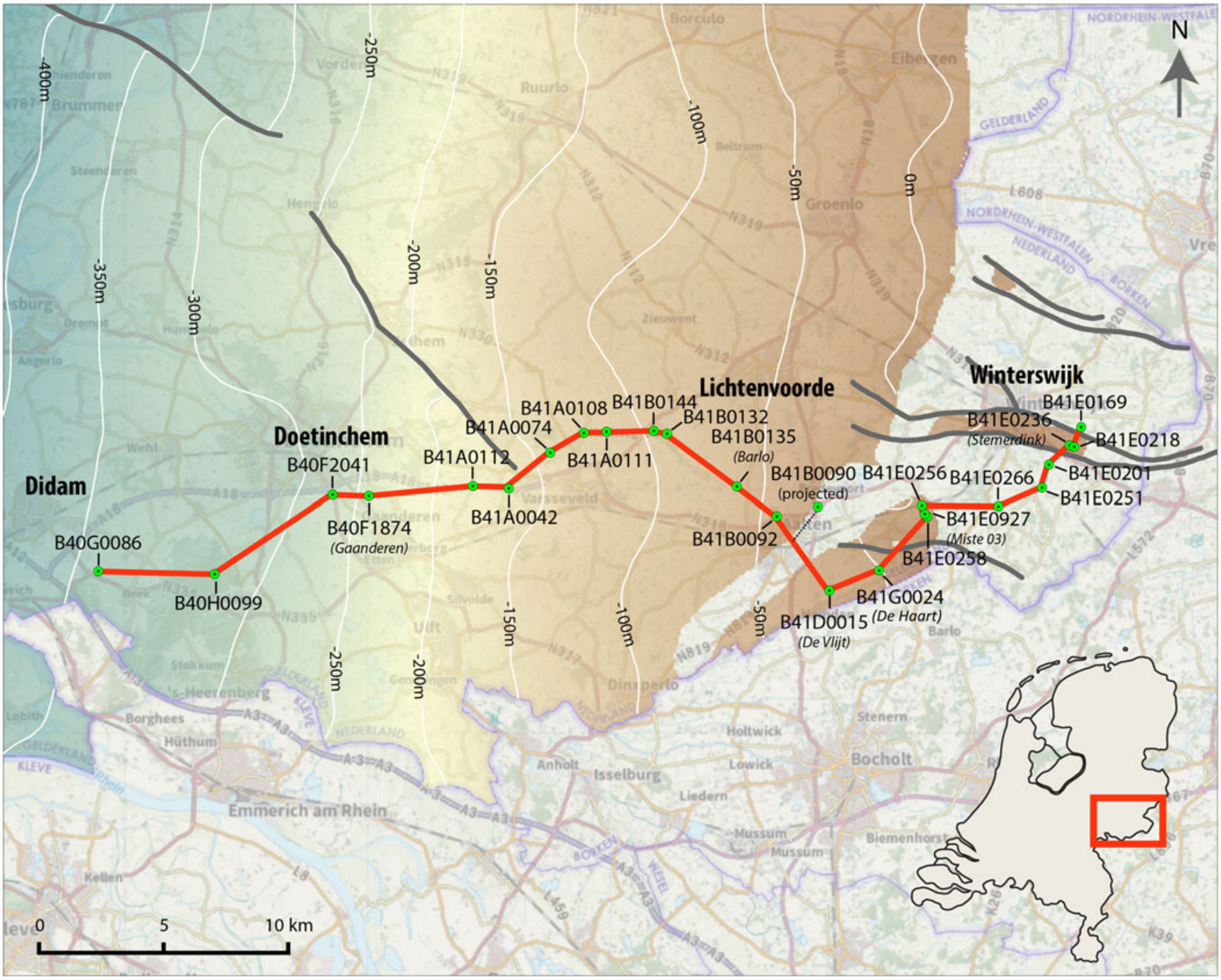

Figure 1. Location map of the eastern part of the Netherlands showing the E-W transect from Winterswijk to Didam including all boreholes and logs (www.dinoloket.nl). The transect is plotted on the Miocene base (DGM v2.2; TNO-GDN, 2023) with the transition from red to blue colors representing increase in depth. Fault lines are indicated in grey (DGM v2.2; TNO-GDN, 2023; supplemented with one fault line of Van den Bos & Brouwer, 2009 south of borehole B41E0258).

et al., 2004; Köthe, 2007; Köthe et al., 2008; Dybkjaer & Piasecki, 2010; Anthonissen, 2012; Quaijtaal et al., 2014; De Schepper et al., 2017; Dybkjaer et al., 2018; Deckers & Louwye, 2019; Everaert et al., 2020; Munsterman & Deckers, 2020). The potential of applying the results of dinoflagellate cyst analyses in biostratigraphic differentiation for Neogene intervals in the Netherlands has also been proven (e.g. Munsterman & Brinkhuis, 2004; Munsterman et al., 2019; Dearing Crampton Flood et al., 2020; Deckers & Munsterman, 2020; Munsterman & Deckers, 2022).

Standard palynological techniques, including HCL and HF digestion, no oxidation and 15 µm sieving, were used. The slides were mounted in glycerine jelly. The dinocyst taxonomy follows that cited in the Lentin and Williams Index 2019 (Fensome et al., 2019). A minimum of 200 palynomorphs (spores, pollen and dinoflagellate cysts) were counted on one microscope slide per sample. The remainder of the slides were scanned for rare taxa. Miscellaneous fossils (including *Pediastrum, Botryococcus*) were also counted, but they are excluded the total sum of 200 specimens.

The Miocene dinoflagellate cyst (dinocyst) zonation was based on Munsterman & Brinkhuis (2004), recalibrated to the Geological Time Scale of Ogg et al., 2016 (Munsterman et al., 2019). This zonation is based on consistent dinocyst events (mainly on last occurrence data points) from available peer-reviewed palynological contributions in NW Europe. It also includes the application of a global compilation calibrated to palaeomagnetic, calcareous plankton and/or foraminifera/bolboforma (De Verteuil and Norris, 1996; Van Leeuwen, 2000; Zevenboom, 1995 and references herein). The age assessments have been cross-validated by correlation to recognised sea-level fluctuations (Hardenbol et al., 1998; Munsterman & Brinkhuis, 2004). The zonation of Dybkjaer and Piasecki (2010) is more detailed for the Early Miocene, but that of Munsterman and Brinkhuis (2004) is more differentiated for the Middle to Late Miocene, most of the interval we are dealing with here. Furthermore the succession of dinocyst events during the Neogene slightly diverges in the Danish and southern Dutch part of the North Sea Basin due to major changes in facies caused by the progradation of the Eridanos delta. Therefore, we selected the recalibrated Dutch dinoflagellate cyst zonation of Munsterman and Brinkhuis (2004) in Munsterman et al. (2019) (Fig. 4).

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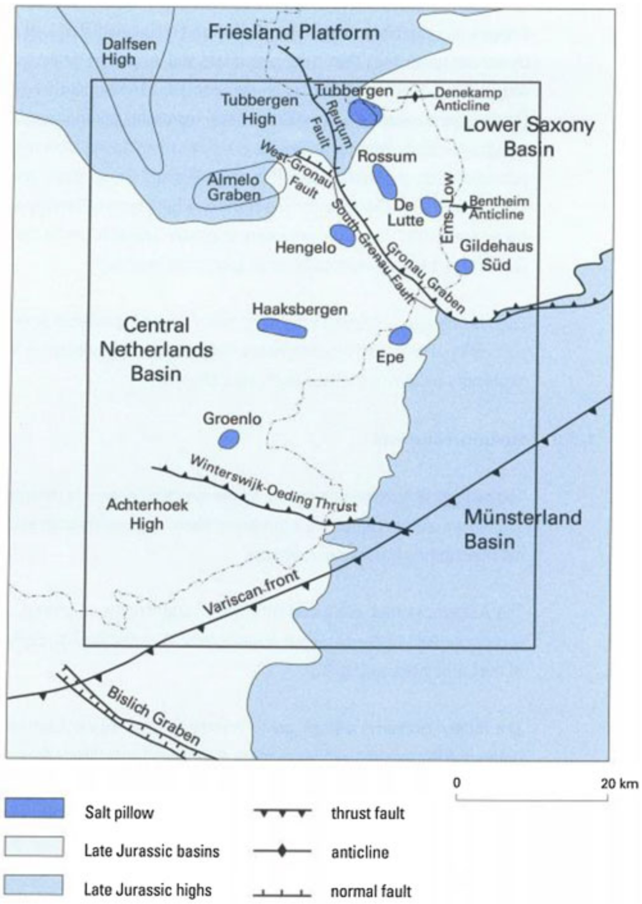

Figure 2. The main structural elements in the eastern part of the Netherlands (after Geluk, 1998).

Mollusc analyses

Molluscan study is included on the Aalten and at the base of the Stemerdink members. In order to be able to compare molluscan evidence from the new boreholes, the authors adopted the methods outlined in De Vogel (1970, 1971). Of the fraction over 1 mm up to 500 countable fragments were picked, identified and counted. A number of indicator species used in the works by De Vogel were also used in this study, with zone attribution following the most abundant occurrence of these species in the studied samples. The mollusc-based divisions are acme zones and have been already shown by De Vogel (op.cit.) to be slightly diachronous in some cases. Within the samples studied, the last occurrence date (LOD) of *Tritia facki* (von Koenen, 1872) provided a recurring biostratigraphic datum consistent with other bio- and lithostratigraphic indicators.

For the newly established De Haart borehole-type section (41G.1-94), half metre samples between 29.00 and 41.00 m depth below the ground surface were analysed. The new borehole is not the same as that reported in De Vogel (1970, 1971 (41E.3-67 interval 11.00–20.80 m below surface). Samples for intervals 36.00–36.50, 38.50–39.00 and 40.00–40.50 m were absent. All samples were washed, picked and identified following methods extensively discussed in De Vogel (1970). Twenty species used by that author to visualise faunal successions were counted. The nomenclature of these taxa was kindly updated with help from Mr. J. van der Voort (Ostercappeln, Germany). From the extensive dataset published by De Vogel (op.cit.), approximate numbers were calculated for the De Vlijt, Stemerdink and Miste boreholes to enable direct comparison. The three boreholes comprised sections that were used for earlier definition of chronostratigraphic units. The recalculation of percentages (provided to two decimal places), using the absolute total number of counted specimens provided by De Vogel (op.cit.), will introduce some very small rounding errors that are expected to be irrelevant in data analyses. The relative abundances of four species that were used in stratigraphic zonation were plotted to investigate visually the mollusc acme zones proposed by De Vogel (1971). The name of the *Spisula* acme zone (based on *Spisula* sp. in de Vogel, 1971) has here been adjusted to *Spisula* aff. *subtruncata* acme zone following identification in Janssen (1984).

Lithostratigraphy and Stratigraphic Nomenclature of the Netherlands

The first edition of the Dutch stratigraphic nomenclature dates from 1929. In 1959, the second edition was published principally because many new terms and geological insights had been introduced in the intervening period. The main language was changed to English, with a translation into Dutch, French and German. Royal Geological and Mining Society of the Netherlands (KNGMG) third edition, NAM & RGD (1980) was published over 20 years later. During the period 1993–1997, new chapter versions of Van Adrichem Boogaert & Kouwe were presented. On 8 June 2020, the revised Stratigraphic Nomenclature of the Netherlands was published online. This version integrated former 'shallow' and a 'deep' versions and is considered as the up-to-date source for stratigraphic information from the Dutch subsurface (https://www.dinoloket.nl/stratigrafische-nomenclator). The latter has served as a foundation of the present contribution. Basically, the rules for stratigraphic classification, defined in the International Stratigraphic Guide (Salvador, 1994), are followed. The strict distinction between lithostratigraphy and chronostratigraphy is maintained, although classification of various facies types without proper lithological markers is occasionally supported by biostratigraphical information and correlation.

Lithostratigraphic update and revision of the Miocene in the Achterhoek

The local lithostratigraphic units of the Achterhoek Miocene, following Van den Bosch et al. (1975), are retained as much as possible. The aim of this study is to link local Miocene-age units to the recently established lithostratigraphy of the online Stratigraphic Nomenclature of the Netherlands. A combined litho-, bio- and sequence-stratigraphic approach has been applied for the improved Neogene lithostratigraphy (Munsterman et al., 2019). This study will focus on necessary adjustments of local lithostratigraphic definitions to align the Groote Heide and Diessen formations, which are distinguished by three regional recognisable unconformities. The results of the adapted local lithostratigraphy in the Achterhoek are as follows:

1. The reintroduction of the Ticheloven bed.
2. The increase in hierarchical status of the Stemerdink Bed to Stemerdink member (amended Aalten Member).

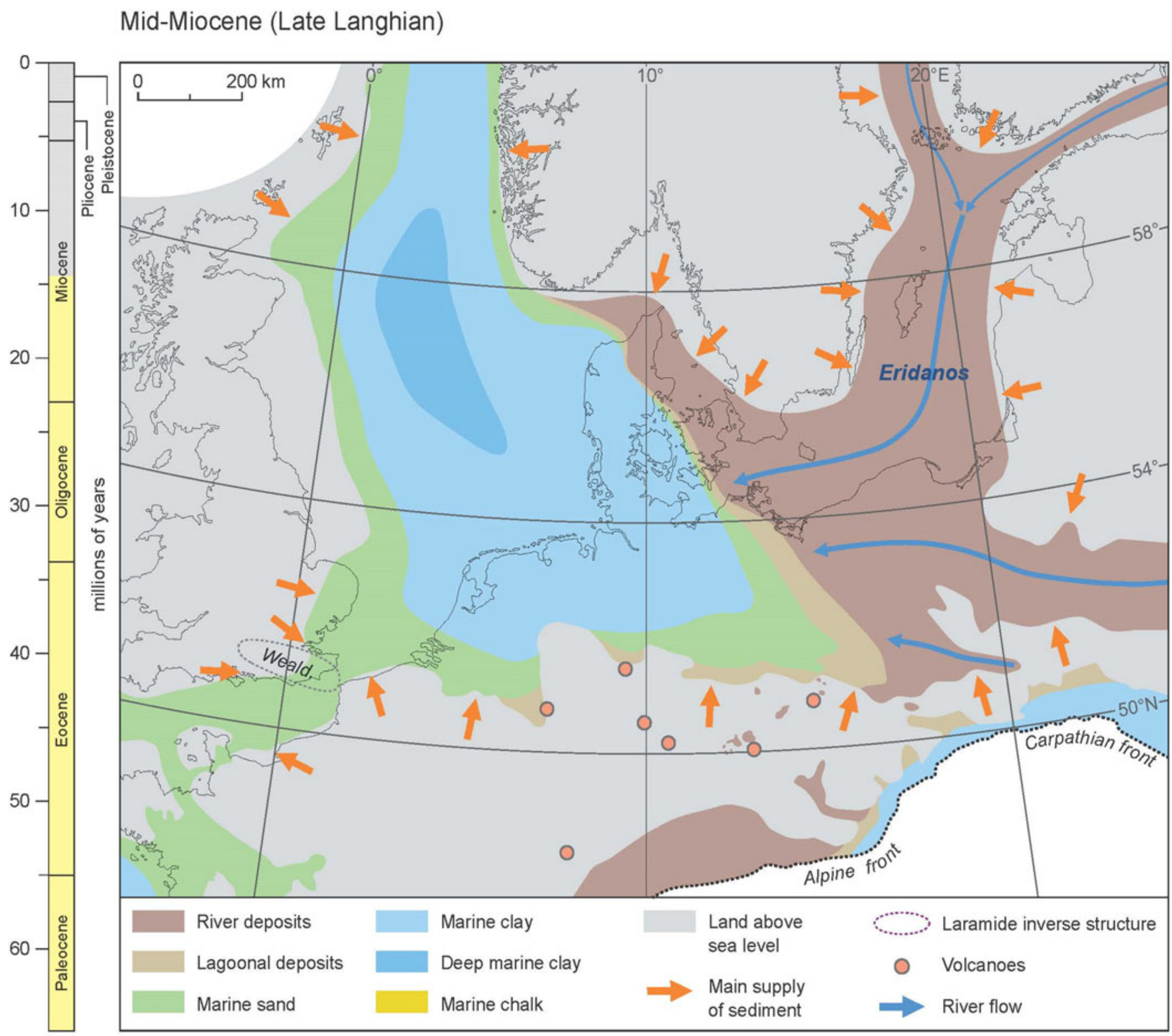

Figure 3. Palaeogeographic map of the mid-Miocene (after Gibbard & Lewin, 2016).

3. The definition of the amended Eibergen and Delden members, and the new Dale and Doetinchem members.
4. The selection of new lectostratotype sections with regard to the Aalten (amended, including beds), Stemerdink (amended), Eibergen (amended), Zenderen and Delden (amended) members in selected air-lift boreholes Gaanderen (B40F1874) and De Haart (B41G0024).

In order to provide a lithostratigraphic context for these amended and newly defined units and their stratotypes, a newly constructed E–W-oriented profile showing the stratigraphy of the Achterhoek between the cities of Doetinchem and Winterswijk is first presented.

Didam – Winterswijk cross section

An approximate east–west oriented cross section was constructed using 21 archived boreholes from the DINO database (Fig. 5). The borehole evidence was primarily collected using air-lift techniques. Fifteen boreholes included gamma ray (well-log) information. Three additional localities were selected that only contained well-log information (i.e. no registered borehole descriptions were available). In addition, lithological data of the Miste-03 exposure was translated into borehole format and depicted as such in the cross section. For all the boreholes, standardised lithological descriptions (SBB5.1, Bosch, 2000) and gamma-ray logs are available in the DINO portal (www.dinoloket.nl).

Table 2. Borehole meta-data information.

Name borehole/quarry	Borehole code	Structural setting	Type	Studied interval (m MD)
De Haart	B41G0024	Achterhoek High	Air-lift*	7–45
Gaanderen	B40F1874	Achterhoek High	Air-lift	21–185
Miste-03	B41E0927	Achterhoek High	Outcrop**	1–4 (below surface)
Barlo	B41B0135	Achterhoek High	Air-lift	29.25–54.25
Goirle	B50H0373	Campine Block	Air-lift	60–471
Groote Heide	B58F0064	Venlo Block	Air-lift	85–689

*Air-lift borehole: addition of air to the drilling fluid reduces the density of the drilling fluid in the drill pipe. Since the density of the drilling fluid is greater on the other side of the drill pipe (i.e. in the borehole), an upward flow is created in the drill pipe. Generally, the air-lifting borehole technology provides mixed samples with an accuracy for every 1 m. Nowadays, however, the sample resolution may be improved up to 0.25 m.
**Temporary: excavated in 2013.

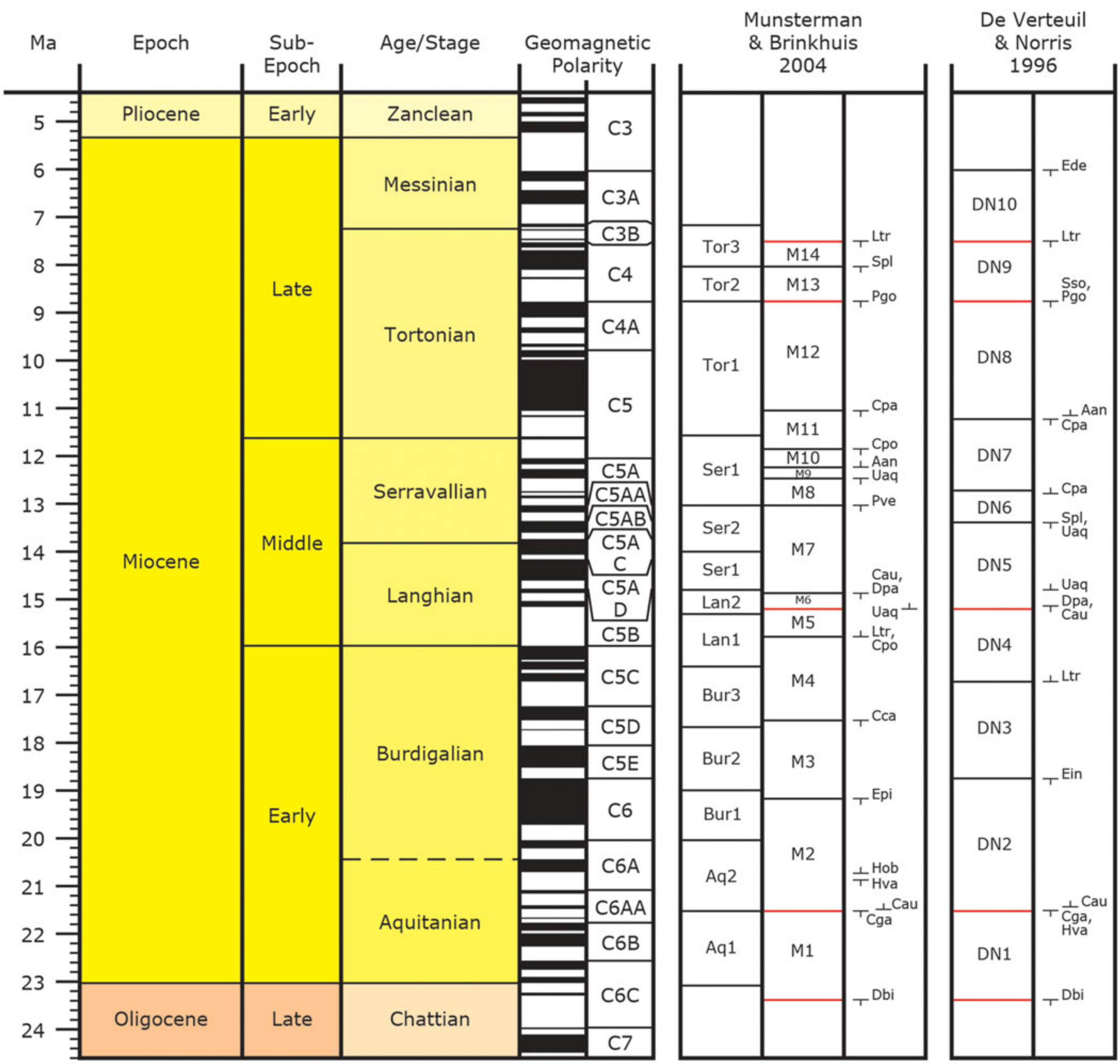

Figure 4. Dinoflagellate cyst zonation *sensu* Munsterman and Deckers (2020).

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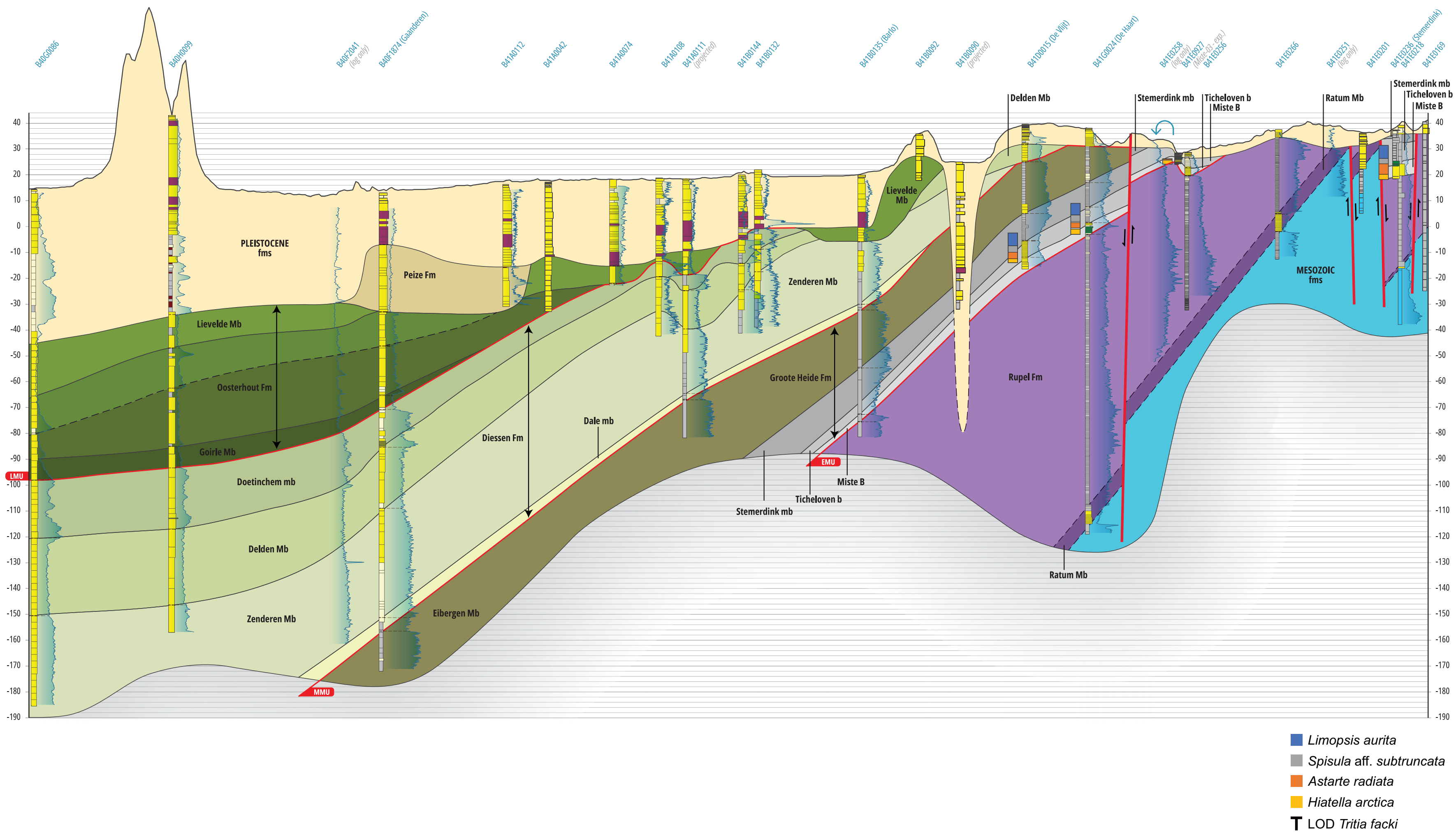

Figure 5. E-W orientated lithostratigraphic cross-section using 21 boreholes (see Figure 1 for position of the boreholes), including gamma-ray logs and molluscan zones, if available (see Table 3 for lithostratigraphic unit codes). Correlation lines follow the litho-logs (correlatable horizons with the gamma-ray log are linked by dotted lines to the right). For explanation of the colours of the columns showing the mollusc zones, located left of selected litho-logs (Aalten Member and base Stemerdink member), see legend in Figure 13.

The cross section was planned on basis of its perpendicular location to the North Sea Basin rim (Gibbard & Lewin, 2016; Lamb et al., 2017), allowing as much Miocene stratigraphic context as possible. The cross section begins immediately south-east of Didam and approximately follows the line Doetinchem, Varsseveld and Winterswijk. The position of main fault lines was taken from Van den Bosch & Brouwer (2009), although the tectonic setting, in particular in the east of the profile, is strongly generalised.

This cross section shows a gently dipping Miocene sequence of the Groote Heide and Diest formations (Fig. 5). In the area east of borehole B41D0015, also referred to as the Achterhoek platform, the Groote Heide Formation occurs at or near the surface. West of this borehole the top of the Miocene is positioned at greater depths resulting from a combination of subsidence and subsequent Quaternary glacial and fluvial erosion. The Miocene sequence overlies very stiff clays of the Rupel Formation and in the easternmost part of the cross section, Mesozoic carbonates and sandstones.

The base of the Groote Heide Formation is defined by the Aalten Member and overlies older sediments of the Rupel and locally Mesozoic formations. The base of the Aalten Member comprises a distinct mollusc-bearing, phosphorite and glauconitic clayey sand that fines westwards into sandy clay (Miste Bed). A peak in gamma-ray logs is shown above the base of the Aalten Member, at the level of the phosphorite level. The gamma-ray peak is explained as phosphorites containing radioactive elements. It is succeeded by a silty to sandy clay with a molluscan-rich basal part (Ticheloven bed). The Aalten Member is, in turn, overlain by clays with silt strata (Stemerdink member). The latter two clay units are characterised by an upward decrease and increase in gamma-ray values, respectively. The upper part of the Groote Heide Formation is composed of clays of the Eibergen Member which consists of stiff, mica-rich silty clays that give high gamma-ray readings.

The transition between the Groote Heide and Diessen formations is characterised by an erosion surface. While the clayey Eibergen Member is non-calcareous, and mostly organic rich, this boundary surface is overlain by calcareous, mica-rich, clayey silt and sandy clay, the latter being marked by relatively low gamma-ray values (Dale member). The Dale member is overlain by glauconitic, mostly calcareous loams and sandy loams (friable mixture of relatively moderate proportions of clay, silt and sand particles, containing organic matter) that grade upwards into fine to moderately silty fine sand (Zenderen Member) with generally higher gamma-ray readings. This member is overlain by fine sands of the Delden Member. The Delden Member is less rich in silt compared to underlying unit and shows lower gamma-ray values. The sands are overlain by the Doetinchem member which consists of a distinct basal concentration of molluscs and overlying alternation of sandy loam and silty clay layers.

Overlying the Diessen Formation is the Oosterhout Formation. The base of this formation comprises clean sands of the Goirle Member which give characteristically low in gamma-ray values. This Goirle Member only occurs in the western part of the transect, the unit giving way to an alternation of sands (with low gamma-ray values) and silt layers (Oosterhout Formation (undiff.). Medium-grained sands with distinctly low gamma-ray values and a locally highly erosional base, form the upper part of the Oosterhout Formation (Lievelde Member, formerly referred to as the Scheemda Formation).

Miste Bed and the reintroduction of the Ticheloven bed; Stemerdink Bed raised in hierarchical rank to the Stemerdink member and the amended Aalten Member

In Van den Bosch et al. (1975), the Ticheloven bed was replaced by the Miste Bed. The reason behind this substitution was, because the Ticheloven bed appeared to correlate with multiple lithostratigraphic units, including parts of the lower Stemerdink and the upper Miste beds (Van den Bosch et al., op.cit.: p.32). Hence, it was recommended to abandon the term Ticheloven bed. During the excavation of the Miste-3 quarry by the Working Group for Tertiary and Quaternary Geology (WTKG-Werkgroep Tertiaire & Kwartaire Geologie) in 2013, the opportunity was taken to sample accurately and describe this profile (Van den Bosch, 2014; Fig. 6). This led to the reintroduction of the Ticheloven bed term.

As a result of this study, the Stemerdink Bed (Aalten Member) is raised in hierarchical status to the Stemerdink member (this paper), because the current lithostratigraphic unit has a thickness up to 12 m, which is too bulky. Salvador (1994) defines a bed as the smallest formal unit customarily applied to layers from a centimetre to a few metres in thickness, hence its change in rank to member status. Changing the rank of a stratigraphical unit does not require the unit's redefinition. It may be raised without changing its name (Salvador, op.cit.). Hence, the Stemerdink member is here split from the Aalten Member, limiting the latter to the Miste and the Ticheloven beds. Both beds reach a thickness of approximately 4 m and fit well within their definition of rank. In addition, the Miste Bed term has a long-standing and common usage which is already sufficiently established to preserve, despite its nomenclature possibly not exactly conforming to modern terminological rules and procedures (cf. Salvador, 1994).

Lithology and facies

The abundance of the mollusc fauna only occurs at the base of the succession, in the basal 30 cm of the Miste Bed. In the overlying interval, the faunal assemblage becomes rapidly impoverished, a shell-poor section occurs, including whale fossils and phosphorites formed *in situ*. These phosphorites could possibly be coprolites from the whales. In the Ticheloven bed at the top of the profile in the Miste-03 quarry, the fauna is completely different, in particular many gastropods have disappeared and are replaced by large bivalves including *Glycymeris* sp. and *Arctica islandica*. The percentage of gastropods is ca. 50% at the base of the Miste Bed and decreases upwards to values approximately 15% of the total assemblage. The number of species and individuals also decreases sharply upwards. This succession, including the faunal material, corresponds to the 'former' Ticheloven bed. This is associated with an increasing water depth. In the transition of the top Miste Bed (top phosphorites)/base, Ticheloven bed sediment changes from sand to clay and becomes richer in glauconite (De Vogel, 1970, 1971). It is also striking that the maximum grain size (i.e. coarser grain size in the clay) increases considerably (Fig. 6). The holostratotype of the Ticheloven bed is defined in borehole 34G1-1/43T in the municipality of Eibergen (coordinates:

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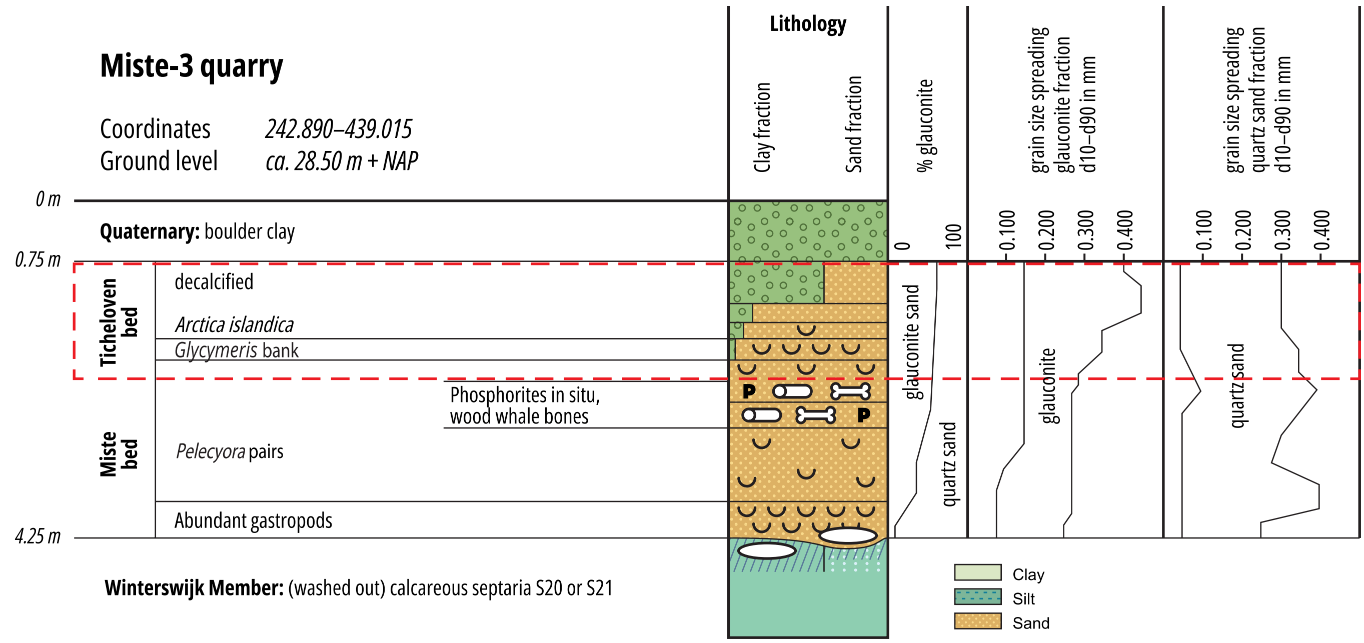

Figure 6. Lithological and lithostratigraphical overview of the temporary Miste-03 outcrop.

$x = +89{,}387$ and $y = -3{,}829$; Janssen, 1967) (see also the discussion, below).

Biostratigraphy and age

The outcrop Miste-03 has also been examined for its contained palynology. The results of the palynological investigation of interval 1.00–4.00 m are described below (cf. Table 4; also Fig. 7).

The palynological yield is very high, with marine dinoflagellate cysts dominating the microfloral spectrum. From 2.5–2.8 m upwards to 1.5–1.75 m, the marine content of the total sum of palynomorphs increases. Among the sporomorphs, the bisaccate pollen (gymnosperms) are dominant. Reworking is absent or very modest, with the exception of the base. At the basal sample 3.75–4.00 m, the percentage is at least 5%. In any case, the origin of most reworking is early Chattian.

Lithostratigraphic position and distribution

The Miste Bed occurs in the region of Miste (Fig. 1) and extends southwards into Germany. Elsewhere, in Barlo, Lievelde, Overkamp Meddo boreholes and that further north as far as Twente, the Miste Bed is absent and the Ticheloven bed occurs at the base of the Aalten Member. Remarkably, the phosphorites in the Miste Bed are always recorded as eroded at the base. Hence, the Miste Bed is older than the initially defined Ticheloven bed and the nature of the transition merits reintroduction of the latter.

The amended Eibergen Member and the new Dale member

In the Achterhoek, there has been a problem with the lithostratigraphic interpretation of the top of the Eibergen Member for many years. Here, a new Dale member of the Diessen Formation is proposed, sandwiched between the underlying Eibergen Member of the Groote Heide Formation and overlying Zenderen Member, also of the Diessen Formation (see Table 3).

Lithology and facies

The basal part of the Eibergen Member comprises black clays, rich in mica and whale skeletal remains. The succession overlying these black clays comprises greenish silty-sandy clays and clayey silts with fine glauconite, the occurrence of which implies a doubtful interpretation whether this unit is an equivalent of the Zenderen Member or still belongs to the Eibergen facies. Advancing insight over the years has indicated more strongly that it represents an as yet (for the Achterhoek) unnamed member overlying the typical black clays of the Eibergen Member. Therefore, here it is proposed to introduce the term Dale member for this interval. The present interval is lithological easily distinguished and recognisable in the RGD (Geological Survey of the Netherlands) borehole Barlo (code B41B0135), interval 49.25–52.25 m (Fig. 8). Here, the base of this new Dale member is clearly visible in the lithological transition from a blackish moderately silty clay (Eibergen Member) to a dark green-grey very strongly clayey silt. The boundary between the Dale and Zenderen Member (Diessen Formation) is determined by an upward gradation from a green-grey strongly clayey silt (Dale) to silts and very fine sands (Zenderen Member). A sharp upward decrease of the gamma-ray values from the Eibergen Member towards relatively low values that characterise the Dale member can be seen in Fig. 8.

Biostratigraphy and age

New palynological analyses have been performed to confirm the current stratigraphic interpretation (Fig. 8). The palynological results from the Barlo borehole (B41B0135) are shown in Table 5.

The palynological results indicate a late Serravallian age (biozones SNSM10 and SNSM11) for the uppermost part of the Eibergen Member and an earliest Tortonian age for the Dale member (boundary Zone SNSM11/12).

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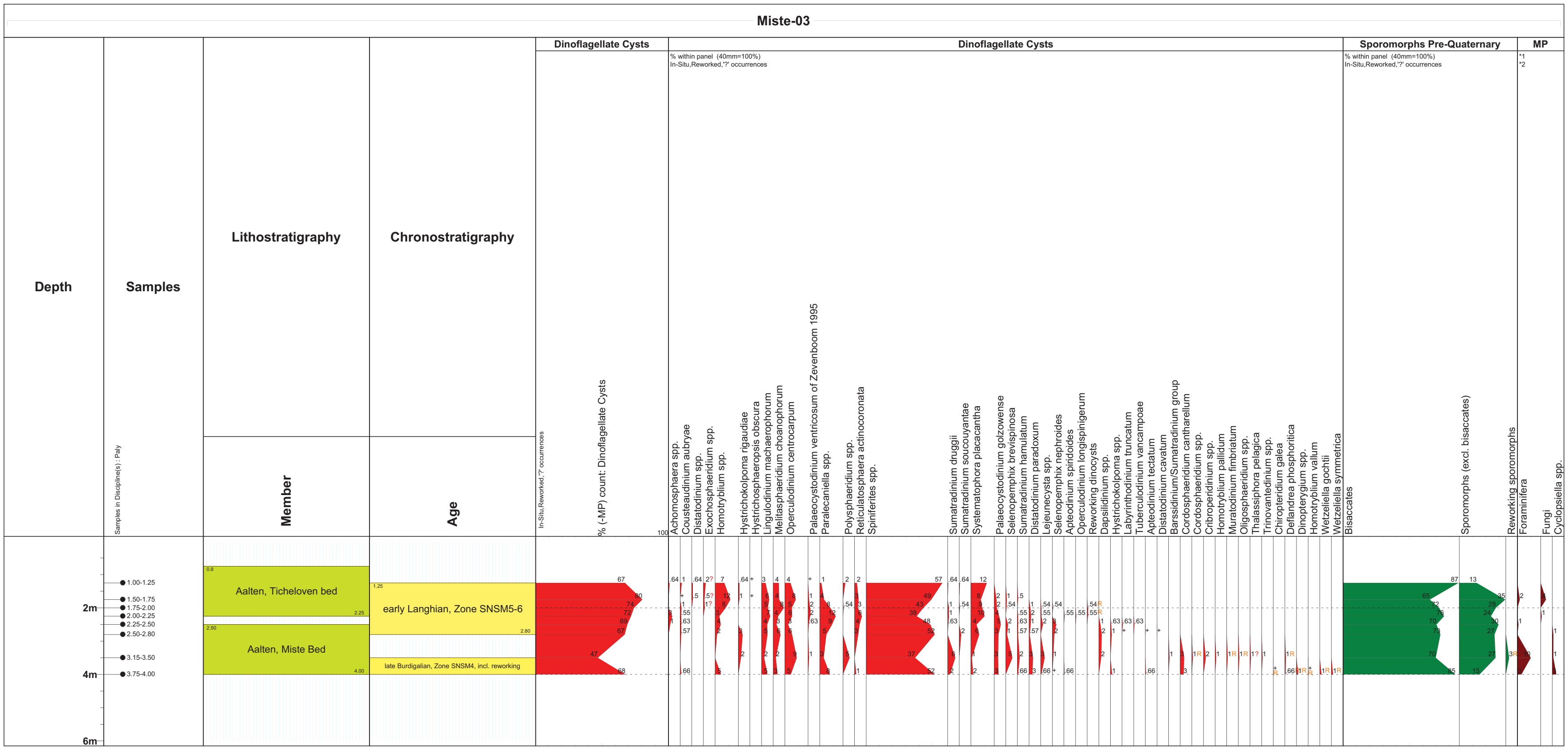

Figure 7. Palynological interpretation and distribution chart of the Miste-03 outcrop.

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Table 3. New (this study) and old (Van den Bosch et al., 1975) lithostratigraphic synthesis of the Miocene Achterhoek (*proposed).

Lithostratigraphic classification (this study)			Lithostratigraphic classification (Van den Bosch et al., 1975)		
Formation	**Member**	**Bed**	**Formation**	**Member**	**Bed**
Diessen	Doetinchem*		Breda	Delden	
	Delden				
	Zenderen			Zenderen	
	Dale*			Eibergen	
Groote Heide	Eibergen				
	Stemerdink*			Aalten	Stemerdink*
	Aalten	Ticheloven*			Miste
		Miste			

Table 4. Overview palynological results including age assessment of the outcrop Miste-03.

Interval m (measured depth)	Age; zone
1.00–2.80	Mid-Miocene, early Langhian, Zone SNSM5-6 *1
3.75–4.00	late Burdigalian, Zone SNSM4, or younger, with reworking from early Chattian-early Miocene *2

The dating is based on:
*1. LODs (Last Occurrence Datum) of *Cousteaudinium aubryae* and *Distatodinium* spp. at 1.00–1.25 m, LOD of *Distatodinium paradoxum* at 1.75–2.00 m, LOD of *Distatodinium cavatum* and FOD (First Occurrence Datum) of *Labyrinthodinium truncatum* at 2.5–2.8 m.
*2. Remarkable is the number of taxa reworked from the late Oligocene, early Chattian with representatives such as: *Deflandrea phosphoritica*, *Dinopterigium* spp., *Wetzeliella gochtii* and *Wetzeliella symmetrica*. Some species even have a LOD in the earliest Miocene, Aquitanian, such as *Chiropteridium galea* and *Homotryblium vallum*, but also occur in the early Chattian. However, these chronostratigraphic ranges do not fit with the FOD of *Sumatradinium druggii* (late Burdigalian, Zone SNSM4, or younger) for example.

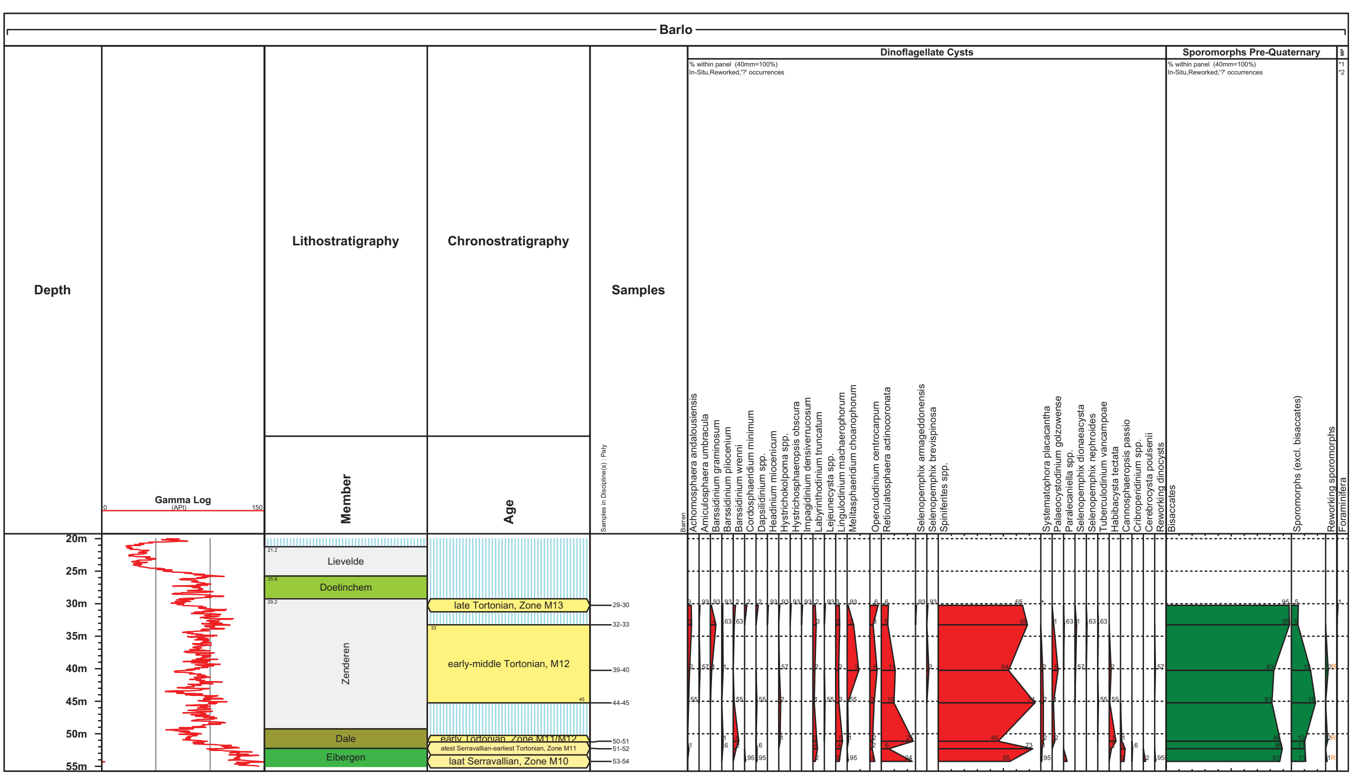

Figure 8. Palynological interpretation and distribution chart of the Barlo borehole (B41B0135).

Table 5. Summary of the palynological results regarding age assessment of the Barlo borehole (B41B0135).

Interval m (measured depth)	Age; Zone
29.25–30.25	Late Miocene, late Tortonian, Zone M13 *1
32.25–45.25	Late Miocene, early-mid Tortonian, Zone M12 *2
50.25–51.25	Late Miocene, early Tortonian, Zone M12 *3
51.25–52.25	Mid-/late Miocene boundary, latest Serravallian/earliest Tortonian transition, top Zone M11 *4
53.25–54.25	Mid-Miocene, late Serravallian, Zone M10 *5

The dating is based on:
*1. LODs of *Labyrinthodinium truncatum, Hystrichosphaeropsis obscura* and *Systematophora placacantha* and the FODs of *Impagidinium densiverrucosum* and *Selenopemphix armageddonensis.*
*2. LOD of *Palaeocystodinium golzowense.*
*3. LOD of 1 (badly preserved) taxon *Cannosphaeropsis passio.* Remarks: *Cannosphaeropsis passio* is possibly reworked here.
*4. LOD of *Cannosphaeropsis passio.*
*5. The occurrence of *Cerebrocysta poulsenii.*

Lithostratigraphic position and distribution

The Dale member has not been established in the boreholes on the East Netherlands Plateau. Here, a major discordance between the Delden Member and underlying succession is shown. The succession here includes many shark teeth from the eroded section of the early Delden Member. The current strata outcrop immediately west of Winterswijk, in the 't Klooster forest, where the current transition is exposed. The Dale member is confirmed in Barlo borehole and the western part of the transect (Fig. 5).

The lithostratigraphic situation is different in Twente, where the Zenderen Member discordantly overlies a decalcified interval that may be attributed to an equivalent of the Aalten Member. A major hiatus is interpreted to occur here.

Amended Delden and new Doetinchem members

Encouraged by recent positive results of research that clarified the previously uncertain and contested stratigraphic succession of the Kasterlee Formation, sandwiched between the Diest and Mol formations in Belgium, the uppermost part of the Dutch Diessen Formation was once again investigated here in order to achieve a higher lithostratigraphic resolution (Louwye et al., 2007; Louwye & Vandenberghe, 2020; Vandenberghe et al., 2020; Verhaegen et al., 2020). Similar lithological observations and trends, such as the higher gamma-ray log values observed at the top of the latter formation, are described below. They have resulted in the establishment of a new lithostratigraphic unit, the Doetinchem member and an amended Delden Member (see discussion below).

Lithology and facies

Evidence obtained from the air-lifted Gaanderen boring show that the 83–96 m interval, here defined as the new Doetinchem member (formerly top part of the Delden Member), consists of a dark green to olive grey loam alternating with silty fine sands and extremely silty clays that are moderately humus (organic matter). Clay and cemented beds are present. Traces of glauconite and iron oxide are also observed. The lithology of the current interval differs from under- and overlying successions that are more continuous sandy. This lithological change is also very prominently visible in the gamma-ray logs, which show overall much higher values for the Doetinchem member. In the Gaanderen boring, the lower boundary of the unit is characterised by a 2-m-thick mollusc-rich bed. These units predominantly reflect marginal to shallow marine sedimentation.

Biostratigraphy and age

The dinoflagellate cyst assemblages from this unit indicates a late Miocene (latest Tortonian-Messinian) age, post-Zone SNSM14 for the Doetinchem member. *Labyrinthodinium truncatum* is no longer observed here, whilst *Impagidinium densiverrucosum* (LOD in the late Miocene) is still present. At the base of this unit, abundant simple trilete fern spores are recorded indicating their colonisation of nearby river banks. Although brackish water algae first occur here, they are restricted to low numbers. The coastal marine dinocyst taxon *Lingulodinium machaerophorum* is also represented in abundance. The Delden Member was equated to the late Tortonian, zones SNSM13-14.

Lithostratigraphic position and distribution

In this paper, the Doetinchem member is presented as the youngest member of the Diessen Formation, formerly being the upper part of the Delden Member. The new unit is (like the former Delden Member) overlain by sediments of the Oosterhout Formation. It is an easily identified in the gamma-ray logs by an evident decrease towards low values upwards. In the western part of the studied area the Doetinchem member grades into the clean sands of the Goirle Member, the letter being associated with characteristic low gamma-ray values. Near Varsseveld, the erosional base increases in the amount of time it represents, and an undifferentiated Oosterhout Formation shows an alternation of sands and silts. Further east, medium-grained sands yielding distinctly low-gamma ray values and a locally highly erosional base form the upper part of the Oosterhout Formation (Lievelde Member, formerly referred to as the Scheemda Formation). In the holostratotype section, the lower boundary of the new unit is on top of 2-m-thick shell bed and underlying succession of fine sands, weakly silty, moderately humic. If the shell bed is absent, a transition from loam to fine sands is present, corresponding to an upward increase in gamma-ray readings towards the Delden Member.

New lectostratotype sections

The holostratotype sections on which present lithostratigraphic units are defined in the Achterhoek have mostly disappeared or sample material of the Miocene-type locality is merely available. Furthermore, the holostratotype sections were drilled with poorly executed straight-flush drillings (cuttings), including a small

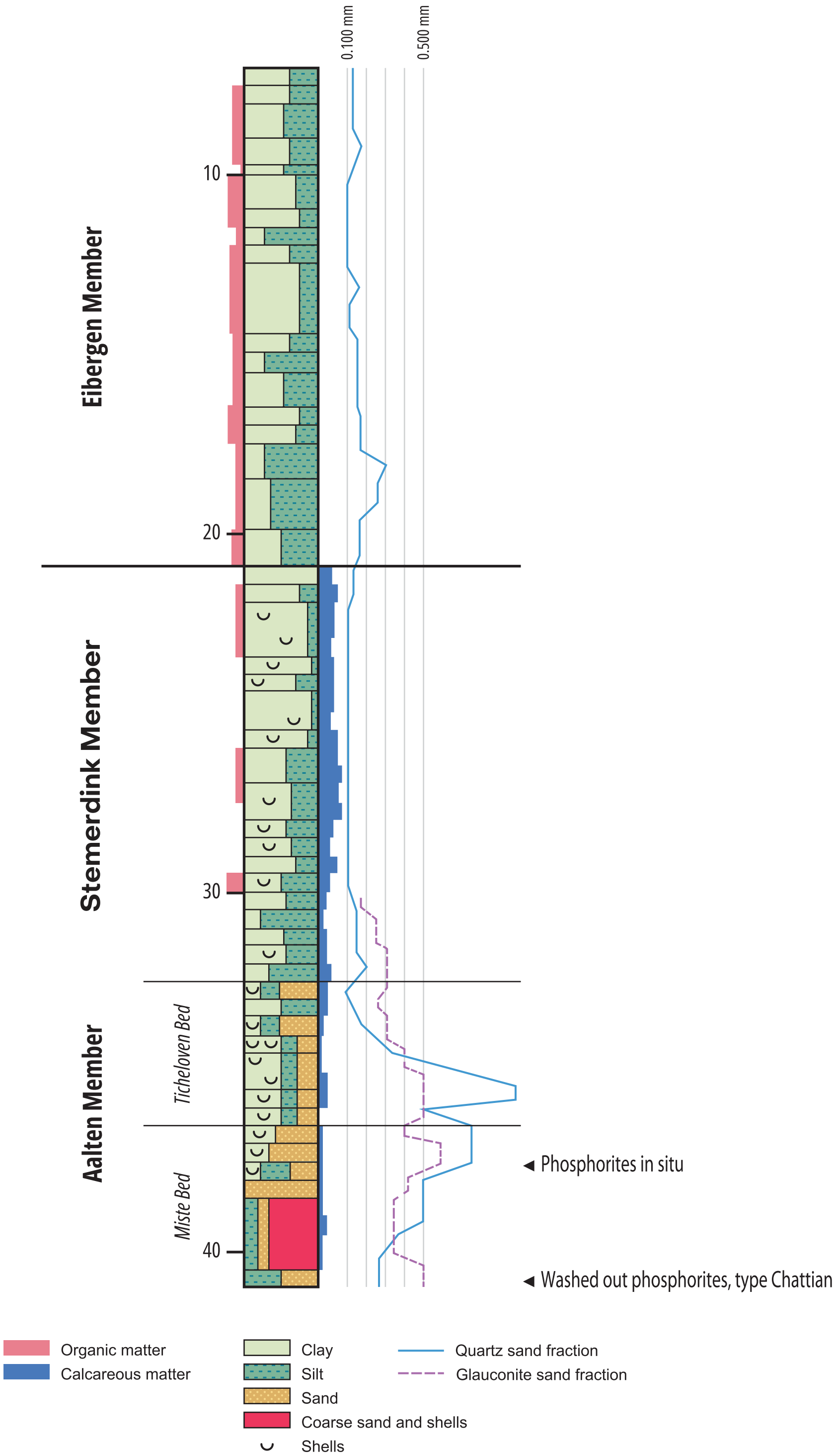

Figure 9. Lithological section of the De Haart borehole (B41G0024).

diameter drill; hence, every lithological detail is missing. Over the past 40 years, advances in understanding and experience developed novel air-lift drilling techniques have increased *in-situ* sample resolution (Van den Bosch, 2015). In addition, in the past the chronostratigraphical position of the units was interpreted in low resolution (Munsterman, 2011a, 2011b). Hence, new lectostratotype sections are proposed in this study and additional palynological analysis for age assessment has been performed on these strata. The type-borings selected are De Haart (B41G0024) and Gaanderen (B40F1874). For information on the lithological description, facies and geographical distribution, the reader is referred to the Addendum (cf. also Figs. 9 and 10 showing the

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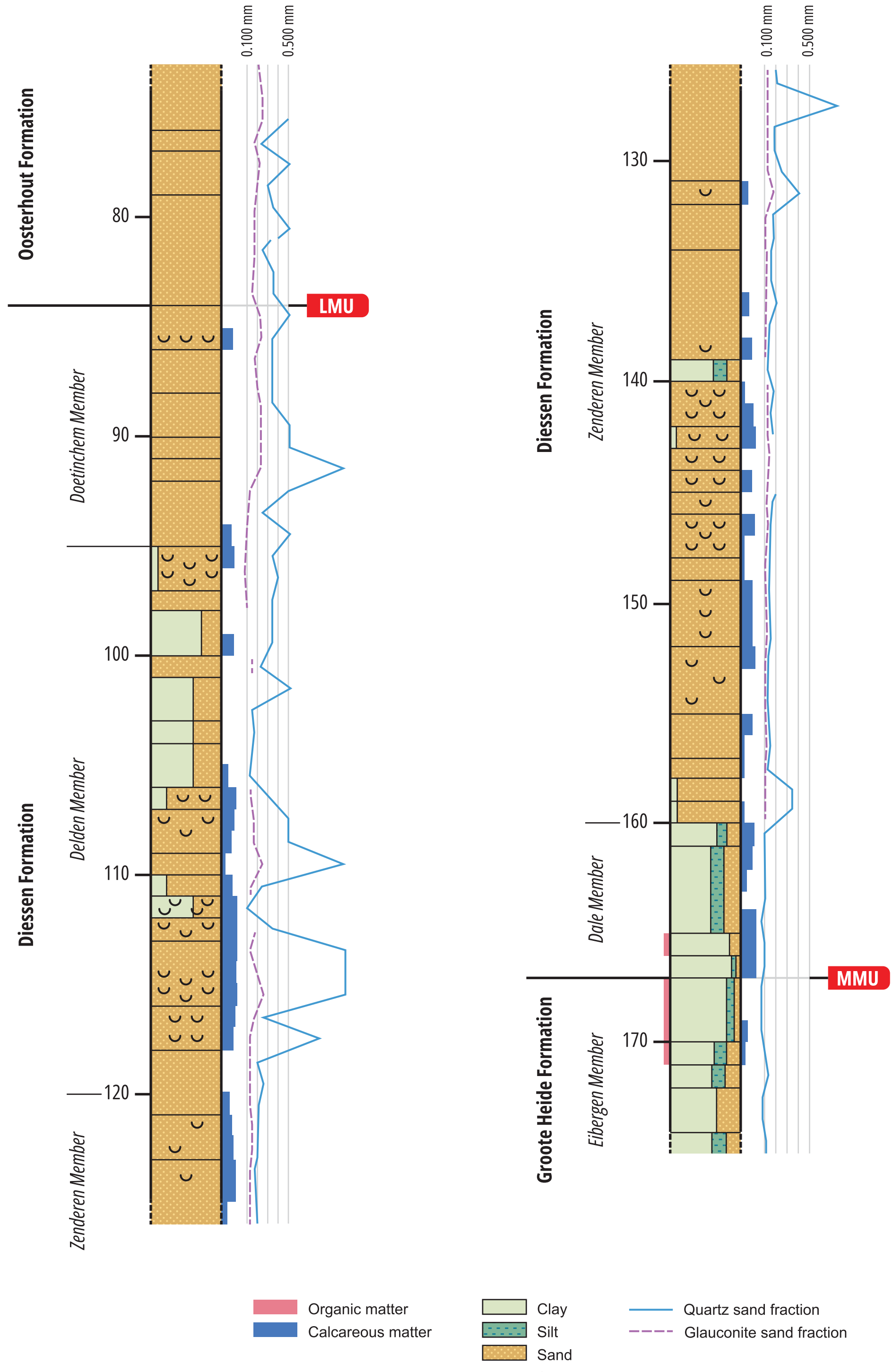

Figure 10. Lithological section of the Gaanderen borehole (B40F1874).

lithological profile of both holes). Here, a summary of the biostratigraphical results from the De Haart and Gaanderen boreholes is compiled.

Biostratigraphy and age

1. ***Borehole De Haart, interval 7–41 m : lectostratotype sections for the Aalten (32.5–41 m), Stemerdink (21–32.5 m), Eibergen (7–21 m) members and Miste (36.5–41 m), Ticheloven (32.5–36.5 m) beds.***

Dinoflagellate cyst biozonation

The stratigraphic interpretation and age are shown in Fig. 11 under the columns 'formation', 'member' and 'age'. The associations are very rich in well-preserved dinoflagellate cysts. What is striking, however, is the presence of caving from higher successions.

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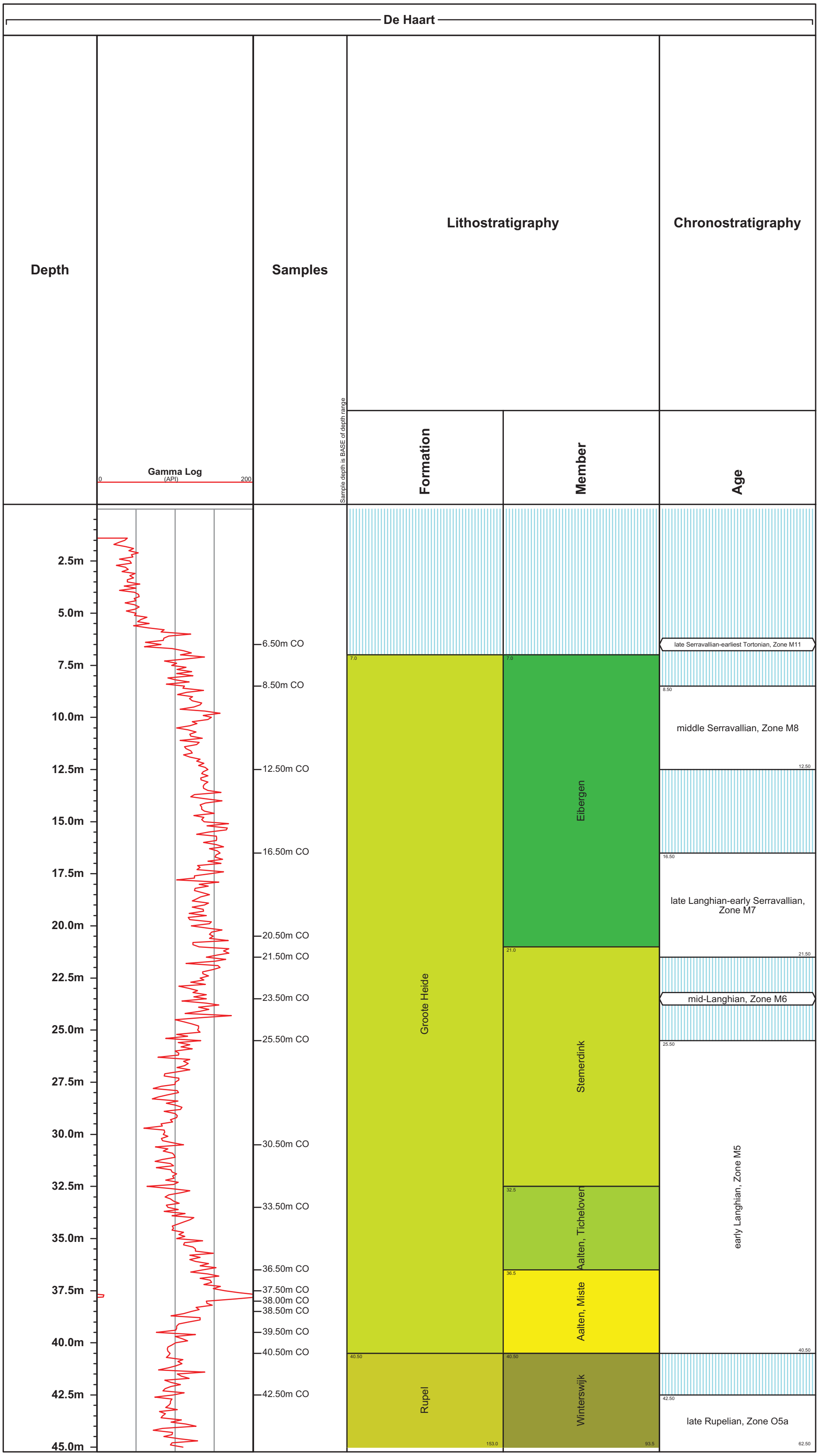

Figure 11. Palynological interpretation of the De Haart borehole. The high peak values in the gamma-ray log at 37.7 m depth are associated with phosphorites.

Table 6. Overview palynological results regarding age assessment borehole De Haart (B41G0024).

Interval m (measured depth)	Age; Zone
6–6.5	Latest middle-earliest late Miocene, late Serravallian-earliest Tortonian, Zone M 11 *1
8–12.5	Middle Miocene, middle Serravallian, Zone M8 *2
16–21.5	Middle Miocene, late Langhian-early Serravallian, Zone M7 *3
23–23.5	Middle Miocene, mid-Langhian, Zone M6 *4
25.5–40.5	Middle Miocene, early Langhian, Zone M5 (incl. reworking from the Oligocene-early Miocene at the base 39-40.5 m) *5
42–62.5	Latest Early Oligocene, latest Rupelian, Zone O 5a *6

The dating is based on:
*1. FOD of *Cannosphaeropsis passio.*
*2. LODs of *Imperfectodinium bulbosum* & *Unipontidinium aquaeductum*.
*3. LOD of *Palaeocystodinium ventricosum*.
*4. LODs of *Distatodinium paradoxum* and *Cousteaudinium aubryae*. And the FOD of *Unipontidinium aquaeductus.*
*5. Superposition and the FODs of *Labyrinthodinium truncatum modicum* and *Labyrinthodinium truncatum truncatum.*
*6. LODs of *Achilleodinium biformoides*, *Membranophoridium connectum* and *Operculodinium xanthium*. And the FOD of *Distatodinium* aff. *biffii.*

Previous and new analytical results of taxa are displayed together (Table 6; Fig. 12).

Mollusc biozones

The successive molluscan zones from the Aalten Member in the De Haart borehole correspond closely to the scheme introduced by De Vogel (1970, 1971). The *Hiatella arctica* zone (39.00–40.00 m b.s.) is succeeded by the *Astarte radiata* zone (36.50–38.50 m below surface, the uppermost part of which corresponds to the LOD of *Tritia facki*), *Spisula* zone (33.50–36.00 m. below surface) and *Limopsis aurita* zone (29.00–33.50 m b.s.). Within the *Spisula* zone, the most common species in sample 35.00–35.50 is *L. aurita;* nevertheless, the common occurrence of *Spisula* aff. *subtruncata* within this interval led the writers to attribute the sample to the *Spisula* zone. The most common species in the lowermost sample in the De Haart borehole (40.50–41.00 m b.s.) is *L. aurita*, leaving the authors uncertain of the attribution to the molluscan biozones proposed by De Vogel (1970, 1971). The molluscan succession corresponds to the regional Oxlundian Substage that has been attributed to the global Langhian Stage (Janssen, 2001).

The molluscan abundances are provided for the De Haart borehole (this work) and those at Miste, De Vlijt and Stemerdink in Table 7. The new De Haart evidence (Fig. 13) shows a succession of four mollusc acme zones identical to the successions described by De Vogel (1971). The lowest acme zone, characterised by common *Hiatella arctica*, is found in the base of the Miste borehole (1.75–4.10 m below surface) in the base of Stemerdink borehole (17.00–18.90 m below surface) and in borehole De Haart (39.00–41.00 m below surface). The overlying *Astarte radiata* acme zone has been encountered in all four studied boreholes (Miste: 1.60–1.75 m b.s.; De Haart: 36.50–38.50 m below surface; De Vlijt: 49.50–51.00 m below surface; Stemerdink: 13.00–17.00 m below surface). Within this acme zone, a Last Occurrence Date (LOD) of *Tritia facki* is found. The overlying *Spisula* aff. *subtruncata* acme zone is found in De Haart (33.50–35.00 m below surface), De Vlijt (47.00–49.50 m below surface) and Stemerdink (11.00–13.00 m below surface). The uppermost *Limopsis aurita* acme zone also occurs in these three boreholes (De Haart: 29.00–33.50 m below surface), De Vlijt (42.00–47.00 m below surface) and Stemerdink (6.00–11.00 m below surface).

Gaanderen Borehole, interval 83–168.5 m: new holo- and lectostratotype sections (Table 8)

Dinoflagellate cyst biozones

The stratigraphical interpretation and age are represented in Fig. 14 under the columns 'formation', 'member' and 'age'. The previous and new palynological analysis results are shown integrated (Fig. 15). The top of the succession, interval 21–47 m (four samples), is poor in palynomorphs, and their preservation is poor. From 50 m and deeper, the associations are rich and well preserved. The palynological results from the Gaanderen borehole (B40F1874) are shown in Table 9.

Discussion

Fossiliferous successions of the Aalten and the base of the Stemerdink members

The fossiliferous successions in the Achterhoek in general represent a fining-up sequence, but especially the lateral and vertical distribution of the *Spisula* aff. *subtruncata* and *Limopsis aurita* acme zones are not distributed congruently with the lithological transitions (De Vogel, 1971; Janssen, 1984). The base of the Miocene succession in the Miste area overlies an unconformable contact the Rupelian Boom clays and contains rounded (reworked) phosphoritic pebbles and nodules containing Chattian and Early- and reworked Middle Miocene taxa (Fig. 6; Janssen, 1984). The transition to the *Hiatella arctica-Astarte radiata* zone is considered to represent an hiatus (Fig. 13; Janssen, 1984) known as the Ticheloven horizon. The layer contains quartz and phosphorites with reworked faunal material, but based on its palynological content all lie within the M5 biozone (Fig. 11). The short Ticheloven borehole (34G.1-24, de Vogel, 1971) located outside the study area has been used to define this horizon. In this borehole, three acme zones have been found. From bottom to top, they are the *Astarte radiata* acme zone (3.00–4.15 m below surface), the *Spisula* aff. *subtruncata* acme zone (1.75–3.00 m below surface) and the *Limopsis aurita* acme zone (0.80–1.75 m below surface).

Apart from the unconformity at the transition of the *Hiatella arctica-Astarte radiata* zone, that possibly represents subaerial

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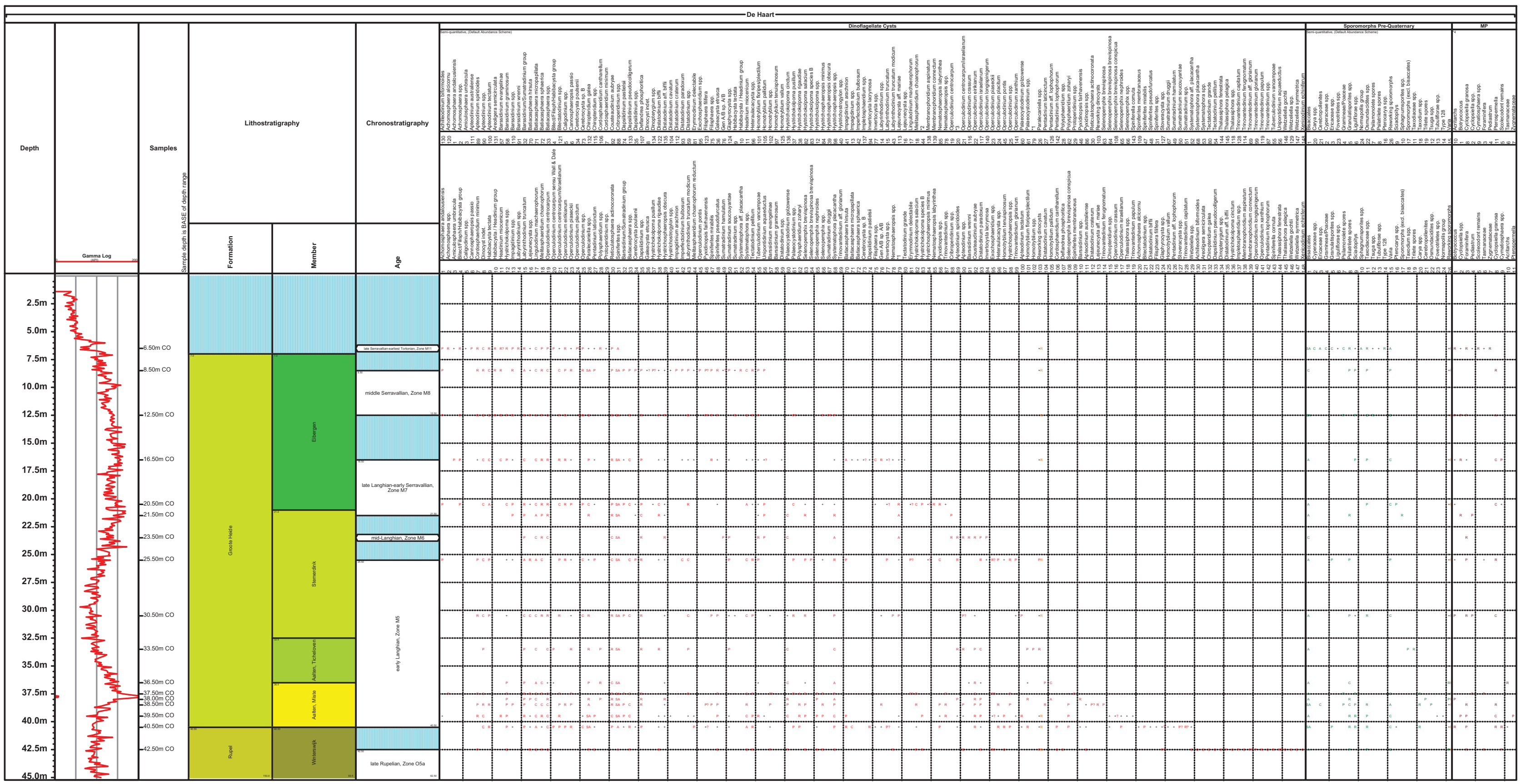

Figure 12. Palynological distribution chart of the De Haart borehole.

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Table 7. Molluscan abundances provided for the De Haart/Langeler borehole (this work) and boreholes Miste, De Vlijt and Stemerdink. L = borehole De Haart/Langeler 41G.1-94, S = Stemerdink borehole 41E.4-387 (De Vogel, 1971), M = Miste borehole 41E.3-75 (De Vogel, 1971), DV = De Vlijt borehole 41D.2-7 (De Vogel, 1971). *This taxon contains likely additional taxa of ribbed *Dentalium* species (J. van der Voort, personal communication).

Species (de Vogel, 1971)	Current name	L29.00-29.50	L29.50-30.00	L30.00-30.50	L30.50-31.00	L31.00-31.50	L31.50-32.00	L32.00-32.50	L32.50-33.00	L33.00-33.50	L33.50-34.00	L34.00-34.50	L34.50-35.00	L35.00-35.50	L35.50-36.00	L36.50-37.00	L37.00-37.50	L37.50-38.00	L38.00-38.50	L39.00-39.50	L39.50-40.00	L40.50-41.00	S6.00-7.00	S7.00-8.00	S8.00-9.00	S9.00-10.00
Portlandia pymaea	*Yoldiella pygmaea* (von Münster in Goldfuss, 1837)	2	0	2	2	0	0	2	0	2	6	1	2	0	0	3	5	7	9	6	2	4	0	1	7	0
Limopsis aurita	*Limopsis aurita* (Brocchi, 1814)	0	1	5	2	0	1	4	18	12	47	6	4	9	4	5	7	2	5	5	3	10	6	32	0	11
Limopsis lamellata	*Aspalima lamellata* (Lehmann, 1885)	0	0	0	0	1	0	1	0	2	19	2	1	3	6	0	0	0	2	0	0	0	0	2	0	2
Astarte gracilis	*Astarte convexior* Anderson, 1959	0	0	0	1	0	0	1	1	1	2	2	6	3	6	15	10	23	19	6	7	11	3	21	1	7
Astarte radiata	*Astarte radiata* Nyst & Westendorp, 1839	0	0	0	0	0	0	0	0	1	1	2	4	3	5	11	10	20	22	6	6	8	0	0	0	0
Astarte waeli	*Goodallia waeli waeli* (Glibert, 1945)	0	0	0	0	0	0	0	0	0	0	0	0	5	7	0	1	2	4	8	0	2	0	0	0	0
Goodallia angulata	*Goodallia angulata* (Lehmann, 1885)	0	0	0	0	0	0	0	1	4	7	6	6	1	3	5	4	5	4	2	0	2	0	0	0	0
Nemocardium cyprium	*Habecardium subturgidum* (d'Orbigny, 1852)	0	2	3	1	0	1	0	1	0	1	0	2	5	7	5	9	21	42	9	4	2	0	1	0	2
Parvicardium straeleni	*Parvicardium straeleni* (Glibert, 1945)	0	0	1	8	6	1	0	2	3	11	4	3	1	1	3	1	3	3	0	0	0	1	3	0	2
Spisula sp.	*Spisula aff. subtruncata* (da Costa, 1778)	0	0	0	0	0	0	1	1	8	57	34	11	5	6	8	6	14	16	2	0	0	0	0	0	1
Gouldia minima	*Gouldia minima* (Montagu, 1803)	0	0	0	0	0	0	0	0	0	2	0	0	2	0	2	4	7	9	8	5	2	0	0	0	0
Varicorbula gibba	*Varicorbula gibba gibba* (Olivi, 1792)	0	0	1	0	0	0	7	5	3	10	0	8	4	5	11	6	10	17	7	1	1	3	4	0	10
Hiatella arctica	*Hiatella arctica arctica* (Linné, 1767)	0	0	0	0	0	0	2	1	0	2	2	2	3	2	2	4	15	19	27	20	7	0	0	0	0
Dentalium mutabile + *D.* sp.	*Dentalium pseudomutabile* Janssen, 1989	0	1	1	1	1	1	0	1	1	3	1	1	1	2	1	1	4	3	1	2	2	2	10	0	2
Archimediella subangulata	*Turritella subangulata* (Brocchi, 1814)	0	1	1	0	0	0	3	1	1	0	0	3	2	0	0	0	2	4	6	1	3	0	1	0	1
Apporhais alata	*Aporrhais proalata* (Sacco, 1893)	0	0	0	1	1	0	0	2	2	9	1	2	2	5	3	5	3	19	40	5	14	1	7	0	14
Naticidae indet.	Naticidae spp.	0	2	1	0	1	0	2	2	0	1	2	0	2	2	7	8	30	24	27	10	12	0	3	0	0
Amyclina facki	*Tritia facki* (von Koenen, 1872)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	7	7	21	29	9	5	0	0	0	0
Streptochetus sexcostatus	*Streptodictyon sexcostatus* (Beyrich, 1856)	0	0	0	0	0	0	0	0	3	6	0	0	1	1	3	9	2	1	4	0	0	0	3	0	2
Ringicula buccinea	*Ringicula promarginata* Sacco, 1892	2	1	1	1	5	3	4	4	6	12	7	2	7	9	5	8	24	22	46	16	19	5	14	0	4
sum		4	8	17	17	15	7	27	40	49	196	70	57	59	71	91	105	201	265	239	91	104	21	103	8	55

exposure, depositional depths must have been below storm wave base (given the occurrence of paired bivalves and common very fine preservation) and below the photic zone (given the near-absence of grazers, such as cerithid gastropods). However, given the common occurrence of byssus bivalves, combined with the very high species numbers, it is likely that the waters were clear. The molluscan faunal association is typical of euhaline salinities (Janssen, 1984). Overall, the character of the Miste fauna is subtropical, given the very high species numbers (501 species according to Janssen, 1984), including several groups that are considered as tropical (such as conid, olivid and terebrid gastropods). The majority of the recovered species are known only from the Miocene of the North Sea Basin, indicating a relatively high degree of prolonged isolation. Several species, however, are known from Middle Miocene deposits of the Aquitaine Basin and some from the Paratethys Basin (Janssen, 1984). This is also seen in the fish-otolith faunas from the same Miocene beds (Schwarzhans, 2010).

Based on this evidence, it is possible that following deposition of fine sand, including rich fauna (Miste Bed), the climate cooled at the end of the mid-Miocene climate optimum, MCO approximately 15 Ma), and hence the coastline became more proximal (coarse grains are mainly transported along the coasts, near the surf zone). The Ticheloven bed represents a subsequent transgression showing, apart from the lithological changes described above ('lithology and facies reintroduction Ticheloven bed'), a gradually increasing bathymetry towards the overlying Stemerdink member. This increase in water depth is reflected in the fining of the grain size the impact of which is also indicated in the resistivity log of the De Haart borehole. The number of both faunal species and individuals decreases sharply upwards, these changes again being a response to an increase in water depth.

S10.00-11.00	S11.00-12.00	S12.00-13.00	S13.00-13.50	S13.50-14.00	S14.00-15.00	S15.00-16.00	S16.00-17.00	S17.00-18.00	S18.00-18.90	M1.60-1.75	M1.75-2.25	M2.25-2.75	M2.75-3.25	M3.25-3.75	M3.75-4.00	M4.00-4.10	DV42.00-42.50	DV43.00-43.50	DV43.50-44.00	DV44.00-44.50	DV44.50-45.00	DV45.00-45.50	DV45.50-46.00	DV46.00-46.50	DV46.50-47.00	DV47.00-47.50	DV47.50-48.00	DV48.00-48.50	DV48.50-49.00	DV49.00-49.50	DV49.50-50.00	DV50.00-50.50	DV50.50-51.00	DV51.00-51.50	DV51.50-52.00	DV52.00-53.00	DV53.00-53.50
3	11	8	22	18	29	45	42	20	16	13	23	20	21	14	16	9	0	0	3	2	1	0	1	2	2	5	4	2	5	2	3	1	11	0	0	0	0
73	37	11	17	8	12	3	4	6	14	5	5	3	3	0	3	1	4	2	9	17	5	5	5	24	38	25	16	8	3	2	2	2	5	1	2	3	1
9	24	16	13	10	13	9	6	5	1	1	0	1	0	1	1	1	1	0	1	0	0	1	3	5	13	26	32	16	8	2	3	1	5	0	1	0	1
20	20	17	16	6	10	5	8	24	27	12	15	14	10	7	10	8	5	1	6	12	6	3	4	9	6	15	19	14	17	8	4	4	0	1	4	1	1
0	2	11	32	35	53	46	60	18	5	58	28	9	8	6	6	12	0	0	0	0	0	0	0	0	0	1	0	4	7	4	17	19	42	7	8	2	2
0	0	1	0	0	1	2	5	12	11	7	9	11	7	5	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0
3	15	23	25	19	19	12	1	2	2	0	2	2	4	5	3	2	0	0	0	0	0	0	0	0	4	14	9	10	15	5	12	4	14	1	2	0	1
2	9	9	12	9	19	29	35	22	22	40	29	28	19	12	8	13	0	0	1	0	1	0	0	3	2	3	3	1	2	1	3	1	8	1	1	1	0
5	21	18	18	12	24	10	8	8	5	0	1	0	0	1	0	1	4	0	4	15	5	3	2	4	8	8	17	6	13	2	3	1	8	1	0	2	0
21	120	72	20	10	18	11	3	6	7	27	21	25	14	6	8	8	0	0	1	0	2	3	3	6	24	59	124	68	25	6	7	1	25	2	3	1	2
0	1	1	3	0	1	3	3	0	2	3	4	1	4	3	9	7	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	1	1	0	0
26	22	30	41	19	23	14	11	13	5	9	10	11	7	8	9	9	5	2	2	5	1	7	10	30	15	22	16	18	22	7	16	15	36	4	3	2	1
1	5	6	7	8	14	24	21	25	36	27	44	53	58	86	71	69	0	0	0	0	0	0	0	2	0	2	2	2	1	1	1	0	8	0	0	0	1
9	15	23	25	13	18	22	27	16	19	30	20	18	5	6	17	25	4	3	3	5	3	6	1	4	5	7	16	11	15	3	5	5	7	3	3	0	1
7	12	7	2	4	12	11	14	10	7	4	4	4	5	2	6	2	0	0	0	0	0	0	2	3	3	4	3	4	2	5	3	3	7	0	1	0	0
32	16	20	12	5	9	11	11	40	34	4	10	27	15	10	27	24	3	2	3	0	1	5	2	7	5	10	20	11	5	5	8	2	3	2	1	0	0
7	5	10	12	8	10	19	10	18	10	10	25	24	23	26	23	23	1	0	1	1	1	5	0	1	4	3	3	5	3	0	3	3	10	0	0	0	0
0	0	0	0	0	1	2	4	6	25	3	15	32	46	38	34	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	2	0	0
7	7	6	12	7	11	7	8	5	4	0	1	3	1	1	1	1	1	0	0	0	0	1	1	4	4	4	3	4	5	0	3	2	3	0	1	1	0
26	27	50	53	29	66	47	60	76	85	18	41	43	36	46	48	49	14	1	5	0	2	10	2	18	22	17	17	16	15	4	34	8	39	5	8	0	0
250	366	337	338	220	361	327	338	330	335	271	305	327	283	280	302	303	41	12	37	58	26	50	35	122	156	224	303	199	163	62	132	71	237	32	44	12	9

Unconformities

The recently distinguished Groote Heide and Diessen formations are bounded by regional discontinuities viz. the Early-, Mid- and Late-Miocene unconformities (EMU, MMU and LMU). The EMU coincides with the base of the Groote Heide Formation, whilst the MMU occurs at the boundary between the Groote Heide and Diessen formations and the LMU is present at the top of the Diessen Formation (Fig. 5). Munsterman et al. (2019) show that both the EMU and MMU of the southern Netherlands correlate remarkably well with the same-named hiati in the Netherlands offshore sector, and in that of the neighbouring countries Belgium, Germany and Denmark (e.g. Kuhlmann et al., 2006; Köthe, 2007; Rasmussen and Dybkjær, 2014; Vandenberghe et al., 2014; De Bruin et al., 2017). In the Achterhoek study, the Miocene unconformities in the De Haart type-borehole (B41G0024) and Gaanderen (B40F1874) are compared with the lectostratotype in the Groote Heide Formation in Groote Heide borehole (B58F0064) and the Diessen Formation in Goirle borehole (B50H0373) (Figs. 16 and 17).

In the Roer Valley Rift System, the EMU is placed between DinoZones M3 and M4, at the boundary between the Veldhoven Formation and Groote Heide Formation (Munsterman et al., 2019). In the Achterhoek area, the Veldhoven Formation is absent and the Groote Heide Formation directly overlies the Rupelian Rupel Formation. A similar situation occurs further south in northern Belgium, where at Zonderschot the glauconitic sands of the lower Langhian Zonderschot Member of the Berchem Formation directly overlies the Rupelian Boom Formation (Louwye, 2000). In fact, the fossil content of the Zonderschot Member is very similar to that of the Miste Bed.

These unconformities generally seem to occur in the North Sea Basin, but their origin and precise ages are still disputed. For example, Rasmussen and Dybkjær (2014) state that various ages

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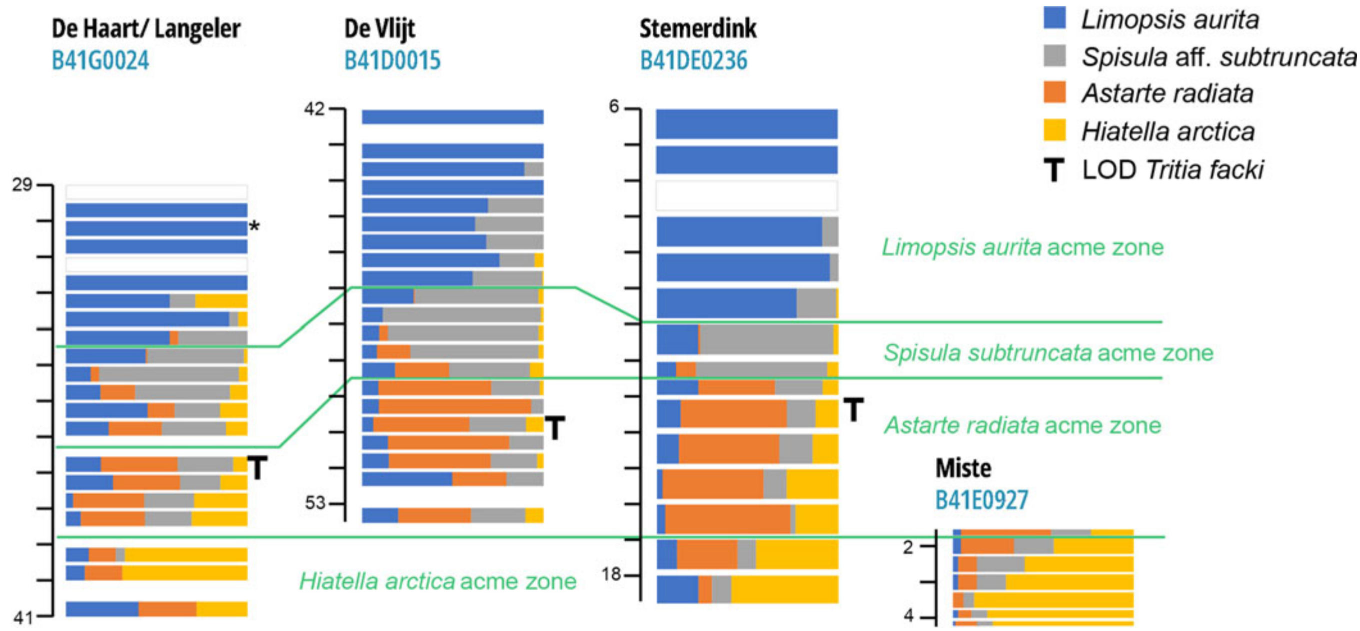

Figure 13. Correlation of molluscan zones from 4 successions in the Groote Heide Formation, Aalten and Stemerdink members. De Vlijt: the farm "De Vlijt", De Haart, Aalten. Note the "De Vlijt"quarry. Stemerdink is located in Brinkheurne, Winterswijk.

and differentiated hypotheses associated with the origin of the MMU are strongly related to the local tectonic settings. On the Venlo Block, Munsterman et al. (2019) describe an MMU at the top of Zone 11 (in the Groote Heide borehole at a depth of 156.8–159.8 m, where the palynofacies changes abruptly. This change is expressed by a decrease in the frequency of *Paralecaniella* from over 60 to 5% of the total marine component, together with the absence of foraminifer Zone FC2B2 (Van Leeuwen, 2000). The variable regional observations of the MMU interval in the southern North Sea Basin (i.e. the Netherlands), as described in Munsterman et al. (2019), seem to be related to the proximal-distal position within the basin and indicate that the MMU is a local expression of an interaction between tectonics and climate on deposition during a phase intermediate between a Maximum Flooding Surface (MFS) at boundary Zone SNSM 7/8; (roughly mid-Serravallian in age) and a Maximum Regressive Surface at the top Zone SNSM 11 (approximately at the Serravallian/Tortonian boundary). In part, it may be related to a convergent phase between tectonic plates (the African Plate, the Arabian Plate and the Indian Plate from the south, and the Eurasian Plate from the north), resulting in long-distance regional structural effects.

The palynological analysis of the Late Miocene succession in the Roer Valley Graben (RVG, southern Netherlands) does not reveal an undisputable hiatus (i.e. the top of the Diessen Formation) associated with the LMU (Munsterman et al., 2019). This is in contrast to its occurrence in the Dutch and German offshore North Sea settings (Benvenuti et al., 2012; Köthe et al., 2008), where part of the Tortonian and Messinian is absent. However, in the RVG a sudden change in depositional style is suggested by both lithological and gamma-ray shifts in the top of the Diessen Formation. These trends are very similar to those observed in the Achterhoek (cf. LMU- top Doetinchem member in the Gaanderen borehole, Fig. 17: gamma-ray decline to lower values, indicating a transition towards clean, early Zanclean 'Goirle-type' sands). The low palynological content of these deposits could be explained by weathering oxidation processes, that is, subaerial exposure, and hence be representative of an hiatus. On the seismic profile, all the topset bed facies are missing, potentially indicating at least a 'limited' hiatus coinciding approximately with the local Miocene/Pliocene boundary (Munsterman et al., 2019).

Sequences and correlation

The underlying strata of the Groote Heide Formation in the Achterhoek are dated to the late Rupelian Zone O5a, suggesting important erosion in the area prior to the late Burdigalian–Langhian Stage transition. Subsequently, sedimentation resumed during the late Burdigalian (Zone M4)–Langhian (Zone M5) transgression, with reworking of the early Chattian-earliest Miocene deposits, the latter based upon the macro- and microfossil content at the base of the Aalten Member (Fig. 18). Likewise, the EMU at the base of the Groote Heide Formation (Aalten Member, Miste Bed) in the De Haart borehole is associated with an even more pronounced hiatus stretching up to the Savian Phase, comprising the Chattian-early Miocene interval, compared to the lectostratotype section in the Venlo Graben (Fig. 16). Based on grain size and resistivity log patterns, a coarsening upward trend from the base of the Miste Bed is seen. This coarsening upward ends in an hiatus at the base of the Ticheloven bed according to molluscan analyses; however, it is not indicated by dinoflagellate cyst assemblage in this study, recording continued deposition during the M5 Zone. Transgression and fining upwards follows within the Langhian Stage Ticheloven bed and Stemerdink member. Deepening of the basin is indicated by the fauna, grain size and an upward decrease in resistivity values. A MFS is recorded at the Stemerdink/Eibergen Member transition at the lower M7 biozone (Fig. 11). This MFS is not found in the Groote Heide Formation further south in the RVRS (Fig. 16). This possibly reflects the greater sediment input in the south-eastern part of the Netherlands, compared to the Achterhoek, where all successions are much more fine-grained (clay). The MFS at the boundary Zone

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Table 8. New holo- and lectostratotype sections for the members of the Diessen Formation.

Formation	Member	Depth (m)	New stratotype
Diessen	Doetinchem	83–96	Holo-
	Delden	96–120	Lecto-
	Zenderen	120–160	Lecto-
	Dale	160–168.5	Holo-
Groote Heide	Eibergen	168.5–185	

Table 9. Overview age assessment of the Gaanderen borehole (B40F1874), based on palynology.

Interval m (measured depth)	Age; Zone
21–47	Not diagnostic *1
50–91	Early Pliocene, early Zanclean or older *2
94–95	Late Miocene (post Zone M14) *3
96–111	Late Miocene, late Tortonian, Zone M14 *4
113–133	Late Miocene, late Tortonian, Zone M13 *5
135–165	Late Miocene, early Tortonian, Zone M12 *6
167–181	Latest middle-earliest late Miocene, late Serravallian-earliest Tortonian, Zone M11 *7
183–185	Late middle Miocene, late Serravallian, Zone M10 *8

The dating is based on:
*1. The sample slides are poor in palynomorphs. Some sporomorphs are present and occasionally rare dinocysts (including fragments). *Spiniferites* and bisaccates (gymnosperms), are all 'of long-term chronostratigraphic range' and are not specific to dating. The presence of dinoflagellate cysts indicates marine influence.
*2. LODs of *Selenopemphix armageddonensis* and *Reticulatosphaera actinocoronata* (ca. 4.5 Ma) and FODs of *Operculodinium tegillatum* and *Ataxiodinium choane* (ca. 6.6 Ma).
*3. LOD of *Impagidinium densiverrucosum*.
*4. LODs of *Hystrichosphaeropsis obscura*, *Sumatradinium soucouyantae*, ?*Gramocysta verricula* and *Labyrinthodinium truncatum*.
*5. LOD of *Systematophora placacantha* and FOD of *Selenopemphix armageddonensis*.
*6. LOD of *Palaeocystodinium golzowense*.
*7. LOD of *Cannosphaeropsis passio* and FOD of *Cannosphaeropsis passio*.
*8. Superposition and FOD of *Achomosphaera andalousiensis*.

SNSM 7/8 (approximately mid-Serravallian in age) in the RVRS is also established in the Achterhoek, such as in De Haart borehole within the Eibergen Member at *c.* 15 m (Fig. 16). After this MFS, a coarsening upward sequence occurs and this continues in the Eibergen Member which is devoid of mollusc shells.

Similar to the Venlo Graben, the uppermost part of the Groote Heide Formation comprises the largest part of the M11 biozone, and the base of the superjacent Diessen Formation, the M12 biozone. Thus, here there is no major hiatus associated with the MMU, although a major facies change, with an upward decrease in gamma-ray values, similar to that boreholes in the northern Roer Valley Graben (Fig. 18) is present. Overall, the lithology of the Diessen Formation is much coarser than that of the Groote Heide Formation in this area, an observation which is consistent with that recorded in the southern Netherlands and neighbouring Belgium. An exception is the newly introduced Dale member in the basal part of the Diessen Formation, which is lithologically similar to that of the subjacent Groote Heide Formation. The Late Miocene age of the Diessen Formation is very similar to that in the northern Roer Valley Graben (Fig. 18; Munsterman et al., 2019). In the boreholes at Gaanderen and Barlo, the uppermost part of the Groote Heide Formation was deposited within the SNSM 11 biozone and the basal part of the Diessen Formation, the SNSM12 biozone (Figs. 8 and 14). Also in borehole Groote Heide, the MMU is situated at the transition between both biozones. Frequently, several zones from the (late) Serravallian are found to be absent, and this hiatus is being associated with the MMU. This is the case in the De Haart borehole zones M9–M10 (Fig. 16) and in that in the Goirle borehole zones M7–M10 (Fig. 17). In addition, the MMU often corresponds to a peak in the gamma-ray plots towards lower values (CF. MMU in both borings in Fig. 17).

The Diessen Formation shows a coarsening upwards from the Zenderen towards the Delden members, based on the granulometry and gamma-ray log of the Gaanderen borehole (Figs. 10 and 14). This coarsening upward trend ends abruptly at the boundary between the Delden and Doetinchem members. The latter shows high gamma-ray values. A very similar log-pattern can be locally seen in northern Belgium, such as in the Turnhout borehole (GSB 017e0398), where the Diest Formation, the equivalent of the Diessen Formation, passes upwards into the Kasterlee Formation, the equivalent of the Doetinchem member. Based on palynologically controlled correlation, the nearby Oud-Turnhout borehole, the high-gamma-ray interval was interpreted by Louwye et al. (2020) as belonging to the Kasterlee Formation, having a latest Miocene (DN10 biozone, Fig. 4) age. A very similar age for the Doetinchem member is established by this study. Moreover, the lithology is quite similar, with both units including olive-grey to green-grey, clayey or silty sands. In the Doetinchem member, the base comprises a shell bed, whereas that of the Kasterlee Formation is represented by a gravel stratum. In the Belgian Oud-Turnhout borehole, the Kasterlee Formation is overlain by the Upper Pliocene (Piacenzian) Poederlee Formation, indicating the presence of a 2.5 Ma hiatus (Louwye and De Schepper, 2010). This hiatus can be related to the LMU, which is

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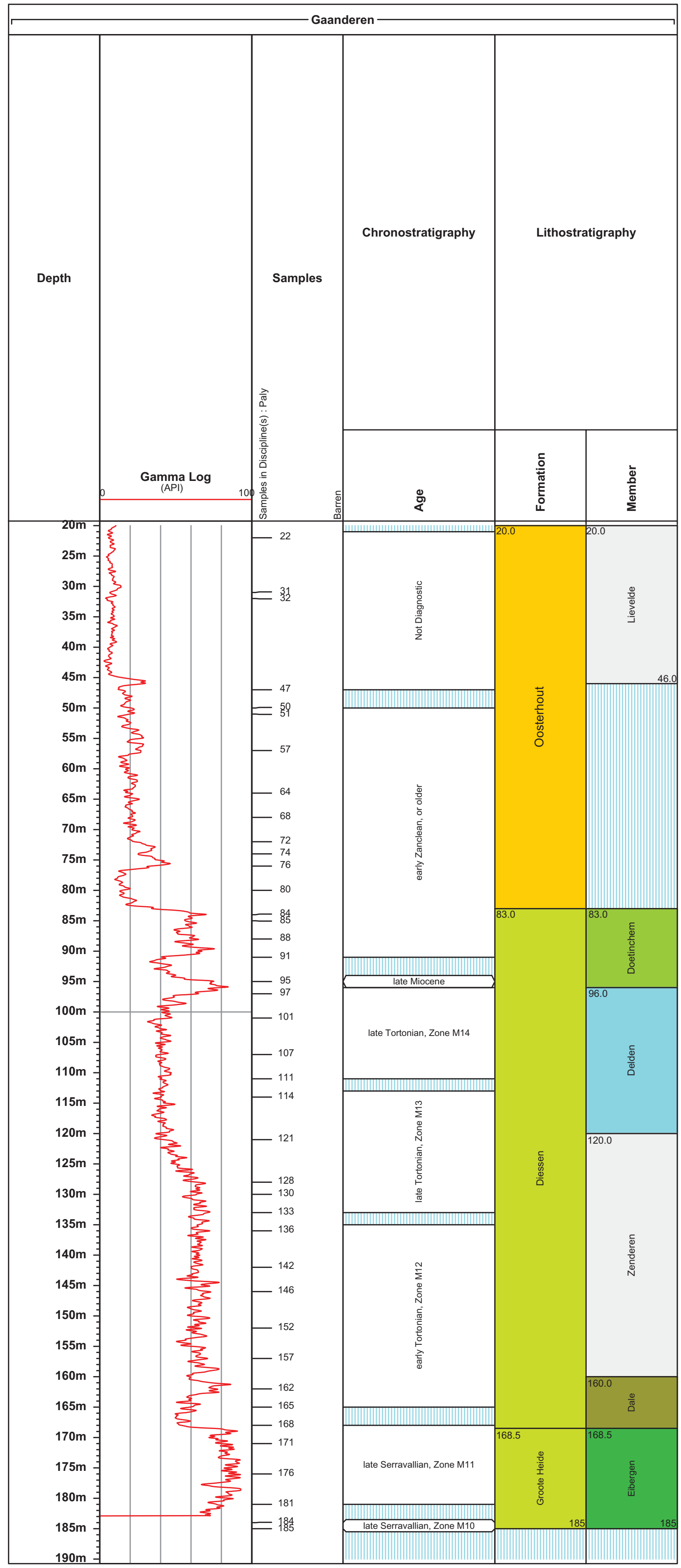

Figure 14. Palynological interpretation of the Gaanderen borehole.

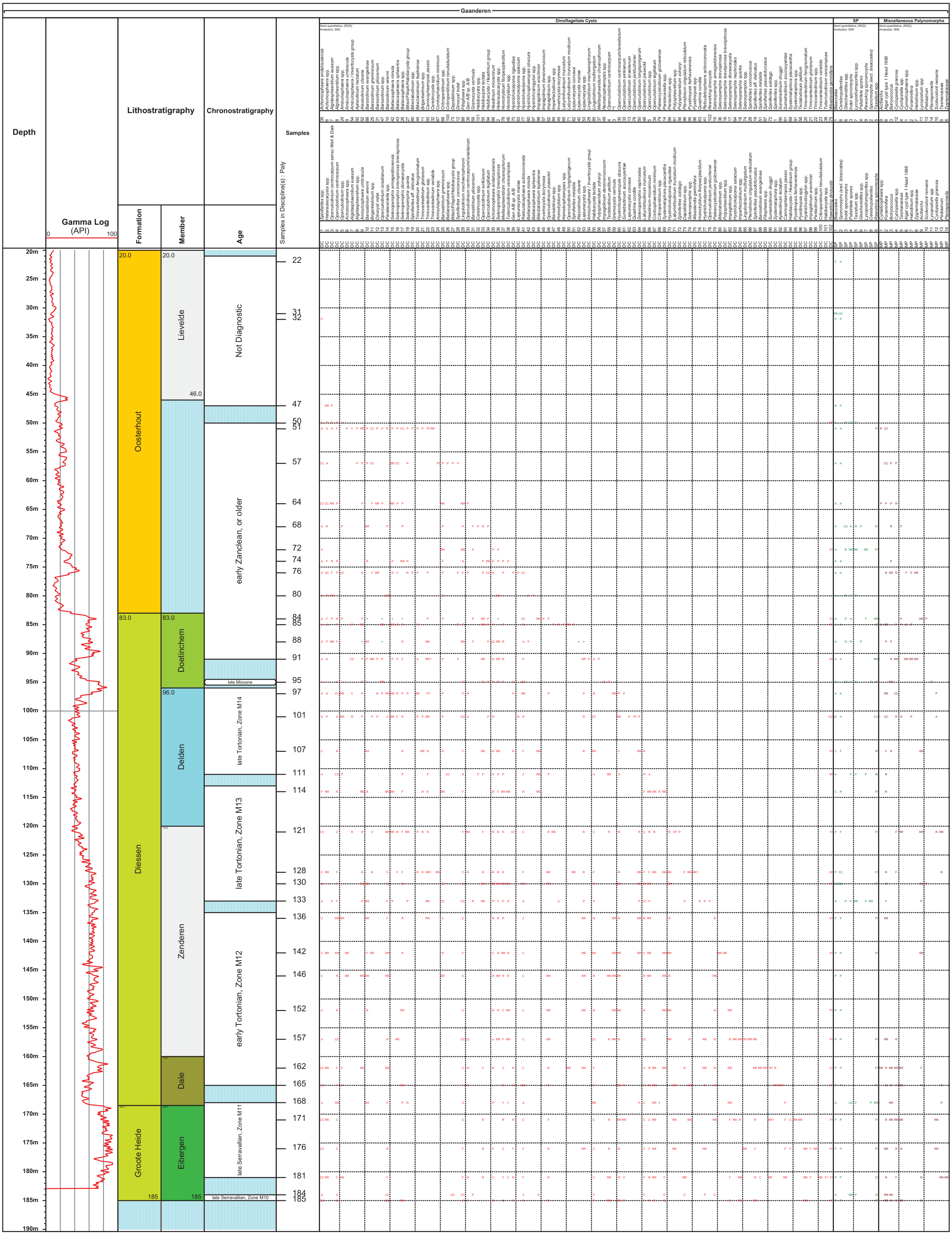

Figure 15. Palynological distribution chart of the Gaanderen borehole.

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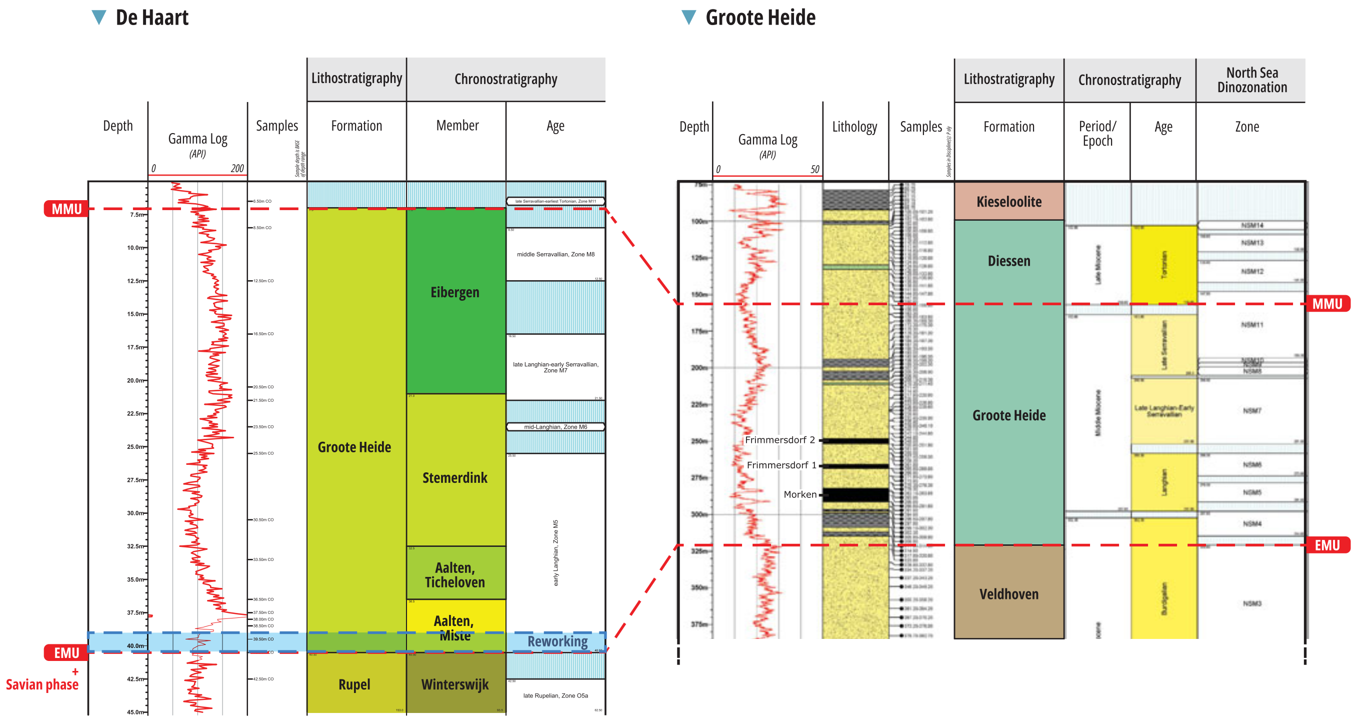

Figure 16. Panel showing the correlation of the Groote Heide Formation in the De Haart borehole and the Groote Heide type section borehole.

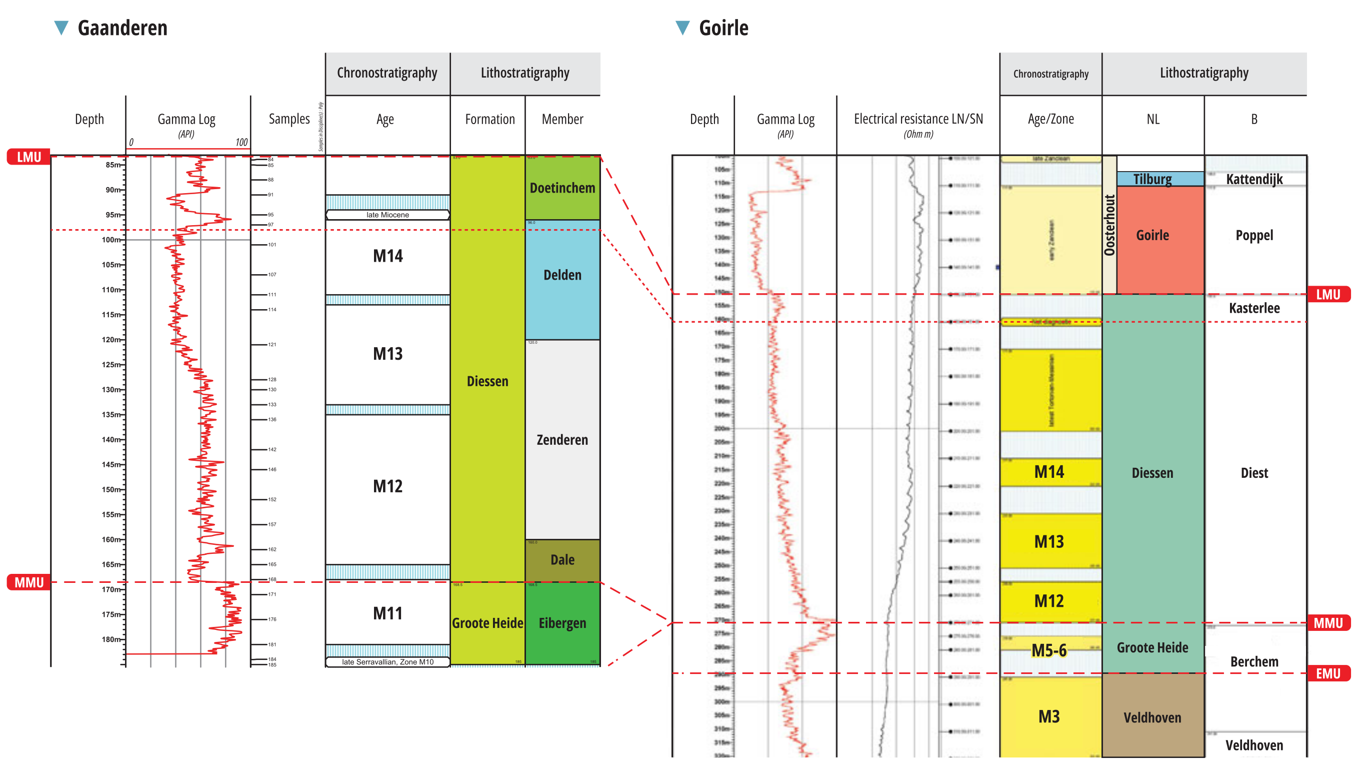

Figure 17. Panel showing the correlation of the Diessen Formation in the Gaanderen borehole and the Goirle type section borehole.

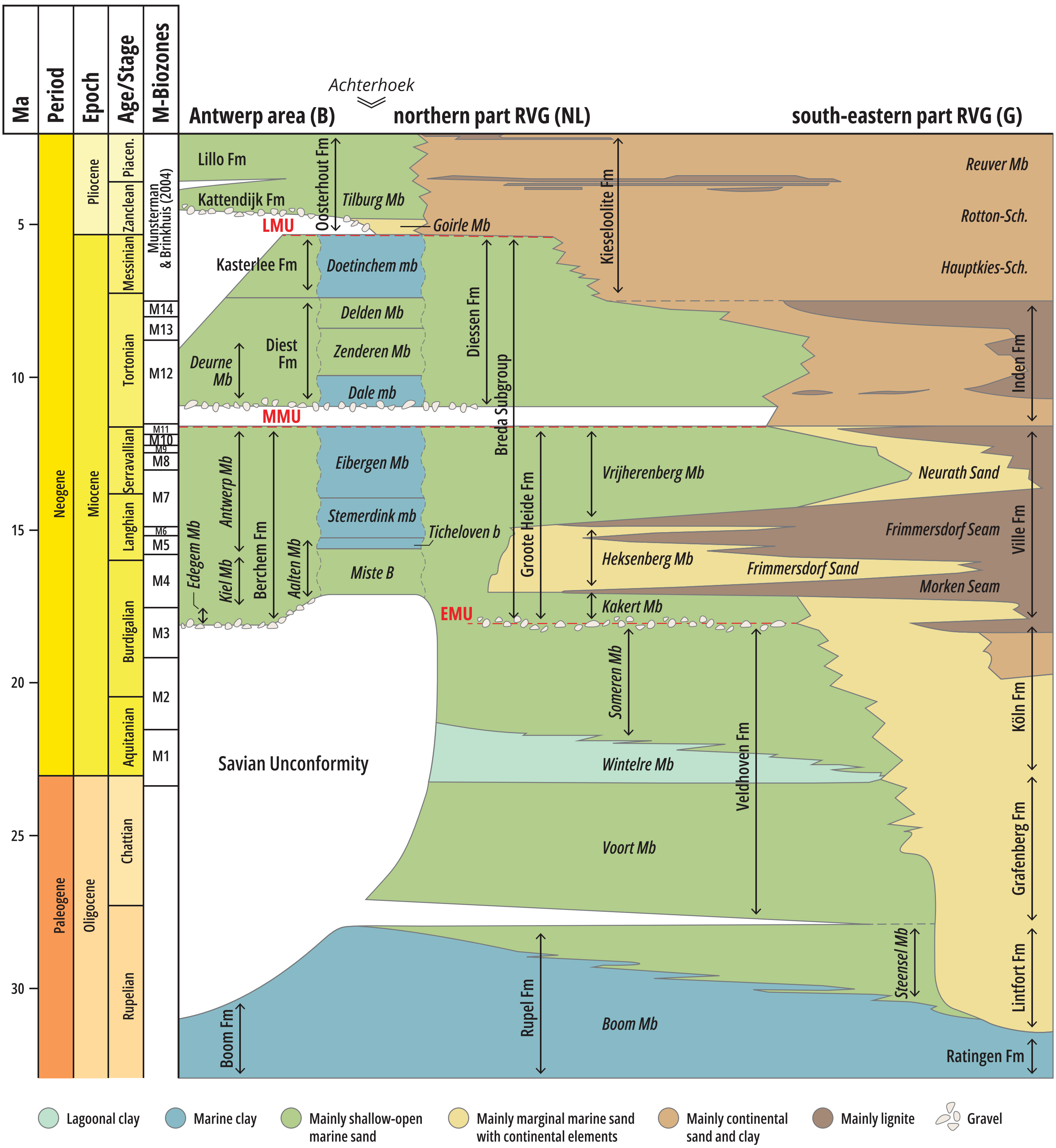

Figure 18. Schematic cross-section of the Oligocene-Pliocene lithostratigraphy and chronostratigraphy from the south-eastern part (Germany; basin margin) to the northern part (the Netherlands; basin centre) of the RVG, and the Achterhoek and Antwerp area (s.l. Campine & City; basin margin). The lithostratigraphy is modified after Deckers & Louwye (2019), Van Adrichem Boogaert and Kouwe (1993–1997) and Munsterman et al. (2019). The Antwerp (City and Campine) area is adjusted after Vandenberghe & Louwye (2020) and Everaert et al. (2020).

also found in the southern Netherlands based mainly on seismic investigations (Munsterman et al., 2019). In the Gaanderen borehole, this hiatus is shorter since the earliest Pliocene overlies the Doetinchem member (Fig. 14).

Houthuys et al. (2020) describe the top of the Belgian Diest Formation, deposited during the late Tortonian, Zone DN9 (Fig. 4). It is characterised by the atypical presence of Fe-vermiculite derived from altered glauconite-bearing soil, thus representing subaerial exposure (Adriaens and Vandenberghe, 2020). This regression marks the boundary between the Diest and the Kasterlee formations (Fig. 18). The overlying clayey Kasterlee Formation is also dated as latest Tortonian-Messinian, biochron

DN10 (Fig. 4). The transition between the formations is marked by lithological change and is conspicuously noted on the gamma-ray logs by a shift towards higher values. The facies of the Kasterlee Formation is interpreted as sublittoral, compared to the Diest Formation in a somewhat shallower marine environment. There is also evidently a short erosional phase followed by a new transgression between both formations with reworking of Diest Formation sediment at the base of the Kasterlee Formation. Kasterlee Formation itself records the final Miocene regression (as demonstrated by palaeogeographic interpretation of Verhaegen et al. (2020).

In the present study, the transition from the Delden to the Doetinchem members, at the top of Zone M14, correlates stratigraphically to the boundary Zone DN9/DN10 (Fig. 4) of the Belgian Diest and Kasterlee formations in the Eastern Campine Area (Fig. 18; Louwye and Vandenberghe, 2020). In addition, the lithology of the Doetinchem member also differs from both under- and overlying Dutch units that are more continuously sandy (Fig. 14). The lithological changes at the boundary of the current lithostratigraphic units in Belgium and the Netherlands are also demonstrable on the basis of gamma-ray logs. The latter showing overall much higher values in the younger units, that is, the Kasterlee Formation and Doetinchem member, as compared to the underlying older Diest Formation and Delden Member. Although this had not yet been described in Munsterman et al. (2019), the same trend at the top of the Dutch Diessen Formation can be seen in the gamma-ray log in the type section Goirle borehole (Fig. 17). Here, the gamma-ray values shift towards higher values at 161 m depth (Fig. 17). Here, the associated lithological change corresponds to an increase in clay strata. Hence, the Dutch equivalent of the Belgian Kasterlee Formation corresponds to the top interval 151–161 m in the Diessen Formation type section (total defined interval 151–272 m) in the Goirle borehole (B50H0373) and to the Doetinchem member in the Achterhoek. The progressive shallowing of the environment in the latest Miocene apparently resulted in a north-westwards migration of the fluvial Inden and Kieseloölite formations in the south-eastern RVRS (Fig. 18). Fluvial deposits are more difficult to correlate with marine successions, although marine incursions into the Inden Formation are dated up to Zone M14 (late Tortonian), demonstrating correlation of this unit to the Delden Member (Munsterman, 2013). Louwye and Vandenberghe (2020) also demonstrate a late Tortonian, Zone DN9 age for the Inden Formation in the Maaseik borehole (Roer Valley Graben) and a Messinian age for the Kieseloölite Formation. The Doetinchem member (post-Zone 14) is the chronostratigraphic equivalent to the base of the fluvial Kieseloölite Formation in the SE Netherlands (Fig. 18).

Conclusions

Based on the lithological, biostratigraphical and petrophysical analyses of the newly selected holo- and lectostratotype sections from boreholes that penetrate the Miocene in the eastern part of the Netherlands, it is concluded that:

1. Cross-border, interregional correlation has yielded a consistent framework of the regional Neogene lithostratigraphy.
2. The Aalten (including Miste and Ticheloven beds), Stemerdink, Eibergen, Zenderen, Delden and Doetinchem members fit into the recently revised lithostratigraphic classification (Stratigraphic Nomenclature of the Netherlands, online) and are a significant improvement over the former holostratotype sections.
3. The base of the Aalten Member is bounded by an hiatus that extends upwards to the Savian phase and the EMU. At the base of the Miste Bed, relatively high values (approximately 5% of the total sum dinoflagellate cysts) of reworking have been recorded from the early Chattian-early Miocene interval.
4. The Ticheloven bed is lithological a clearly distinguishable unit and the term is reintroduced here.
5. The Stemerdink Bed is changed to the Stemerdink member, because its thickness of 12 m exceeds the definition of a bed. It is split from the Aalten Member.
6. Lithostratigraphical problems with the top of the Eibergen and the base of the Zenderen members in the Achterhoek are resolved by revision of the Eibergen Member and the introduction of a new Dale member.
7. The Dale member is defined here, interbedded between underlying Eibergen and overlying Zenderen members. The holostratotype section is selected in Gaanderen borehole, and palynological analysis confirms its age assessment as early Tortonian. The transition from the Eibergen Member to the Dale member coincides with the MMU.
8. The Delden Member is amended to become restricted to the occurrence of fine sands.
9. At the top of the Miocene succession, a new Doetinchem member is established. It is characterised by green-grey to brownish loam, which is mirrored by an increase in gamma-ray log values, compared to over- and underlying sandy units. The unit is associated with the Belgian Kasterlee Formation. The top of the Doetinchem member is limited by the LMU.
10. The three oldest members in this study, the Aalten (including the Miste and Ticheloven beds), Stemerdink and the Eibergen members are included within the new Groote Heide Formation.
11. The youngest four units, the Dale, Zenderen, Delden and Doetinchem members, fall within the new Diessen Formation.

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Addendum: proposed lithostratigraphical definitions for the Miocene of the eastern Netherlands

Aalten Member (Fig. 9)

Status
Formal (Van den Bosch et al., 1975). Amended (this paper): classified as member in newly defined Groote Heide Formation, new lectostratotype section assigned. The Stemerdink unit is split of the member.

Lithological description
The Aalten Member starts at the base with a blackish sand with many molluscs, increasing glauconite content and increasing grain size upwards over a few metres, passing into clay with a high glauconitic content and coarser quartz grains. Further upwards, the glauconite and quartz sand content are decreasing to the top, changing into fatty clay. The succession is calcareous.

Depositional setting
Shallow near shore marine conditions.

Definition of lower boundary
Discordant contact (Savian phase and possibly also including the 'Early-Miocene Unconformity') from dark black-green glauconitic clay with shells (Miste Beds) to shallow marine dark grey clay and loam (Rupel Formation and local Veldhoven Formation). A lot of Chattian-early Miocene reworking was recorded at the base.

Definition of upper boundary
Sharp transition from a fatty, calcareous open-marine clay (traces of molluscs) to calcareous, silty layered brownish-grey clay (Stemerdink member).

Thickness indication
Ca. 3–8 m.

Geographical distribution
Achterhoek

Regional correlation
UK: absent; Germany: Formation of Ville; Belgium: Berchem and Bolderberg formations.

Age
Late Early-early Mid Miocene, late Burdigalian-Langhian. In any case, a lot of reworking with an origin from Chattian-early Miocene is recorded at the base of the Miste Bed.

Holostratotype

Well: NITG-number, name
Well 41E.3-67 (coördinates: +85.935, −25.025)

Depth (thickness) AH: x–x m (x m) below land surface
Interval 16.0–20.8 m (4.8 m)

Lectostratotype

Well: NITG-number, name
Boring B41G0024, De Haart (coördinates: 241020, 436702 (RD))

Depth (thickness) AH: x–x m (x m) below land surface
Interval 32.5–40.5 m (8 m)

Origin of name
Named after Aalten, a municipality in the east of the Dutch province of Gelderland, located near the German border.

Previous name(s)
None

Miste Bed

Status
Formal (Van den Bosch et al., 1975). Amended (Munsterman & Van den Bosch, 2021): classified as bed in newly defined Groote Heide Formation, new lectostratotype section assigned. Ticheloven bed has been reintroduced and split off at the top.

Lithological description
Miste always consists of sand, with increasing glauconite and coarser grain content upwards, but also a bit more clayey. Very molluscs-rich, in particular at the base. Glauconite, fossil-rich, 'bed' of shells forms the base of the Aalten Member, including a lot of reworking from Chattian-early Miocene. Horizon with phosphorite concretions near the apex.

Depositional setting
Warm shallow marine conditions (Van den Berg et al., 2000).

Definition of lower boundary
Discordant contact (Savian phase, possibly including 'Early-Miocene Unconformity') from dark black-green glauconitic sand with molluscs (Miste

Bed) to shallow marine dark grey clay and loam (Rupel Formation and local Veldhoven Formation). Late Oligocene, Chattian-early Miocene reworking was recorded at the base.

Definition of upper boundary
The lithology changes to clay and is less glauconite rich (minor). Maximum grain size increases (Ticheloven bed). Mollusc fauna is changing, especially the many Gastropods have disappeared and been replaced by large bivalves such as *Glycymeris* and *Arctica islandica*.

Thickness indication
Up to 4–5 m.

Geographical distribution
Very locally (Miste and south towards the German border) in the Achterhoek (Van den Bosch et al., 1975).

Regional correlation
UK: absent; Germany: Formation of Ville; Belgium: Berchem and Bolderberg formations

Age
Late Early-early Middle Miocene, late Burdigalian-early Langhian

Holostratotype

Well: NITG-number, name
Well 41E.3-75, Miste (coördinates: +87.880, Y = −24.000).

Depth (thickness) AH: x–x m (x m) below land surface
Interval: 1.25–4.10 m (2.85 m).

Lectostratotype

Well: NITG-number, name
Boring B41G0024, De Haart (coördinaten: 241020, 436702 (RD));

Depth (thickness) AH: x–x m (x m) below land surface
Interval: 36.5–41 m (4.5 m).

Origin of name
Miste is a hamlet in the municipality of Winterswijk, Gelderse Achterhoek, the Netherlands.

Previous name(s)
None

Ticheloven bed

Status
New. Formal (Munsterman & Van den Bosch 2021): reintroduced bed belonging to the Aalten Member, assigned new lectostratotype.

Lithological description
Dark grey-green to dark green-brown strong silty to sandy clay, changing into highly clayey and sandy loam. Few shells and glauconite are present. Usually glauconite-rich clay (= depending on the proximity of the coast), but for example in well Overkamp, there is a shell-rich sand with coarse glauconite present (= along the paleo-coast).

Depositional setting
Shallow marine.

Definition of lower boundary
Transition from strongly silty to sandy clay to strongly clayey sand with a phosphorite bed (Miste Bed) in the proximity and an increase in the number of gastropods.

Definition of upper boundary
Diffuse transition to shallow marine, clayey sand and clay (Stemerdink member). Maximum grain size (minimum values gamma-ray log, end of trend to lower values). Sometimes, sharply discordant contact with fluvioglacial gravel (Schaarsbergen Member, Drenthe Formation).

Thickness indication
Up until 4–5 m.

Geographical distribution
Common occurrence in Achterhoek (Van den Bosch et al., 1975).

Regional correlation
UK: absent; Germany: Formation of Ville; Belgium: Berchem and Bolderberg formations.

Age
middle Miocene, Langhian.

Holostratotype

Well: NITG-number, name
Well 34G1-1/43T (coördinates: $x = +89{,}387$ and $y = -3{,}829$; Janssen, 1967).

Depth (thickness) AH: x–x m (x m) below land surface
Interval

Lectostratotype

Well: NITG-number, name
Boring B41G0024, De Haart (coördinates: 241020, 436702 (RD))

Depth (thickness) AH: x–x m (x m) below land surface
Interval 32.5–36.5 m (4 m).

Origin of name
The name is derived from the Ticheloven farm, near the manually dug outcrop in the hamlet of Loo near Eibergen. In the 18th and 19th centuries, this was a brickyard.

Previous name(s)
(Upper part of and included in) Miste Bed

Stemerdink member (Fig. 9)

Status
Formal (Van den Bosch et al., 1975). Amended (in this paper): raised in hierarchy from bed and defined as member in Groote Heide Formation, assigned new lectostratotype section.

Lithological description
Silty layered brownish-grey clay, fatter towards the top with decreasing shell content (deepening sea), calcareous. Minor mica and glauconite are present.

Depositional setting
Shallow marine near-shore conditions.

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Definition of lower boundary
Diffuse transition to shallow marine, highly clayey and sandy loam (Ticheloven bed). Decrease in grain size, decrease in sand addition (minimum values gamma-ray log, trend break to higher values).

Definition of upper boundary
Sharp or sudden transition from grey-brown marine clay (with a trace of shells) to blackish non-calcareous, micaceous, shallow marine clay (Eibergen Member). Sharply discordant contact with fluvioglacial gravel (Schaarsbergen Member, Drenthe Formation).

Thickness indication
Until approximately 12 m.

Geographical distribution
Common occurrence in Achterhoek (Van den Bosch et al., 1975).

Regional correlation
UK: absent; Germany: Ville Formation; Belgium: Berchem and Bolderberg formations.

Age
middle Miocene, Langhian-early Serravallian

Holostratotype

Well: NITG-number, name
Well 41E.4-566 (coördinates: +93.990, −21.280).

Depth (thickness) AH: x–x m (x m) below land surface
Interval 2.3−8.5 m.

Lectostratotype

Well: NITG-number, name
Well B41G0024, De Haart (coördinates: 241020, 436702 (RD)).

Depth (thickness) AH: x–x m (x m) below land surface
Interval 21−32.5 m.

Origin of name
Named after the estate Stemerdink near Winterswijk.

Previous name(s)
None

Eibergen Member (Fig. 9)

Status
Formal (Van den Bosch et al., 1975). Amended (Munsterman & Van den Bosch 2021). Classified as member in a newly defined Groote Heide Formation, new lectostratotype section assigned (sample material holostratotype is insufficient). The upper part of the Eibergen Member, above the MMU, has been split off into the new Dale member.

Lithological description
Stiff blackish clay, moderately silty, glistening. Beds of very fine, low-glauconitic sand and loam. Decalcification of sand due to solution immediately after deposition. In the Achterhoek: stiff, mostly black clay with a high content of organic matter, strongly micaceous, silty beds in which little fine glauconite, a few metres above the base a very fine-sandy, somewhat greenish bed. Almost completely non-calcareous, microfossils are rare.

Depositional setting
Shallow marine near-shore conditions. The origin of the organic matter is unclear (detritus washed in from the hinterland or remains of seaweed?). A manatee was discovered in the type locality of the Eibergen Member, which live on 'kelp forests'. Virtually no benthic fauna, but bones of whales and large sharks.

Definition of lower boundary
Sharp transition to shallow marine calcareous clay. The Stemerdink member is about 10 to 15 m thick and is sharply distinguished at the top from Eibergen Member. This is immediately recognisable in boreholes: about a metre above the base of the Eibergen Member there is a striking sandy bed, this deposit is mostly completely non-calcareous. In contrast, the top of the Stemerdink Bed is always very calcareous and a much fatter clay, in particular westward. The gamma-ray log image shows a trend towards lower values.

Definition of upper boundary
Transition from black clay with a lot of mica, to greenish silty-sandy clay and clayey silts with fine glauconite (Dale member). The erosive contact is associated with the 'Mid-Miocene Unconformity'.

Thickness indication
Approx. 14 m.

Geographical distribution
Limited to eastern Netherlands (Achterhoek and Twente; Van den Bosch et al., 1975).

Regional correlation
UK: absent; Germany: Ville Formation; Belgium: Berchem and Bolderberg formations.

Age
middle Miocene, late Langhian- Serravallian.

Holostratotype

Well: NITG-number, name
Well 34G.3-13 (coördinates: +88.100, −11.640)

Depth (thickness) AH: x–x m (x m) below land surface
Interval 0–8.50 m

Lectostratotype

Well: NITG-number, name
Well B41G0024, De Haart (coördinates: 241020, 436702 (RD))

Depth (thickness) AH: x–x m (x m) below land surface
Interval 7–21 m (14 m).

Origin of name
Eibergen (Low Saxon: 'Eibarge') is a place in the municipality of Berkelland in the Achterhoek, province of Gelderland. The village of Eibergen is located along the small river Berkel, which flows into the Netherlands east of Eibergen and continuing onto the IJssel in Zutphen.

Previous name(s)
None

Dale member (Fig. 10)

Status
New. Formal (Present paper).

Lithological description
Dark grey-green clayey silt changing into green-grey silty clay, much glimmer and with little fine glauconite, non-calcareous.

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Depositional setting
Near coastal, shallow marine conditions

Definition of lower boundary
Transition from greenish clayey silt/silty clay with minor fine glauconite, to black clay with a lot of mica (Eibergen Member). The erosive contact is associated with the 'Mid-Miocene Unconformity'.

Definition of upper boundary
Erosive contact with shallow marine sand (Zenderen Member). Lithological transition from silty clay to sandy loam/silt to very fine sand.

Thickness indication
Up to 9 m

Geographical distribution
Limited to eastern Netherlands (Achterhoek and Twente; Van den Bosch et al., 1975).

Regional correlation
UK: absent; Germany: Inden Formation; Belgium: Diest Formation (p.p.)

Age
Late Miocene, early Tortonian

Holostratotype

> **Well: NITG-number, name**
> Well B40F1874, Gaanderen (coördinates: 219990, 439748 (RD))
>
> **Depth (thickness) AH: x–x m (x m) below land surface**
> Interval 160–168.5 m (8.5 m).

Origin of name
Dale is a hamlet in the Achterhoek municipality of Aalten, in the Dutch province of Gelderland. 'Dale' means valley. The hamlet is located at the low end of the western slope of the East Netherlands Plateau.

Previous name(s)
None

Zenderen Member (Fig. 10)

Status
Formal (Van den Bosch et al., 1975). Amended (Munsterman & Van den Bosch, 2021). Classified as member in a newly defined Diessen Formation, assigned new lectostratotype section.

Lithological description
Loam at the base, moderately humous, weakly sandy, changing to dark green extremely fine to moderately fine sand (63–210 µm), weakly silty, glauconitic, mostly non-calcareous.

Depositional setting
Near coastal, shallow marine conditions

Definition of lower boundary
Erosive contact with green silty-sandy clay, firm, moderately silty, lot of mica and fine glauconite. (Dale member, Diessen Formation). Often large shift to high values on the gamma-ray log.

Definition of upper boundary
Often, discordant contact with shallow marine, consolidated cohesive fine sands (Delden Member) or with various Quaternary units. The gamma-ray values are significantly lower in the Zenderen Member.

Thickness indication
Until 50 m.

Geographical distribution
Limited to eastern Netherlands (Achterhoek and Twente; Van den Bosch et al., 1975).

Regional correlation
Germany: Inden Formation; Belgium: Diest Formation (p.p.).

Age
late Miocene, Tortonian.

Holostratotype

> **Well: NITG-number, name**
> Well B28G172 (coördinates: +90.520, +18.240)
>
> **Depth (thickness) AH: x–x m (x m) below land surface**
> Interval 16.50–23.46 m (6.96 m)

Lectostratotype

> **Well: NITG-number, name**
> Well B40F1874, Gaanderen (coördinates: 219990, 439748 (RD))
>
> **Depth (thickness) AH: x–x m (x m) below land surface**
> Interval 120–168.5 m (48.5 m).

Origin of name
Zenderen is the second largest village in the Twente municipality of Borne in the Dutch province of Overijssel.

Previous name(s)
None

Delden Member (Fig. 10)

Status
Formal (Van den Bosch et al., 1975). Amended (Present paper). The Doetinchem member is split of at the top. Classified as member in a newly defined Diessen Formation, assigned new lectostratotype section.

Lithological description
Fine sands, weakly silty, moderately humous. Glauconite rich, goethite and phosphorite concretions. The phosphorite nodules (sandstone-like) with shell cores and impressions occur in beds, sometimes hard banks. The goethite consists of 'small coffee beans' in the coarse to extremely coarse fraction and occurs in beds. Very characteristic is the sudden appearance of the coarse grains in the succession.

Depositional setting
Marginal-shallow marine

Definition of lower boundary
Discordant contact with extremely fine sands, weakly silty, glauconitic, mostly calcareous (Zenderen Member).

Definition of upper boundary
Transition to dark green-grey to brown loam, strongly sandy, and clay, extremely silty. In the holostratotype section, the boundary is on top of 2 m shell bed.

Thickness indication
Up to 30 m

Geographical distribution
Limited to eastern Netherlands (Achterhoek and Twente; Van den Bosch et al., 1975).

Regional correlation
Offshore North Sea: absent; UK: absent; Germany: Inden Formation (Schophoven Seam); Belgium: Diest Formation (p.p.).

Age
late Miocene, late Tortonian

Holostratotype

Well: NITG-number, name
28G.3-1 (X-coördinates: +89.600; Y-coördinates: +15.790)

Depth (thickness) along hole: x–x m (x m)
Interval 1.40–7.50 (6.10)

Lectostratotype

Well: NITG-number, name
B40F1874, Gaanderen (coördinates: 219990, coördinates: −439748 (RD))

Depth (thickness) along hole: x–x m (x m)
Interval 96–120 m (24)

Origin of name
Delden is a small town in the Dutch province of Overijssel. It has been located in the municipality of 'Hof van Twente' since January 1, 2001. Before that, Delden was the capital of the Municipality of Delden.

Previous name(s)
None

Doetinchem member (Fig. 10)

Status
New. Formal. Classified as new member in a newly defined Diessen Formation, assigned new holostratotype section

Lithological description
Dark green-grey to brown loam, strongly sandy, and clay, extremely silty. Clay- and cemented beds are present.

Depositional setting
Marginal to shallow marine

Definition of lower boundary
In the holostratotype section, the boundary is on top of 2 m shell bed and underlying succession of fine sands, weakly silty, moderately humous. If the shell bed is absent, a transition from loam to fine sands is present, mirrored by a negative shift on the gamma-ray logs.

Definition of upper boundary
Discordant contact with coarse, molluscs-containing marine sand (Oosterhout Formation). The transition to the Oosterhout Formation coincides with the 'Late Miocene Unconformity'. The course of the gamma-ray log shows a remarkable jump to lower values.

Thickness indication
Up to 20 m

Geographical distribution
Limited to eastern Netherlands (Achterhoek and Twente; Van den Bosch et al., 1975).

Regional correlation
Offshore North Sea: absent; UK: absent; Germany: Kieseloölite Formation (Hauptkies Schichten); Belgium: Kasterlee Formation

Age
Late Miocene, latest Tortonian-Messinian.

Holostratotype

Well: NITG-number, name
B40F1874, Gaanderen (coördinates: 219990, coördinates: −439748 (RD))

Depth (thickness) along hole: x–x m (x m)
Interval 83–96 m (13)

Origin of name
Doetinchem is a municipality in the Achterhoek, in the Dutch province of Gelderland. Gaanderen is a village in the municipality of Doetinchem.

Previous name(s)
(Upper part of the) Delden Member