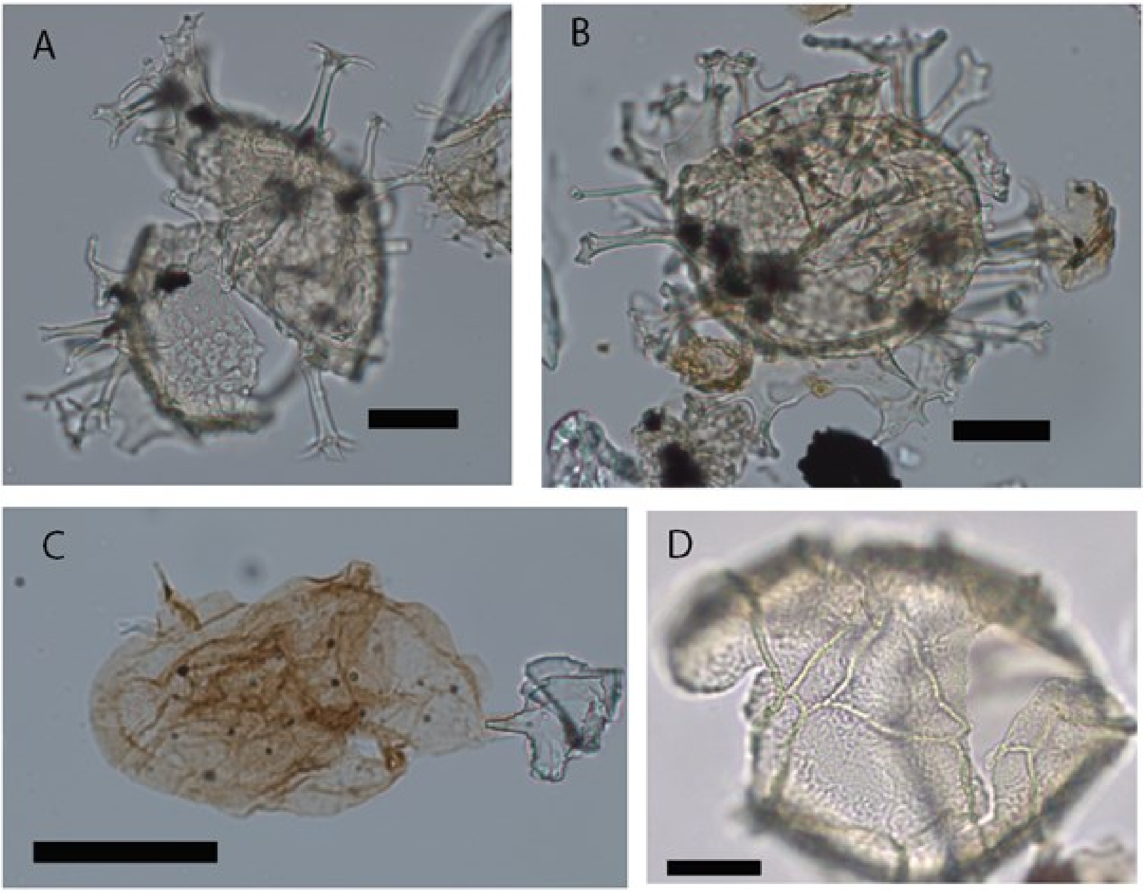
WarmingUPGOO
Geothermie & Opslag Opschaling



Biostratigraphy of Miocene strata in the Netherlands

door
A.J.P. Houben
17 januari 2025

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Inhoudsopgave

Executive summary

The subsurface within the ~300 – ~1500 m depth range is of particular interest for heat storage applications as it hosts a number of potential aquifers. This so-called ‘middle-deep’ domain, is relatively poorly mapped and subsurface data and models are scattered. By combining seismic interpretation and stratigraphic information from both ‘deep’ (hydrocarbon and geothermal) and ‘shallow’ (groundwater) boreholes, the quality of subsurface models of this depth domain can be updated. However, this requires a systematic approach to simultaneously address ‘deep’ and ‘shallow’ borehole stratigraphies and interpret seismic lines with a focus on important depositional surfaces and discontinuities (sequence stratigraphy framework) as well as the age of the sediments. This report presents a systematic dinoflagellate-cyst-based, biostratigraphic age-dating of 11 key deep wells and shallow boreholes comprising 189 samples capturing the Oligocene – Pleistocene interval. In addition, this report summarizes and synchronizes interpretations from 11 legacy wells and boreholes. Collectively this provides a good spatial cover of the onshore Netherlands. This is particularly important because hitherto the available biostratigraphic data were very skewed towards the Roer Valley Graben (RVG) in Noord-Brabant, for which a specific sequence stratigraphic framework was constructed.

The results are very encouraging. They allow for the identification of 5 key ‘unconformity bound units’, thereby confirming that the RVG-based framework can be extended into the rest of the Netherlands. Nevertheless, the study also addresses some concerns with regard to the diachronicity of Upper Miocene and younger lithostratigraphic units as defined in the Nomenclator for the Dutch subsurface. This new dataset serves as a foundation for ensuing seismic interpretation of the Paleogene - Neogene succession of the Netherlands. An initial inventory shows already that the results of this study align very well with seismically-traceable horizons. The latter will be worked out as part of WP1.1.2 in Warming^UP^*GOO* in 2025.

1 Introduction

Geothermal energy and subsurface heat storage are important aspects of the transition towards a sustainable heat-supply for the Netherlands. About 26% of the total heat demand can be provided by geothermal energy (MMIP4, update 2021) and large-scale heat storage (Aquifer Thermal Energy Storage or ATES, in Dutch referred to as hoge-temperatuuropslag, HTO) can substantially contribute to the efficiency of heat-supply systems (MMIP4, update 2021). Challenges for geothermal energy extraction and ATES with regards to derisking of the subsurface are - to some extent - comparable. Similarly, parallels exist when it comes to societal, financial and legal bottlenecks of both techniques. Previous activities of the WarmingUP program have indicated that the combined application of both techniques can yield an increase in efficiency. The WarmingUP Geothermal and Storage Upscaling (Warming^UP *GOO* in Dutch) program aims to expedite the application of these techniques in the Netherlands.

ATES and shallow geothermal energy production both utilize the subsurface. Although the depth-range for ATES (<~500 m) is typically different from the geothermal energy one (~500 - ~1500 m), on a regional to nation-wide scale, similar geological units (formations) are concerned. A firm knowledge and understanding of these units and the lateral continuity of their properties within this ~300 – ~1500 m depth is a pivotal requirement for ATES and shallow-mid-range geothermal energy. Subsurface characterization contributes to a reliable assessment of the potential, efficiency, business case and effects of individual projects. Reliable information results in faster and better supported decision-making and licensing processes. Inadequate subsurface characterization may lead to higher uncertainties, possible risk of failure and will increase exploration costs, which obstructs the initiation of new projects.

A major challenge is that the subsurface structure within the ~300 – ~1500 m depth range, the so-called ‘Middle-deep’ subsurface, is relatively poorly documented. Current data and associated subsurface models are on the one hand derived from ground-water-related activities (predominantly the Upper 100 m). On the other hand, decades of exploration for and exploitation of hydrocarbons and deep geothermal energy have predominantly addressed the >1500 m depth range and respective models are based on the integration on seismic interpretation, with the use of depth calibration from ‘deep’ legacy wells.

An assessment of the data used in TNO-GDN’s DGM, REGIS and DGM-Deep subsurface models in WP1.1.1 of the Warming^UP *GOO* project (Houben et al., 2023a) has shown that through combining seismic interpretation and stratigraphic interpretations from both ‘deep’ (hydrocarbon and geothermal) and ‘shallow’ (groundwater) boreholes, the quality of subsurface models of the ‘Middle-deep’ domain can be improved. However, this requires a systematic way to simultaneously interpret seismic lines, and ‘deep’ wells and ‘shallow’ borehole stratigraphies. This can be achieved by recognizing depositional surfaces and discontinuities (sequence stratigraphy).
Over the past few years, it has emerged that the marine Miocene strata that reach substantial thicknesses in the Roer Valley Graben (RVG) can be clearly differentiated based on their sequence stratigraphic character (Munsterman et al., 2019). These authors in fact proposed that the (former) Miocene Breda Formation (now Breda Subgroup), is to be subdivided into two formations; which are bounded by stratigraphic surfaces (by Munsterman et al., 2019 termed ‘unconformities’); viz. the Early Miocene Unconformity (EMU, base of the ‘new’ Groote Heide Formation), Middle Miocene Unconformity (MMU, base of the ‘new’ Diessen Formation) and the Late Miocene

Unconformity (LMU, top of the Diessen Formation, Table 1). Albeit this framework is clEarly suitable for establishing subsurface model units in the RVG (see Siebels et al., 2024), it has not been applied outside this basin and its immediate vicinity, with the exception of the Achterhoek area (Munsterman et al., 2024).

Table 1.1: Schematic overview of approximate ages of the lithostratigraphic units of the marine Eocene-Pleistocene strata in het Netherlands. Note that the Groote Heide and Diessen Formations now reflect the subdivision of the former Breda Fm. The stratigraphic surfaces provide a link to the seismo- and sequence stratigraphic interpretation of the North Sea Group surfaces.

Epoch	Stage	Group	Formation (1)	Formation (2)	Stratigraphic surface
Pleistocene	Gelasian	Upper North Sea	Maassluis Fm.	Maassluis	Base Pleistocene
Pliocene	Piacenzian		Oosterhout Fm.	Oosterhout	
	Zanclean				LMU
Miocene	Messinian		Breda Fm.	Diessen	
	Tortonian				MMU
	Serravallian			Groote Heide	
	Langhian				
	Burdigalian				EMU
	Aquitanian	Middle North Sea	Veldhoven Fm.	Veldhoven	
Oligocene	Chattian				Savian
	Rupelian		Rupel Fm.	Rupel Fm.	Pyrenean
Eocene	(...)	Lower North Sea	Dongen Fm.	Dongen Fm.	

The present study provides an important step for systematic sequence stratigraphic mapping and modelling of the Middle-deep subsurface of the onshore Netherlands, by age dating marine-influenced Paleogene-Neogene successions. This is achieved through the analysis of organic-walled dinoflagellate cysts (dinocysts) in 11 wells and boreholes, encompassing 189 newly analyzed samples, and a consistent review of 11 recent legacy biostratigraphic studies, spread out across the Netherlands. The latter activity was included to make sure that this report serves as a standard for future mapping and modelling activities in the 'Middle-deep' depth domain. This also allows for an extension of the approach and proposed lithostratigraphy outlined by Munsterman et al. (2019) into areas other than the RVG and its immediate surroundings.

The 22 respective age-breakdowns allow for the identification of sequence stratigraphically significant surfaces as depicted in Table 1.1. The results are used to explore the expression of the surfaces on petrophysical logs and seismic data. Note that this study purely deals with biostratigraphic age dating and does not entail a 'relabeling' of the lithostratigraphic interpretations.

2 Approach, materials and methodology

2.1 Approach

A first step in the construction of a sequence-stratigraphically based modelling of the marine Neogene of the Netherlands is to stratigraphically constrain surfaces or 'unconformities' in the depth domain. Over the past years extensive studies focused on the Roer Valley Graben area specifically (Munsterman et al., 2019; Siebels et al., 2024), which led these authors describe a number of key surfaces and to propose an updated lithostratigraphic nomenclature, in which the (former) Breda Fm. was subdivided in the Groote Heide (base is EMU) and Diessen (Base is MMU, top is LMU) formations respectively (Munsterman et al., 2019). Albeit these authors consistently refer to these surfaces as unconformities and suggest the presence of (minor) discontinuities, evident time-hiatuses are not necessarily applicable, since they can also represent phases of transgression, winnowing and condensation (see e.g., Rasmussen and Dybkjær, 2014).
According to Siebels et al. (2024), the Early Miocene Unconformity (EMU) occurs as a Middle Burdigalian to Early Langhian hiatus. The Middle Miocene Unconformity (MMU) is a Latest Serravallian to earliest Tortonian hiatus. The Late Miocene Unconformity (LMU) is to be sought at the base of the Pliocene, albeit its precise chronostratigraphic context is not further elucidated. In addition to correlating these Miocene surfaces, some other (younger as well as older) important age-transitions, viz. the Eocene-Oligocene boundary (by some referred to as the Pyrenean tectonic phase), the base of the Miocene (linked to the Savian phase), the Early-Late (Zanclean-Piacenzian) Pliocene boundary and the base of the Quaternary (base Pleistocene) are also highlighted in this study.
In order to arrive at biostratigraphic age-interpretations, this study relies on the analysis of organic-walled dinoflagellate cysts (dinocysts), which are retrieved from sedimentary material from a nation-wide selection of wells and boreholes. Dinocysts are resistant capsules (cysts), which are, as part of a complex life-cycle, produced by dinoflagellates, a group of unicellular eukaryotic algae (Figure 2.1).

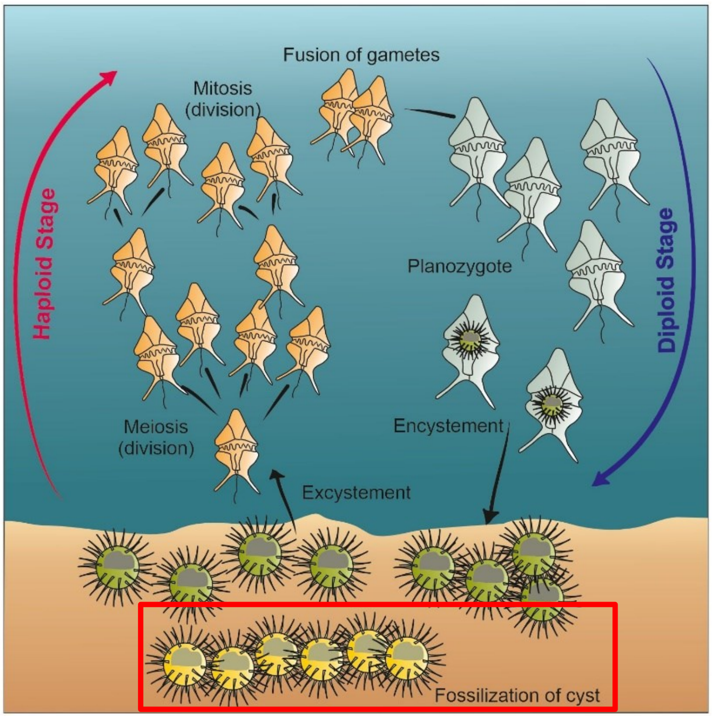

Figure 2.1: Schematic representation of dinoflagellate life cycle. Dinoflagellates divide and reproduce in the water column. After encystment and subsequent excystment the empty cyst is highly resistant and typically fossilizes in the sediment. Adapted from Marret and De Vernal (2024).

They are morphologically very diverse and generally distinct, which leads the taxonomy of this microfossil group to be very well-resolved. Dinocysts are very abundant in the typical shallow marine, siliciclastic dominated depositional settings such as those of the Paleogene and Neogene of northwestern Europe. Therefore, they are considered as the primary means of biostratigraphic correlation in this setting. The isolation of dinocysts requires a laboratory treatment (Section 2.3) involving the use of acids to dissolve mineral components (silicates and carbonates) and subsequent sieving.

The biostratigraphic interpretation is based on originations and extinctions of specific dinocyst species, which are calibrated to the geological time in so-called reference sections. Some of these events provide the foundation for so-called “zones”, which may include multiple simultaneous events. Conventionally, the zonation of Munsterman and Brinkhuis (2004) is used in the Netherlands. However, several new reference sections and zonations have been made over the past two decades, thereby including more potentially relevant events/species and a better understanding of potential diachronicity. An overview of relevant zonations and events is presented in Section 2.4.

The results section (Section 3) of this report consists simply of biostratigraphic age-breakdowns per well/borehole, including those based on legacy data (Section 3.2). Points of uncertainty are indicated by providing remarks. Detailed range-charts, displaying the species composition per sample are included as appendices. The results are graphically compared to the available petrophysical log data for each borehole, in order to assess the position and expression of the respective ‘unconformities’.
The combined results are discussed (Section 4) and the significance of the biostratigraphic results for seismic interpretation is briefly illustrated by discussing preliminary seismic interpretation results from a parallel mapping project within the Geological Survey.

2.2 Borehole selection and sampling

Because this study will contribute to a foundation for mapping and modelling of the 'Middle-deep' subsurface of the Netherlands, a sampling strategy was adopted that focused on selecting boreholes in (a) areas that lack reliable biostratigraphic control, (b) proximity to high-quality SCAN or other seismic lines and/or (c) are in a critical position to link with the area that is well mapped/modelled on the basis of 'shallow' boreholes (in DGM-Regis, see Houben et al., 2023). We consider the RVG and its immediate vicinity and the Achterhoek area to be sufficiently studied with the disclosed in the publications of Munsterman et al. (2019), Siebels et al., (2024) and Munsterman et al. (2024), which is why no wells/boreholes from these regions were selected. As can be seen in Figure 2.2 and Table 2.1, the area in the central part of the Netherlands where the base of the North Sea Group reaches substantial thickness (Zuiderzee Low area) is already covered by four wells, therefore no new wells were selected. These legacy data are however included in the inventory (section 3.2).

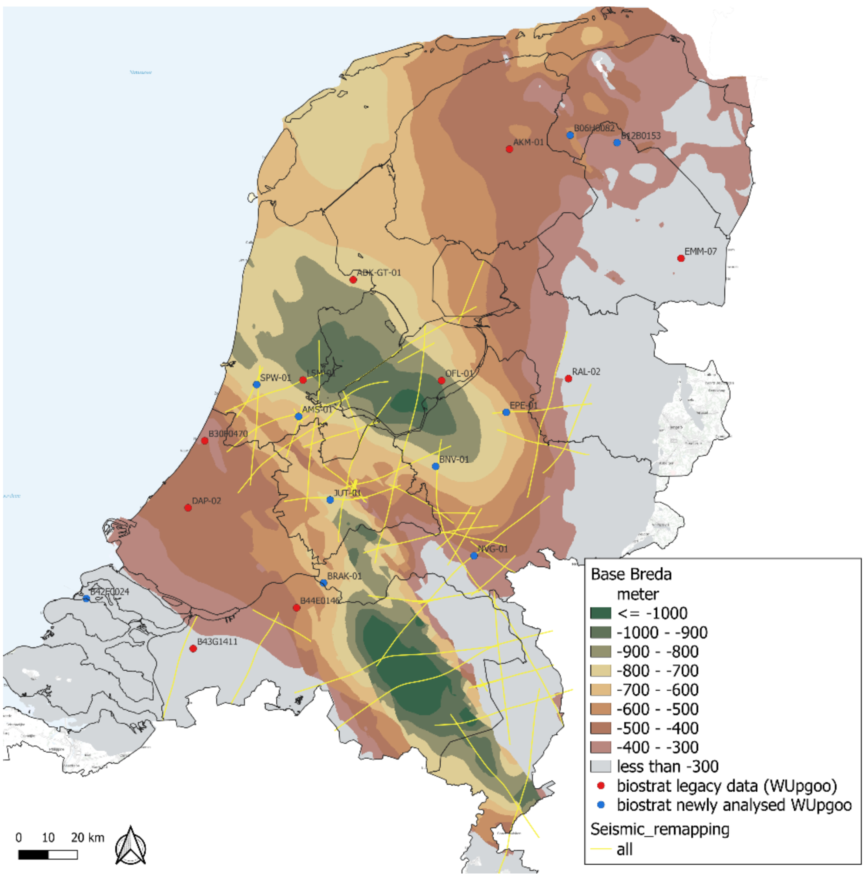

Figure 2.2 Map displaying the base of the Upper North Sea Group and the position of wells/boreholes that were sampled and analyzed in this study (blue) and discussed as part of the legacy data inventory (red dots). The yellow lines indicate the position of high-quality seismic lines that were acquired as part of the SCAN-program.

Table 2.1 Wells and boreholes included in this report: sample type, depth trajectory and number of samples. CUT= Ditch cutting sample, AL= Airlift sample, CO=Core sample. Newly analysed boreholes indicated in bold.

Well/Borehole	New /Legacy	Reference (legacy)	Sample Type	Interval (m MD)	Number of samples	Processing Lab
ADK-GT-01	Legacy	Houben (2023b)	CUT	510 – 1000	13	TNO
AKM-03	Legacy	Munsterman (2020)	CUT	200 – 600	13	TNO
AMS-01	**New**		**CUT**	**160 – 660**	**18**	**CGG**
B06H0082 (Marum)	**New**		**AL**	**230 -570**	**16**	**CGG**
B12B0153 (Peize)	**New**		**AL**	**172 – 380**	**13**	**TNO**
B30F0470 (Noordwijk)	Legacy	Munsterman (2021)	AL	130 – 454	80	TNO
B42F0024 (Den Osse)	**New**		**AL**	**118 – 216**	**9**	**TNO**
B44E0146 (Hank)	Legacy	Munsterman (2016)	AL	100 – 404	75	TNO
B43G1411 (Kruisland)	Legacy	Houben (2023c)	AL	202 – 252	13	TNO
BNV-01-S1	**New**		**CUT**	**240 – 1080**	**23**	**CGG**
BLA-01	Legacy	Houben (2023b)	CUT	400 – 950	12	TNO
BRAK-01	**New**		**CUT**	**300 – 800**	**16**	**TNO**
DAP-GEO-2 (Delft)	Legacy	Munsterman (2023)	CO	364 – 415	16	TNO
EMM-07	Legacy	Munsterman (2019)	CUT	70 – 370	17	TNO
EPE-01	**New**		**CUT**	**220 – 810**	**26**	**TNO**
JUT-01	**New**		**CUT**	**230 – 900**	**21**	**TNO**
LSM-01	Legacy	Houben (2023b)	CUT	550 – 940	9	TNO
NVG-01	**New**		**CUT**	**140 – 650**	**12**	**TNO**
OFL-01	Legacy	Houben (2023a)	CUT	400 – 1110	15	TNO
RAL-02	Legacy	Munsterman (2022)	CUT	60 - 500	28	TNO
SPL-01	**New**		**CUT**	**210 - 645**	**11**	**TNO**
SPW-01	**New**		**CO**	**438 – 868**	**24**	**CGG**

All studied wells/boreholes, except SPW-01, which uniquely had extensive core material from the Neogene succession preserved, have a gamma-ray log available. All other ‘deep’ wells were rotary drilled, from which only ditch cuttings were recovered. This implies that downhole contamination of ‘younger’ fossils is an issue. The selected ‘shallow’ boreholes (B-numbers), were drilled using airlift technology, which yields mixed samples from one meter thick intervals. Nevertheless, this sample type bears a minimal likelihood of downhole contamination. All samples are taken from the collection of the TNO-GDN Core Repository in Zeist.

Combined the new sampling and legacy data will provide quite a balanced coverage across the Netherlands, including "basins" in which the Upper North Sea Group is developed in great thickness and in areas where it is present, but thin. A gap remains in the northwestern and far northern extremities, this may be filled in the future as part of other, ensuing mapping activities in the north, outside of this project Warming^UP *GOO*.

2.3 Palynological processing, analysis and taxonomic identification

The majority of the samples were processed by Nico Janssen using the facilities of Utrecht University and TNO-GDN. In those instances, 35% hydrochloric acid and 30% hydrofluoric acid were used for carbonate and silicate digestion respectively. The resultant kerogens were sieved over a 10 µm mesh. Slides were mounted in glycerine jelly and sealed with a cover slip.

The samples processed by CGG in Conwy (UK) followed another procedure, including acid digestion with hydrochloric acid (HCl) and subsequently macerated by leaving the sample in 75% hydrofluoric acid overnight. The resulting residue was strained and filtered through 125 µm and 15 µm nylon sieve meshes to concentrate the dinoflagellate cysts. No oxidation was applied, kerogens transferred to a coverslip, air-dried and mounted onto glass slides using Petropoxy 154 resin as permanent mounts.

The slides were microscopically examined using a transmissive light Leica DM-LB2 microscope fitted with a Leica MC170 digital camera on 787.5× magnification. All slides were analyzed quantitatively (up to about 150 palynomorphs). Quantitative trends are not discussed in this study, but the palynological assemblage data can be assessed in terms of paleo-environmental significance in the future.

Dinocyst taxonomy follows that cited in Williams et al. (2017). *?Heteraulacacysta* sp. 1 and *Impagidinium "densiverrucosum"* and *Spiniferites pseudofurcatus* ssp. *reticulatus* are not listed in this lexicon.

The specimens here assigned to ?*Heteraulacacysta* sp. 1 are very thin-walled, small (<50 µm), lacking indications of paratabulation other than their epicystal archaeopyle. The latter feature places them in the Subfamily Goniodomoideae. Their lack of processes excludes them from the genera *Homotryblium* and *Polysphaeridium* and their absent paratabulation excludes inclusion in *Dinopterygium*. Well known species of *Heteraulacacysta* are typically significantly larger and thicker walled. Other species of *Heteraulacacysta* have an extinction in Eocene or older strata. Albeit calibration is lacking, it seems this taxon is constrained to Upper Miocene and Pliocene assemblages. Illustrative photomicrographs are depicted in Plate 1C.

Impagidinium "densiverrucosum" was proposed by Zevenboom (1995), but was not validly published. It is therefore still considered a manuscript name. *Impagidinium densiverrucosum* is morphologically comparable to *I. verrucosum*, but differs by having more closely spaced and larger verrucae. It furthermore differs by also having verrucae on the paracingular paraplates. A representative specimen is depicted in Plate 1D.

Spiniferites pseudofurcatus ssp. *reticulatus* is an unpublished species of *Spiniferites* that is relatively large (>150 µm) that in terms of process termination approximates *Spiniferites pseudofurcatus.* It is distinct in having a fairly coarse reticuLate surface of the ectophragm. Kothe and Andruleit (2007) report similar, albeit by these authors referred to as "granulate" specimens from the Upper Miocene in Germany as *Spiniferites pseudofurcatus granulatus*. In the present study, these specimens typically occur within Upper Miocene and Lower Pliocene assemblages. A representative specimen is depicted in Plate 1A-B.

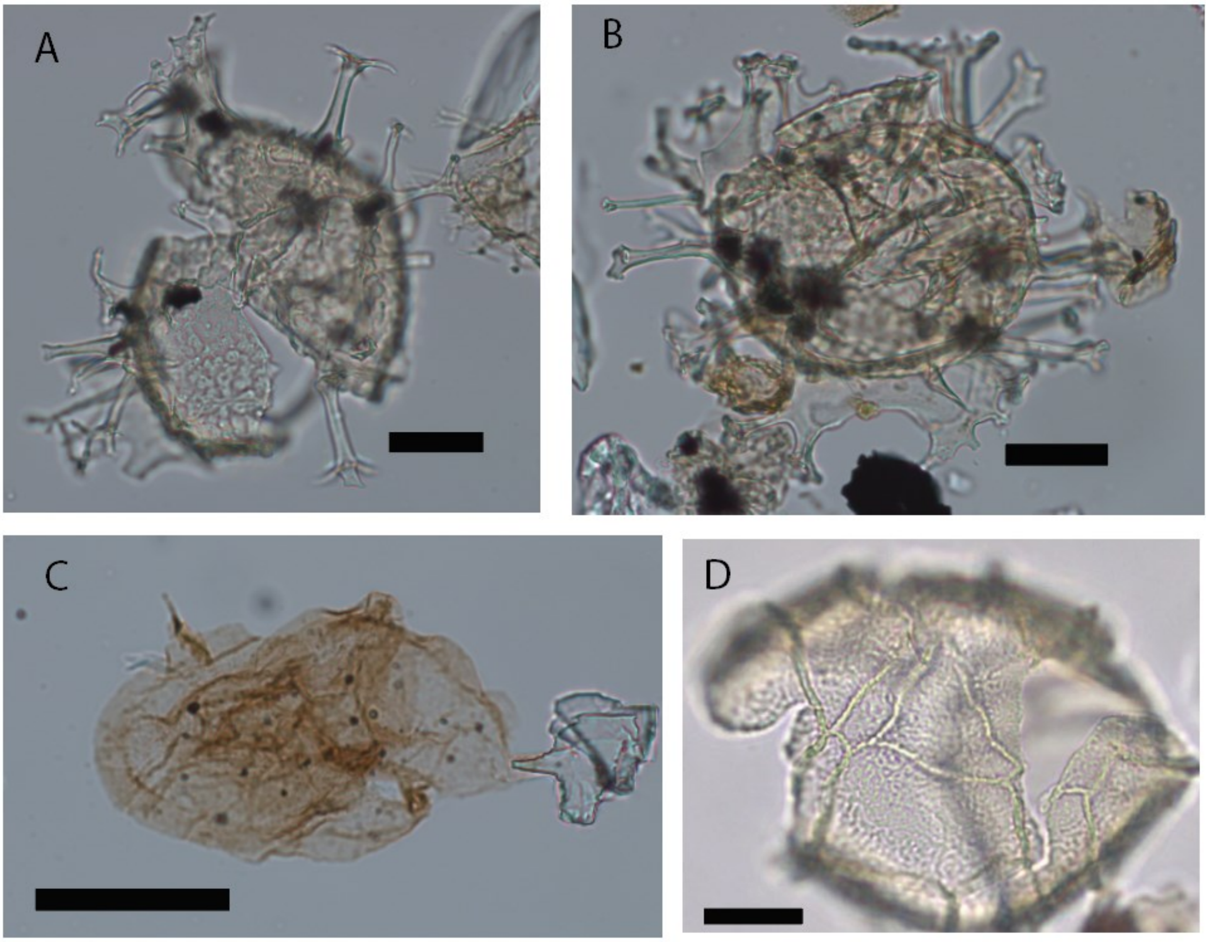

Plate 1: Photomicrographs of new, or informally described dinocysts encountered in this study; A-B: *Spiniferites pseudofurcatus* ssp. *reticulatus*, C: ?*Heteraulacacysta* sp.1 and D: *Impagidinium 'densiverrucosum'* Zevenboom 1995. The scale bare is 20 um.

2.4 Chronostratigraphic and biozonal interpretation

TNO-GDN typically uses the Miocene dinocyst zonation of Munsterman & Brinkhuis (2004) and the Oligocene zonation of Van Simaeys et al. (2005). Both zonations are based on consistent dinocyst events recognized in a number of Dutch and Belgian boreholes. They lack firm chronostratigraphic calibration and are indirectly tied to palaeomagnetic, calcareous plankton and/or foraminiferal calibrations (Zevenboom, 1995; De Verteuil and Norris, 1996). Over the past two decades substantially more work on the Oligocene-Pliocene was carried out, within the North Sea and more distant Atlantic basins (e.g., Louwye et al., 2004; Dybkjær and Piasecki, 2010; Louwye and De Schepper, 2010; Schreck et al., 2012; De Schepper et al., 2017; Dybkjær et al., 2021) . Because these studies provide additional, potentially significant events and elucidate some of the uncertainty reLated to diachronicity of events, a synthesis of events and zonations, now re-calibrated against the Latest version of the geological timescale (Gradstein et al, 2020) is here presented (Figure 2.3). This now also provides a comprehensive view of the Early Oligocene to Early Pleistocene in one graph. Distinction is made between taxa that are zonal indicators (black in Figure 2.3) and those that are additional events (grey in Figure 2.3).
The zonation of Dybkjaer & Piasecki (2010) and Dybkjaer et al. (2021) is more detailed for the Early Miocene, while that of Munsterman & Brinkhuis (2004) is more differentiated for the Middle to Late Miocene. It hampers from the same lack of calibration as the scheme of Munsterman and Brinkhuis (2004). Substantial work has been carried out on the Upper Miocene and Pliocene of Belgium (Louwye et al., 2004; Louwye and De Schepper, 2010), where nannofossil-based independent control is available. While a zonation is not constructed, some potentially significant first and last occurrence events are identified. The largest progress has been made in the north Atlantic region, where through International Ocean Drilling numerous paleomagnetically dated reference sections became available (summarized by Schreck et al., 2012). While these sites are clEarly distant from the North Sea Basin, their reliable calibration warrants consideration while interpreting the Pliocene successions of the Netherlands.
In general, it is clear that most of the Miocene last occurrences that define zonal boundaries are more or less synchronous, at least on a stage-level. A conspicuous exception is the last occurrence of *Systematophora placacantha*, which is anomalously young in the Netherlands and Italy. Potentially significant events that are not included in zonal scheme of Munsterman and Brinkhuis (2004) are the first occurrence of *Habibacysta* plexus in the Langhian, the first and last occcurrence of *Gramocysta verricula* (Serravallian and Late Tortonian respectively), the short Tortonian range of *Impaginium 'densiverrucosum'* of Zevenboom 1995 and the Tortonian first occurrence of *Barssidinium evangelineae*. Numerous events allow for a fairly robust Pliocene statigraphy, at least allowing for a differentiation of the Zanclean and the Piacenzian. A whole series of dinocyst species goes extinct at the base of the Quaternary, notably the genus *Barssidinium*. Further differentiation of the Lowermost Pleistocene (Lower Gelasian) are based on specific assemblages associated with Gelasian glacial phases (see Kuhlmann et al., 2006; Dearing Crampton-Flood et al., 2020). These are discussed whenever applicable. Typically dinocyst-based stratigraphy becomes difficult after the Early Gelasian, due to scarce assemblages and low diversity.
For the sake of comparability to the previous studies, the zonation of Munsterman and Brinkhuis (2004) is still used in this study. However, additional events are considered for age-determination.

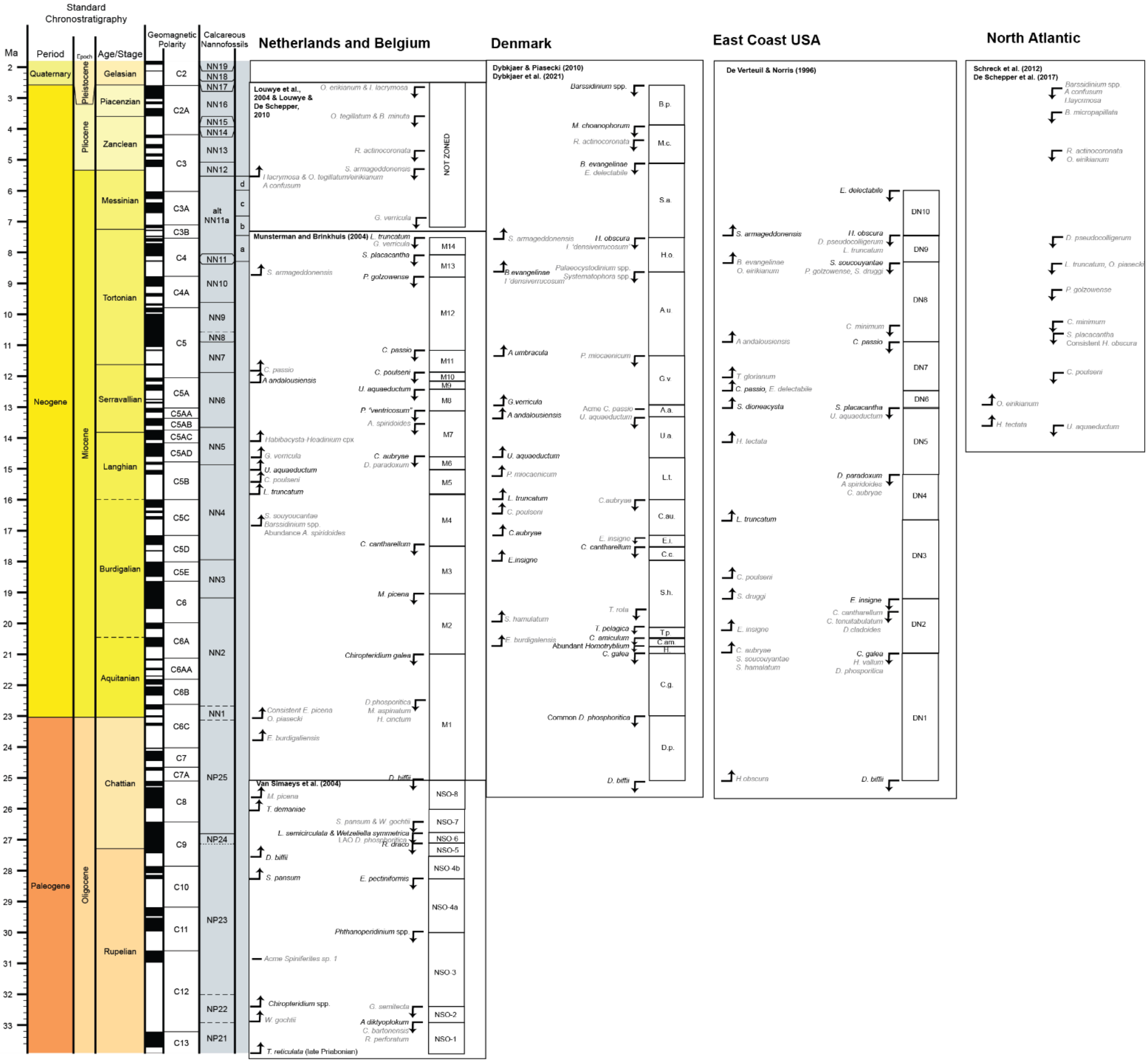

Figure 2. Overview of the regional zonations and frameworks now recalibrated to the most recent geological timescale of Gradstein et al. (2020). Upward arrows indicate first occurrences and downward arrows indicate last occurrences. Events indicated in black are zonal boundary criteria.

3 Results

3.1 New data

The palynological yield of all samples was very good. However, the quality and richness of palynological preparations by CGG is substantially poorer. CGG did not employ any active oxidation agents and used similar sieving techniques. Therefore it seems that the prolonged (overnight) hydrofluoric exposure had a negative impact on the quality of the processing. Nevertheless, the quality of most of the wells/boreholes processed by CGG was still acceptable for further interpretations. The only exception is an interval in well BNV-01-S1, which is marked accordingly. Albeit the quantitative trends are not specifically considered in this study, it is clear that the Oligocene to earliest Pleistocene is consistently marine influenced. Dinocysts are consistently present in abundance. Only in the Uppermost samples selected from boreholes, dinocysts are absent. A more detailed paleo-environmental analysis of this dataset is currently ongoing and will appear as a separate TNO-GDN-report.

The following section outlines the biostratigraphic arguments for age-dating of the respective intervals. The biostratigraphic results are subsequently transposed to a well-section figure in which the petrophysical log-response (gamma-ray, GR and/or sonic velocity, DT) is evaluated. This is then used to identify the stratigraphic surfaces (EMU, MMU and LMU, others only when distinctive). Each section is concluded with a summary table in which the approximate extent of temporal hiatuses in association with the surfaces is indicated.

3.1.1 Amstelland-1 (AMS-01)

Interval 180 – 220 m (2 samples): age dating impossible
Remark: Only reworked and long-ranging taxa were recorded. Particularly Upper Cretaceous reworking is abundant.

Interval 250 – 420 (5 samples): likely Early Pleistocene, Gelasian
This interpretation is based on:

- LOD of *Habibacysta tectata* at 340 – 360 m MD
- LOD of *Operculodinium israelianum* at 240-250 m MD
- First downhole abundant reworking at 420 m MD

Remark: The recovered associations are sparse. However, no Pliocene markers were recorded. This suggests the base Pleistocene is located between 420 and 460 m.

Interval 460 – 500 (2 samples): Late Pliocene, Piacenzian
This interpretation is based on:

- LOD of *Barssidinium* spp. at 500 m MD

Sample 500 – 520: Uncertain
Remark: Possibly this interval, which is also reflected by high sonic velocities (Figure 3.9), is developed as a so-called ‘crag’; a sedimentary package consisting of shallow-marine shell hash. A similar unit is seen in the south of Netherlands where it is referred to as the Sprundel Member of

the Oosterhout Fm. The dominance of the inner linings of benthic foraminifera, with the absence of dinocysts corroborates this hypothesis.

Sample 520 – 540 m: Late Miocene, Late Tortonian (Zone M13), or older

This interpretation is based on:

- LOD of *Systematophora placacantha*
- LOD of *Labyrinthodinium truncatum*
- LOD of *Reticulatosphaera actinocoronata*

Sample 540 – 560 m: Middle Miocene, Late Serravallian (Zone M11)

This interpretation is based on:

- FOD+LOD of *Cannosphaeropsis passio*
- FOD of *Labyrinthodinium truncatum*

Sample 560 – 580 m: Early-Middle Miocene, Late Burdigalian (Zone M4)

This interpretation is based on:

- LOD of *Cousteaudinium aubryae* at 580 m MD
- LOD of *Distatodinium paradoxum* at 580 m MD
- LOD of *Apteodinium spiridoides* at 580 m MD
- Absence of *Labyrinthodinium truncatum* and *Cerebrocysta poulseni*

Sample 580 – 600 m: Early Miocene, Aquitanian (Zone M2)

This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum* at 600 m MD
- LOD of *Thalassiphora pelagica* at 600 m MD

Sample 600 – 610 m: Oligocene, Late Rupelian to Early Chattian (Zone NSO-6)

This interpretation is based on:

- LOD of *Membranophoridium aspinatum* at 610 m MD
- LOD of *Wetzeliella symmetrica* at 610 m MD

Sample 620 – 630 m: Early Oligocene, Middle Rupelian (Zone NSO-3)

This interpretation is based on:

- LOD of *Chiropteridium galea* at 630 m MD
- LOD of *Enneadocysta pectiniformis* at 630 m MD
- LOD of *Phthanoperidinium* spp. at 630 m MD

Interval 650 – 670 m Middle Eocene (2 samples): Early Lutetian Zone E3 of Mudge and Bujak (1996)

This interpretation is based on:

- LOD of *Eatonicysta ursulae* at 650 m MD
- LOD of *Phthanoperidinium distinctum* at 650 m MD
- LOD of *Diphyes colligerum* at 650 m MD
- LOD of *Hystrichosphaeridium tubiferum* at 650 m MD
- LOD of *Areosphaeridium michoudii* at 650 m MD

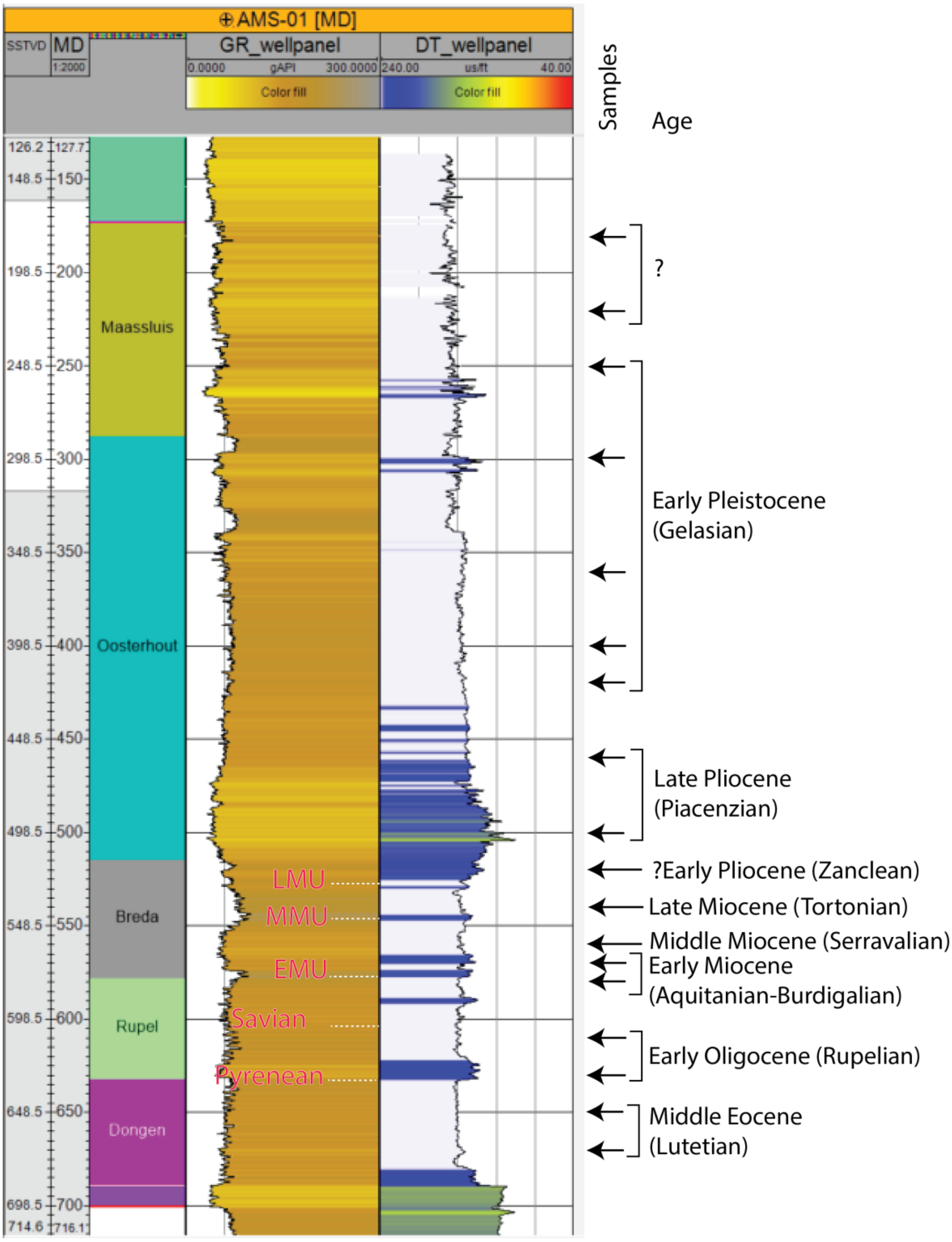

Figure 3.1: Summary of age-interpretation transposed on combined GR-DT-log for well AMS-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). The EMU and MMU are picked at the maximum GR-value, which likely represents a transgressive surface and consequent glauconite-muscovite enrichment at/above the 'unconformity'. The LMU lacks a clear log-response, but signifies the base of a number of cleaning upward cycles. The base Pleistocene cannot be precisely picked based on log-character, but is sufficiently deeper than the base Maassluis Fm. as currently interpreted.

Table 3.1: Summary age breakdown of well AMS-01 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Phase
180 - 220	ND
250 - 420	Early Pleistocene, Gelasian
>420 Base Pleistocene	
460 – 500	Late Pliocene, Piacenzian
530 LMU (*Latest Tortonian-Messinian, Zanclean absent or condensed*)	
540	Late Miocene, Late Tortonian (Zone M13)
540 MMU (*Early Tortonian absent*)	
560	Middle Miocene, Serravallian (Zone M11)
580	Early Miocene, Late Burdigalian (Zone M4)
582 EMU (*Early Burdigalian absent*)	
600	Early Miocene, Aquitanian (Zone M2)
607 Savian (*Late Chattian – Early Aquitanian absent*)	
610	Early – Late Oligocene, Late Rupelian to Early Chattian (Zone NSO-4)
630	Early Oligocene, Early Rupelian (Zone NSO-3)
632 Pyrenean (*Middle-Late Eocene absent*)	
650 - 670	Early Eocene, Early Lutetian (Zone E3)

Remark: The sequence between the EMU and MMU, which corresponds to the Groote Heide Fm. is very thin, and likely very condensed.

3.1.2 Marum (B06H0082)

Sample 230 m: Early Pleistocene, Gelasian

This interpretation is based on:

- Increased reworking
- LOD of *Filisphaera filifera*

Interval 240 – 271 m (3 samples): Late Pliocene, Piacenzian

This interpretation is based on:

- LOD of *Barssidinium* spp. at 240 m MD
- LOD of ?*Heteraulacacysta* sp. 1 at 240 m MD
- LOD of *Operculodinium eirikianum* at 240 m MD

Interval 289.5 – 340 m (3 samples): Early Pliocene, Early Zanclean

This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata* at 289.5 m MD
- FOD of *Invertocysta lacrymosa – tabulata* at 310 m MD
- FOD of *Barssidinium pliocenicum* at 340 m MD

Interval 370 – 460 m (4 samples): Late Miocene, Late Tortonian (Zone M13), or older

This interpretation is based on:

- FOD of *Selenopemphix armageddonensis* at 370 m MD
- FOD of *Barssidinium evangelineae* at 370 m MD
- FOD of *Amiculosphaera umbracula* at 429 m MD
- FOD of *Impagidinium "densiverrucosum"* at 460 m MD

- LOD of *Systematophora placacantha* at 460 m MD
- FOD of *Operculodinium eirikianum* at 460 m MD
- FOD of *Achomosphaera andalousiensis* at 460 m MD

Interval 491 – 520: Early Langhian (Zone M5)

This interpretation is based on:

- FOD of *Cerebroycsta poulseni* at 491 m MD
- LOD of *Cousteaudinium aubryae* at 491 m MD
- LOD of *Distatodinium paradoxum* at 491 m MD
- LOD of *Apteodinium spirioides* at 491 m MD

Sample 548 m: Early Miocene, Late Burdigalian (Zone M4)

This interpretation is based on:

- FOD of *Cousteaudinium aubryae*
- FOD of *Sumatradinium soucouyantae*

Sample 560 m: Early Miocene, Late Aquitanian - Early Burdigalian (Zone M3, or older)

This interpretation is based on:

- FOD of *Apteodinium spiridoides*
- LOD of *Cordosphaeridium cantharellum*

Sample 570 m: Oligocene, Early Chattian (NSO-6), or older

This interpretation is based on:

- LOD of *Wetzeliella symmetrica*
- LOD of *Homotryblium floripes*

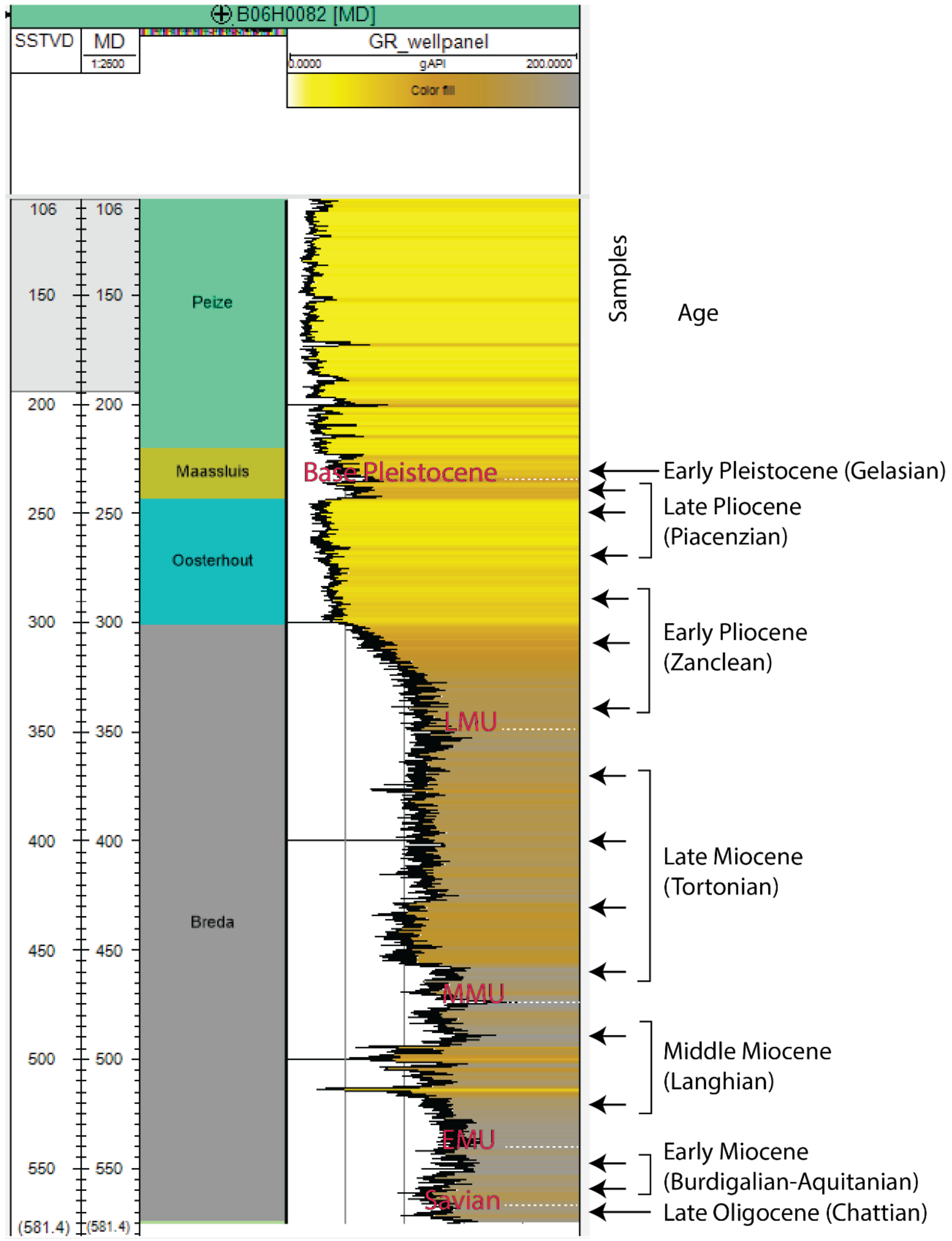

Figure 3.2: Summary of age-interpretation transposed on combined GR-DT-log for borehole B06H0082. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). The EMU and MMU are picked based at GR-maxima (see caption to Figure 3.1). The LMU corresponds to the base of a cleaning/coarsening upward trend into the Lower Pliocene.

Table 3.2: Summary age breakdown of borehole B06H0082 and suggested position of regional unconformities.

Interval / Sample (m MD)	Age / Phase
230	Early Pleistocene, Gelasian
237 Base Pleistocene	
240 - 271	Late Pliocene, Piacenzian
289.5 – 340	Early Pliocene, Zanclean
350 LMU (*Messinian absent*)	
370 - 460	Late Miocene, Late Tortonian (Zone M13)
475 MMU (*Early Tortonian absent*)	
491 - 520	Middle Miocene, Early Langhian (Zone M5-6)
548	Early Miocene, Late Burdigalian (Zone M4)
540 EMU (*no hiatus discernable*)	
560	Early Miocene, Late Aquitaninian to Early Burdigalian (Zone M3), or older
565 Savian (*Late Chattian to Early Aquitanian absent*)	
570	Late Oligocene, Early Chattian (NSO-6), or older

Remark: The Middle Miocene succession is likely condensed, the Serravallian may be present between 460 and 490 m.

3.1.3 Peize (B12B0153)

Sample 171-172: Uncertain – not marine

Interval 191 – 210 (2 samples): Late Pliocene, Piacenzian

This interpretation is based on:

- LOD of *Barssidinium* spp. at 191 m MD
- LOD ?*Heteraulacacysta* sp. 1 at 191 m MD

Interval 230 - 330 m (9 samples): Early Pliocene, Early Zanclean

This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata* at 230 m MD
- LOD of *Melitasphaeridium choanophorum* at 230 m MD

Interval 350 - 365 m: Late Miocene, Latest Tortonian (Zone M14)

- LOD of of *Spiniferites pseudofurcatus* ssp. *reticulatus* at 350 m MD
- LOD of *Ataxiodinium zevenboomi* at 350 m MD
- FOD of *Operculodinium eirikianum* at 350 m MD
- FOD+LOD of *Impagidnium "densiverrucosum"* at 365 m MD
- FOD of *Invertocysta lacrymosa-tabulata* at 365 m MD

Sample 380 m: Early Oligocene, Middle Rupelian (Zone NSO-3)

This interpretation is based on:

- LOD of *Phthanoperidinium* spp.
- LOD of *Chiropteridium galea*
- FOD of *Chiropteridium galea*
- LOD of *Deflandrea phosphoritica*

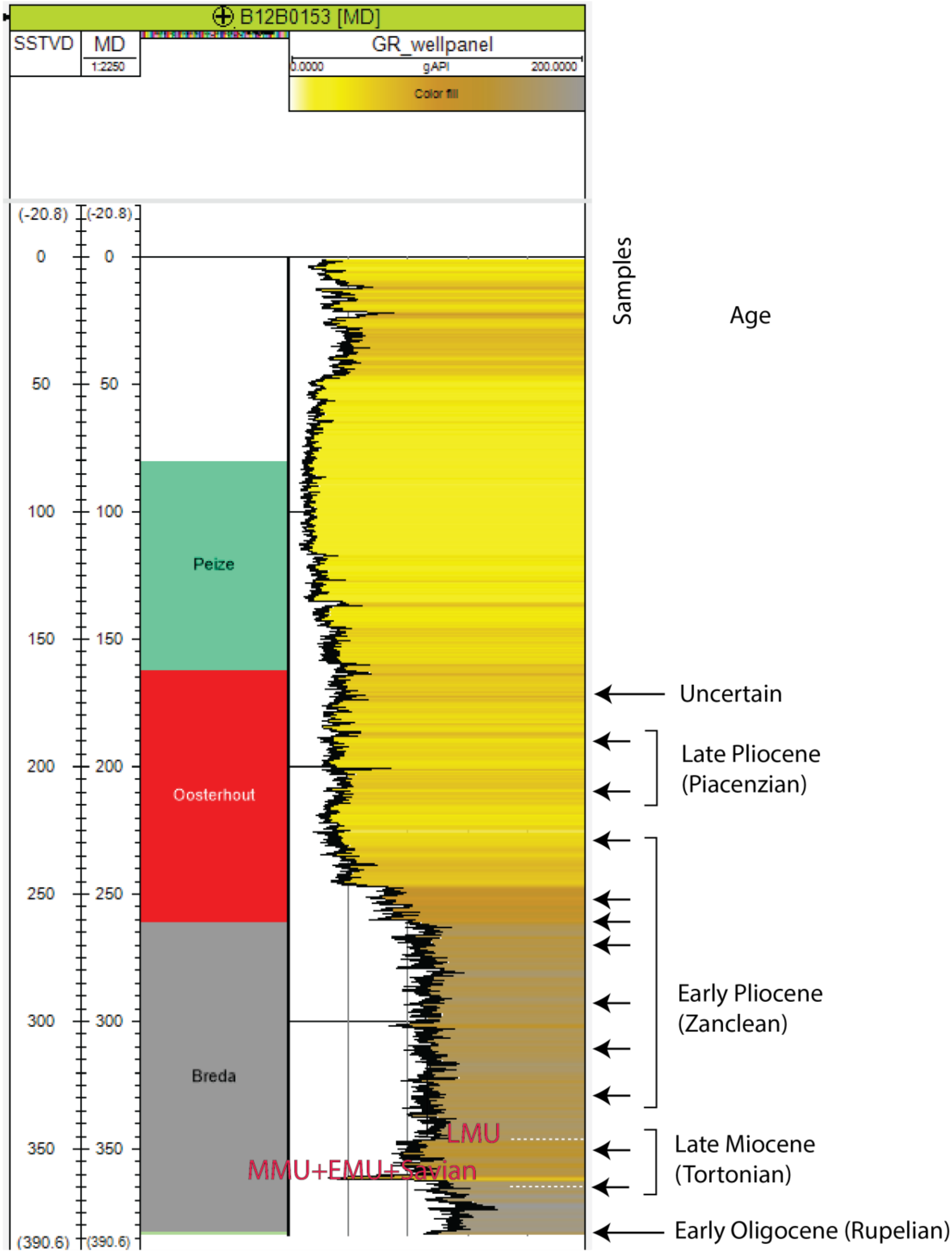

Figure 3.3: Summary of age-interpretation transposed on combined GR-DT-log for borehole B12B0153. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). The (Upper) Miocene sequence is very thin, which contradicts the thick interpreted Breda Subgroup equivalent as provided on Dinoloket.

Table 3.3: Summary age breakdown of borehole B12B0153 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Phase
191 - 210	Late Pliocene, Piacenzian
230 - 330	Early Pliocene, Early Zanclean
350 LMU (*Messinian absent*)	
350 – 650	Late Miocene, Late Tortonian (Zone M14)
365 MMU + EMU + Savian (*Late Rupelian to Early Tortonian is absent*)	
380	Early Oligocene, Middle Rupelian (Zone NSO-3)

3.1.4 Den Osse (B42F0024)

<u>Samples 118 m MD: Early Pleistocene, Gelasian</u>
This interpretation is based on:

- LOD of *Habibacysta tectata*

<u>Interval 130 – 149 m MD (2 samples): Uncertain</u>
<u>Remark:</u> These two samples are barren. These samples are taken from shell hash dominated material. These may correspond to the Pliocene Sprundel Mb.

<u>Interval 169.5 - 190 m MD (2 samples): Late Pliocene, Piacenzian, or older</u>
This interpretation is based on:

- LOD of *Operculodinium tegillatum* at 169.5 m MD
- LOD of *Invertocysta lacrymosa* at 169.5 m MD
- LOD of *Barssidinium graminosum* at 190 m MD

<u>Remark:</u> Abundant *Pediastrum* indicates fresh-water influence at 169.5 m. Abundant Paleo-and Mesozoic reworking is noted at 169.5 m.

<u>Sample 200 MD: Early Pliocene, Early Zanclean</u>
This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata* at 200 m MD
- LOD of *Melitasphaeridium choanophorum* at 200 m MD

<u>Sample 205 m: Late Miocene, Late Tortonian (Zone M14)</u>

- FOD of *Invertocysta lacrymosa – tabulata* 205 m MD
- FOD of *Achomosphaera andalousiensis* at 205 m MD
- FOD of *Amiculosphaera umbracula* at 205 m MD
- FOD of *Ataxiodinium zevenboomii* at 205 m MD
- FOD of *Barssidinium evangelineae* at 205 m MD
- LOD of *Cordosphaeridium minimum* at 205 m MD
- LOD of *Impagidinium "densiverrucosum"* at 205 m MD
- FOD of *Operculodinium eirikianum* at 205 m MD

<u>Sample 210 m: Middle Miocene, Late Langhian - Early Serravallian (Zone M6-7)</u>
This interpretation is based on:

- LOD of *Hystrichosphaeropsis obscurum*
- LOD of *Systematophora placacantha*

- LOD of *Labyrinthodinium truncatum*
- FOD of *Labyrinthodinium truncatum*
- FOD of *Habibacysta-Headinium* group
- LOD of *Unipontedinium aquaeductus*
- FOD of *Unipontedinium aquaeductus*
- LOD of *Apteodinium spiridoides*

<u>Sample 216 m: Early Oligocene, Late Rupelian (NSO-5)</u>

This interpretation is based on:

- LOD of *Rhombodinium draco*
- LOD of *Deflandrea phosphoritica*
- LOD of *Wetzeliella gochtii*
- LOD of *Licracysta semicirculata*
- FOD of *Distatodinium* cf. *biffii*

<u>Remark:</u> Abundant Middle Eocene (Bartonian) reworking is recorded.

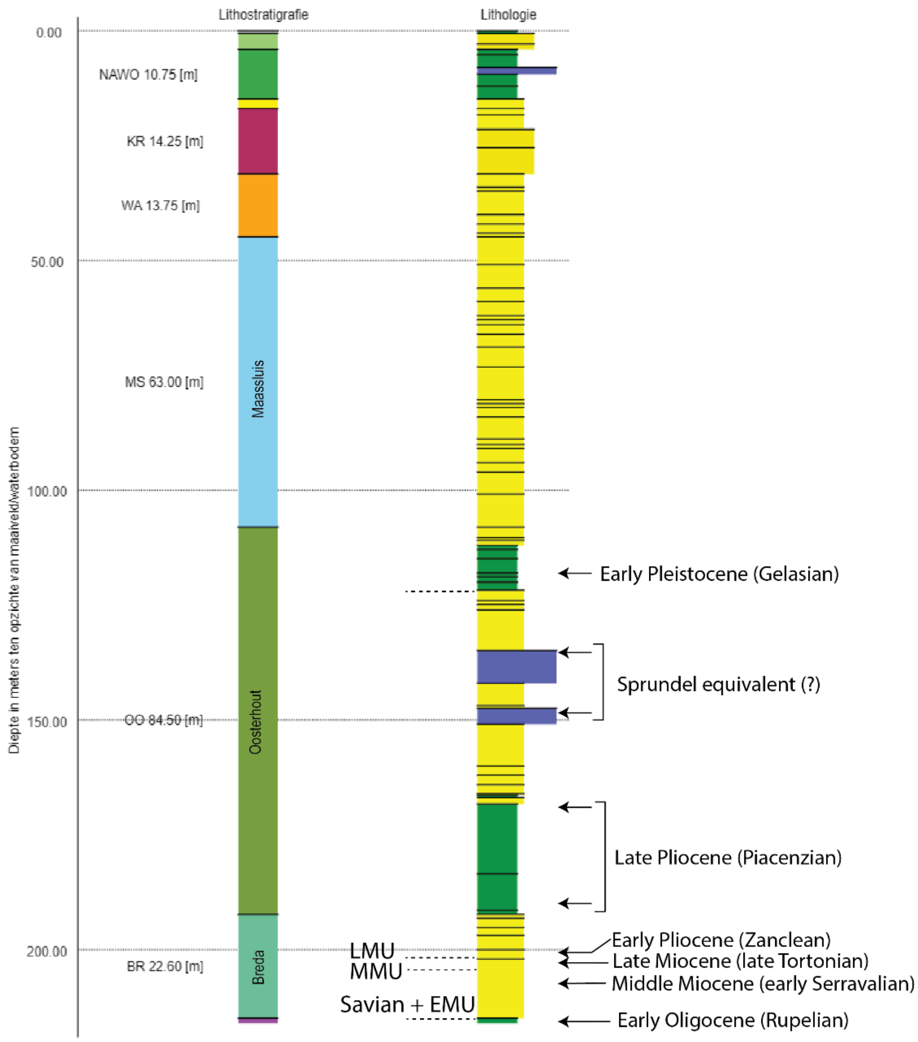

Figure 3.4: Summary of age-interpretation compared to lithostratigraphic and lithology interpretation for borehole B42F0024. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). The Savian and the EMU amalgamate. The same applies to the MMU and the LMU. The base of the Pleistocene appears to be deeper than the base of the Maassluis Fm.

Table 3.4: Summary age breakdown of borehole B42F0024 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Phase
118	Early Pleistocene, Gelasian
?? Base Pleistocene	
169.5 - 190	Late Pliocene, Piacenzian
200	Early Pliocene, Zanclean
205 LMU (*Latest Tortonian – Messinian absent*)	
205	Late Miocene, Late Tortonian (Zone M14)
207 MMU (*Late Serravallian - Early Tortonian absent*)	
210	Middle Miocene, Late Langhian - Early Serravallian (Zone M6-7)
EMU + Savian (*Chattian to Langhian absent*)	
216	Early Oligocene, Late Rupelian

3.1.5 Barneveld-1-S1 (BNV-01-S1)

The sample set was processed by CGG, with poor palynological recovery. Therefore it is likely that quite some markers are not recognizable. The results of this well are to be considered of relatively low confidence (see note on interval 720 – 800 m).

<u>Interval 240 – 320 m (4 samples): Likely Pleistocene</u>

This is interpretation is based on:

- Absence of marine palynomorphs

<u>Interval 350 – 470 m (4 samples): Pliocene, not further differentiated</u>

This interpretation is based on:

- LOD of ?*Heteraulacacysta* sp. 1 at 350 m MD
- LOD of *Melitasphaeridium choanophorum* at 350 m MD
- LOD of *Barssidinium graminosum* at 390 m MD
- FOD of *Achomosphaera andalousiensis* at 470 m MD

<u>Interval 510 – 680 m (5 samples): Late Miocene, Late Tortonian (Zone M14)</u>

This interpretation is based on:

- LOD of *Hystrichosphaeropsis obscura* at 510 m MD

<u>Interval 720 – 800 m (3 samples): uncertain, older than Late Tortonian (Zone M12)</u>

This interpretation is based on:

- LOD of *Systematophora placacantha* at 720 m MD
- LOD of *Palaeocystodinium golzowense* at 720 m MD

<u>Remark:</u> The samples from this interval are very poorly preserved and of low-diversity. They lack Middle Miocene markers, but this does not exclude a Middle Miocene age.

<u>Sample 840 m: Middle Miocene, Late Langhian (Zone M7), or older</u>

This interpretation is based on:

- LOD of *Apteodinium spiridoides*

<u>Interval 880 – 1040 m (5 samples): Late Burdigalian (Zone M4), or older</u>

This interpretation is based on:

- LOD of *Cousteaudinium aubryae* at 880 m MD

- LOD of *Distatodinium paradoxum* at 920 m MD

<u>Sample 1080 m: Early Miocene, Early Burdigalian (Zone M2)</u>

This intperetation is based on:

- LOD of *Cordosphaeridium cantharellum*
- LOD of *Membranilarnarcia picena*

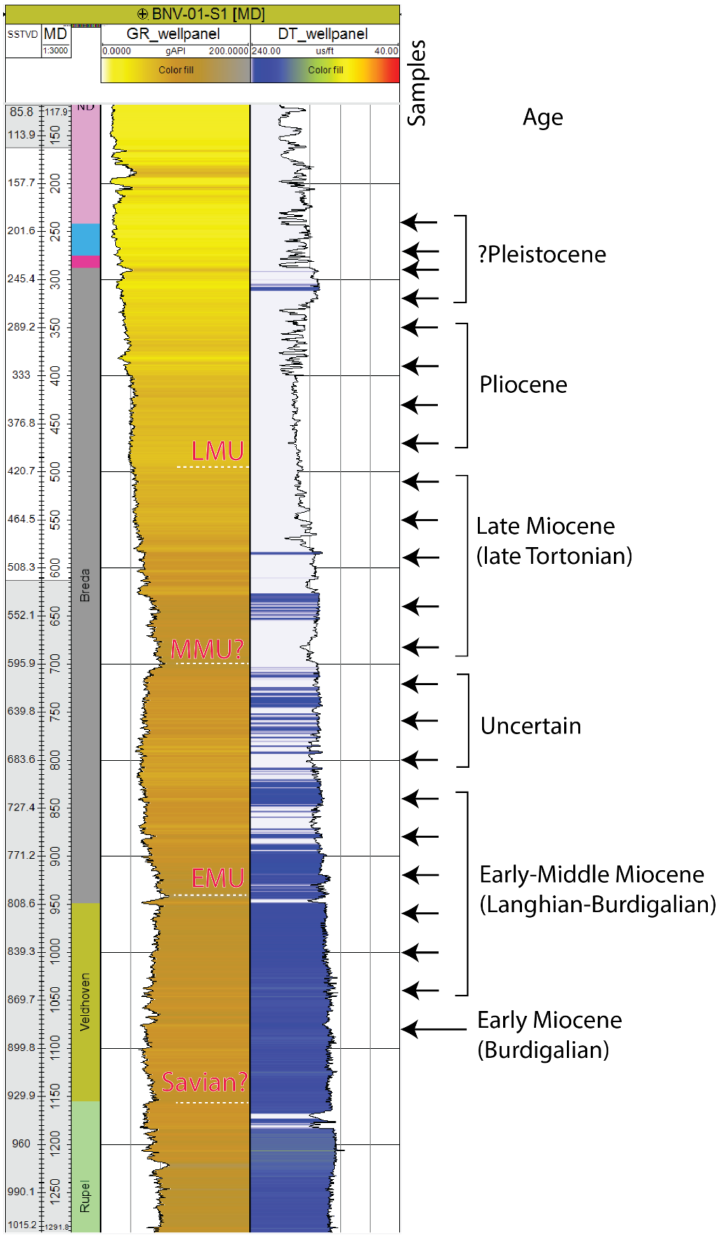

Figure 3.5: Summary of age-interpretation transposed on combined GR-DT-log for well BNV-01-S1. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). The EMU can be confidently picked within the Burdigalian on the basis of a GR-maximum, signifying a transgressive surface on top of the Veldhoven Fm. Due to poor preservation the precise position of the MMU is uncertain. It is provisionally picked on the basis of a GR maximum entangled between Langhian and Tortonian age sediments. The LMU lacks a conspicuous log-response and occurs within a gradual cleaning/coarsening upward trend. The base Pleistocene is not confidently recorded.

Table 3.5 Summary age breakdown of well BNV-01-S1 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	**Age / Unconformity**
350 - 470	Pliocene, Piacenzian, or older
500 LMU (*Messinian absent, Zanclean probably condensed*)	
510 – 680	Late Miocene, Late-Latest Tortonian (Zone M13 -14)
?700 MMU (*Early Tortonian absent*)	
720 - 800	Uncertain: Middle Miocene, Serravallian?
840	Middle Miocene, Late Langhian-Early Serravallian (Zone M7)
880 - 1040	Early Miocene, Late Burdigalian (Zone M4), or older
?940 EMU (*no hiatus discernable*)	
1080	Early Miocene, Early Burdigalian (Zone M2)

3.1.6 Brakel-1 (BRAK-01)

Sample 300 m: Late Pliocene, Piacenzian

This interpretation is based on:

- LOD of *Barssidinium* spp.
- LOD of ?*Heteraulacacysta* sp.1
- LOD of *Invertocysta lacrymosa – tabulata*

Sample 360 m: Late Pliocene, Early Piacenzian

This interpretation is based on:

- LOD of *Batiacasphaera micropapillata* at 360 m MD

Sample 410 m MD: Early Pliocene, Early Zanclean, or older

This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata*
- LOD of *Operculodinium eirikianum*
- LOD of *Melitasphaeridium choanophorum*

Interval 460 – 610 m MD (6 samples): Late Miocene, Latest Tortonian (Zone M14)

This interpretation is based on:

- LOD of *Barssidinium evangelineae* at 460 m MD
- LOD of *Hystrichosphaeropsis obscura* at 460 m MD
- LOD of *Impagidinium "densiverrucosum"* at 460 m MD
- LOD of *Gramocysta verricula* at 490 m MD
- LOD of *Labyrinthodinium truncatum* at 520 m MD
- LOD of *Dapsilidinium pseudocolligerum* at 520 m MD
- FOD of *Operculodinium eirikianum* at 550 m MD
- FOD of *Barssidinium evangelineae* at 550 m MD

Sample 640 m: Middle Miocene, Middle Langhian (Zone M5), or older

This interpretation is based on:

- LOD of *Cousteaudinium aubryae* at 640 m MD
- LOD of *Systematophora placacantha* at 640 m MD
- LOD of *Palaeocystodinium golzowense* at 640 m MD

Sample 670: Uncertain

Remark: The sample at 670 m MD is anomalous; it is overwhelmingly dominated by open marine organic-walled dinoflagellate cysts of the *Spiniferites* complex and *Systematophora placacantha*. As a consequence stratigraphic marker taxa were not recorded.

Interval 700 - 720 m MD: Early Miocene, Middle Burdigalian (Zone M3)

This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum* at 700 m MD
- LOD of *Exochosphaeridium insigne* at 700 m MD
- LOD of *Cribroperidinium tenuitabulatum* at 700 m MD
- FOD of *Cousteaudinium aubryae* at 700 m MD

Interval 740 – 760 m: Early Miocene, Late Aquitanian to Early Burdigalian (Lower Zone M2)

This interpretation is based on:

- LOD of *Thalassiphora pelagica* at 740 m MD

Sample 800 m MD: Late Oligocene, Early Chattian (Zone NSO-6), or older

This interpretation is based on:

- LOD of *Distatodinium biffii* at 800 m MD
- LOD of *Wetzeliella gochtii* at 800 m MD
- LOD of *Chiropteridium galea* at 800 m MD
- LOD of *Deflandrea phosphoritica* at 800 m MD
- LOD of *Membranophoridium aspinatum* at 800 m MD
- LOD of *Homotryblium* spp. at 800 m MD

Remark: Several occurrences of reworked Eocene to Early Oligocene taxa were recorded.

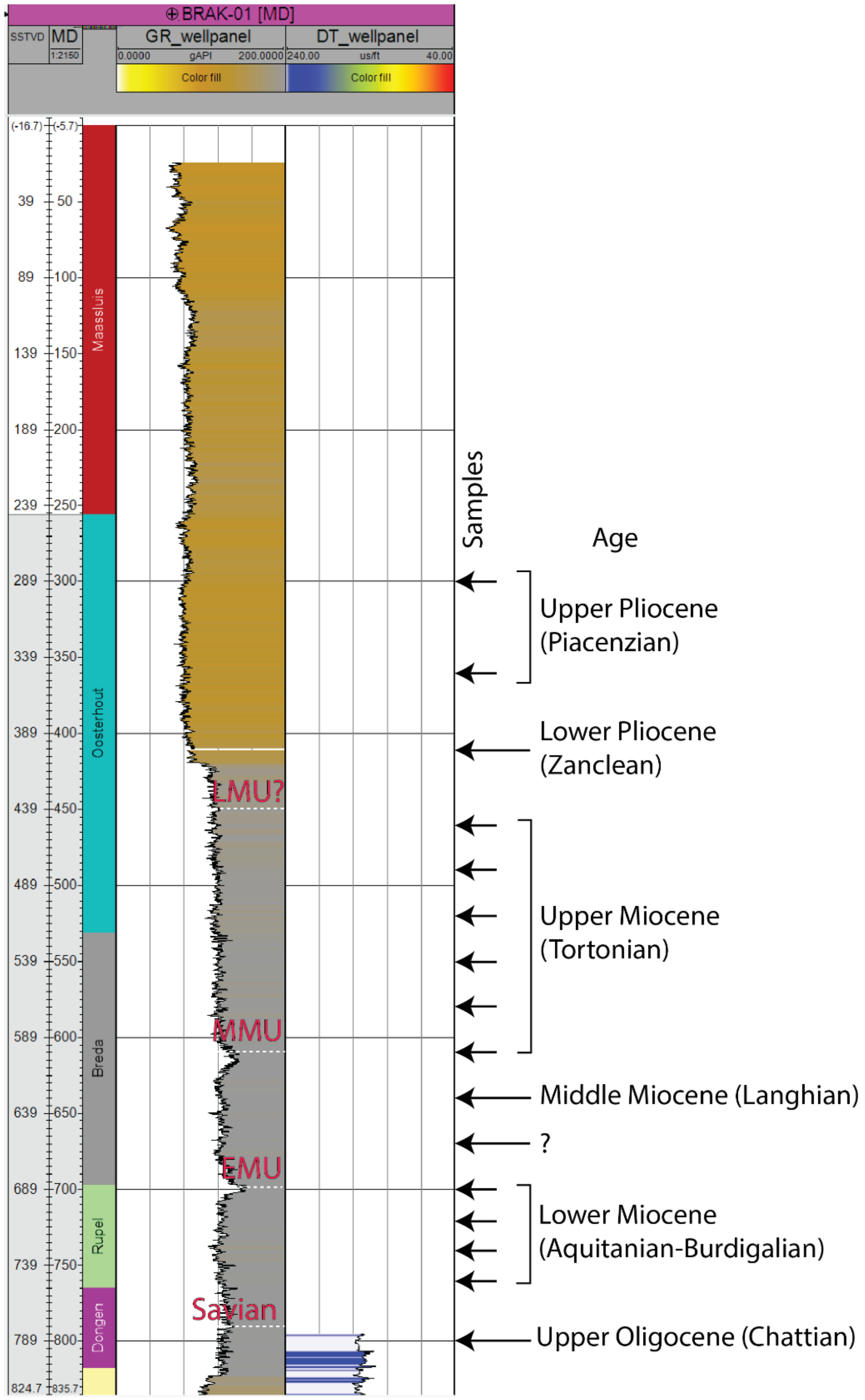

Figure 3.6: Summary of age-interpretation transposed on combined GR-DT-log for well BRAK-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). The identification of the expanded Lower Miocene (Aquitanian – Burdigalian) and Upper Oligocene sediments below 700 m challenges the interpreted Rupel and Dongen Fm. It seems more likely the Veldhoven Fm. is developed here. The EMU and MMU are indicated by GR-maxima, ascribed to transgressive surfaces above the respective 'unconformities'. Again the LMU is difficult to pick based on log-character. The conspicuous shift to cleaner values at about 425 m is due to a casing shoe and does not reflect a major lithological change. Nevertheless, the base of the Pliocene does not coincide with the currently interpreted base of the Oosterhout Fm., which lies at a deeper level (535 m).

Table 3.6 Summary age breakdown of well BRAK-01 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	**Age / Unconformity**
300 - 360	Late Pliocene, Piacenzian
410	Early Pliocene, Early Zanclean
?450 LMU (*Messinian absent*)	
460 - 610	Late Miocene, Latest Tortonian (Zone M14)
610 MMU (*Early-Middle Tortonian absent, Serravallian possibly condensed below*)	
640	Middle Miocene, Early Langhian (Zone M5)
700 - 720	Early Miocene, Late Burdigalian (Zone M3)
700 EMU (***no hiatus discernable***)	
740 - 760	Early Miocene, Late Aquitanian to Early Burdigalian (Zone M2)
790 Savian (*Middle Chattian – Early Aquitanian absent*)	
800	Late Oligocene, Early Chattian (NSO-6)

3.1.7 Epe-1 (EPE-01)

Interval 220 – 270: Earliest Pleistocene, Early Gelasian

This interpretation is based on:

- LOD of *Impagidinium multiplexum* at 220 m MD
- LOD of *Operculodinium israelianum* at 220 m MD

Remark: The abundant presence of *Impagidinium multiplexum* suggests a correlation to the specific Marine Isotope Stages 96 – 97 (2.46 Ma).

Interval 300 – 360 m (2 samples): Late Pliocene, Piacenzian, or older

This interpretation is based on:

- LOD of *Barssidinium graminosum* at 300 m MD

Interval 390 - 420 m (2 samples): Early Pliocene, Early Zanclean

This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata* at 390 m MD
- LOD of *Melitasphaeridium choanophorum* at 390 m MD
- LOD of *Operculodinium eirikianum* at 390 m MD
- FOD of *Invertocysta lacrymosa – tabulata* group at 420 m MD

Remark: The LMU is positioned between 450 and 420 m MD. It seems that Messinian strata are not present, but this solely based on negative evidence (lack of Messinian markers). If indeed correct, about 2 Myr is missing in the hiatus associated with the LMU.

Interval 450 – 590 m MD (8 samples): Late Miocene, Latest Tortonian (Zone M14)

This interpretation is based on:

- FOD of *Barssidinium evangelineae* at 450 m MD
- LOD of *Impagidinium "densiverrucosum"* at 450 m MD
- LOD of *Gramocysta verricula* at 470 m MD
- FCOD of *Achomosphaera andalousiensis* at 490 m MD
- LOD of *Hystrichosphaeropsis obscura* at 490 m MD
- FCOD of of *Impagidinium "densiverrucosum"* at 530 m MD

- LOD of *Labyrinthodinium truncatum* at 550 m MD
- FOD of *Operculodinium eirikianum* at 590 m MD

Remarks: At 570 m and 590 m MD occurrences of the Serravallian marker *Cannosphaeropsis passio* are recorded. These are interpreted as reworked in association with erosion of Serravallian to Lower Tortonian strata in association with the MMU, near the base of the Tortonian depositional sequence. The absence of *Systematophora placacantha* (albeit poor calibration) and *Palaeocystodinium golzowense* suggest that only the youngermost portion of the Tortonian is preserved above the MMU.

Sample 610 m: Middle Miocene, Late Langhian (Zone M6)
This interpretation is based on:
- LOD of *Systematophora placacantha* at 610 m MD
- LOD of *Palaeocystodinium golzowense* at 610 m MD
- LOD of *Cousteaudinium aubryae* at 610 m MD
- FOD of *Unipontedinium aquaeductus* at 610 m MD
- LOD of *Unipontedinium aquaeductus* at 610 m MD

Interval 630 – 650 m (2 samples): Middle Miocene, Early Langhian (Zone M5)
This interpretation is based on:
- FOD of *Cerebrocysta poulseni* at 630 m MD
- LOD of *Apteodinium spiridoides* at 650 m MD
- FOD of *Labyrinthodinium truncatum* at 650 m MD

Interval 670 – 730 m (4 samples): Early Miocene – Late Burdigalian (Zone M4), or older
This interpretation is based on:
- LOD of *Distatodinium paradoxum* at 670 m MD
- FCOD of *Apteodinium spirioides* at 710 m MD
- FOD of *Cousteaudinium aubryae* at 670 m MD
- LOD of *Exochosphaeridium insigne* at 730 m MD

Remark: The contact between the Burdigalian and Chattian strata corresponds to the Savian U/C. This implies that an approximately 8 Myr hiatus is associated. Based on log-character the Savian U/C is placed at 745 m MD.

Interval 750 – 810 m (3 samples): Late Oligocene – Early Chattian (NSO-6), or older
This interpretation is based on:
- LOD of *Distatodinium biffii* at 750 m MD
- LOD of *Wetzeliella symmetrica* at 750 m MD
- LOD of *Chiropteridium galea* at 750 m MD
- LOD of *Cordosphaeridium cantharellum* at 750 m MD
- LOD of *Homotryblium floripes* at 750 m MD
- LOD of *Deflandrea phosphoritica* at 750 m MD

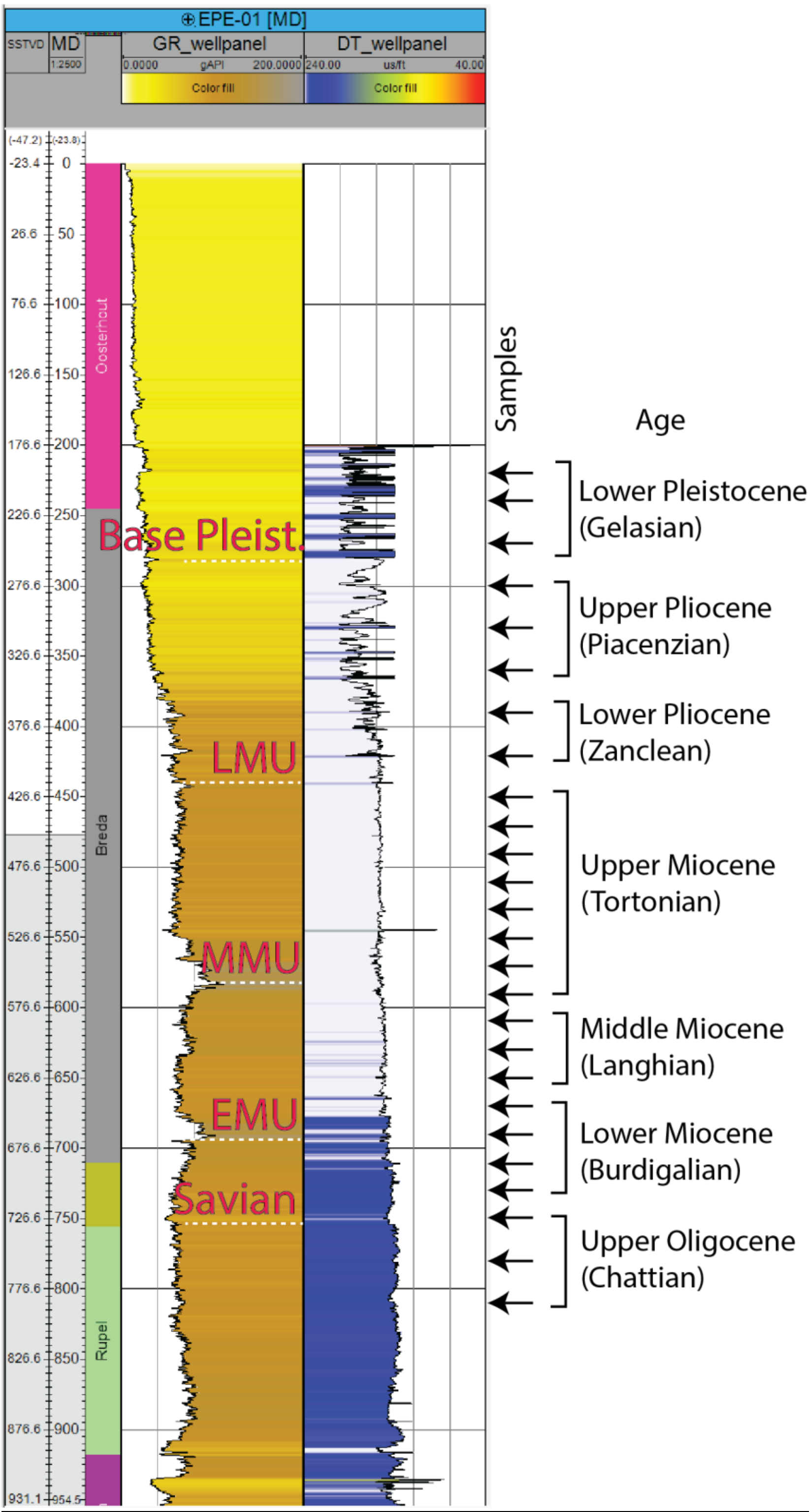

Figure 3.7: Summary of age-interpretation transposed on combined GR-DT-log for well EPE-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). The Savian unconformity is clearly defined separating Lower Chattian from Burdigalian strata. The EMU and the MMU are picked at higher GR-values signifying transgressive surfaces. At the LMU-level a change in GR-cyclicity is discernable, after which a gradual cleaning/coarsening upward trend is observed. This borehole is another example in which the base of the Pliocene (LMU) and the base of the Oosterhout are far (>200 m) apart. In fact, the base of the Oosterhout Fm. almost coincides with the base of the Maassluis Fm.

Table 3.7 Summary age breakdown of well EPE-01 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Unconformity
220 – 270	Early Pleistocene, Early Gelasian
290 m Base Pleistocene	
300 – 360	Late Pliocene, Piacenzian
390 – 420	Early Pliocene, Early Zanclean
430 LMU (*Messinian absent*)	
450 – 590 m	Late Miocene, Latest Tortonian (Zone M14)
590 MMU (*Early Tortonian absent, Serravallian very condensed/absent below*)	
610 – 650	Middle Miocene , Early – Middle Langhian (Zones M5-6)
670 – 730	Early Miocene, Late Burdigalian (Zone M4)
690 EMU (*no hiatus discernable*)	
750 Savian (*Upper Chattian - Lower Aquitanian absent*)	
750 – 810	Late Oligocene, Early Chattian (NSO-8), or older

3.1.8 Jutphaas-1 (JUT-01)

Interval 230 – 300 m (3 samples): Early Pleistocene, Gelasian

This interpretation is based on:

- LOD of *Amiculosphaera umbracula* at 230 m MD
- LOD of *Habibacysta tectata* at 230 m MD

Interval 400 – 430 m (2 samples): Late Pliocene, Piacenzian

This interpretation is based on:

- LOD of *Barssidinium* spp. at 400 m MD
- LOD of ?*Heteraulacacysta* sp. 1 at 430 m MD

Sample 490 m: Early Pliocene, Late Zanclean

This interpretation is based on:

- LOD of *Melitasphaeridium choanophorum*
- LOD of *Operculodinium eirikianum*

Interval 510 - 690 m: Late Miocene, Latest Tortonian (Zone M14)

This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata* at 510 m MD
- LOD of *Impagidinium "densiverrucosum"* at 510 m MD
- FOD of *Invertocysta lacrymosa-tabulata* complex at 510 m MD
- LOD of *Hystrichosphaeropsis obscura* at 530 m MD
- LOD of *Gramocysta verricula* at 530 m MD
- LOD of *Labyrinthodinium truncatum* at 590 m MD
- FOD of *Achomosphaera andalousiensis* at 630 m MD
- FOD of *Impagidinium "densiverrucosum"* at 630 m MD
- FOD of *Selenopemphix armagedonnensis* at 630 m MD
- FOD of *Barssidinium evangelineae* at 690 m MD

Sample 720 m: Middle Miocene, Late Serravallian (Zone M9)

This interpretation is based on:

- LOD of *Cannosphaeropsis passio*
- LOD of *Systematophora placacantha*

Remark: *Achomosphaera andalousiensis* is not recorded

Sample 760 m: Middle Miocene, Middle Langhian (Zone M6)

This interpretation is based on:

- LOD of *Distatodinium paradoxum*
- FOD of *Gramocysta verricula*

Sample 790 m: Middle Miocene, Early Langhian (Zone M5)

This interpretation is based on:

- FOD of *Labyrinthodinium truncatum*
- FOD of *Cerebrocysta poulseni*

Sample 850 m: Early Miocene, Late Burdigalian (Zone M4), or older

This interpretation is based on:

- LOD of *Cousteaudinium aubryae*

Sample 900 m: Early Miocene, Late Aquitanian to Early Burdigalian (Zone M2 to M3)

This interpretation is based on:

- FOD of *Cousteaudinium aubryae*
- LOD of *Cordosphaeridium cantharellum*
- LOD of *Homotryblium* spp.
- LOD of *Thalassiphora rota*

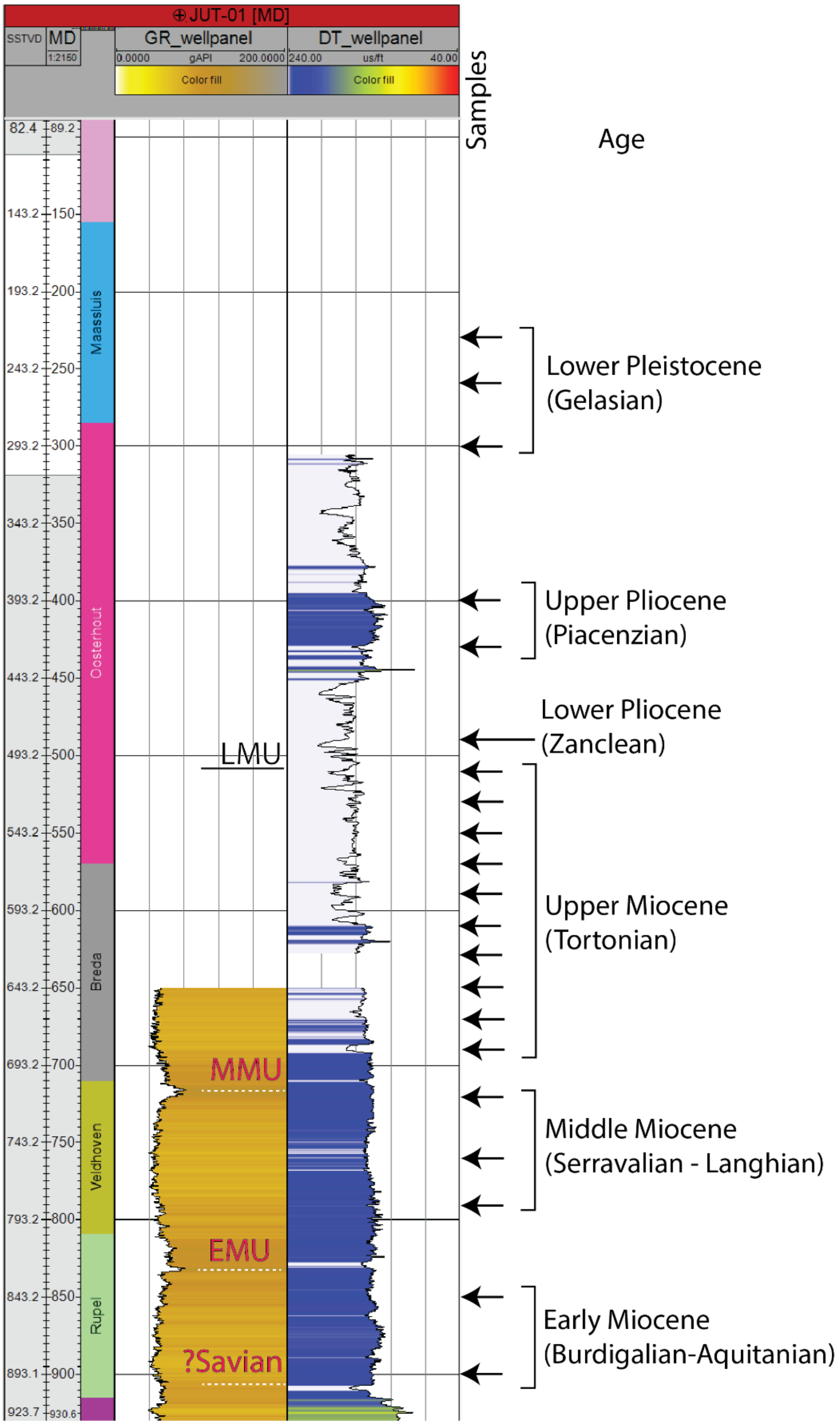

Figure 3.8: Summary of age-interpretation transposed on combined GR-DT-log for well JUT-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). Near the base of the Rupel Fm., the Savian unconformity forms the base of the Lower Miocene sequence. The EMU and MMU are positioned at GR-maxima, associated with transgressive surfaces. The Upper part of the section lacks GR-data. However, the base of the Pliocene sequence (LMU) marks a transition to a more serrate DT-pattern. Again, a high velocity interval is recorded in the Pliocene sequence. No data are available to characterize the base Pleistocene on the basis of logs.

Table 3.8: Summary age breakdown of well JUT-01 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Unconformity
230 - 300	Early Pleistocene, Gelasian
Base Pleistocene	
400 - 430	Late Pliocene, Piacenzian
490 - 510	Early Pliocene, Zanclean
510 m LMU (*Messinian-Early Zanclean absent*)	
510 - 690	Late Miocene, Latest Tortonian (Zone M14)
715 MMU (*Early-Late Tortonian absent*)	
720	Middle Miocene, Late Serravallian (Zone M9)
760	Middle Miocene, Middle Langhian (Zone M6)
790	Middle Miocene, Early Langhian (Zone M5)
850	Early Miocene, Late Burdigalian (Zone M4), or older
835 EMU (*no hiatus discernable*)	
900	Early Miocene, Late Aquitanian to Early Burdigalian (Zone M2-3)

3.1.9 Nijmegen-Valburg-1 (NVG-01)

Sample 150 m MD: Early Pleistocene, Gelasian

This interpretation is based on:

- Lack of Pliocene markers

Sample 230 m MD: Latest Miocene, Latest Tortonian (Zone M14)

This interpretation is based on:

- LOD of *Gramocysta verricula*
- LOD of *Impagidinium densiverrucosum*
- LOD of *Reticulatosphaera actinocoronata*
- LOD of *Melitasphaeridium choanophorum*

Interval 260 - 310 m MD: Late Miocene, Late Tortonian (Zone M13)

This interpretation is based on:

- LOD of *Systematophora placacantha* at 260 m MD
- LOD of *Labyrinthodinium truncatum* at 260 m MD
- FOD of *Barssidinium evangelineae* at 260 m MD
- FOD of *Achomosphaera andalousiensis* at 310 m MD

Sample 360 m MD: Middle Miocene, Serravallian (Zone M8), or older

This interpretation is based on:

- LOD of *Palaeocystodinium golzowense*
- LOD of *Unipontedinium aquaeductum*

Sample 410 m MD: Middle Miocene, Langhian (Zone M5-6)

This interpretation is based on:

- LOD of *Distatodinium paradoxum*
- FOD of *Labyrinthodinium truncatum*

<u>Sample 470 m MD: Early Miocene, Late Aquitanian to Early Burdigalian (Zone M2)</u>

This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum* at 470 m MD
- LOD of *Homotryblium* spp. at 470 m MD

<u>Sample 505 m MD: Late Oligocene, Late Chattian to Early Miocene, Early Aquitanian (Zone M1)</u>

This interpretation is based on:

- LOD of *Deflandrea phosphoritica* at 505 m MD

<u>Sample 560 m: Early Oligocene, Late Rupelian (Zone NSO-5), or older</u>

This interpretation is based on:

- LOD of *Rhombodinium draco* at 560 m MD

<u>Interval 625 - 635 m (2 samples): Early Oligocene, Early Rupelian (Zones NSO2-3)</u>

This interpretation is based on:

- LOD of *Enneadocysta pectiniformis* at 625 m MD
- LOD of *Phthanoperidinium* spp. at 625 m MD
- LOD of *Spiniferites* sp. 1 of Manum 1989 at 625 m MD
- FOD of *Reticulatosphaera actinocoronata* at 635 m MD

<u>Remark:</u> The sample at 635 m contains abundant Early Eocene reworking.

<u>Interval 650 – 685 m (2 samples): Paleocene, Thanetian (Zone P6 of Mudge and Bujak, 1996)</u>

This interpretation is based on:

- LOD of *Alisocysta* sp. 2 of Heilmann Claussen 1985 at 650 m MD
- LOD of *Hafniasphaera septata* at 650 m MD

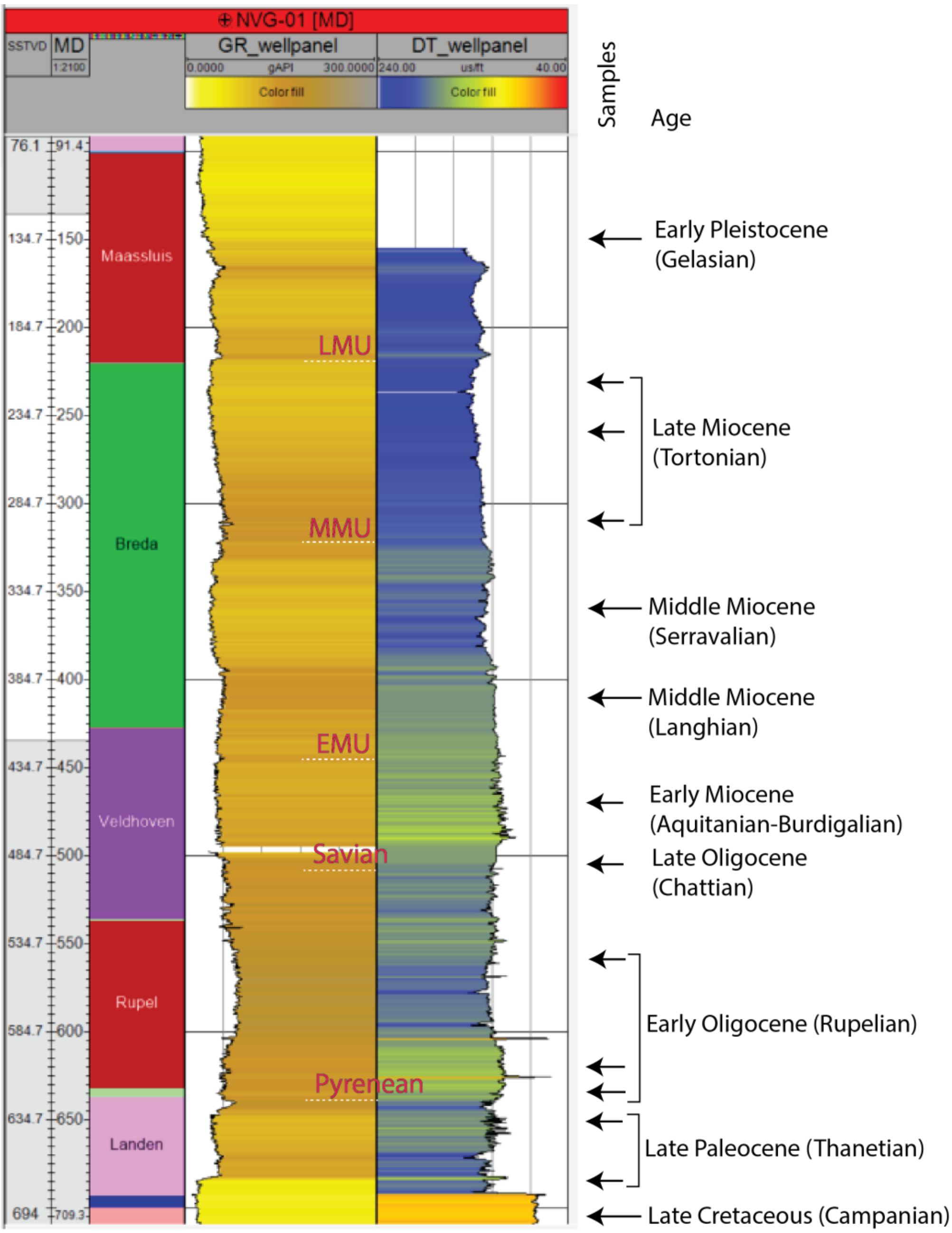

Figure 3.9: Summary of age-interpretation transposed on combined GR-DT-log for well NVG-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024).

Table 3.9: Summary age breakdown of well NVG-01 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Phase
150	?Early Pleistocene, Gelasian
155 ~~?Base Pleistocene~~	
220 LMU	
230 - 310	Late Miocene, Late Tortonian (Zone M13-14)
330 MMU (Early *Tortonian absent*)	
360	Middle Miocene, Serravallian, or older (Zone M8)
410	Middle Miocene, Langhian (Zone M5-6)
430 EMU (*no hiatus discernable*)	
470	Early Miocene, Late Aquitanian to Early Burdigalian (Zone M2)
505	Early Miocene, Early Aquitanian (Zone M1), or older
505 Savian (*Early Chattian absent*)	
560	Early Oligocene, Late Rupelian (Zone NSO-5)
625 - 635	Early Oligocene, Early Rupelian (Zoen NSO02-3)
637 Pyrenean (*entire Eocene absent*)	
650 - 685	Paleocene, Thanetian (Zone P6)

3.1.10 Schiphol-1 (SPL-01)

<u>Interval 210 – 440 m MD (5 samples): Early Pleistocene, Gelasian</u>

This interpretation is based on"

- LOD of *Habibacysta tectata* at 210 m MD

<u>Sample 510 m MD: Likely Pliocene</u>

<u>Remark:</u>

This sample yields only rare dinoflagellates, no age-determination is possible. This sample is likely taken from the shell hash layers characteristically found in the (Upper) Pliocene sequence.

<u>Interval 550 – 580 m MD (2 samples): Late Pliocene, Piacenzian</u>

This interpretation is based on:

- LOD of *Barssidinium graminosum* at 550 m MD
- LOD of ?*Heteraulacacysta* sp. 1 at 580 m MD

<u>Sample 610 m MD: Middle Miocene, Late Serravallian (Zone M11)</u>

This interpretation is based on:

- LOD of *Cannosphaeropsis passio* at 610 m MD
- LOD of *Systematophora placacantha* at 610 m MD
- LOD of *Palaeocystodinium golzowense* at 610 m MD
- LOD of *Labyrinthodinium truncatum* at 610 m MD

<u>Interval 635 – 645 (2 samples): Middle Miocene, Langhian (Zone M6) or older</u>

This interpretation is based on:

- LOD of *Cousteaudinium aubryae* at 635 m MD
- LOD of *Distatodinium paradoxum* at 635 m MD

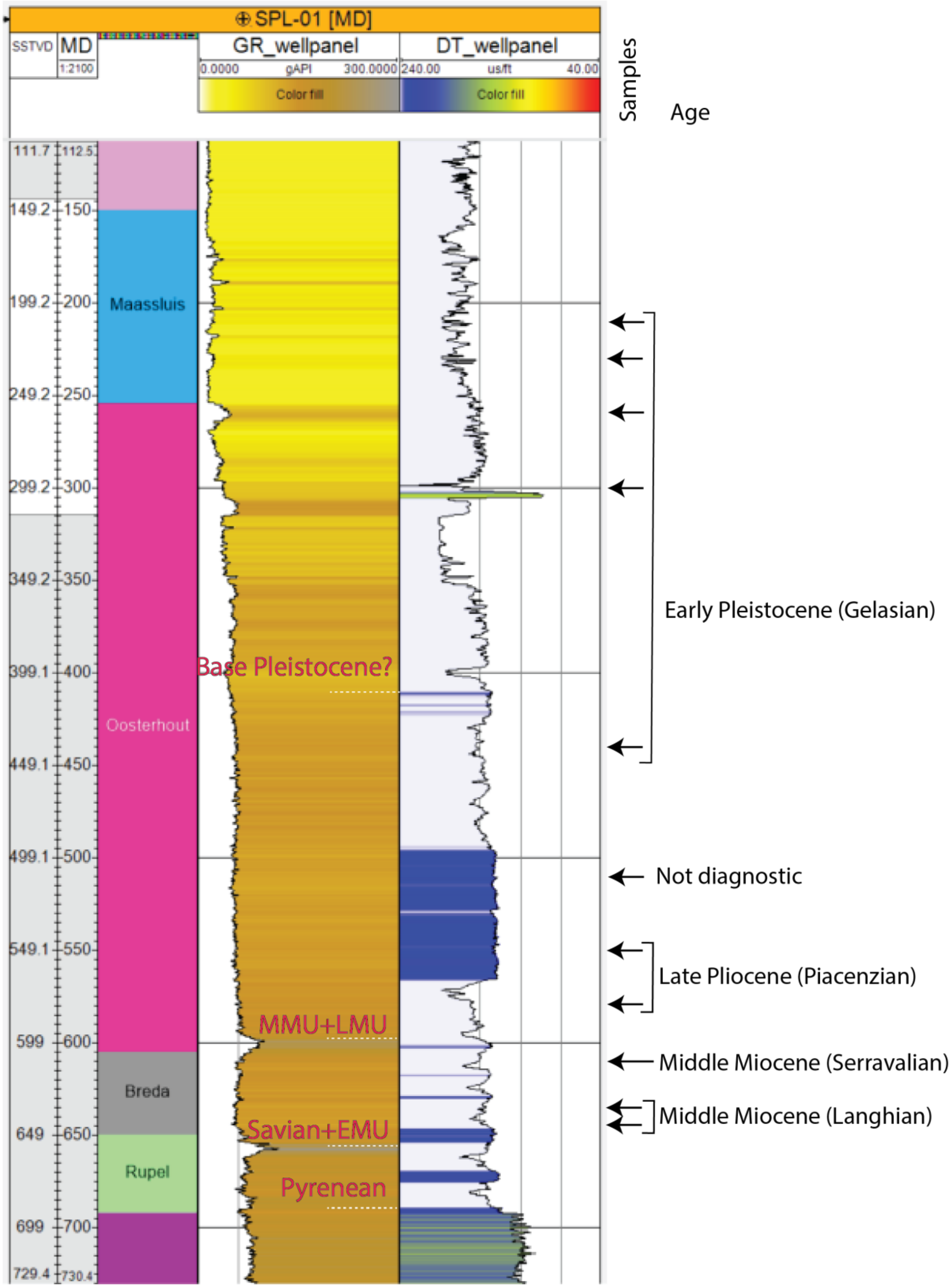

Figure 3.10: Summary of age-interpretation transposed on combined GR-DT-log for well SPL-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). It is clear that the EMU and Savian amalgamate, with Middle Miocene strata immediately overlying the Oligocene Rupel Fm. The MMU and LMU also amalgamate; the Upper Miocene and Zanclean are absent. It seems that the Upper part assigned to the Oosterhout Fm. is actually Early Pleistocene in age. Possibly the change in sonic velocity observed around 415 m depth is the base Pleistocene.

Table 3.10: Summary age breakdown of well SPL-01 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Unconformity
210 - 440	Early Pleistocene, Gelasian
415 ~~Base Pleistocene~~	
510 - 580	Late Pliocene, Piacenzian
595 LMU+MMU (*Tortonian-Zanclean absent*)	
610	Middle Miocene, Late Serravallian
635 - 645	Middle Miocene, Langhian, or older
655 Savian + EMU	

3.1.11 Spaarnwoude-1 (SPW-01)

Interval 442 – 624 (7 samples): Early Pleistocene, Gelasian

This interpretation is based on:

- Change in pollen assemblage composition between samples 620-624 and 636-640 m MD
- LOD of *Amiculosphaera umbracula* in sample 554-558 m MD
- LOD of *Habibacysta tectata* in sample 554-558 m MD
- LOD of *Operculodinium israelianum* in sample 554-558 m MD

Remark: A major increase in Meso- and Paleozoic reworking is observed above 640 m MD.

Interval 640 – 660 (2 samples): Late Pliocene, Piacenzian

This interpretation is based on:

- LOD of ?*Heteraulacacysta* sp. 1 at sample 636-640 m
- LOD of *Barssidinium* spp. at sample 656-660 m

Interval 668 – 700 (3 samples): Late Miocene: Latest Tortonian (Zone M14)

This interpretation is based on:

- FOD of *Barssidinium evangelineae* at sample 668 - 672
- LOD of *Labyrinthodinium truncatum* at sample 680 – 684 m
- LOD of *Reticulatosphaera actinocoronata* at sample 680 – 684 m
- FOD of *Amiculosphaera umbracula* at sample 696 – 700 m

Sample 716 -720: Middle Miocene, Late Serravallian (Zone M11)

This interpretation is based on:

- FOD of *Headinium – Habibacysta* group
- LOD of *Cannosphaeropsis passio*
- LOD of *Systematophora placacantha*

Sample 736 – 740: Middle Miocene, Middle Langhian – Early Serravallian (Zones M7-8)

This interpretation is based on:

- LOD of *Unipontedinium aquaeductum* at sample 736-740 m
- FOD of *Unipontedinium aquaeductum* at sample 736-740 m
- FOD of *Achomosphaera andalousiensis* at sample 736-740 m

Sample 756 -760: Middle Miocene, Early Langhian (Zone M5)

This interpretation is based on:

- LOD of *Cousteaudinium aubryae*
- LOD of *Distatodinium paradoxum*
- FOD of *Labyrinthodinium truncatum*

Sample 774 - 778: Early Miocene, Late Burdigalian (Zone M4)

- FOD of *Cousteaudinium aubryae*
- Absence of *Labyrinthodinium truncatum*

Interval 786 – 798: Early Miocene, Middle Burdigalian (Zone M3)

This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum* at sample 782-786

Interval 806 – 814: Early Miocene, Late Aquitanian to Early Burdigalian (Zone M2)

This interpretation is based on:

- LOD of *Homotryblium* spp. at sample 802-806 m
- LOD of *Thalassiphora pelagica* at sample 810-814 m

Interval 826 – 840 (2 samples): Early Oligocene, Middle Rupelian (Zone NSO-3)

This interpretation is based on:

- LOD of *Chiropteridium* galea at 826 m MD
- LOD of *Enneadocysta pectiniformis* at 826 m MD
- LOD of *Licracysta semicirculata* at 826 m MD
- LOD of *Phthanoperidinium* spp. at 826 m MD
- LOD of *Membranophoridium aspinatum* at 826 m MD
- FOD of Chiropteridium galea at 838 – 840 m MD
- FOD of *Phthanoperidinium comatum at* 838 – 840 m MD
- FOD of *Reticulatosphaera actinocoronata* at 838 - 840 m MD

Sample 864 - 868 m: Early-Middle Eocene, Ypresian – Early Lutetian

This interpretation is based on:

- LOD of *Apectodinium* spp.
- LOD of *Diphyes colligerum*
- LOD of *Hystrichosphaeridium tubiferum*

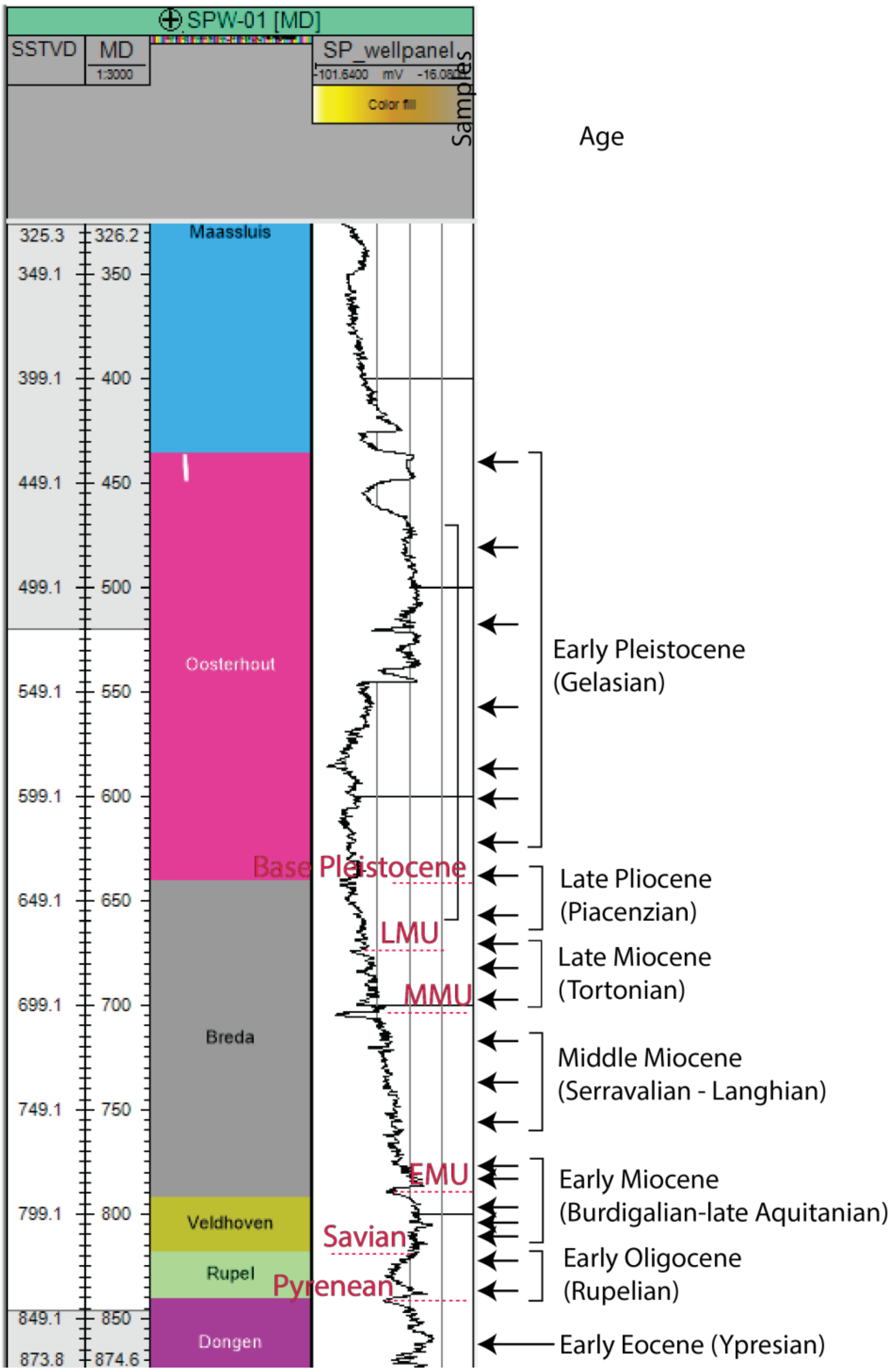

Figure 3.11: Summary of age-interpretation transposed on Spontaneous Potential (SP) log for well SPW-01. Due to absence of a GR & DT-log (the well was drilled in 1951) it is difficult to compare the log-response to others. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). A remarkable result is the very thin Pliocene and expanded Lower Pleistocene sequence.

Table 3.11: Summary age breakdown of well SPW-01 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Phase
442 - 624	Early Pleistocene, Gelasian
638 Base Pleistocene	
640 - 660	Late Pliocene, Piacenzian
660 LMU (*Zanclean absent*)	
668 - 700	Late Miocene, Latest Tortonian (Zone M14)
706 MMU (*Early-Late Tortonian absent*)	
716 – 720	Middle Miocene, Late Serravallian (Zone M11)
736 - 760	Middle Miocene, Early Langhian (Zones M5-6)
774 - 778	Early Miocene, Late Burdigalian (Zone M4)
780 EMU (*no hiatus discernable*)	
786 - 798	Early Miocene, Middle Burdigalian (Zone M3)
806 - 814	Early Miocene, Late Aquitanian to Early Burdigalian (Zone M2)
820 Savian (*Late Rupelian - Chattian absent*)	
826 – 840	Early Oligocene, Rupelian (Zone NSO-3)
844 Pyrenean (*Middle-Late Eocene absent*)	
864 - 868	Early-Middle Eocene, Ypresian-Lutetian

3.2 Inventory of legacy data

3.2.1 Andijk-GT-1 (ADK-GT-01)

<u>Sample 510 m MD: Likely Early Pleistocene, Gelasian</u>

This interpretation is based on:

- LOD of *Operculodinium israelianum*

<u>Interval 550 – 650 m MD (3 samples): Late Pliocene, Piacenzian</u>

This interpretation is based on:

- LOD of *Achomosphaera andalousiensis* at 550 m MD
- LOD of ?*Heteraulacacysta* sp. 1 at 550 m MD
- LOD of *Barssidinium graminosum* at 605 m MD

<u>Interval 700 – 775 m MD (3 samples): Early Pliocene, Early Zanclean</u>

This interpretation is based on:

- LOD of *Melitasphaeridium choanophorum* at 700 m MD
- LOD of *Reticulatosphaera actinocoronata* at 750 m MD

<u>Sample 800 m MD: Middle Miocene, Late Serravallian (Zone M10)</u>

This interpretation is based on:

- LOD of *Cannosphaeropsis passio*
- LOD of *Cerebrocysta poulseni*
- LOD of *Palaeocystodinium golzowense*
- LOD of *Systematophora placacantha*

<u>Sample 835 m MD: Middle Miocene, Early Langhian (Zones M5-6)</u>

This interpretation is based on:

- LOD *Apteodinium spiridoides*
- LOD of *Cousteaudinium aubryae*
- LOD of *Distatodinium paradoxum*

<u>Sample 850 m MD: Early Miocene, Late Burdigalian (Zone M4)</u>

This interpretation is based on:

- FOD of *Cerebrocysta poulseni*
- FOD of *Cousteaudinium aubryae*

<u>Sample 875 m MD: Early Miocene, Aquitanian to Early Burdigalian (Zone M1-3)</u>

This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum*
- LOD of *Cribroperidinium tenuitabulatum*
- LOD of *Homotryblium vallum* at 875 m MD

<u>Remark:</u> Although this level is already interpreted as Rupel Fm., it is evident that it is substantially younger than Rupelian in age. It seems that Rupel Fm. is substantially thinner/absent and that a Veldhoven equivalent is present in this well.

Interval 955 - 1000 m MD: Middle Eocene: Early Lutetian Zone E4

This interpretation is based on:

- LOD of *Diphyes colligerum* at 955 m MD
- LOD of *Dracodinium/Wetzeliella varielongitudum* at 955 m MD
- LOD of *Hystrichosphaerdium tubiferum* at 955 m MD

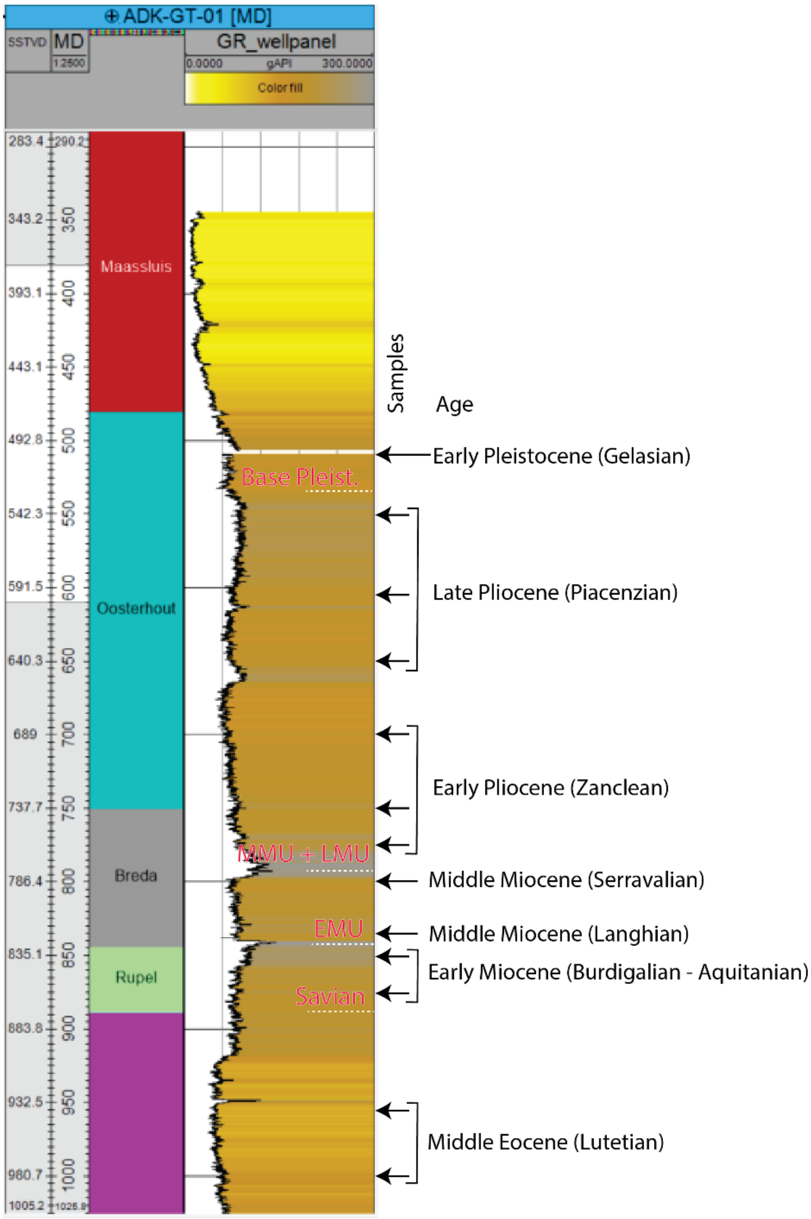

Figure 3.12: Summary of age-interpretation transposed on combined GR-DT-log for well ADK-GT-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024).

Table 3.12: Summary age breakdown of well ADK-GT-01 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Unconformity
510	?Early Pleistocene, Gelasian
530 Base Pleistocene	
550 – 650	Pliocene, Late Zanclean to Piacenzian
700 – 775	Early Pliocene, Early Zanclean
795 MMU+LMU (*Tortonian-Messinian absent*)	
800	Middle Miocene, Serravallian (Zone M10)
835	Middle Miocene, Langhian (Zones M5-6)
850	Early Miocene, Late Burdigalian (Zone M4)
845 EMU (*no hiatus discernable*)	
875	Early Miocene, Aquitanian to Early Burdigalian (Zone M1-2)
880 Savian (*Late Eocene and Oligocene absent*)	
955 – 1000	Middle Eocene (Lutetian), Rupelian present above

3.2.2 Oudega-Akkrum-3 (AKM-03)

Interval 207-228 m (2 samples): Not diagnostic – Middle Pleistocene, or older

Sample 251 m: Early Pleistocene (Gelasian)
This interpretation is based on:
- LOD *Habibacysta tectata*

Sample 267 m: Late Pliocene (Piacenzian)
This interpretation is based on:
- LOD *Barssidinium pliocenium*

Sample 288 m: Early Pliocene (Early Zanclean), or older
This interpretation is based on:
- LOD of *Reticulatosphaera actinocoronata*
- LOD *Selenopemphix armaggedonensis*

Interval 390-441 m (2 samples): Late Miocene, Tortonian (Zones M12-13)
This interpretation is based on:
- LOD *Labyrinthodinium truncatum* at 390 m
- LOD *Systematophora placacantha* at 390 m
- LOD of *Palaeocystodinium golzowense* at 441 m

Sample 474 m : Late Oligocene, Chattien (Zone O6), or older
This interpretation is based on:
- LOD *Wetzeliella gochtii*

Remarks: Numerous Early-Middle Miocene taxa were recorded as downhole contamination. These include *Cerebrocysta poulseni*, *Cousteaudinium aubryae* and *Cordosphaeridium cantharellum*. This implies that an Early – Middle Miocene sequence is present between 441 and 474 m depth.

Sample 522 m: Early Oligocene, Rupelian

This interpretation is based on:

- LOD *Achilleodinium biformoides*
- LOD *Membranophoridium intermedium*

Since no digital logs are available – a precise calibration of the stratigrahic horizons to the well log response is impossible. Nevertheless, the LMU seems to have led to erosion/non-deposition of the Uppermost Tortonian-Messinian. An Early-Middle Miocene sequence seems present. A precise characterization of the EMU and MMU is impossible.

Table 3.13 Summary age breakdown of well AKM-03 and suggested position of regional unconformities.

Interval / Sample (m MD)	Age / Unconformity
207 - 228	Pleistocene
Base Pleistocene	
267	Late Pliocene, Piacenzian
288	Early Pliocene, Early Zanclean
LMU	
390 - 441	Late Miocene, Tortonian
EMU+MMU+Savian	
474	Late Oligocene, Early Chattian (NSO-6), or older
522	Early Oligocene, Early Rupelian

3.2.3 Noordwijk (B30F0470)

<u>Interval 385.1 – 425.1 m (6 samples): Late Pliocene, Piacenzian</u>

This interpretation is based on:

- LOD of *Barssidinium* spp. at 385.1 m
- LOD of *Operculodinium eirikianum* at 385.1 m
- LOD of *Invertocysta lacyrmosa* at 385.1 m

<u>Remark:</u> Munsterman (2021) places the Plio-Pleistocene boundary at 383.6 m MD.

<u>Sample 429 – 430 m: Middle Miocene, Late Serravallian (Zone M10)</u>

This interpretation is based on:

- LOD of *Cannosphaeropsis passio*
- LOD of *Cerebrocysta poulseni*

<u>Interval 437 – 440 (3 samples): Middle Miocene, Middle Langhian (Zone M5-6)</u>

This interpretation is based on:

- LOD of *Cousteaudinium aubryae* at 437 m
- FOD of *Labyrinthodinium truncatum* at 439 m

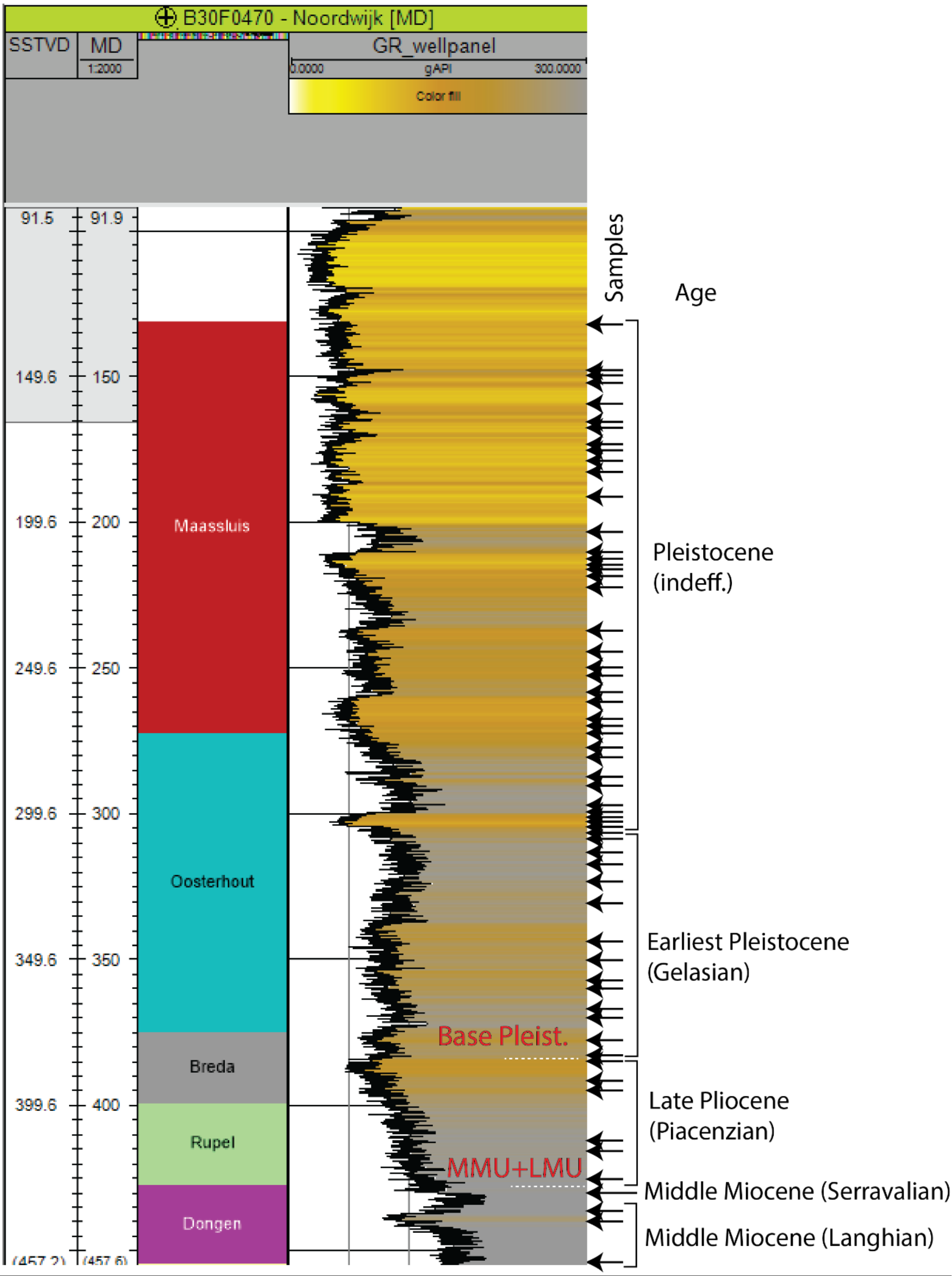

Figure 3.13: Summary of age-interpretation transposed on GR-log for borehole B30F0470. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). In complete contrast to what the lithostratigraphic interpretation suggests, a thin Middle Miocene sequence is overlain by a thin Pliocene and a thick Pleistocene sequence. Hence, the MMU and LMU amalgamate and the base of the Pleistocene approximates the base of the Oosterhout Fm.

Table 3.14: Summary age breakdown of well B30F0470 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Unconformity
383.6 Base Pleistocene	
385.1 – 425.1	Late Pliocene, Piacenzian
429 LMU+MMU (*Late Miocene - Early Pliocene absent*)	
429 – 430	Middle Miocene, Late Serravallian
437 - 440	Middle Miocene, Middle Langhian

3.2.4 B43G1411 (Kruisland)

<u>Interval 201 – 206 m (2 samples): Pliocene, Late Zanclean or Piacenzian</u>
This interpretation is based on:

- LOD of *Barssidinium* spp. at 201 – 202 m

<u>Sample 211 – 212 m: Pliocene, Early Zanclean</u>
This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata* at 211 – 212 m
- LOD of *Melitasphaeridium choanophorum* at 211 – 212 m
- FOD of *Achomosphaera andalousiensis* at 211 – 212 m

<u>Sample 216 – 217 m: Middle Miocene, Late Langhian - Early Serravialian (Zone M7)</u>
This interpretation is based on:

- LAOD of *Systematophora placacantha* at 216 – 217 m
- LOD of *Paleocystodinium ventricosum* at 216 – 217 m
- LOD of *Paleocystodinium golzowense* at 216 – 217 m
- LOD of *Reticulatosphaera acticoronata* at 216 – 217 m
- LOD of *Labyrinthodinium truncatum* at 216 – 217 m
- LOD of *Unipontidinium aquaductus* at 216-217 m
- LOD of *Hystrichosphaeropsis obscura* at 216 – 217 m

<u>Sample 223 – 224 m: Not diagnostic</u>
<u>Remark:</u> The sample is sterile

<u>Interval 229 – 236 m (3 samples): Early Miocene, Late Burdigalian (Zone M4)</u>
This interpretation is based on:

- LOD of *Coustodinium aubryae* at 229 – 230 m
- LOD of *Apteodinium spiridoides* at 229 – 230 m
- LOD of *Distatodinium paradoxum* at 229 – 230 m

<u>Remarks</u>: The absence of *Labyrinthodinium truncatum* and *Unipontidinium aquaductum* suggest an age older than Langhian (Zone M5). The interval contains substantial reworking of Middle and Late Eocene palynomorphs.

<u>Sample 241 – 242 m: Early Miocene, Early Burdigalian (Zone M3), or older</u>
This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum* at 241 – 242 m
- LOD of *Homotryblium* spp. at 241 – 242 m
- FOD of *Apteodinium spiridoides* at 241 – 242 m

Interval 246 – 252 m (4 samples): Oligocene, Latest Rupelian – earliest Chattian (Zone NSO-5)
This interpretations is based on:
- LOD of *Rhombodinium draco* at 245 – 246 m
- LOD of *Wetzeliella* spp. at 245 – 246 m
- LOD of *Chiropteridium* spp. at 245 -246 m
- LOD of *Thalassiphora pelagica* at 245 – 246 m
- FOD of *Distatodinium biffii* at 251 – 252 m

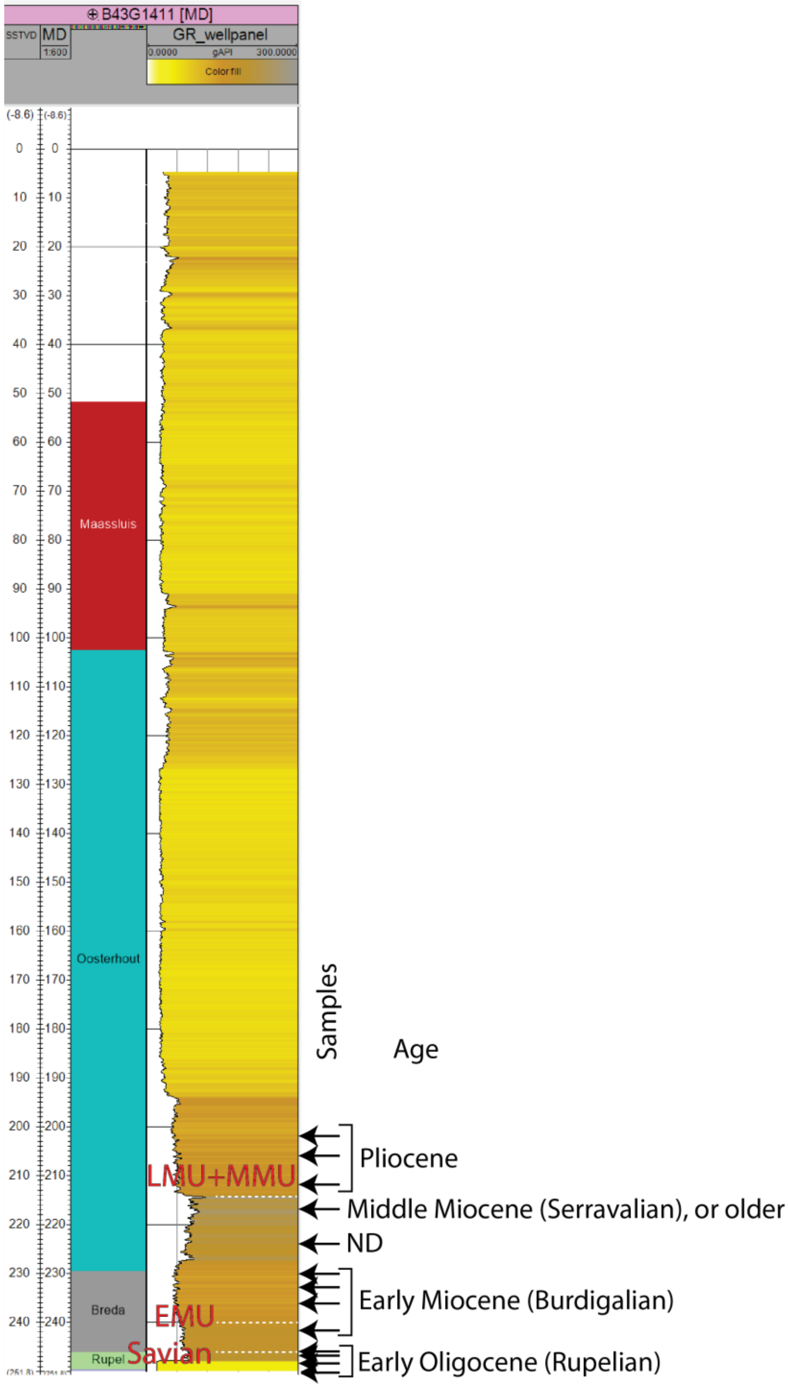

Figure 3.14 Summary of age-interpretation transposed on GR-log for borehole B43G1411. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). A thin Middle Miocene sequence is positioned between Rupelian and Pliocene strata.

Table 3.15 Summary age breakdown of well B43G1411 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	**Age / Phase**
201 - 212	Pliocene
215 LMU+MMU (*Late Serravallian-Latest Miocene absent*)	
216 - 217	Middle Miocene (Early Serravallian), or older
229 - 242	Early Miocene, Burdigalian
242 EMU (*no hiatus discernable*) **246 Savian (*Late Chattian-Early Burdigalian absent*)**	
246 - 252	Early Oligocene (Latest Rupelian)

3.2.5 Hank (B44E0146)

Interval 79-155 m (27 samples): Early Pleistocene, Gelasian
This interpretation is based on:
• LOD *Habibacysta tectata* at 79 m
Remarks: At 136 the Gelasian Marine Isotope Stage (MIS) 95 is identified based on an acme of *Operculodinium israelianum*. At 151 m MIS-97 is identified based on an acme of *Impagidinium multiplexum*.

Interval 156-338 m: Late Pliocene, Piacenzian
This interpretation dating is based on:
- LOD of *Barssidinium* spp. at 157 m
- LOD of *Operculodinium eirikianum* at 202 m
- LOD of *Invertocysta lacrymosa* at 279 m

Interval 340-404 m: Early Pliocene, Zanclean
This interpretation is based on:
- LOD of *Operculodinium tegillatum* at 341 m
- LCOD of *Reticulatosphaera actinocoronata* at 356 m

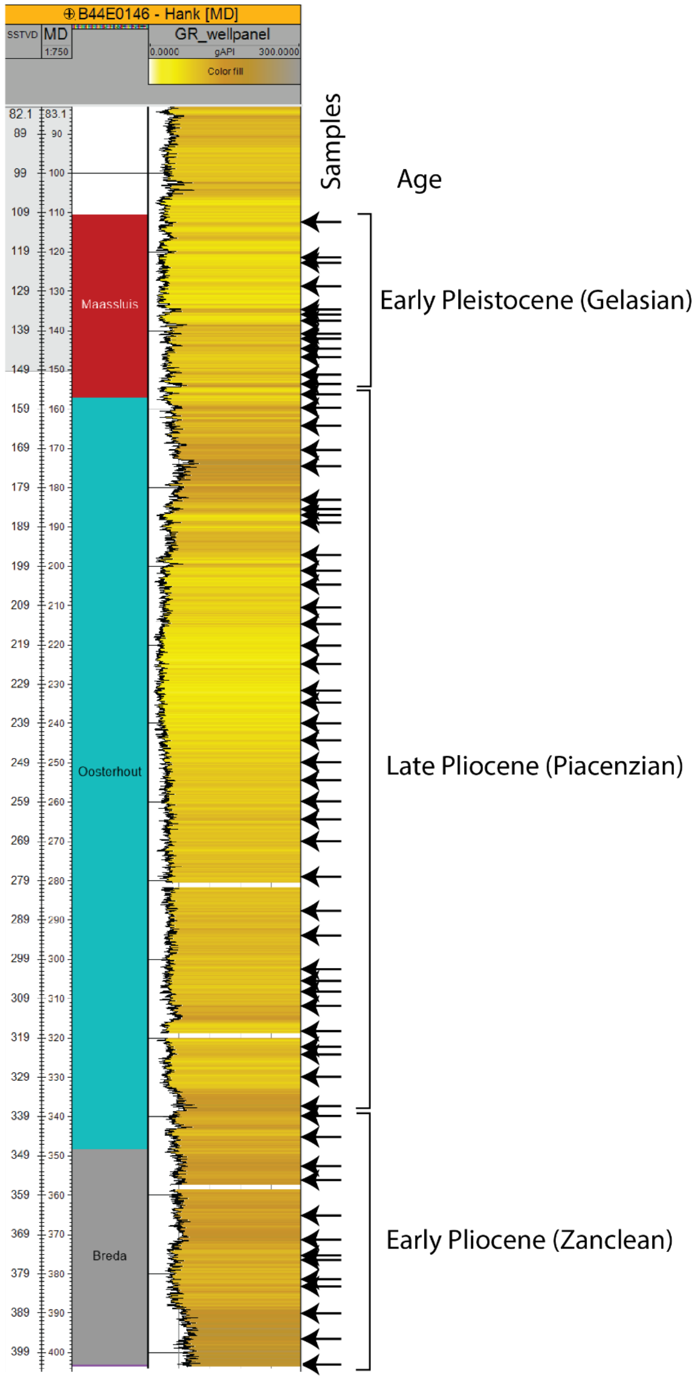

Figure 3.15: Summary of age-interpretation transposed on GR-log for borehole B44E0146. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024).

Table 3.16 Summary age breakdown of well B44E0146 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Phase
79-155	Early Pleistocene, Gelasian
Base Pleistocene	
156 - 338	Late Pliocene, Piacenzian
340 - 404	Early Pliocene, Zanclean
Below 404: LMU	

3.2.6 Blaricum-1 (BLA-01)

Sample 400 m MD: Likely Early Pleistocene, Gelasian

This interpretation is based on:

- Lack of Pliocene markers

Sample 450 m MD: Late Pliocene, Piacenzian

This interpretation is based onL

- LOD of *Barssidinium* spp

Sample 500 m MD: Early Pliocene, Zanclean, or older

This interpretation is based on:

- LOD of *Melitasphaeridium choanophorum* at 500 m MD

Interval 550 – 600 m MD: Late Miocene, Late Tortonian (Zone M13-14)

This interpretation is based on:

- LOD *Hystrichosphaeropsis obscura* at 550 m MD
- LOD of *Reticulatosphaera actinocoronata* at 550 m MD
- FOD of *Invertocysta lacrymosa-tabulata* at 550 m MD
- FOD of *Amiculosphaera umbracula* at 600 m MD

Interval 650 - 700 m MD: Late Miocene, Middle Tortonian (Zone M12)

This interpretation is based on:

- LOD of *Palaeocystodinium golzowense* at 650 m MD

Remark: The occurrence of *Cannosphaeropsis passio* at 700 m MD is considered reworked. Ample reworking is noted in this particular sample

Sample 750 m MD: Middle Miocene, Late Serravallian, or older (Zone M11)

This interpretation is based on:

- LOD of in-situ *Cannosphaeropsis passio*

Sample 800 m MD: Middle Miocene, Langhian (Zone M7)

This interpretation is based on:

- LAOD of *Systematophora placacantha*
- Absence of older markers

Interval 850 – 900 m MD: Early Miocene, Middle Burdigalian, Zone M3, or older

This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum* at 850 m MD
- LOD of *Cousteaudinium aubryae* at 850 m MD

- LOD of *Apteodinium spiridoides* at 850 m MD

Sample 950 m MD: Early Miocene, Late Aquitanian Zone M2, or older

This interpretation is based on:

- LOD of *Homotryblium plectilum*

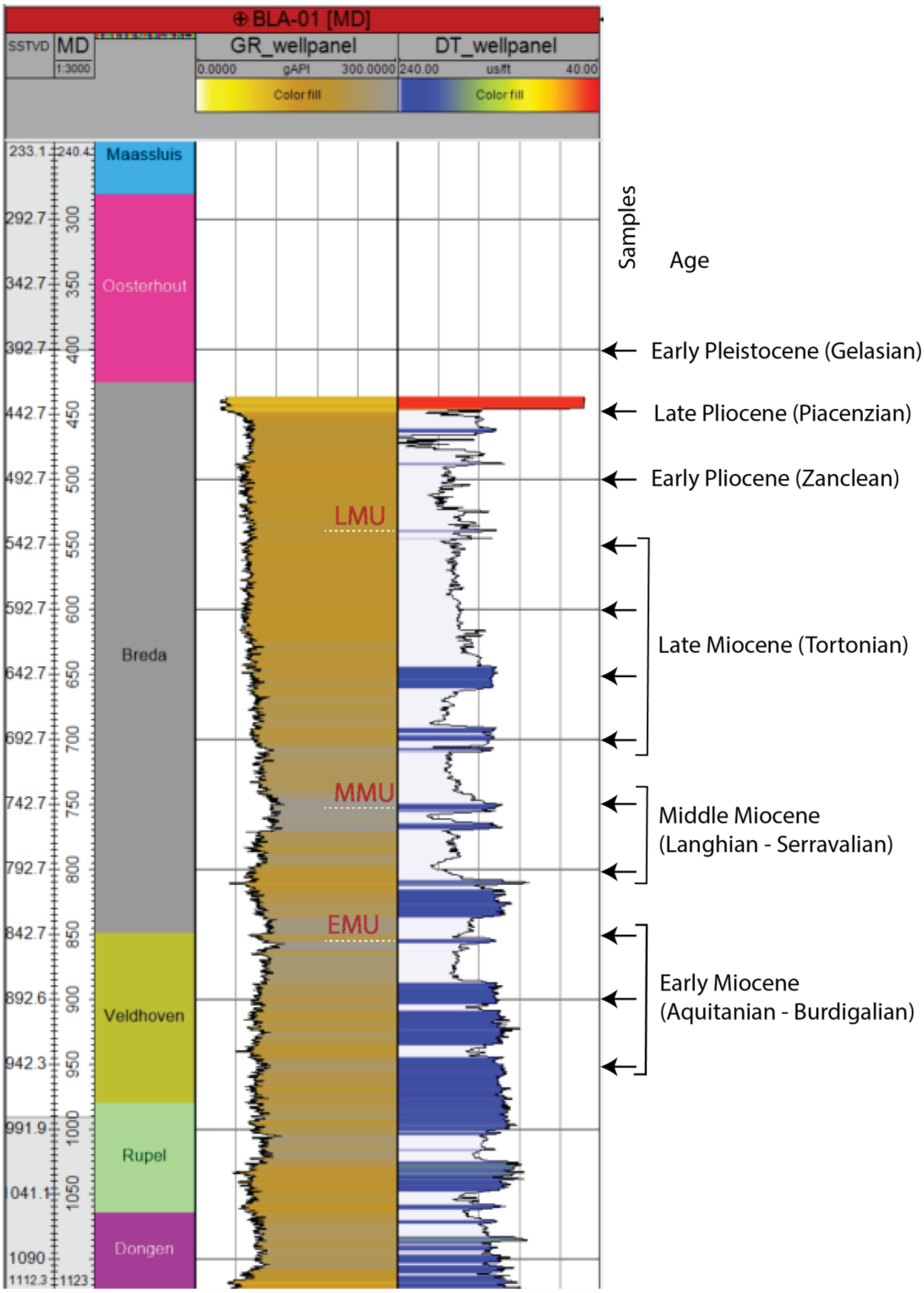

Figure 3.16: Summary of age-interpretation transposed on combined GR-DT-log for well BLA-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024).

Table 3.17: Summary age breakdown of well BLA-01 and suggested position of regional unconformities.

Interval / Sample (m MD)	Age / Phase
400	?Early Pleistocene, Gelasian
440 Base Pleistocene	
450	Late Pliocene, Piacenzian
500	Early Pliocene, Zanclean
540 LMU *(Latest Tortonian-Messinian absent)*	
550 - 700	Late Miocene, Late Tortonian (Zone M12 to M14)
750 MMU *(Early Tortonian missing)*	
750	Middle Miocene, Late Serravallian (Zone M11), or older
800	Middle Miocene, Langhian (Zone M7)
852 EMU *(no hiatus discernable)*	
850 - 900	Early Miocene, Middle Burdigalian (Zone M3), or older
950	Early Miocene, Late Aquitanian (Zone M2), or older

3.2.7 Delft-Aardwarmte-Geo-2 (DAPGEO-2)

Sample 364.1 m: Late Miocene, Latest Tortonian

This interpretation is based on:

- LOD of *Hystrichosphaeropsis obscura*

Remark: Munsterman (2023) identifies a specific assemblage with numerous 'cold-water elements'. This is typical for the Latest Tortonian (see e.g., Donders et al.., 2008).

Interval 370.76 – 377.7 m: Late Miocene, Tortonian (Zones M12 to M14)

This interpretation is based on:

- LOD of *Labyrinthodinium truncatum* at 370.76 m
- LOD of *Systematophora placacantha* at 372.95 m
- LOD of *Palaeocystodinium golzowense* at 377.7 m
- FOD of *Barssidinium evangelineae* at 377.7 m

Sample 382.95: Middle Miocene, Late Serravallian (Zone M10)

This interpretation is based on:

- LOD of *Cerebrocysta poulseni*
- LOD of *Achomosphaera andalousiensis*
- LOD of *Cannosphaeropsis passio*

Since no digital logs are available – a precise calibration of the stratigrahic horizons to the well log response is impossible. Nevertheless, it is evident that the MMU led to erosion/non-deposition of the Lower Tortonian.

Sample 386.05: Middle Miocene, Middle Langhian (Zone M6)

This interpretation is based on:

- LOD of *Cousteaudinium aubryae*
- FOD of *Unipontidinium acquaeductum*

Sample 389.69 m: Middle Miocene, Early Langhian (Zone M5)

This interpretation is based on:

- FOD of *Labyrinthodinium truncatum*
- FOD of *Cerebrocysta poulsenii*

Sample 393.66 m: Early Eocene, earliest Ypresian

This interpretation is based on:

- FOD of abundant *Apectodinium* spp.
- LOD of *Cerodinium speciosum*

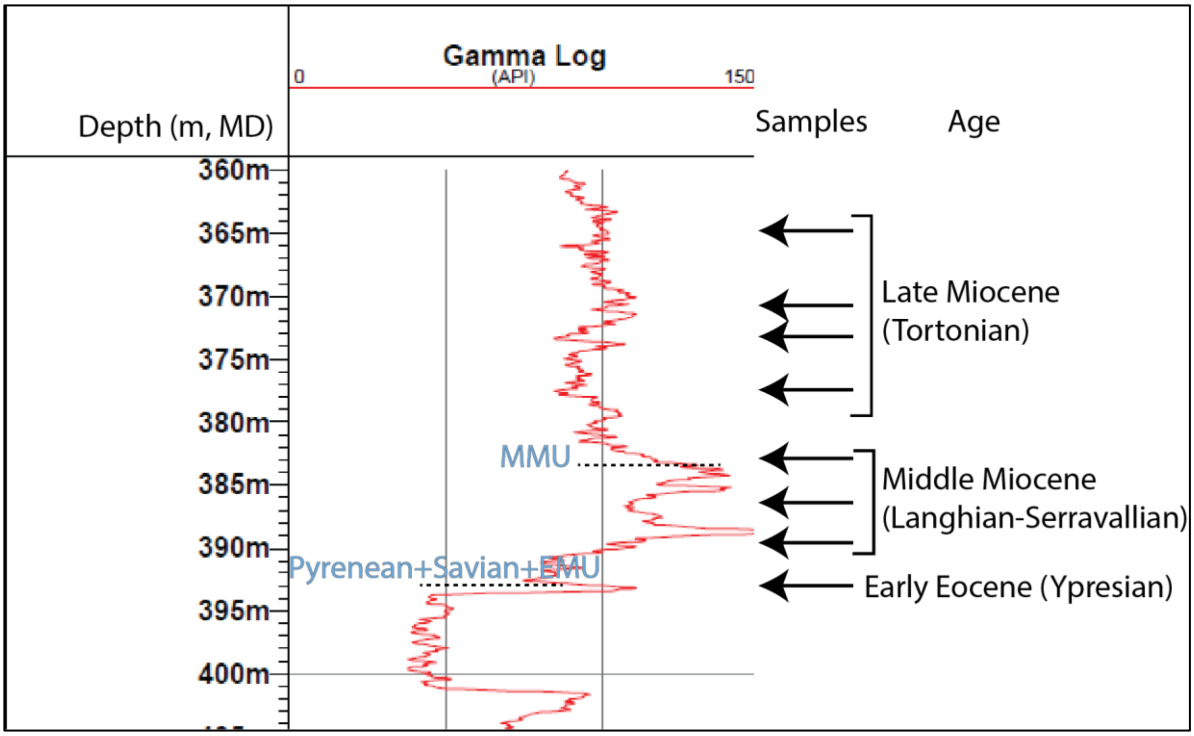

Figure 3.17 Summary of age-interpretation transposed on GR--log for well DAP-GEO-2. The log-trace is taken from Munsterman (2019) because no digital log data were available. There is no llithostratigraphic interpretation available on Dinoloket (2024).

Table 3.18 Summary age breakdown of Delft-Aardwarmte-Geo-2 and suggested position and temporal extent of regional unconformities.

Interval / Sample (m MD)	Age / Phase
364.1	Late Miocene, Latest Tortonian
370 – 377.7	Late Miocene, Tortonian
MMU	
382.95 – 389.69	Middle Miocene, Langhian-Serravalian
Pyrenean+Savian+EMU	
393.66	Early Eocene, Ypresian

3.2.8 Emmen-7 (EMM-07)

Interval 90 – 160 m MD (5 samples): Early Pliocene, Zanclean
This interpretation is based on:
- LOD of *Reticulatosphaera actinocoronata* at 90 m MD
- LOD of *Melitasphaeridium choanophorum* at 90 m MD

Remark: Munsterman (2019) interpreted a Latest Miocene (Messinian) sequence between 140 – 160 m, based on the LOD of *Impagidinium 'densiverrucosum'* at 140 m MD. This interpretation is hereby revised given the recalibration of this event and the high likelihood of reworking of this taxon.

Sample 170-180 m: Late Miocene, Tortonian, or older
This interpretation is based on:
- LOD of *Impagidinium densiverrucosum*

Remark: Munsterman (2019) interprets this sample as part of the underlying Middle Miocene sequence. However the range-tops of Middle Miocene markers are recorded one sample below.

Interval 180 – 200 m (2 samples): Middle Miocene, Middle Serravallian, or older
This interpretation is based on:
- LOD of *Unipontedinium aquaductum* at 190 m MD
- LOD of *Cerebrocysta poulseni* at 190 m MD
- LOD of *Systematophora placacantha* at 190 m MD

Remark: Munsterman (2019) interprets sample 190 – 200 m MD as Eocene, based on a series of Eocene taxa (e.g., *Areosphaeridium ebdonii, Areoligera tauloma* and *Melitasphaeridium pseudorecurvatum*). These occurrencesare, seen in the light of overall assemblage structure of the sample, considered as reworked. The absence of *Cannosphaeropsis passio* indicates the age is older than Late Serravallian.

Sample 210-220 m: Middle Eocene, Lutetian (Zone E3 of Bujak and Mudge, 1994).
This interpretation is based on:
- LOD of *Eatonicysta ursulae* at 220 m MD
- LOD of *Adnatosphaeridium multispinosum* at 220 m MD

For the stratigraphy of older Cenozoic strata see Munsterman (2019).

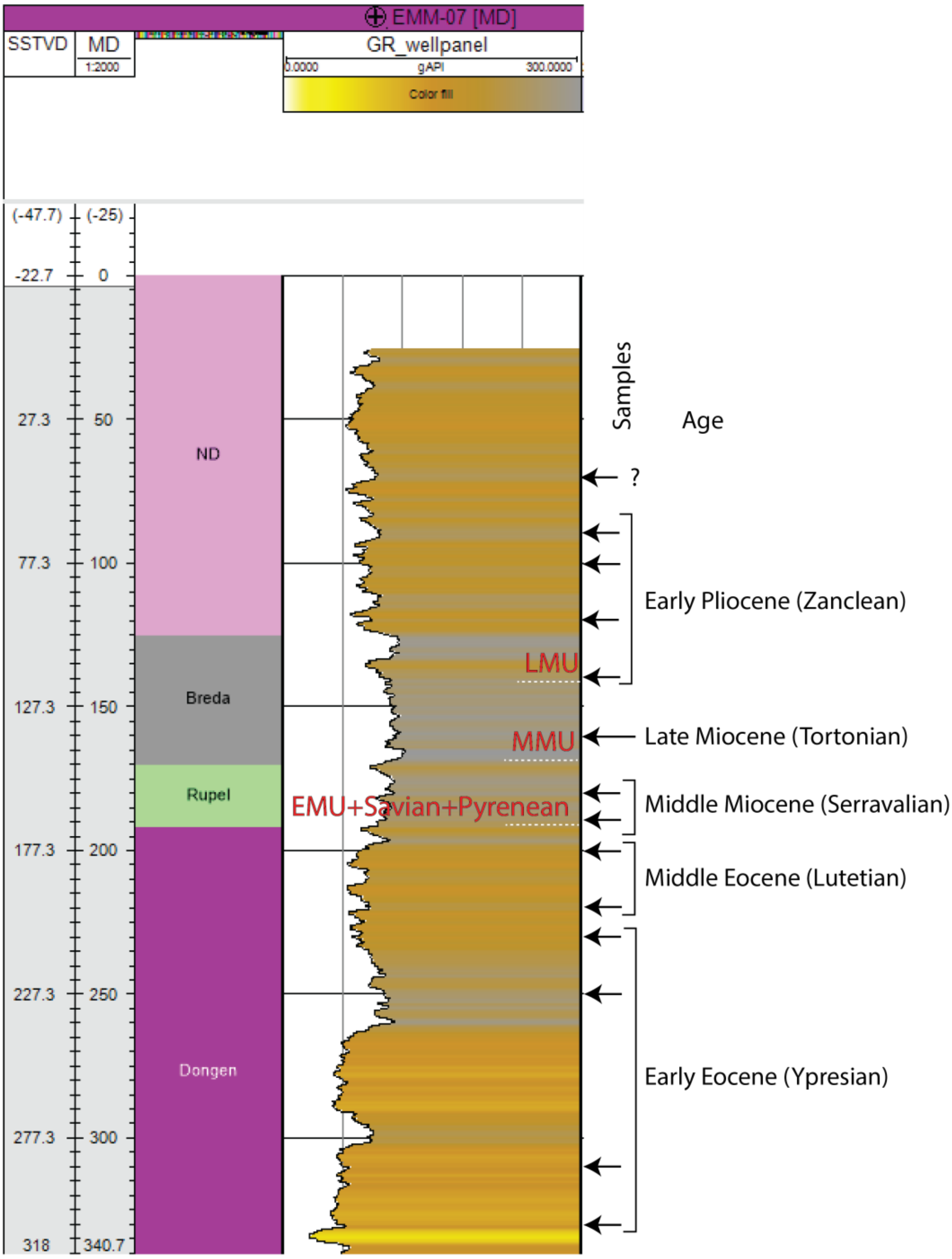

Figure 3.18: Summary of age-interpretation transposed on GR-log for well EMM-07. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). With Middle Miocene sediments overlying Middle Eocene sediments, it is clear that the EMU, Savian and Pyrenean unconformities amalgamate. The Miocene succession is very thin, but chronostratigraphically extensive. The Miocene is overlain by Lower Pliocene.

Table 3.19: Summary age breakdown of well EMM-07 and suggested position of regional unconformities.

Interval / Sample (m MD)	Age / Phase
90 -160	Early Pliocene, Zanclean
140 LMU *(Latest Tortonian-Messinian absent)*	
170 - 180	Late Miocene, Late Tortonian
170 MMU *(Late Serravallian – Early Tortonian absent)*	
180 - 200	Middle Miocene, Early Serravallian, or older
200 EMU + Savian + Pyrenean *(Late Eocene - Early Miocene absent)*	
210 - 220	Middle Eocene, Early Lutetian

3.2.9 Landsmeer-1 (LSM-01)

Sample 550 m MD: Early Pleistocene, Gelasian

This interpretation is based on:

- LOD of *Habibacysta tectata* at 550 m MD

Sample 600 m MD: Late Pliocene, Piacenzian

This interpretation is based on:

- LOD of *Barssidinium* spp. at 600 m MD

Sample 650 m – 700 m MD: Early Pliocene, Zanclean

This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata* at 650 m MD
- FOD of *Invertocysta lacrymosa-tabulata* at 650 m MD

Remark: The identification of *Impagidinium "densiverrucosum"* at 750 m MD indicates that a very thin Tortonian sequence might be present between 700 and 750 m MD.

Interval 750 - 800 m MD (2 samples): Middle Miocene, Langhian (Zone M6)

This interpretation is based on:

- LOD of *Cousteaudinium aubryae* at 750 m MD
- FOD of *Unipontedinium aquaeductum* at 800 m MD
- LOD of *Systematophora placacantha* at 750 m MD

Sample 840: Early Miocene, Late Aquitanian to Early Burdigalian (Zone M3), or older

This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum*
- LOD of *Apteodinium spiridoides*

Remark: *Distatodinium biffii* and *Enneadocysta pectiniformis* are reworked/mixed from underlying Oligocene strata.

Interval 900-940 m MD: Early Oligocene, Middle Rupelian (NSO-3)

This interpretation is based on:

- LOD *Enneadocysta pectiniformis* at 900 m MD
- LOD of *Chiropteridinium galea* at 900 m MD
- LOD of *Phthanoperidinium comatum* at 940 m MD

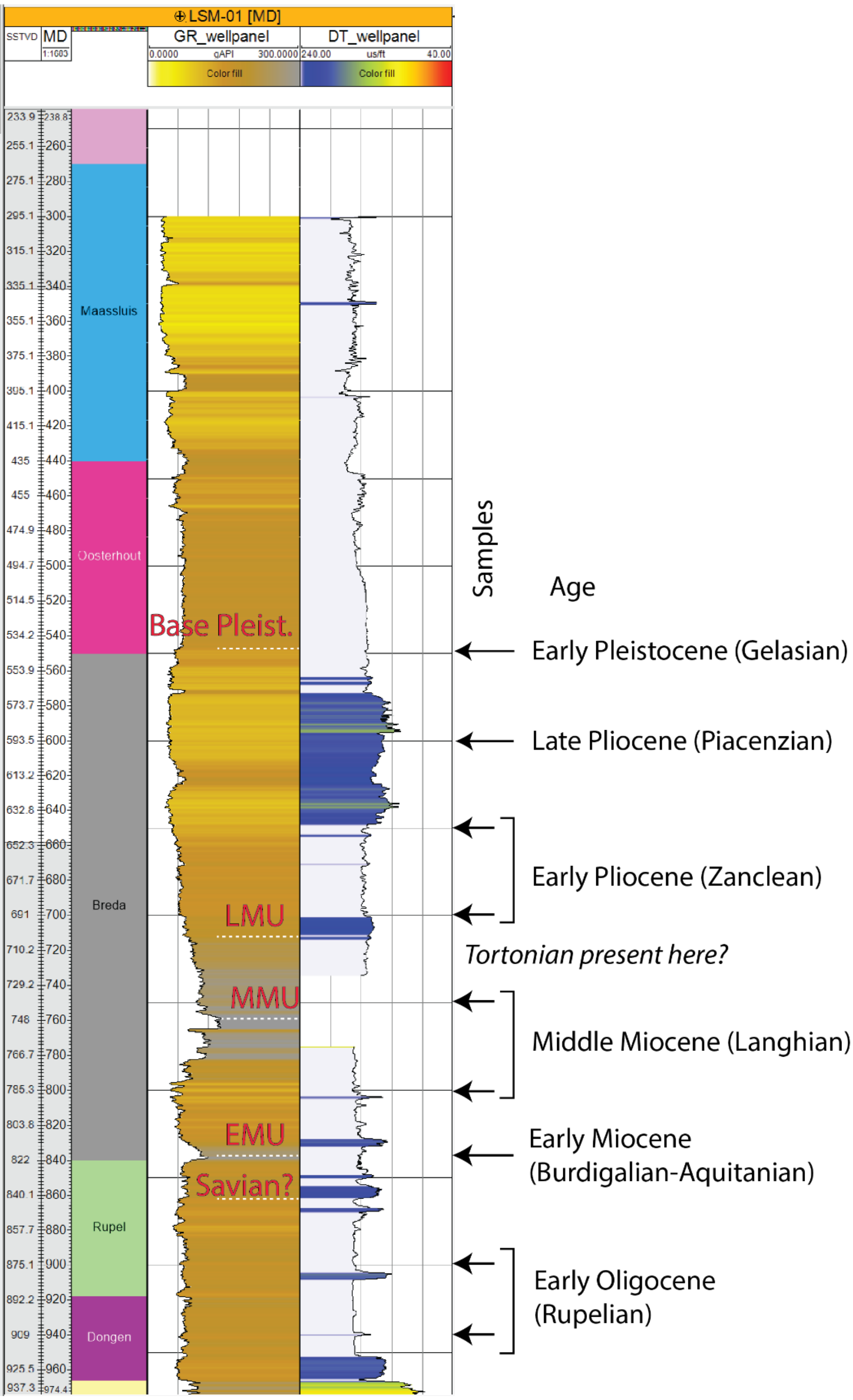

Figure 3.19: Summary of age-interpretation transposed on combined GR-DT-log for well LSM-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024). The base of the Oosterhout corresponds to the base of the Pleistocene. The EMU and MMU can be clEarly recognized. The LMU is less clear, also due to the absence/condensation of the Upper Miocene sequence. Possibly the LMU lies at the base of the progressive coarsening-upward cycle that characterizes the Pliocene.

Table 3.20: Summary age breakdown of well LSM-01 and suggested position of regional unconformities.

Interval / Sample (m MD)	Age / Phase
550	Early Pleistocene, Gelasian
560 Base Pleistocene	
600	Late Pliocene, Piacenzian
650	Early Pliocene, Zanclean
710 LMU *(Messinian absent)*	
700	Late Miocene, Late Tortonian
760 MMU *(**Early Tortonian absent**)*	
750 - 800	Middle Miocene, Late Langhian – Early Serravallian (Zone M6-7)
840 EMU *(**no hiatus discernable, note low sample density**)*	
850	Early Miocene, Late Aquitanian to Early Burdigalian (Zone M3), or older
880 ?Savian *(Upper Rupelian – Chattian absent)*	
900 - 940	Early Oligocene, Middle Rupelian (NSO-3)

3.2.10 Oost-Flevoland-1 (OFL-01)

Interval 400 – 440 m MD (2 samples): Uncertain

Remark: No definite Pliocene markers were encountered. Yet the consistent presence of Tsuga pollen suggests an earliest Pleistocene or Pliocene age.

Interval 500 – 550 m MD (2 samples): Early Pliocene, Zanclean

This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata* at 500 m MD
- LOD of *Melitasphaeridium choanophorum* at 500 m MD
- LOD of *Barssidinium* spp. at 500 m MD

Interval 610 – 660 m: Late Miocene, Latest Tortonian (Zone M14)

This interpretation is based on:

- LOD of *Impagidinium "densiverrucosum"* at 610 m MD
- FOD of *Invertocysta lacyromosa – tabulata* at 660 m MD

Interval 710 – 760 m (2 samples): Late Miocene, Middle-Late Tortonian (Zones M12-13)

This interpretation is based on:

- LOD of *Dapsilidinium* spp. at 710 m MD
- LOD of *Systematophora placacantha* at 710 m MD
- FAOD of *Achomosphaera andalousiensis* at 710 m MD

Interval 810 – 860 m (2 samples): Middle Miocene, Early Langhian (Zone M5)

This interpretation is based on:

- LOD of *Cousteaudinium aubryae* at 810 m MD
- LOD of *Distatodinium paradoxum* at 810 m MD
- LOD of *Apteodinium spiridoides* at 860 m MD
- FOD of *Labyrinthodinium truncatum* at 810 m MD

Interval 910 – 990 m (3 samples): Early Miocene, Middle Burdigalian (Zone M3), or older

This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum* at 910 m MD
- LOD of *Cribroperidinium tenuitabulatum* at 910 m MD

Sample 1040 m: Oligocene, Early Chattian (Zones NSO-6), or older

This interpretation is based on:

- LOD of *Chiropteridium galea*
- LOD of *Wetzeliella symmetrica*

Sample 1110: Middle, Early Lutetian (Zone E4), or older

This interpretation is based on:

- LOD of *Areosphaeridium diktyoplokum* at 1110 m MD
- LOD of *Hystrichosphaeridium tubiferum* at 1110 m MD

Table 3.21: Summary age breakdown of well OFL-01 and suggested position of regional unconformities.

Interval / Sample (m MD)	Age / Unconformity
500 - 550	Early Pliocene, Zanclean
575 LMU	
610 - 760	Late Miocene, Late Tortonian (Zone M12-14)
765 MMU *(Early Tortonian absent, possibly Serravallian too)*	
810 - 860	Middle Miocene, Early Langhian (Zones M5)
910 EMU *(no hiatus discernable)*	
910 - 990	Early Miocene, Middle Burdigalian (Zone M3), or older
1000 Savian *(Late Chattian-Early Aquitanian absent)*	
1040	Oligocene, Early Chattian (Zone NSO-6), or older
1090 Pyrenean *(Late Eocene absent)*	
1110	Middle Eocene, Lutetian (Zone E4), or older

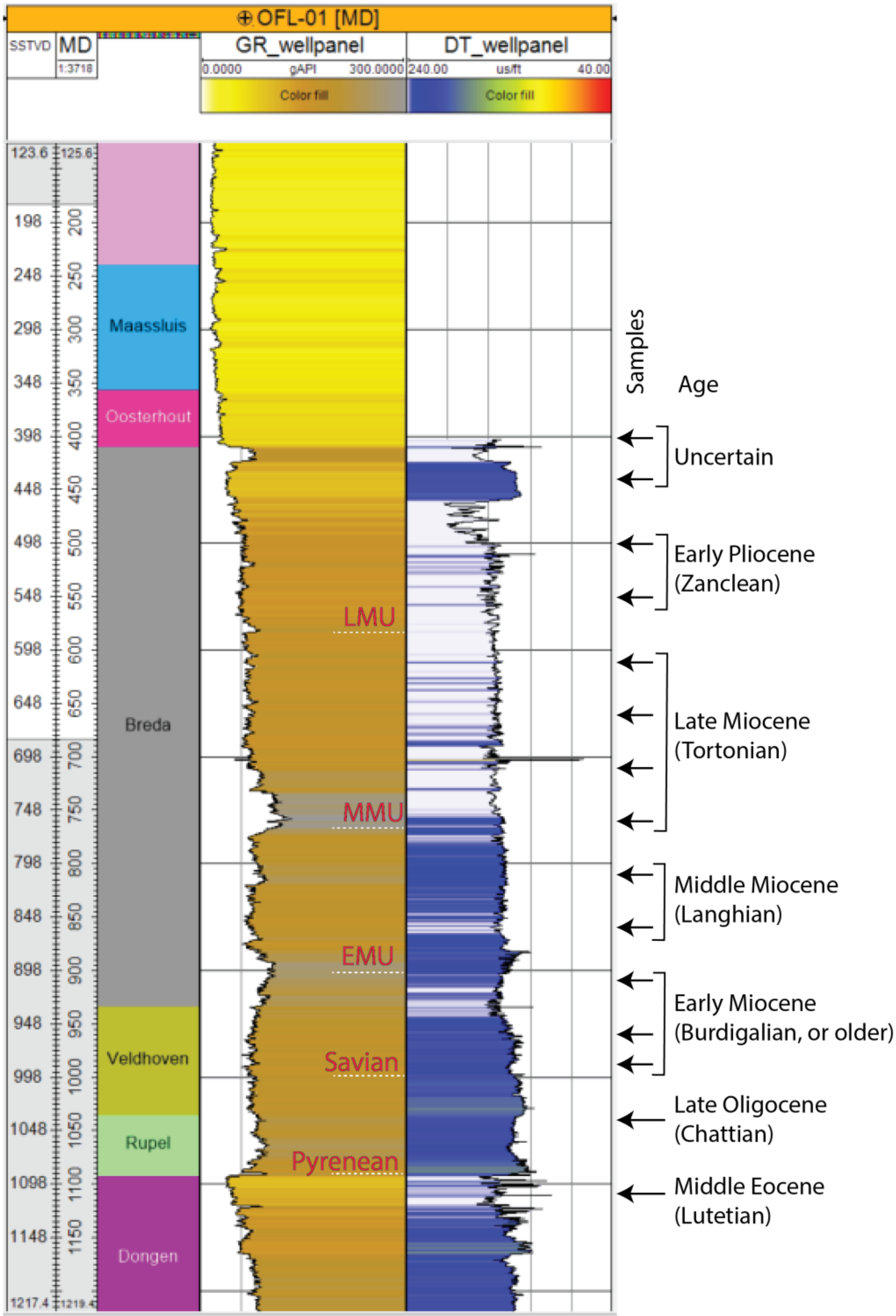

Figure 3.20: Summary of age-interpretation transposed on combined GR-DT-log for well OFL-01. The lithostratigraphic interpretation predates the subdivision of the Breda Fm. and is after Dinoloket (2024).

3.2.11 Raalte-2 (RAL-02)

Sample 60 m MD: Uncertain

Remark: The sample is dominate by Paleogene reworking

Interval 100-140 m MD (2 samples): Late Pliocene, Piacenzian

This interpretation is based on:

- LOD of *Barssidinium* spp. at 100 m MD

Interval 160 – 220 m MD (4 samples): Early Pliocene, Zanclean

This interpretation is based on:

- LOD of *Reticulatosphaera actinocoronata* at 160 m MD
- LOD of *Melitasphaeridium choanophorum* at 160 m MD

Sample 240 m MD: Late Miocene, Late Tortonian

This interpretation is based on:

- LOD of *Impagidinium "densiverrucosum"* at 240 m MD

Sample 260 m MD: Middle Miocene, Late Serravallian (Zone M11)

This interpretation is based on:

- LOD of *Cannosphaeropsis passio* at 260 m MD
- FAOD of *Achomosphaera andalousiensis* at 260 m MD

Sample 270 m MD: Middle Miocene, Early-Middle Langhian (Zone M5)

This interpretation is based on:

- LOD of *Cousteaudinium aubryae* at 270 m MD
- LOD of *Distatodinium paradoxum* at 270 m MD
- FOD of *Labyrinthodinium truncatum* at 270 m MD

Sample 280 m MD: Early Miocene, Middle Burdigalian (Zone M3), or older

This interpretation is based on:

- LOD of *Cordosphaeridium cantharellum*

Interval 300-320 m MD (2 samples): Early Miocene, Aquitanian to Early Burdigalian (Zone M2), or older

This interpretation is based on:

- LOD of *Ectosphaeridium picenum* at 300 m MD
- FOD of *Cousteaudinium aubryae* at 320 m MD

Interval 340 – 420 m MD (2 samples): Early Oligocene, Middle-Late Rupelian (NSO3-4)

This interpretation is based on:

- LOD *Enneadocysta pectiniformis* at 340 m MD
- LOD of *Phthanoperidinium* spp. at 360 m MD

Sample 440: Latest Eocene, Latest Priabonian (Zone NSO-1)

This interpretation is based on:

- LOD of *Areosphaeridium diktyoplokum*

Sample 460 - 480: Late Middle Eocene to Late Eocene, Bartonian to Priabonian (Zone E7-8 of Mudge and Bujak, 1996)

This interpretation is based on:

- LOD of *Areosphaeridium michoudii* at 460 m MD
- LOD of *Heteraulacacysta porosa* at 480 m MD

For deeper section see Munsterman (2022)
No logs are available for this part of the well

Table 3.22: Summary age breakdown of well RAL-02 and suggested position of regional unconformities.

Interval / Sample (m MD)	Age / Unconformity
100 – 140	Late Pliocene, Piacenzian
160 - 220	Early Pliocene, Zanclean
LMU *(Latest Tortonian-Messinian absent)*	
240	Late Miocene, Late Tortonian
MMU *(Early Tortonian absent)*	
260	Middle Miocene, Late Serravallian (Zone M14)
270	Middle Miocene, Early-Middle Langhian (Zone M5-6)
EMU *(Late Burdigalian absent)*	
280	Early Miocene, Middle Burdigalian (Zone M3), or older
300 - 320	Early Miocene, Late Aquitanian to Early Burdigalian (Zone M2), or older
Savian *(Chattian-Aquitanian absent)*	
340 - 420	Early Oligocene, Middle-Late Rupelian (Zone NSO3-4)
Pyrenean, *(no hiatus inferred)*	
440	Latest Eocene, Latest Priabonian (Zone NSO-1)
460 – 480	Late Middle to Late Eocene, Bartonian-Priabonian (Zone E7-8)

4 Discussion

The biostratigraphic age-interpretations for all investigated wells are of sufficient detail and confidence for recognition of the regional Miocene unconformities, even though cuttings were sampled for most wells. Only for well BNV-01-S1 this is not the case, which is ascribed to compromised palynological processing. As far as sampling allows, also the top and base of the Pliocene was confidently identified in most wells. The overlying Pleistocene is somewhat more subjectively interpreted, typically on the basis of absence of Pliocene markers and a progressive up-section diminishment of marine influence. Only in a few wells/boreholes objective Early Pleistocene markers were identified. A further pinpointing of the Plio-Pleistocene transition requires a separate, dedicated high-resolution study.

In all examined wells/boreholes, the EMU and the MMU can identified clearly on the basis of GR-signature. Two zones with elevated GR-values are consistently observed within the, now biostratigraphically constrained, stratigraphic envelopes. These are interpreted to represent transgressive surfaces at/above the 'unconformities'. It remains somewhat unclear how much geological time, if at all, is missing in association with the EMU. Given its correspondence to the Late Burdigalian onset of the Mid-Miocene Climatic Optimum (Steinsdottir et al., 2021), a single eustatic-driven transgression seems plausible.

The MMU, on the other hand is consistently characterized by an hiatus, or an highly condensed section. Across the MMU, the lower part of the Tortonian is consistently missing/condensed. The above implies that the Groote Heide Formation can be consistently interpreted on the basis of well-logs. It represents the interval intertwined between these GR-maxima.
The LMU, which in virtually all wells is associated with an Messinian-Early Zanclean (or more extensive) hiatus, is not characterized by a consistent log-response. A change in sequence stratigraphic regime may be linked to the end of the Mid-Miocene Climatic Optimum by Latest Serravlain times, and subsequent increase in amplitudes of eustatic sea-level variation (Steinsdottir et al., 2021). The base Pleistocene is recorded in most wells, and in many instances it lies substantially deeper than the base of the Maassluis Fm. This illustrates that the definition of the Formation of Maassluis is inadequate for sequence stratigraphic purposes. The interval is currently under discussion and review, together with the definition of the top of the Fm of Oosterhout. In summary one can state that for the predominantly progradational setting of the Late Miocene – Pleistocene, lithostratigraphic units are strongly diachronous, posing problems if they are to be considered in a sequence stratigraphic context.
From a more regional perspective, it has become clear that if Miocene strata are indeed present in significant thickness (>50 m) and these always include the interval between the EMU and MMU (corresponding to the Groote Heide Fm., Figure 4.1). Significant deposits, straddled by MMU and the LMU (corresponding to the Diessen Fm.) in contrast, are confined to the RVG (Siebels et al., 2004), the Zuiderzee Low area and as newly demonstrated, also the Central Netherlands area (e.g. wells JUT-01, BRAK-01 and NVG-01) and the Lauwerszee area (AKM-03 and B06H0082, see Figure 4.1). The areas fringing these depocenters typically seem to be characterized by a very thin Tortonian sequence (see the results from well DAP-GEO-2), meaning that in those areas, condensation occurred, rather than significant erosion.

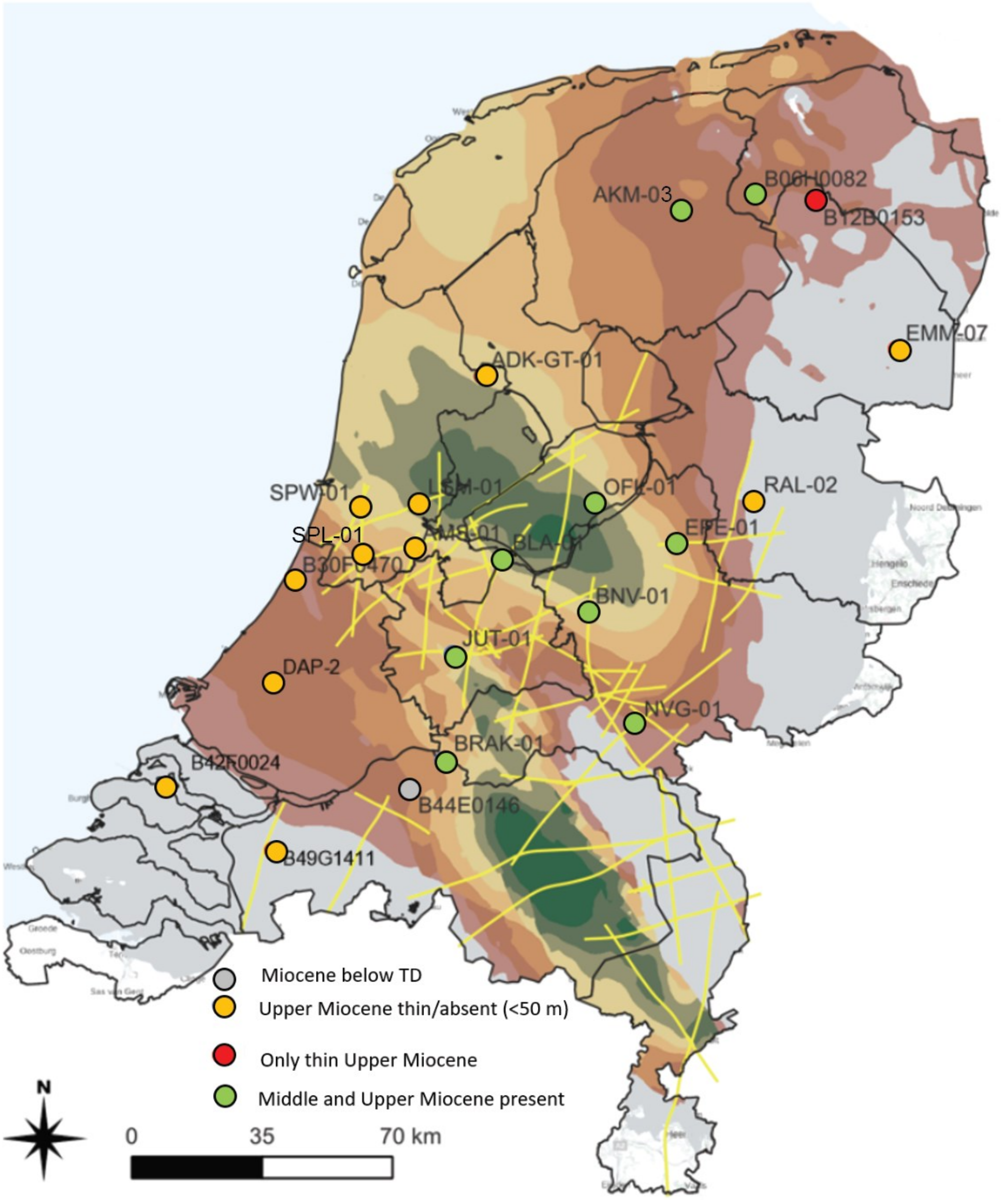

Figure 4.1 Overview map of what stratigraphic architecture was encountered in the investigated wells (colored dots). The map depicts the thickness of the Upper North Sea Group.

Although a full-scale integration with seismic observations of the Neogene in the Netherlands clearly exceeds the scope of this report, Figure 4.2 illustrates that these biostratigraphic data are critical for the interpretation of seismic lines. By using the VELMOD time-depth model for seismic time to depth conversion, the positions of the respective surfaces in well JUT-01 are projected in seismic time on SCAN-line 23. An important observation is that the unconformities as recorded in the well, correspond to clearly traceable impedance contrasts. The Middle Miocene sequence (between EMU and MMU, Groote Heide Fm.) is of uniform thickness and the Upper Miocene sequence (between MMU and LMU, Diessen Fm.) thickens substantially. Because of the E-W orientation of this line, it is difficult to see whether direct sequence stratigraphic indicators (e.g., clinoforms) are developed in the Upper Miocene. Nevertheless, clear clinoforms are recognized below the base of the Pleistocene in the well. A seismic interpretation study, using the constraints provided in this report started within a mapping project at the GDN and will be extended and provided as part of WarmingUP*GOO* work packages 1.1.2 and 1.2 .

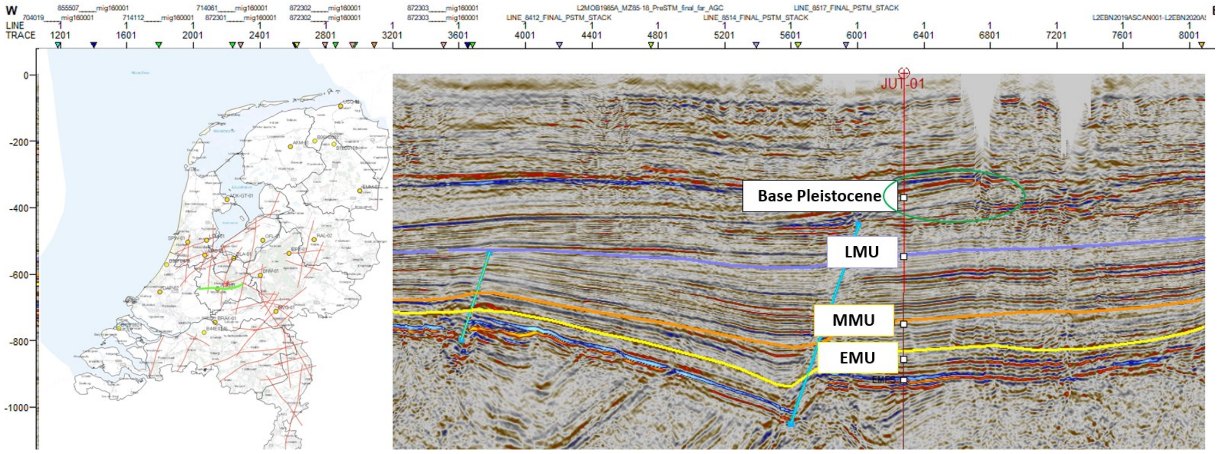

Figure 4.2 Example illustrating the expression of the biostratigraphically constrained contact/surfaces on SCAN seismic-line 23 in two way time. The colored lines and boxes reflect the respective stratigraphic horizons. The green circle highlights a Pliocene clinoform development, thus with a (partial) westward direction.

The current study thus clearly supports the proposition by Munsterman et al. (2019) that a sequence stratigraphic approach is suitable for mapping Neogene marine strata in the Netherlands. Nevertheless, a serious complication is arising if lithostratigraphic units are to be considered as the main building blocks for these sequence-stratigraphically constrained models. Whereas it seems that Groote Heide Fm., as a lithostratigraphic unit, can be readily considered as a contemporaneous unconformity bound unit, this is not case for the Diessen, Oosterhout and Maassluis Formations in which the lithofacies development across the LMU is strongly diachronous. The results of this study thus show that the existing lithostratigraphic interpretations of wells and boreholes cannot be considered to reflect geological time-lines. Hence, as part of future mapping and modelling a precise definition of the model units is required.

5 Conclusions

- Dinocyst biostratigraphy has successfully been applied to obtain detailed chronostratigraphic interpretations for 11 newly analyzed and 11 wells and boreholes for which legacy data were available. This new dataset serves as a foundation for ensuing seismic interpretation of the Paleogene-Neogene-base Quaternary of the Netherlands.
- In all 22 wells the Early (EMU), Middle (MMU) and Late (LMU) Miocene Unconformity were identified. Whenever sampling and preservation of material were sufficient, also the base of the Pleistocene and/or the Savian and Pyrenean unconformities were identified.
- The EMU and MMU can be readily recognized as a transient increase on the GR-log. It is hypothesized that this reflects a transgressive surface, and through winnowing and condensation an enrichment of glauconite and/or muscovite, in association with the respective unconformities. The LMU is not characterized by a uniform log-response.
- The above means that the lithostratigraphic unit, Groote Heide Formation, sensu Munsterman et al. (2019), can be interpreted on the basis of well-logs with great confidence. Interpretation of the top of the lithostratigraphic defined Diessen Formation is more problematic.
- The MMU and LMU are associated with significant depositional hiatuses. In association with the MMU the lower part of the Upper Miocene is absent. The LMU is accompanied by a Messinian – Lower Zanclean hiatus, or a zone of severe condensation.
- A significant thickness of the Middle Miocene sequence bounded by the MMU (Groote Heide Fm.) is more spatially more widespread than Upper Miocene deposits (Diessen Fm.). Based on records with sufficient resolution, it seems that the latter is very condensed, but not completely absent outside of the main depocenters.
- The base of the Pleistocene is also recorded in 15 of the 22 wells. In many cases, it lies substantially deeper than the base of the Maassluis Fm. This altogether shows that within the largely progradational setting of the Late Miocene – Pleistocene, lithostratigraphic units are strongly diachronous, posing problems if they are to be considered in a sequence stratigraphic context, without having age-control.
- An initial inventory shows that the results of this study align very well with seismically-traceable horizons. Updating national scale surfaces for the Breda Subgroup formations Groote Heide and Diessen, where necessary, based on the biostratigraphy results, will be conducted within the framework of another work package in the Warming-UP GOO project.

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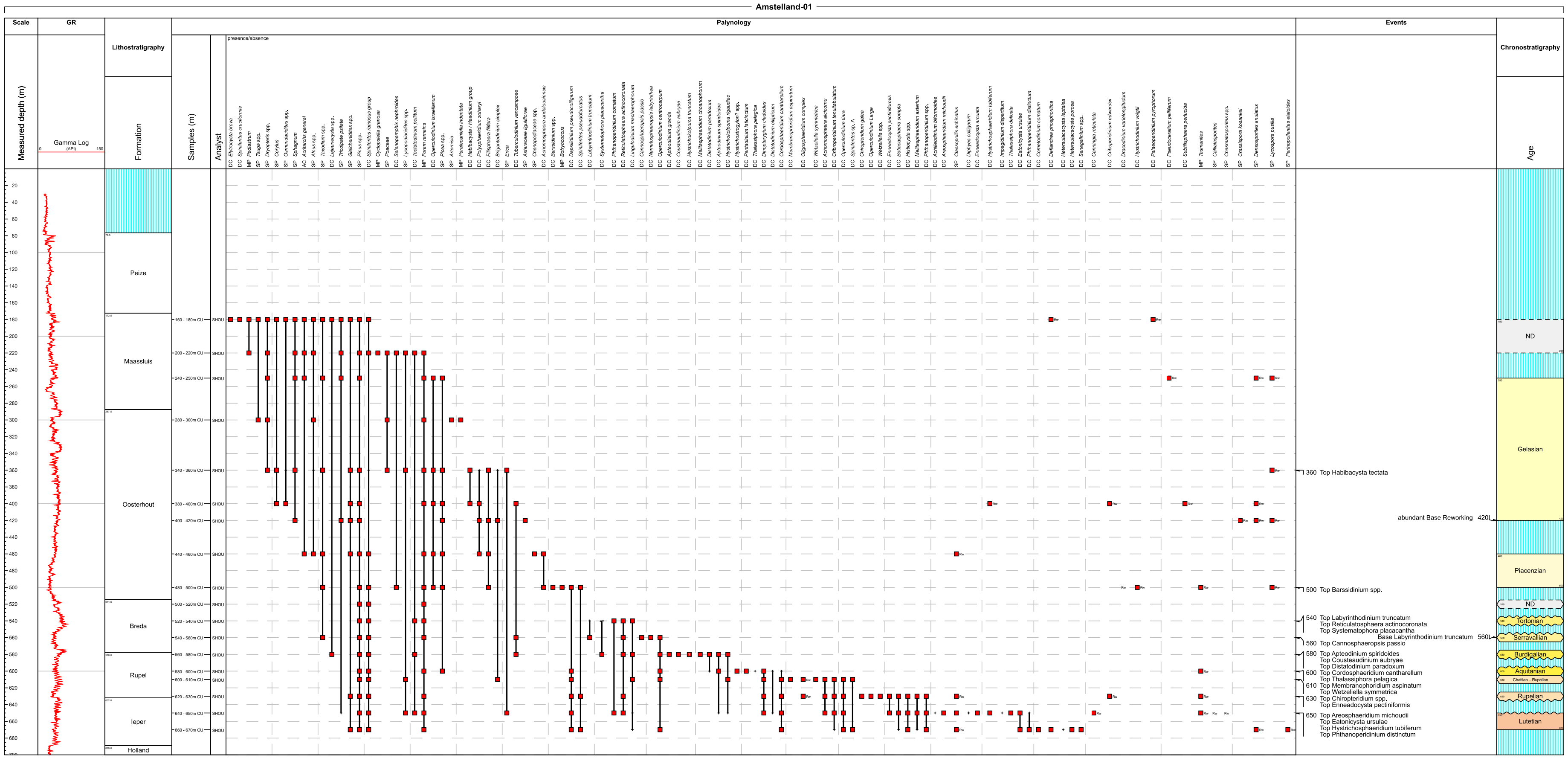
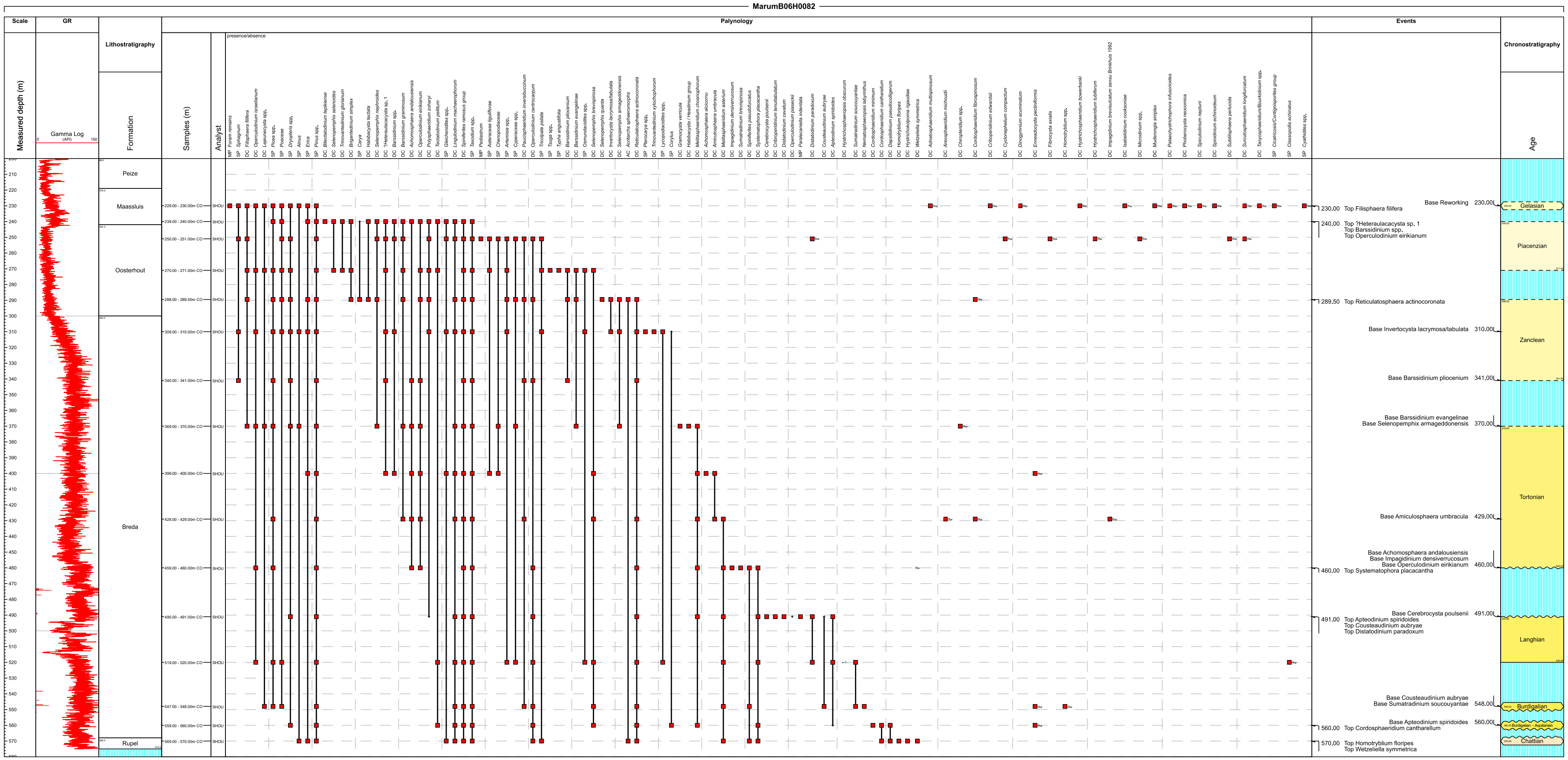
Appendix: Detailed range-charts per well

Amstelland-1 (AMS-01)



Marum (B06H0082)



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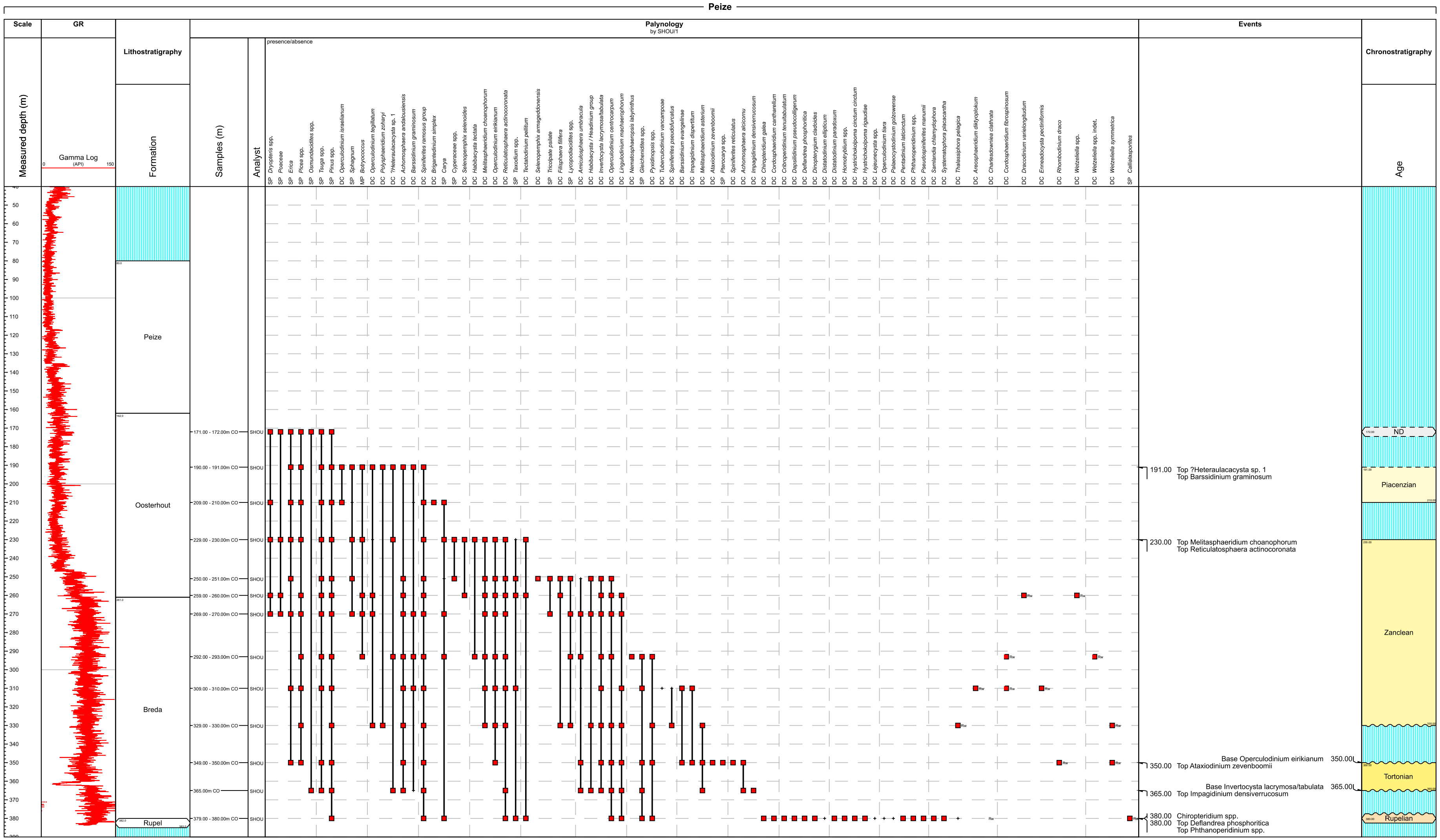
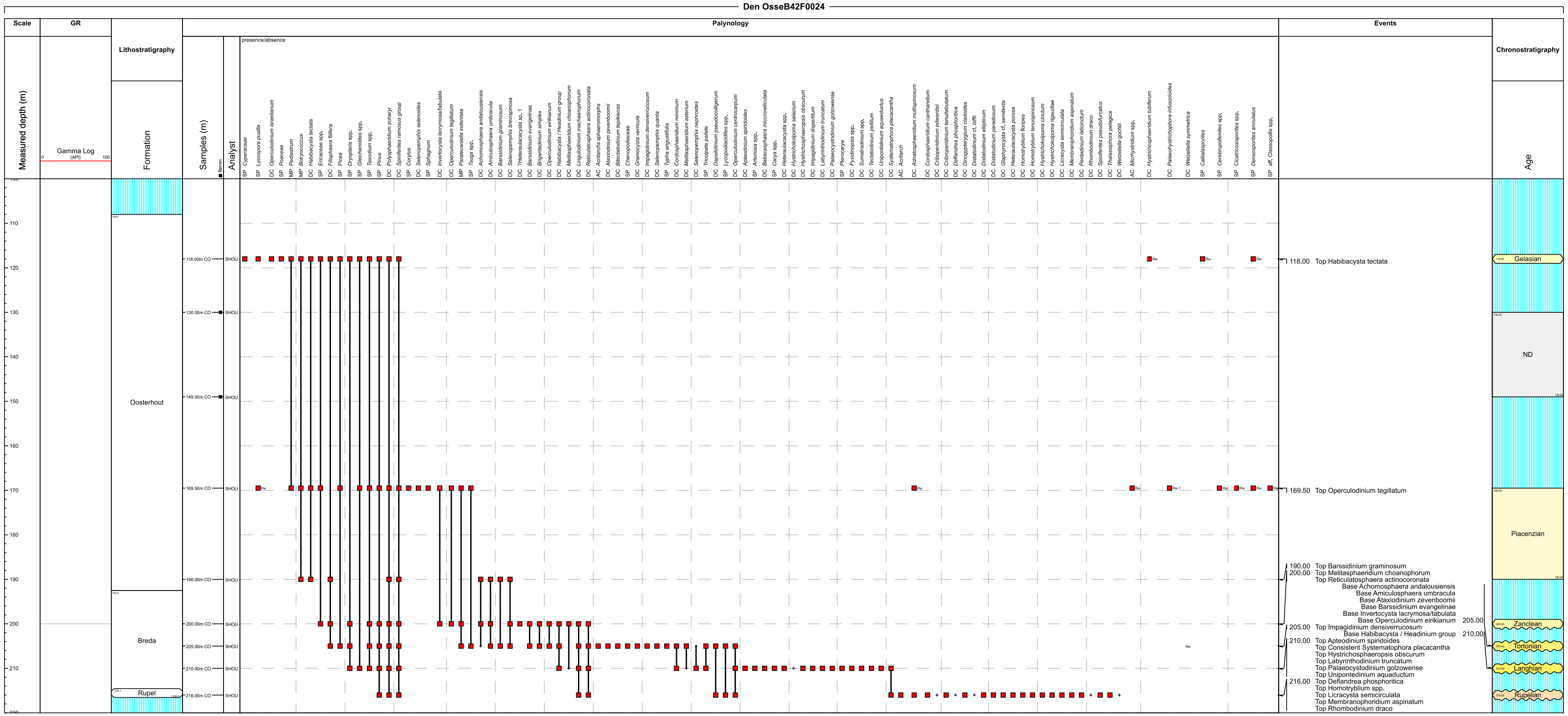
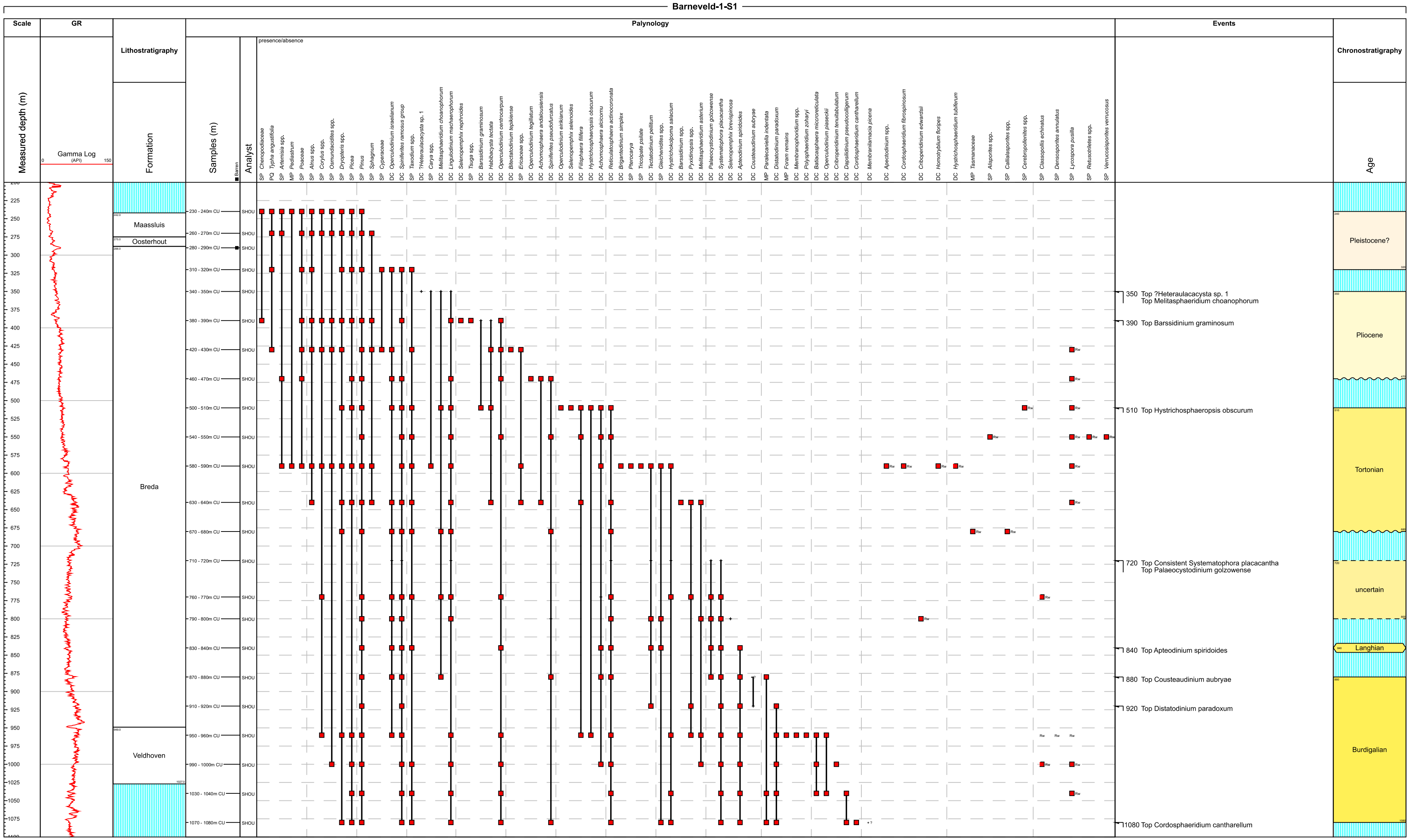


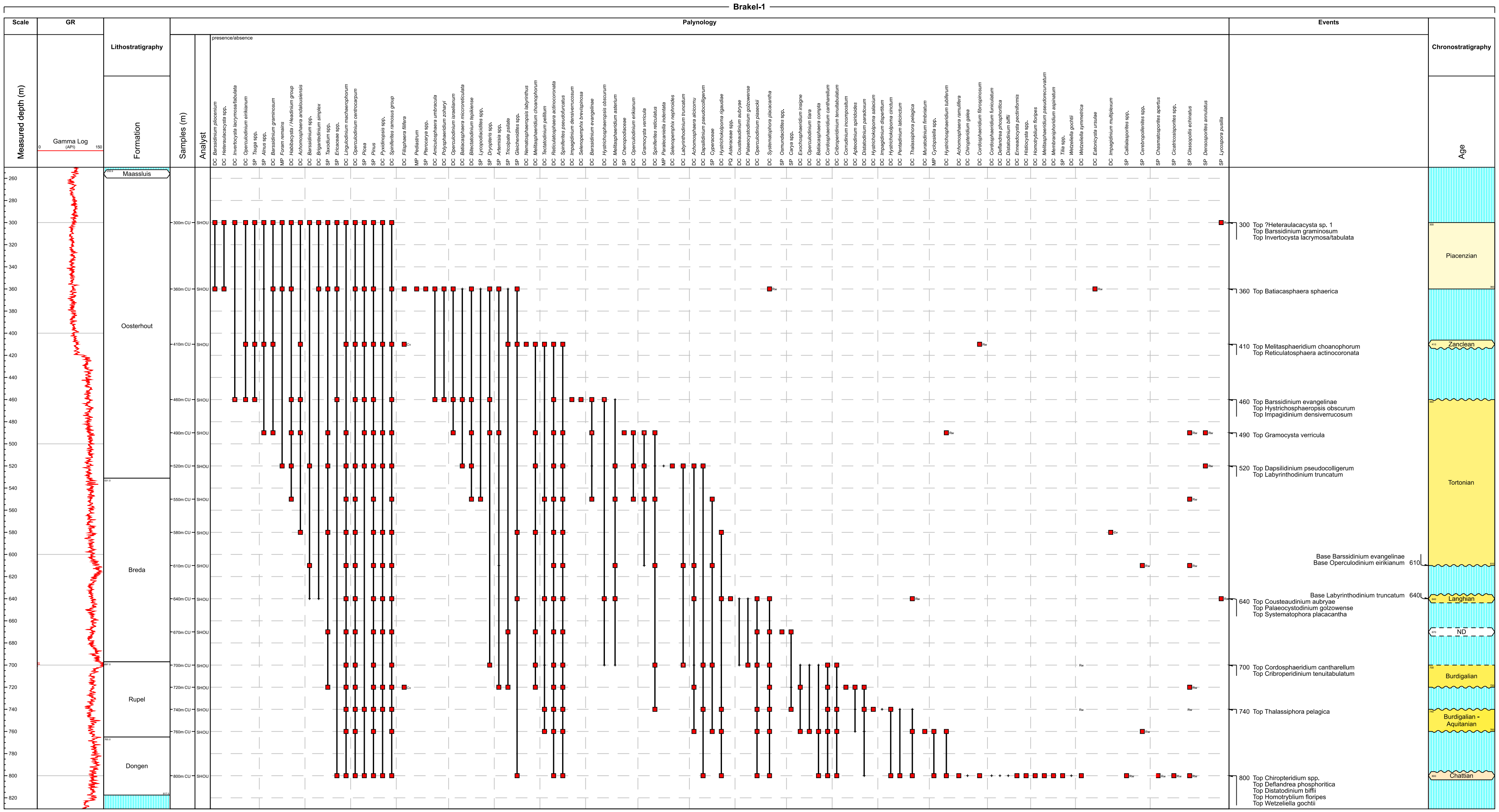
Den Osse (B42F0024)



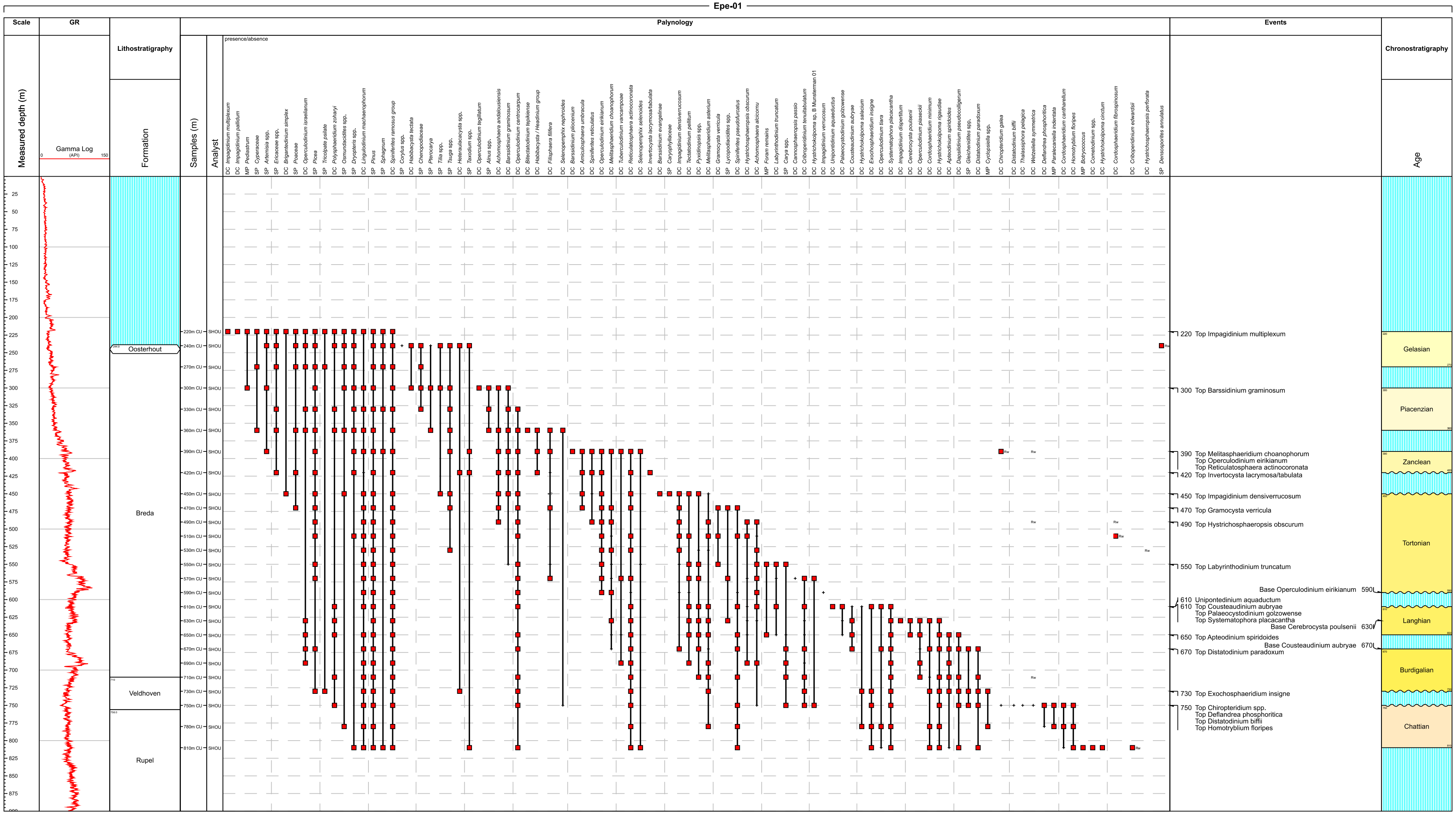
Barneveld-1-S1 (BNV-01-S1)



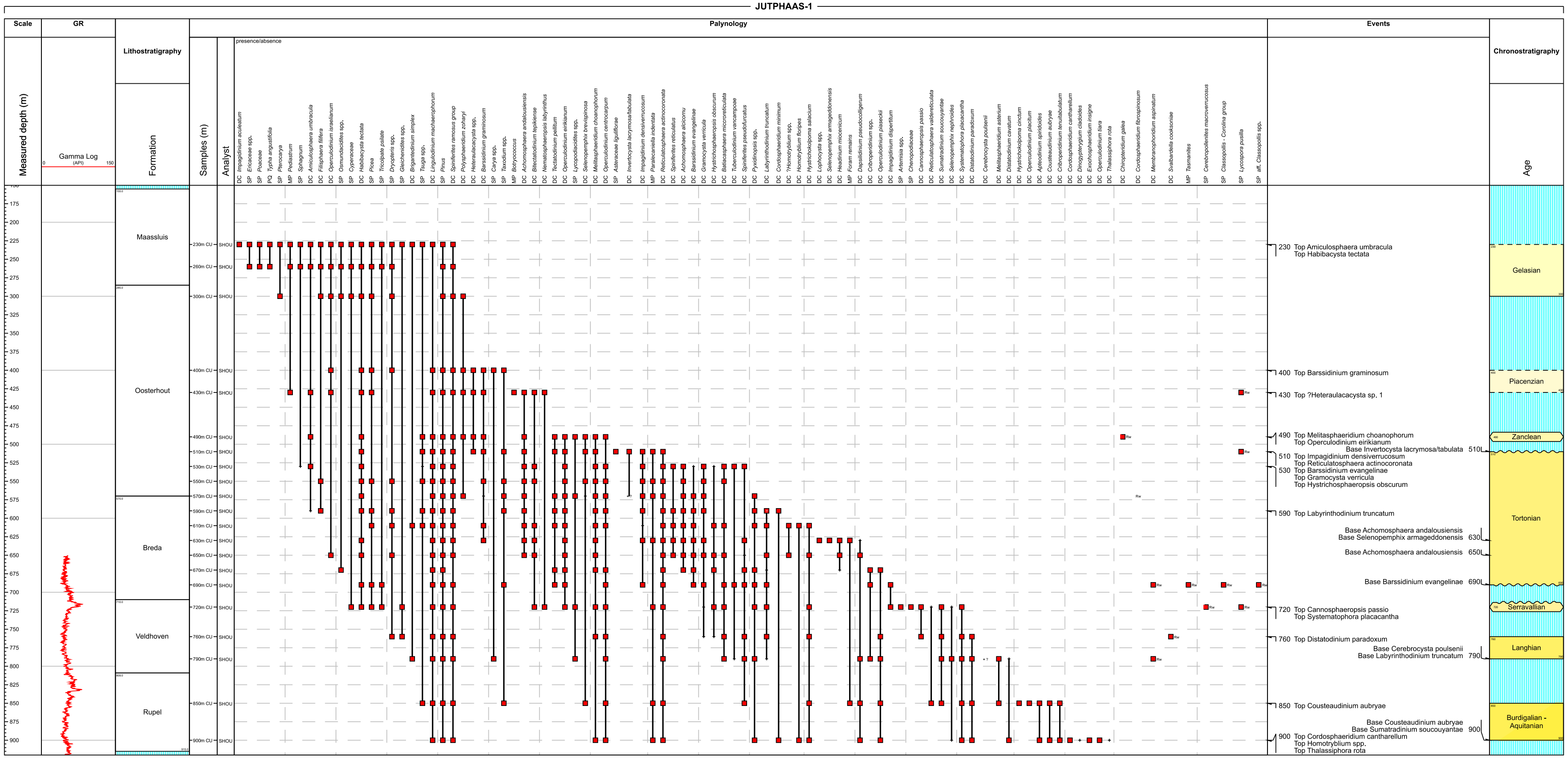
Brakel-1 (BRAK-01)



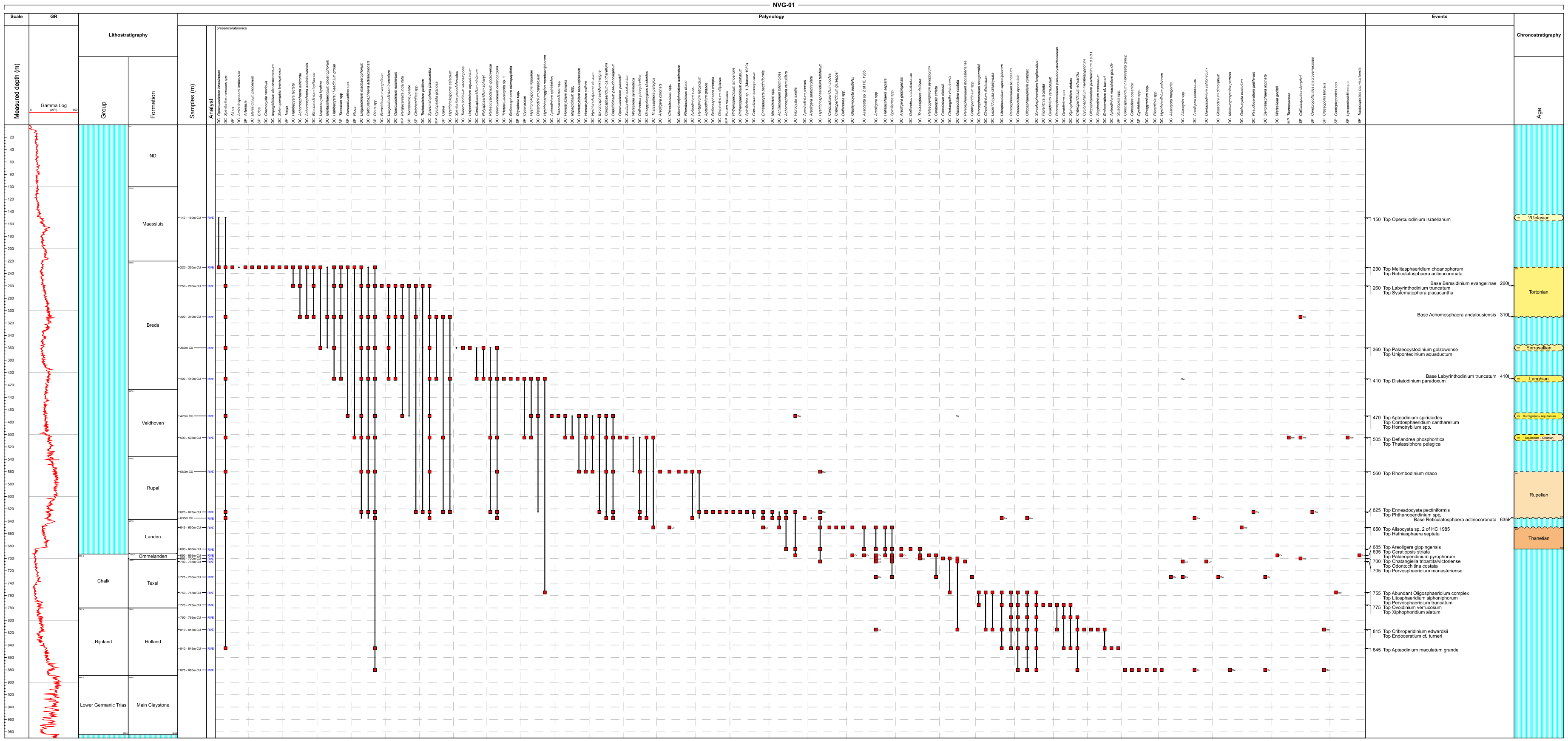
Epe-1 (EPE-01)


Epe-01
Scale
GR
Palynology
Events
Lithostratigraphy
Chronostratigraphy
Measured depth (m)
Gamma Log
Formation
Samples (m)
Analyst
presence/absence
Age
Oosterhout
Breda
Veldhoven
Rupel
220 Top Impagidinium multiplexum
300 Top Barssidinium graminosum
390 Top Melitasphaeridium choanophorum
Top Operculodinium eirikianum
Top Reticulatosphaera actinocoronata
420 Top Invertocysta lacrymosa/tabulata
450 Top Impagidinium densiverrucosum
470 Top Gramocysta verricula
490 Top Hystrichosphaeropsis obscurum
550 Top Labyrinthodinium truncatum
Base Operculodinium eirikianum 590L
610 Unipontedinium aquaductum
610 Top Cousteaudinium aubryae
Top Palaeocystodinium golzowense
Top Systematophora placacantha
Base Cerebrocysta poulsenii 630
650 Top Apteodinium spiridoides
Base Cousteaudinium aubryae 670L
670 Top Distatodinium paradoxum
730 Top Exochosphaeridium insigne
750 Top Chiropteridium spp.
Top Deflandrea phosphoritica
Top Distatodinium biffii
Top Homotryblium floripes
Gelasian
Piacenzian
Zanclean
Tortonian
Langhian
Burdigalian
Chattian

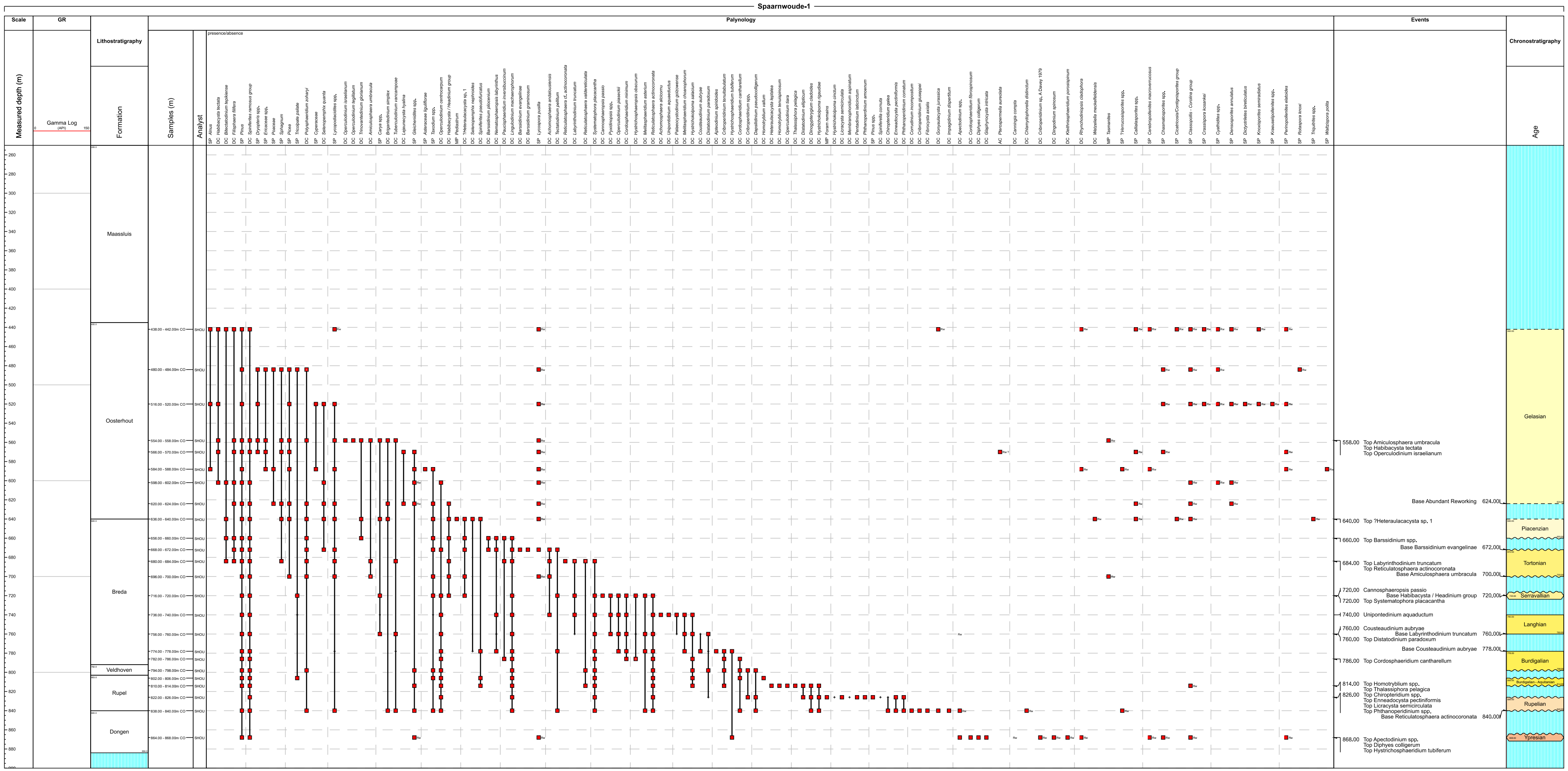
Jutphaas-1 (JUT-01)



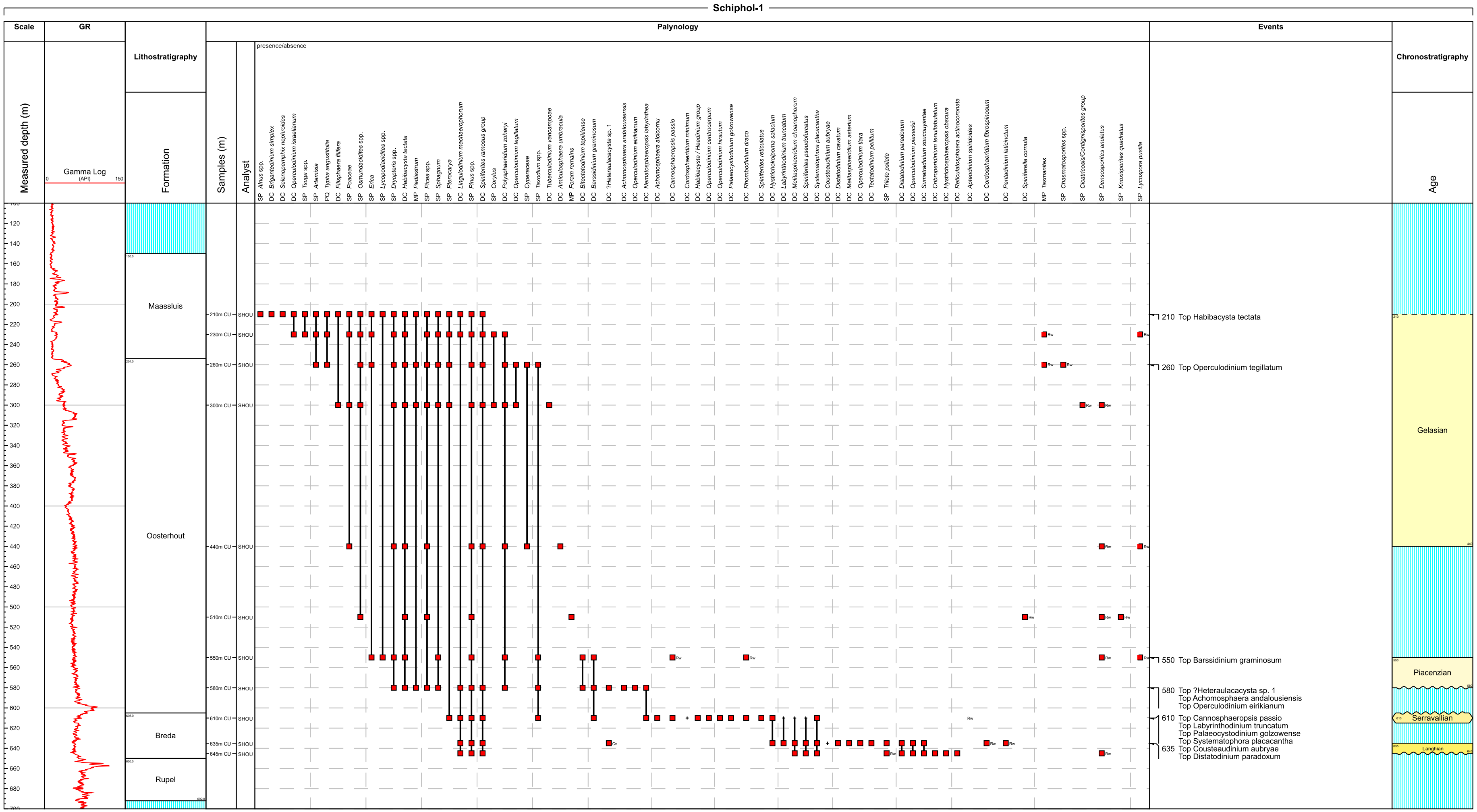
Nijmegen-Valburg-1 (NVG-01)



Schiphol-1 (SPL-01)



Spaarnwoude-1 (SPW-01)



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