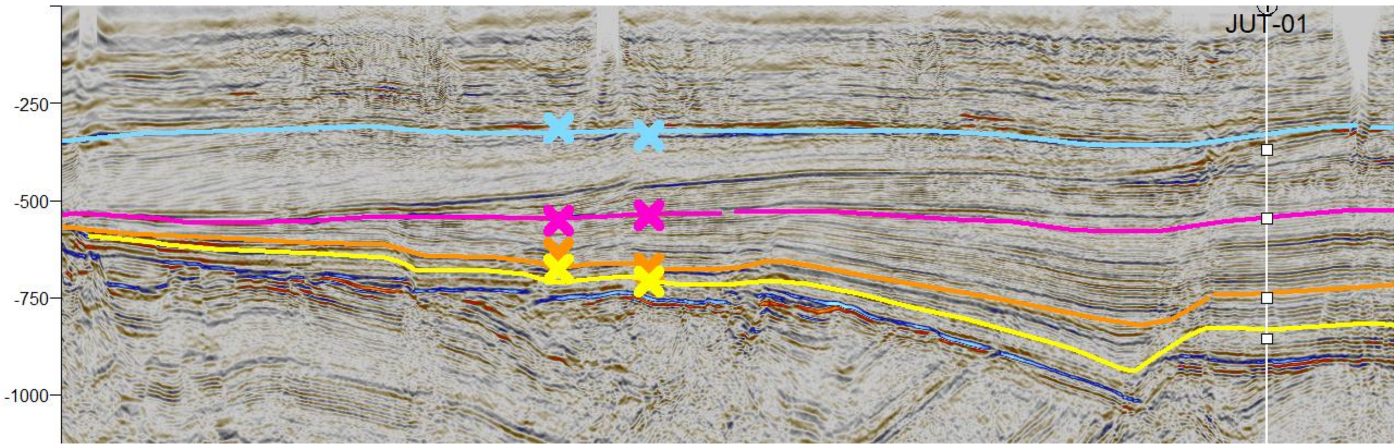
WarmingUPGOO
Geothermie & Opslag Opschaling



Towards National Mapping of the Breda Subgroup and Oosterhout Formation

Rixt Altenburg, Marianne van Unen

August 2025

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Summary

The report presents a comprehensive geological study aimed at improving the understanding of the intermediate-depth subsurface (250–1500 m) in the Netherlands, which is crucial for geothermal energy and heat storage applications. The study focuses on mapping and modeling key horizons—specifically the Early, Mid, and Late Miocene Unconformities (EMU, MMU, LMU) and the top of the Oosterhout Formation—using seismic interpretation, biostratigraphic data, and AI-assisted tools.

The study integrates seismic data from the SCAN program and composite lines with biostratigraphic interpretations from key wells (Houben, 2025). These data were used to trace seismic reflectors and convert them from time to depth using the Velmod 3.1 velocity model. The resulting depth and thickness maps reveal significant regional variations, with the Roer Valley Graben (RVG) and Zuiderzee Low (ZZL) emerging as major depocenters, as expected.

Seismic facies analysis shows the distinct patterns for the different mapped units, between the unconformities. The EMU-MMU interval is characterized by high-amplitude, continuous reflectors, while the MMU-LMU interval displays more variable amplitudes and, in places, clinoform structures. The Oosterhout Formation is marked by low-amplitude reflectors and widespread clinoforms. A Petrel-built in AI-tool was applied to 3D seismic surveys available in the northern Netherlands to automatically trace reflectors and hence facilitate mapping, but its effectiveness was limited due to the complexity of the seismic facies and the lack of strong acoustic contrasts.

The modeling efforts produced depth and thickness surfaces for each horizon, revealing trends such as thinning of Miocene intervals in the north and thickening in the RVG and ZZL. Comparisons with existing models (REGIS II and DGM-Deep) highlighted differences, particularly in the Zuiderzee Low, where the EMU surface mapped in this study is positioned significantly deeper. These differences are attributed to the use of different input data; updated seismic and biostratigraphic data in the current study, versus older, and often shallower borehole data in previous models.

In conclusion, this study establishes a robust stratigraphic framework for the intermediate-depth subsurface of the Netherlands. It confirms the utility of the EMU and MMU as seismic mappable unconformities, while suggesting revisions for the LMU due to its inconsistent seismic expression of this so called ''unconformity''. The findings provide a foundation for future geothermal and heat storage exploration and subsurface modeling efforts.

1. Introduction

Geothermal energy and subsurface heat storage are important prerequisites of the transition towards a sustainable heat-supply for the Netherlands. The WarmingUP Geothermal and Storage Upscaling program (Warming^{UP}*GOO*) aims to expedite the application of these techniques in the Netherlands. Therefore, firm knowledge and understanding of the subsurface is a crucial requirement.

A major challenge is that the subsurface within the ~300 – ~1500 m depth range, the so-called intermediate depth subsurface, is relatively poorly mapped and characterized. On the one hand, shallow subsurface data and models are derived from groundwater-related activities predominantly up-to depths of ~250 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. Therefore, a knowledge gap exists between the ~250 to ~1500 meter depth range in the subsurface of the Netherlands. By combining seismic and stratigraphic interpretations from both 'deep' (hydrocarbon and geothermal) and 'shallow' (groundwater) boreholes, the quality of subsurface models of this intermediate depth domain can be significantly improved (cf. Houben et al., 2023). This requires synchronic interpretation of both seismic lines and 'deep' and 'shallow' well (chrono-)stratigraphy in a systematic and consistent way.

The Miocene aged Breda Subgroup and Pliocene aged Oosterhout Formation are positioned within the intermediate depth interval and form a potential target for geothermal or storage projects in the Netherlands (Hollebeek et al., 2018; Mijnlieff, 2020). To assess the geothermal potential, the depth and thickness of these Formations are important parameters to establish. This study describes the results of the seismic interpretation of the Miocene unconformities that limit the Breda Subgroup and the top of the Oosterhout Formation (the latter only where the seismic data is of sufficient resolution). In conjunction, the re-evaluated chronostratigraphic interpretations of these horizons from the biostratigraphic analysis of key wells throughout the Netherlands from Houben (2025), provided the depth of seismic reflectors for the horizons.

Recent insights by Munsterman et al., (2019) have led to a proposed revision of the stratigraphy of these Miocene strata. The Breda Formation has been updated and elevated in rank and is now referred to as the Breda Subgroup, which is proposed to comprise two new formations. These (not formalized yet) formations are distinguished by three regionally recognizable unconformities: the Groote Heide Formation, located between the Early Miocene Unconformity (EMU) and Mid-Miocene Unconformity (MMU), and the Diessen Formation, situated between the MMU and the Late Miocene Unconformity (LMU) (Figure 1). However, the definitions of the Groote Heide and Diessen formations were initially proven for the Roer Valley Graben (RVG) where the Breda Subgroup reaches substantial thickness and differentiation between the Groote Heide and Diessen Formations is based on sequence-stratigraphic arguments. These are supported by chronostratigraphic and lithostratigraphic analyses, well-log correlation, and the analysis of seismic reflection data (Munsterman et al., 2019). 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, with the exception of the Achterhoek area and Belgium (Munsterman et al., 2024; Deckers et al., 2025). Therefore, we will not refer to the Diessen and Groote Heide Formations, but the intervals between the EMU and MMU, and between the MMU and LMU.

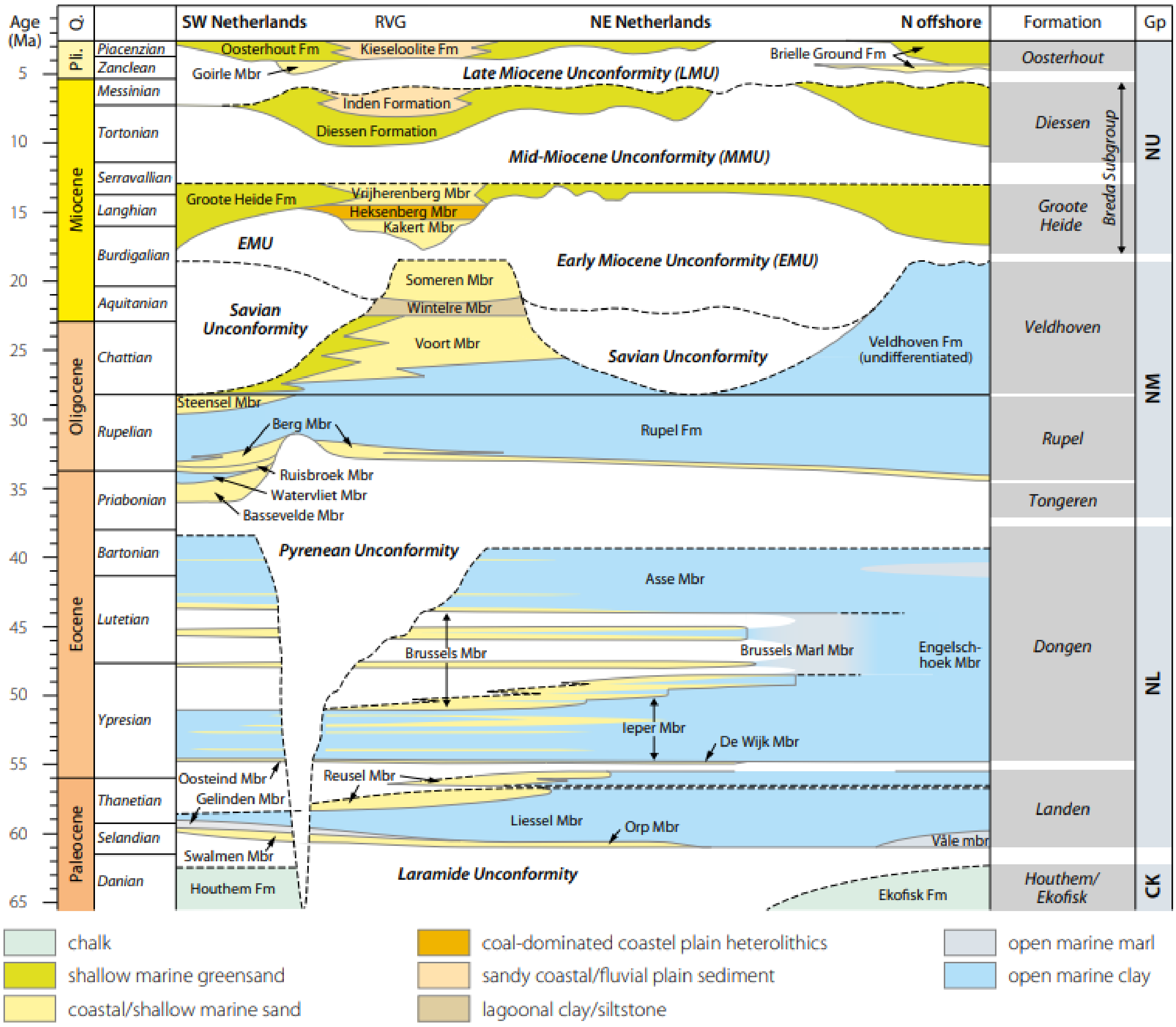

Figure 1. Stratigraphic scheme (Wheeler diagram) of the Lower (NL), Middle (NM) and Upper (NU) North Sea Groups in the Netherlands (with the exception of the Quaternary interval) (from Munsterman et al., 2025). The Breda Subgroup marks the base of the Upper North Sea Group, the Groote Heide is the interval between the EMU and MMU and the Diessen is the interval between the MMU and LMU.

This study sets an important step towards systematic sequence stratigraphic mapping and modelling of the intermediate depth subsurface of the onshore Netherlands, by seismic mapping of the marine Paleogene-Neogene successions. The current work builds upon earlier mapping of the Breda Subgroup that was carried out in the context of ThermoGIS (www.thermogis.nl). ThermoGIS is a public, web-based geographic information system that displays the regional potential of geothermal energy and high temperature aquifer thermal energy storage (HT-ATES) in the Netherlands to support the development of geothermal heat extraction and find suitable locations for HT-ATES (www.thermogis.nl). The study reported here expands and improves the earlier ThermoGIS mapping and will be used in planned, future ThermoGIS updates..

In this study, the 'unconformity' surfaces EMU, MMU and LMU and the top of the Oosterhout Formation, were mapped by interpretation of new seismic data provided by the SCAN programme and carefully selected seismic composites. The formal lithostratigraphic unit names in between these horizons (Diessen, Groote Heide and the Oosterhout Formation) remain to be decided. Each unit in between these mapped horizons has its own seismic characteristics associated with their own lithostratigraphic characteristics. Subsequently, the seismic interpretation has been validated with chronostratigraphic interpretations of the Miocene unconformities that are studied alongside this study (Houben, 2025) (Fig. 2).

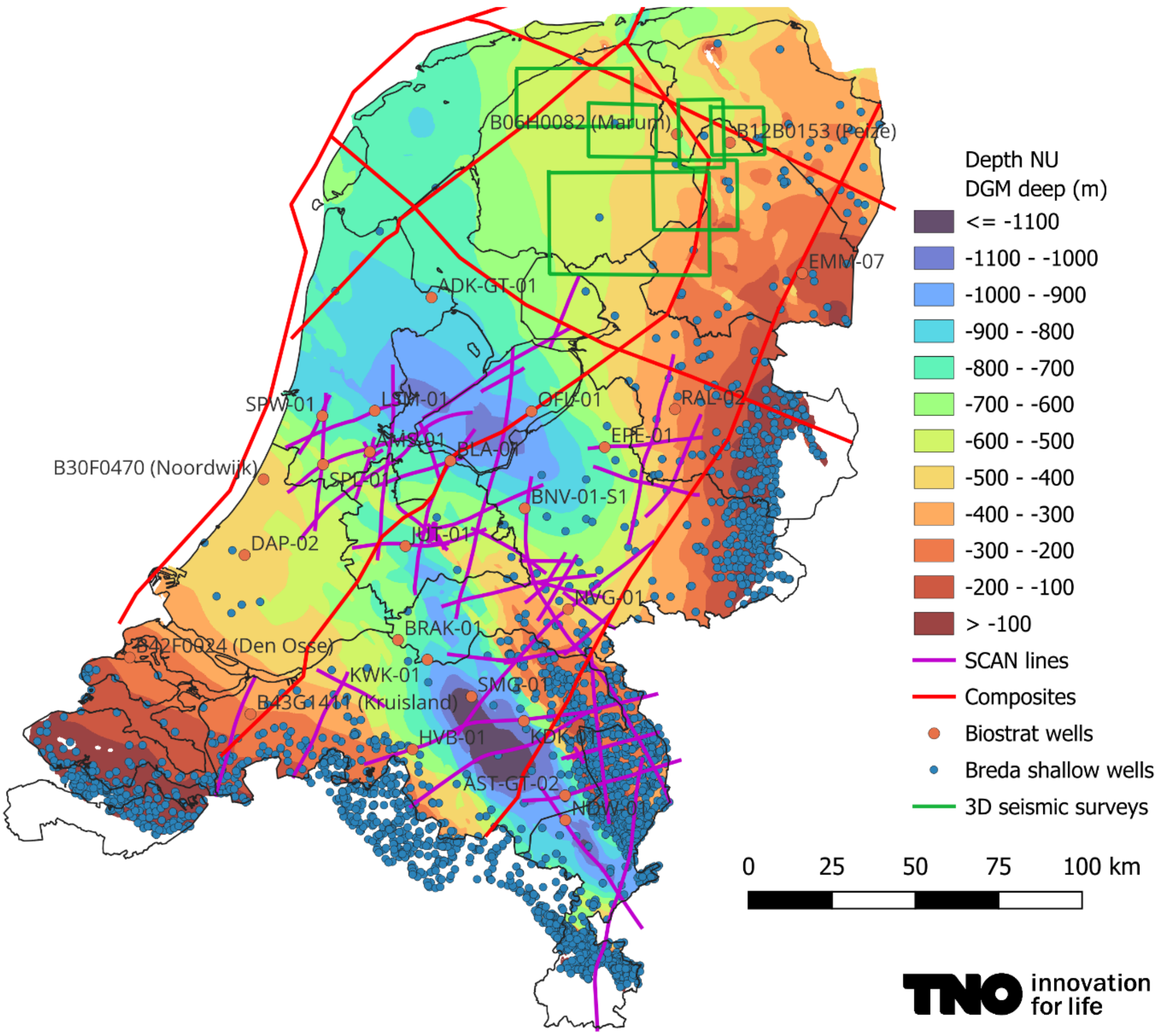

Figure 2 Depth surface of the Upper North Sea Group (NU) from DGM which is the Base of the Breda Subgroup. The interpretation in this study is done for the composite lines (red lines) and SCAN seismic lines (pink lines) which are tied to chronostratigraphic interpretations (red dots) The shallow wells in this figure (blue dots) correspond to the shallow borehole data that is used in the REGIS model of the Breda. The green squares in the north of the Netherlands show the seismic surveys that are interpreted using the AI tool that is available in Petrel.

1.2 Paleogeography

In the Netherlands, sediments of the Breda Subgroup were sourced by fluvial systems from different directions, varying from north, east and south (Fig. 3; Gibbard and Lewin, 2016). The Breda Subgroup features two major depocenters: the Roer Valley Graben (RVG) and the Zuiderzee Low (ZZL) where the thickness of the subgroup exceeds 500 meters. The depocenters are separated by the Mid Netherlands Fault Zone (MNFZ), which became active throughout the Miocene (Fig. 3) (Munsterman et al., 2019; Siebels et al., 2024). In areas outside these depocenters, sediment thickness is generally less than 100 meters. However, towards the offshore the thickness of the Breda Subgroup significantly increases.

The Mid-Miocene Climatic Optimum triggered widespread transgression marked by sediment onlap on tectonic highs and which is represented by the EMU (Fig. 1; Munsterman et al., 2019; Siebels et al., 2024).

During subsequent sea-level high stand, prograding sequences developed along the basin margins. Hereafter, tectonic uplift, in conjunction with a cooling climate and an associated eustatic sea-level drop, led to widespread erosion and development of the MMU (Sangiorgi et al., 2021). The MMU is not the result of a single tectonic- or sea-level event, but is the result of a complex interplay between tectonics, climate, and sediment supply (Siebels et al., 2024). The strata between the MMU and LMU can be characterized by clinoforms, where foresets and toesets are preserved. Topsets are largely missing, which Munsterman et al. (2019) attributes to erosion during the formation of the LMU. During the Early Pliocene, the prodeltaic depositional environment transitioned into a fluvial setting, marking the onset of the proto Rhine-Meuse River systems. During this period shell rich marine sands of the Oosterhout Formation were deposited (Fig. 1; Munstermann et al., 2019; Siebels et al., 2024).

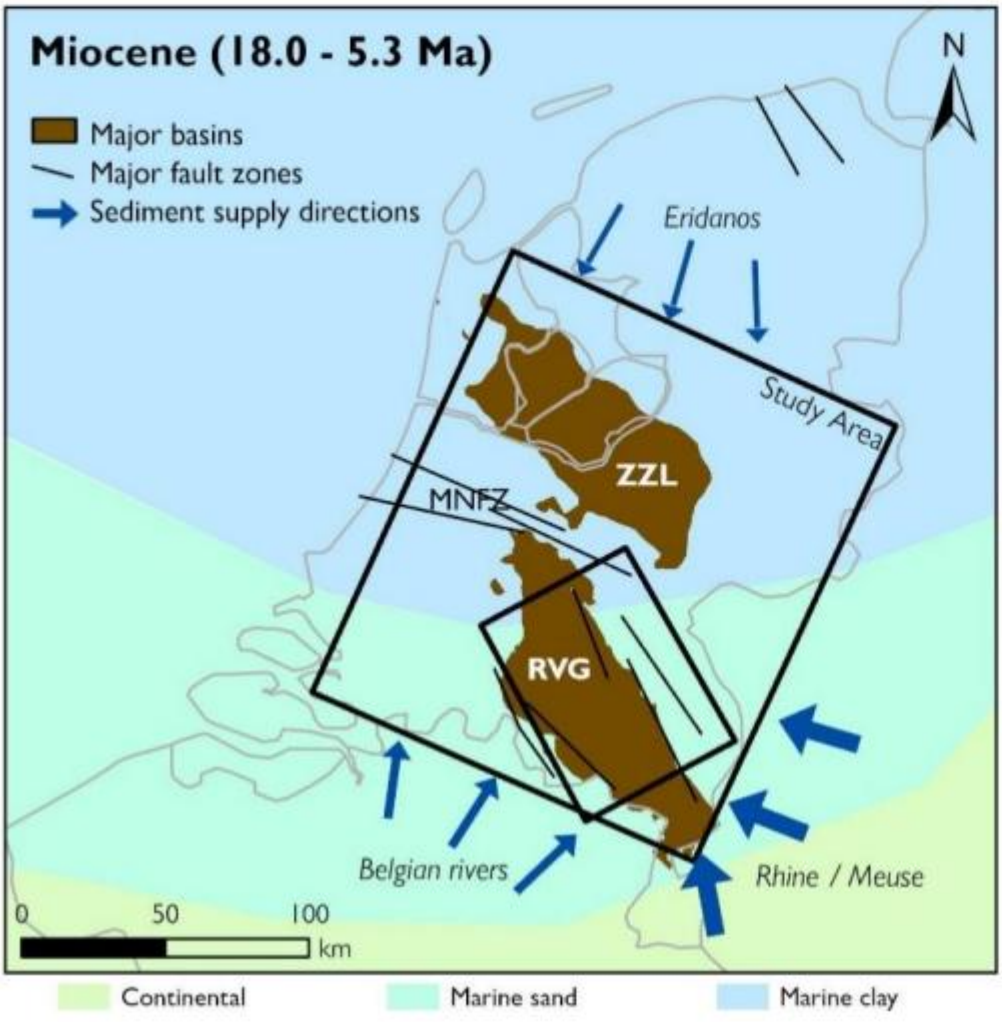

Figure 3. Paleogeography of the Netherlands during the Miocene (18 - 5.3 Ma). Blue arrows show the location of three sediment sources (Eridanos, proto Rhine-Meuse and Belgian river systems. MNFZ, Mid-Netherlands Fault Zone; RVG, Roer Valley Graben; ZZL, Zuiderzee Low. (Figure modified after Kleijbeuker, 2025). Note that the study area does not relate to this study.

2. Data and workflow

Within this study, seismic interpretation of the EMU, MMU, LMU and top Oosterhout was done on SCAN seismic lines and composite seismic lines (Fig. 2). The available seismic data was compiled from different vintages (different operators, year of acquisition and processing sequences). No reprocessing has been carried out as part of this present study.

These interpretations were tied to 11 deep and shallow wells that were reinterpreted by a biostratigraphic analysis from Houben (2025). Additionally, 11 legacy wells (Houben et al., 2023; Houben, 2023a, b; Munsterman et al., 2019; Munsterman, 2016, 2020, 2021, 2022) from biostratigraphic studies were used for calibration (Fig. 2).

Subsequently, the seismic interpretation was translated from velocity (TWT) to depth by the use of the velocity model Velmod 3.1. Thereafter, depth and thickness maps have been made by the use of the convergent gridding algorithm in Petrel (Fig. 4).

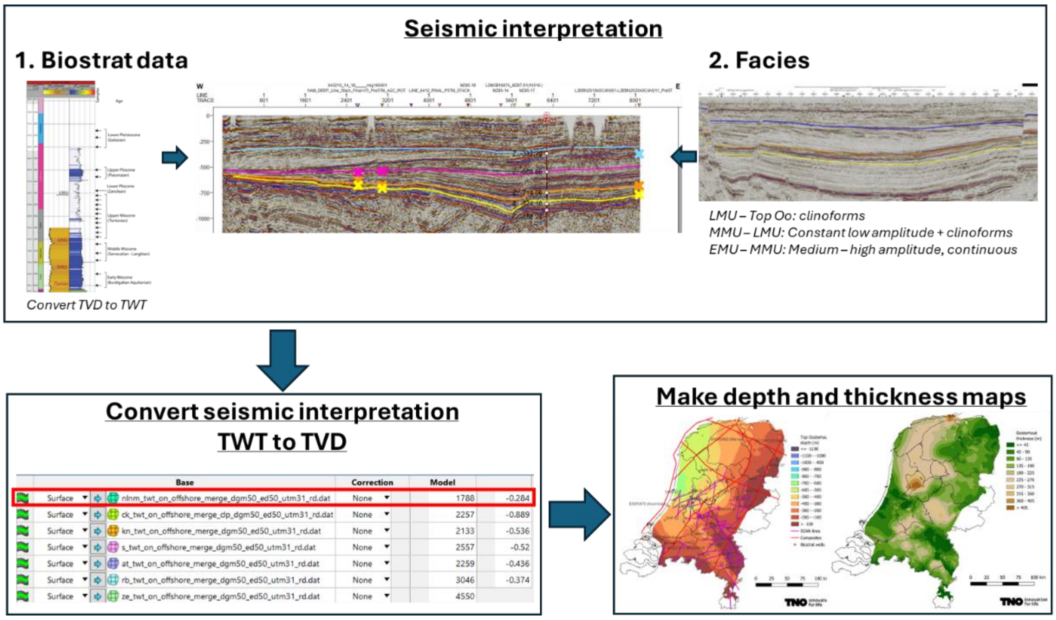

Figure 4. Workflow applied in this study. First biostratigraphic data was plotted on the seismic lines in order to determine the reflectors associated with the horizons. Second, facies characteristics were used to determine the position of the seismic reflectors. The seismic interpretation was then converted from TWT to TVD by the use of Velmod 3.1 for the entire North Sea Group (nlnm in figure). From this, depth and thickness maps for each horizon could be made.

2.1 Seismic interpretation

The horizons interpreted in this study include the EMU, MMU, LMU and Top Oosterhout for the northern part of the Netherlands. In a previous study for ThermoGIS, the LMU, MMU and EMU were interpreted on the SCAN lines. Within this study we also interpreted the Top Oosterhout on the SCAN lines. Furthermore, we extended the interpretations of the LMU, MMU, EMU and Top Oosterhout towards the north. First, seismic interpretation was done on composite seismic lines (Fig.2; Fig. 4). Whereafter, we focused on 3D seismic interpretations in between these composites (Fig. 2), focusing on urban areas where the highest demand for geothermal energy and HTO exists. See also section 3.1 for more details on the 3D seismic interpretation. For the horizon interpretation, various techniques were used, applied in a strict order:

1. Biostratigraphic data
2. Seismic facies
3. Uncertainties

Biostratigraphic data

The biostratigraphic data from the study by Houben (2025) for Warming^{UP}*GOO* was a crucial factor in validating the seismic interpretation. This data, gathered from key wells, provided insight into the depths of the different horizons. By the use of Velmod 3.1 the depth of these horizons were translated in time. By doing this, the corresponding seismic reflectors (TWT) could be determined (Fig. 4). It must be noted that there are uncertainties in some of the biostratigraphy results, in which occasionally a range in depth for the horizons is given. For plotting the well tops on the seismic lines we always took the average of the range. We always sticked in this range and subsequently made the interpretations based on seismic characteristics and facies as described next.

Seismic Facies

The seismic interpretation method is closely linked to the different seismic facies (Fig. 5 and 6). Various patterns have been determined. The facies between the EMU and MMU can often be described as high amplitude and continuous reflectors (Figure 6a-d). The facies between the MMU and LMU can often be described as low to high amplitude reflectors (Figure 6a-c) with sometimes clinoform structures in basin areas (Figure 6a). The Oosterhout Formation can often be characterized by low amplitude reflectors and often clinoform structures can be found. These clinoform structures of the Oosterhout Formation is not concentrated in one specific area, but spreads across the entire Netherlands (Fig. 8).

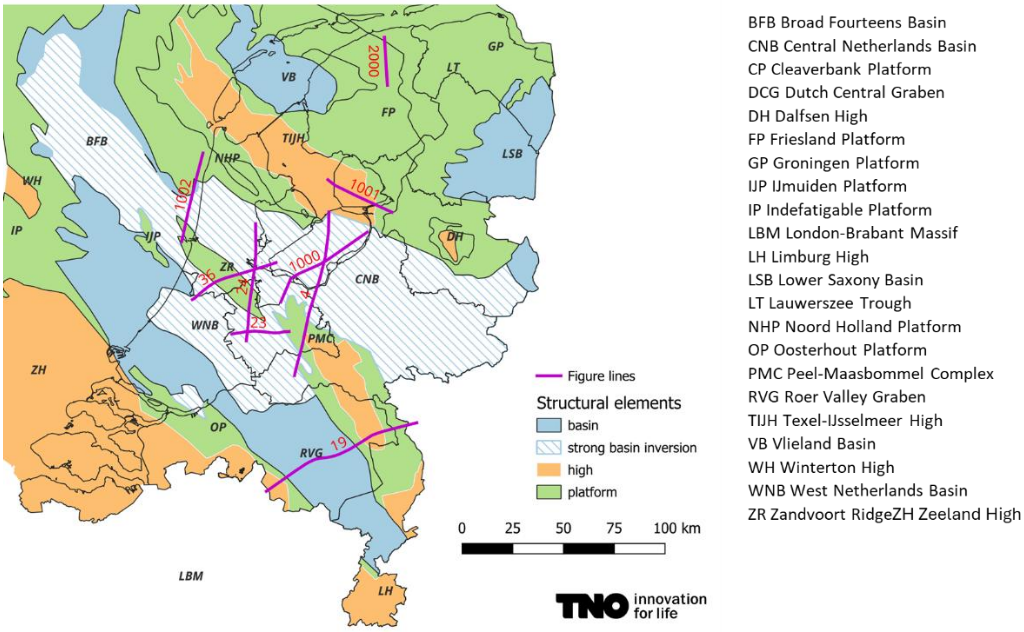

Figure 5. Structural elements map of the Netherlands demonstrating the basins, highs and platforms. Purple lines are the seismic sections detailed in this report (modified after Ten Veen et al., 2025).

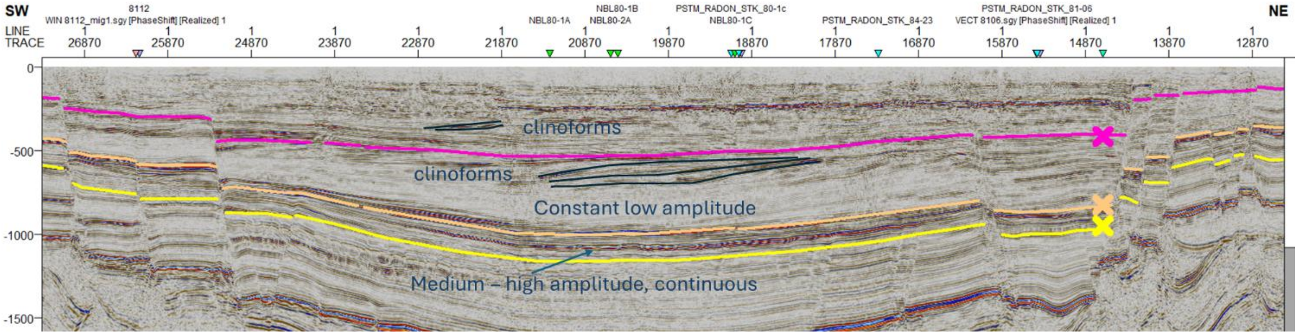

Figure 6a. Example of the facies of the Breda Subgroup and Oosterhout Formation that can be seen in the RVG with the EMU (yellow), MMU (orange) and LMU (purple). For location of the seismic line see Line 19 in Figure 5.

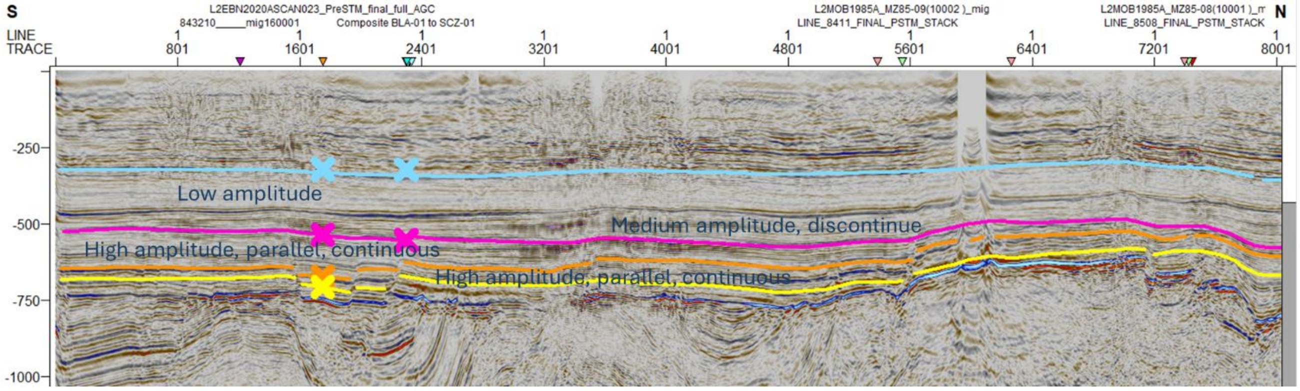

Figure 6b. Example of the facies of the Breda Subgroup and Oosterhout Formation that can be seen in the strongly inverted WNB and the platform of the PMC with the EMU (yellow), MMU (orange), LMU (purple) and Top Oosterhout (blue). For location of the seismic line see Line 24 in Figure 5.

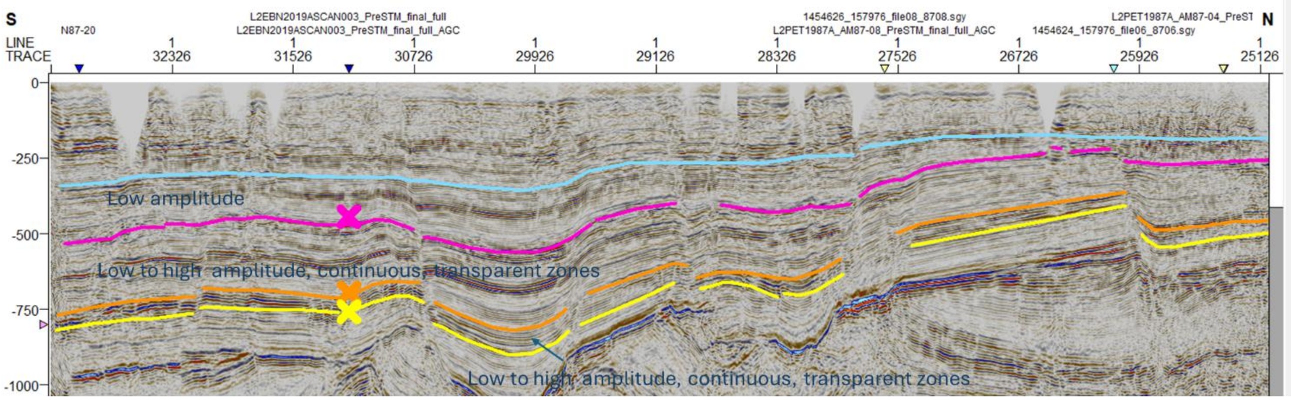

Figure 6c. Example of the facies of the Breda Subgroup and Oosterhout Formation that can be seen in the PMC and CNB with the EMU (yellow), MMU (orange), LMU (purple) and Top Oosterhout (blue). For location of the seismic line see Line 4 in Figure 5.

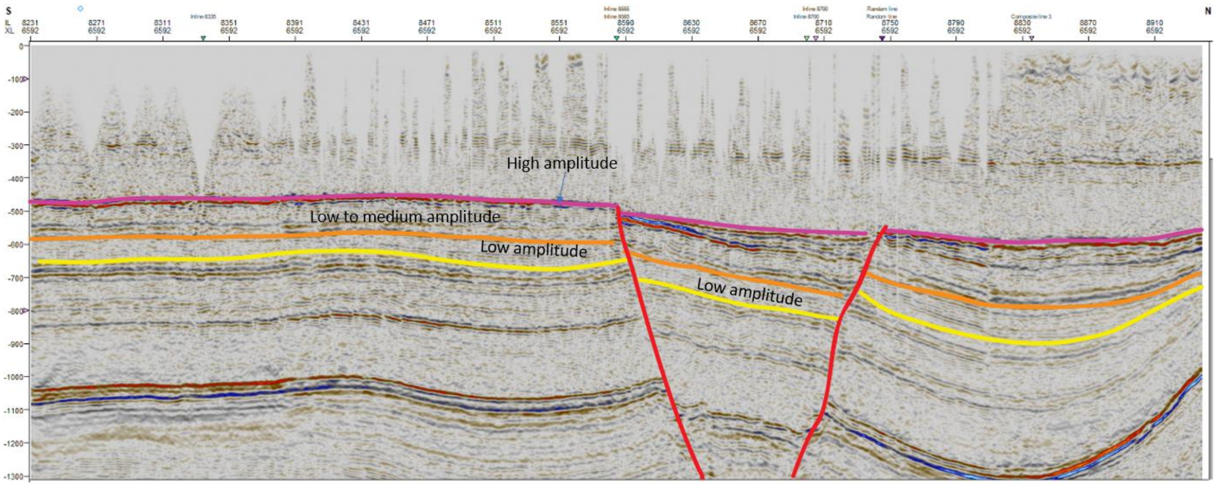

Figure 6d. Example of the facies of the Breda Subgroup that can be seen in the North of the Netherlands that has been interpreted with AI, with the EMU (yellow), MMU (orange) and the LMU (purple). For location of the seismic line see Line 2000 in Figure 5.

Uncertainties

After cross-referencing biostratigraphic data and seismic facies, some horizon positions remained unclear. In cases where the seismic facies were not well-defined, interpretation became challenging. When this occurred, we documented the areas of uncertainty and discussed these uncertainties with senior geologists and the team of this WP.

2.2 Interpretation with AI

While the 2D scan lines and composites are interpreted manually, 3D seismic surveys in the North of the Netherlands are interpreted with an AI tool that is provided in Petrel 2024 software.

In the north of the Netherlands, which was the focus area of this study, AI interpretation was used on the following surveys (Fig. 2):

- Ameland_Zuid_Blija_L3NAM1992A
- Donkerbroek_L3NAM1997F
- Lemmer_Joure_L3PET1999A
- Tietjerkstradeel_West_L3NAM1987F
- Groningen_Stad_L3NAM1987C
- Grootegast_2_L3NAM1985L

2.3 Modelling

Within Petrel, depth and thickness surfaces were made of the top Oosterhout, LMU, MMU and EMU from the seismic- and biostratigraphic interpretations. The following steps were taken (as is also shown in Fig. 7):

1. Convert seismic interpretations to points

First the seismic interpretation in TWT was converted into points. This was done in order for us to easily add other point data from previous studies such as interpretations from the H3O study.

2. Time-depth conversion by the use of Velmod 3.1

The points in TWT were converted by the use of the velocity model Velmod 3.1 into TVD (Fig. 4).

3. Make surface in Petrel:

Depth and thickness maps were made from the points in TVD. For this the following input was applied:

a. Algorithm: Convergent gridding
b. Grid increment: 1000x1000m
c. Trend surface REGIS Base Breda map
d. Well adjustment: use well tops for each horizon

Difference maps with the established surfaces and current REGIS surfaces were made and compared. For comparison purposes we assume that the EMU is the Base Breda Subgroup and the LMU the Top Breda Subgroup.

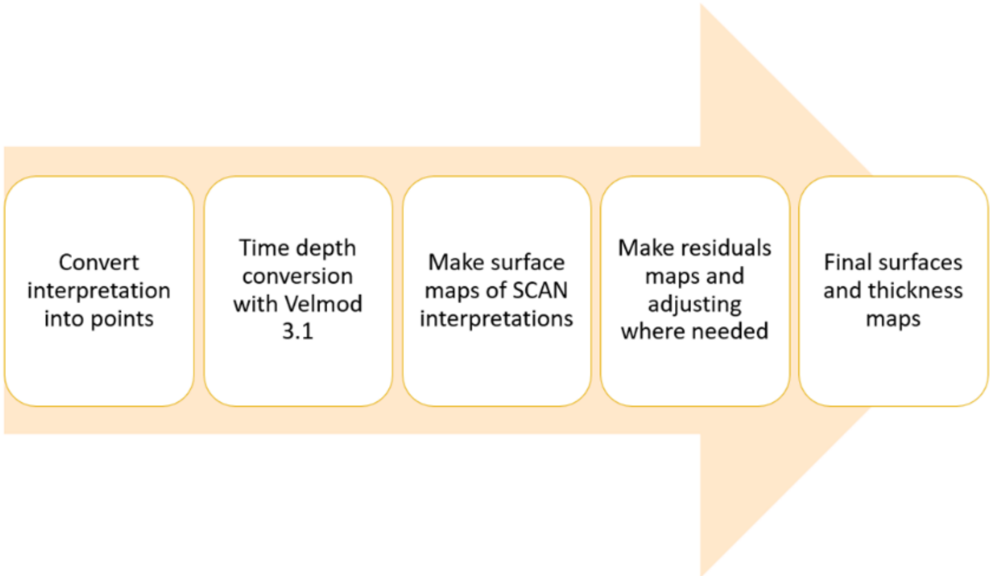

Figure 7. The surface modelling workflow process.

3. Results

3.1 Seismic interpretation

Figure 8 demonstrates a selection of seismic lines that have been interpreted in this study. The locations of the seismic lines can be found in Figure 5. Figure 8a demonstrates that the biostratigraphic data from the JUT-01 well perfectly matches with the seismic reflectors for the LMU and MMU. However, based on the seismic characteristics the Top Oosterhout and the MMU is traced just above the biostrat values. As the biostratigraphic data demonstrates (Houben, 2025) that the MMU is positioned between 690-720 m (range of 30m and the top Oosterhout between 300-400m (range of 100m) our interpretation is still in the right position. Two expansion directions have been interpreted in the Oosterhout (Figure 8a and b), first towards the east and second towards the west. A thinning towards the west of the intervals between the LMU, MMU and EMU is observed (Fig. 8a, b; see also thickness maps of Fig.12).

In the Central Netherlands Basin (Fig. 5) a deepening and thickening in the center of the basin takes place (Fig. 8c). The biostratigraphic data of BLA-01 and OFL-01 matches very well with the seismic characteristics of the NAM deep line (Line 1000 in Figure 5).

Towards the north(west) of the Netherlands the intervals between the EMU and MMU, and MMU and LMU become thin with values of less than 45m compared to the Oosterhout Formation (Fig. 8d, e) (see also thickness maps of Fig. 12).

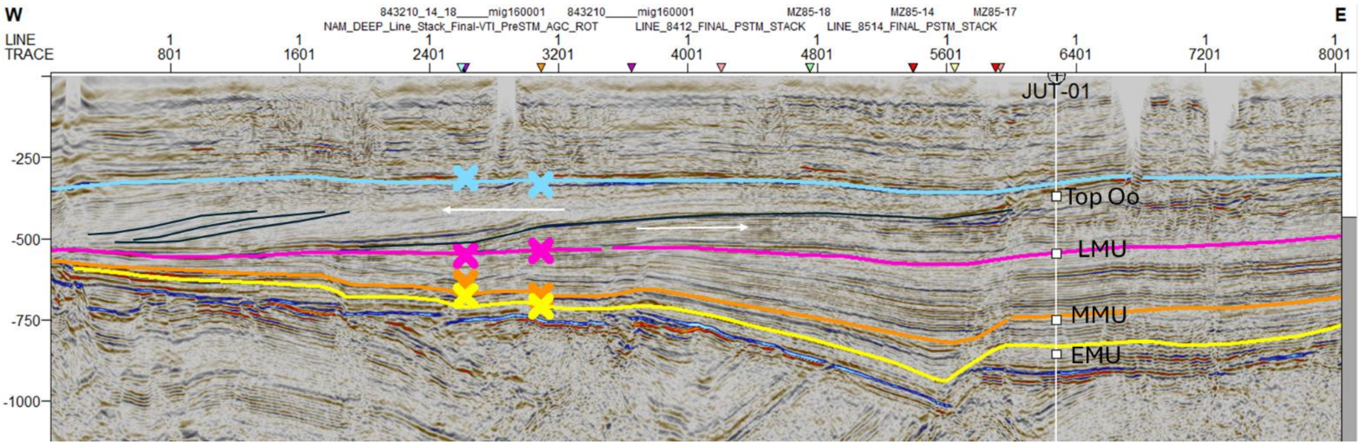

Figure 8a. SCAN line 23 with location indicated in Figure 5. Light blue: Top Oosterhout, pink: LMU, orange: MMU and yellow: EMU. Biostrat interpretation for the Top Oosterhout, LMU, MMU and EMU have been plotted with a white square for JUT-01.

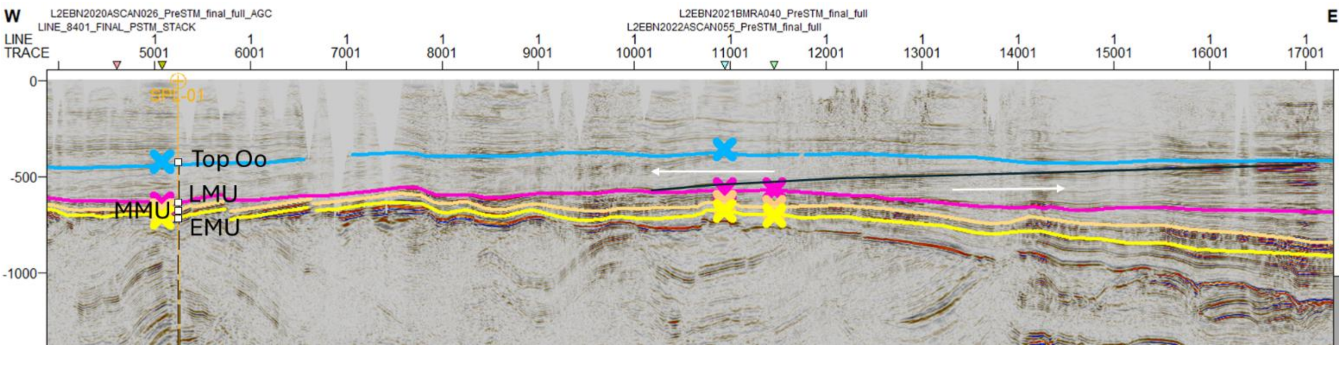

Figure 8b. *SCAN line 36 with location indicated in Figure 5. Light blue: Top Oosterhout, pink: LMU, orange: MMU and yellow: EMU.* Biostrat interpretation for the Top Oosterhout, LMU, MMU and EMU have been plotted with a white square for SPL-01.

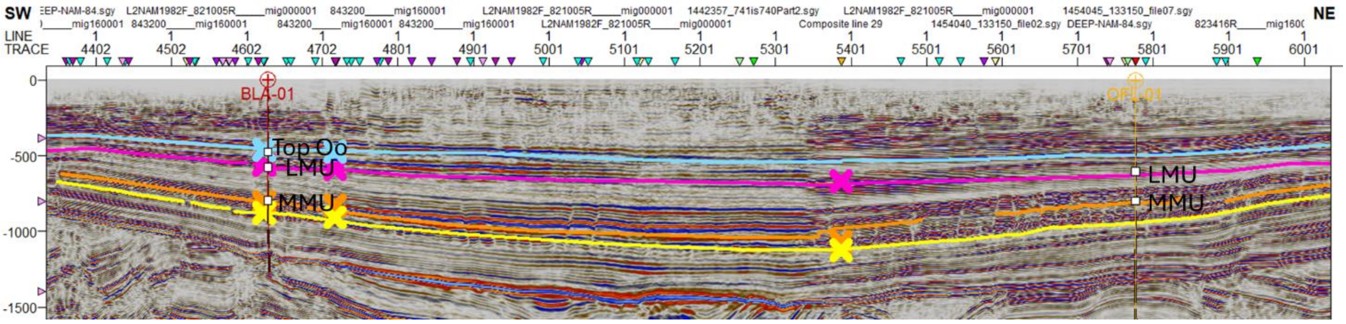

Figure 8c. NAM deep line with location 1000 in Figure 5. *Light blue: Top Oosterhout, pink: LMU, orange: MMU and yellow: EMU*. Biostratigraphic well tops of Top Oosterhout, LMU and MMU for BLA-01 is used, and of LMU and MMU for OFL-01 is used.

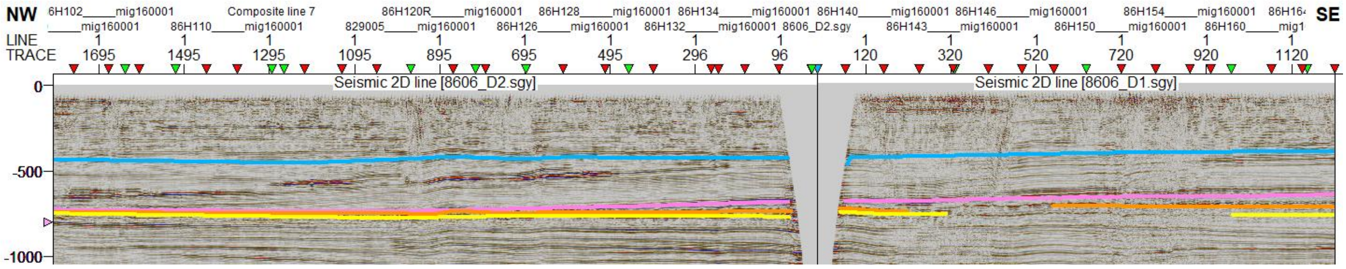

Figure 8d. Seismic line with location 1001 in Figure 5. Light blue: Top Oosterhout, pink: LMU, orange: MMU and yellow: EMU. Towards the north of the Netherlands the intervals between the EMU and MMU, and MMU and LMU become thinner. However, the Oosterhout Formation remains thick and even becomes thicker towards the north.

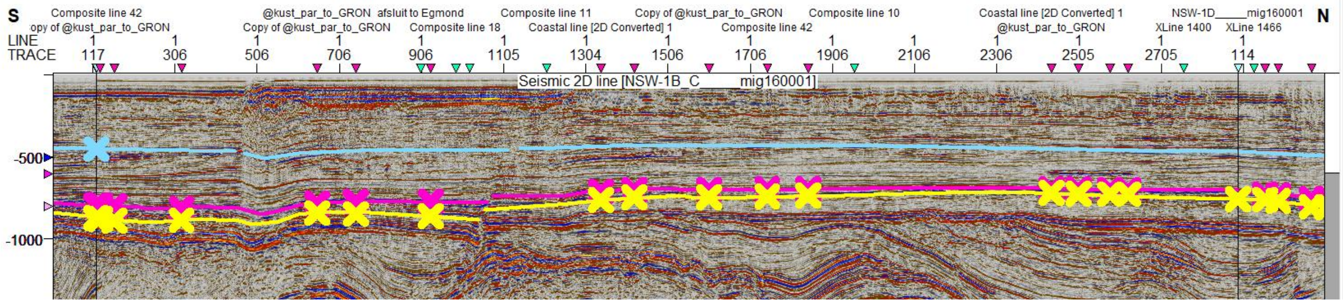

Figure 8e Coastal line with location 1002 in Figure 5. Light blue: Top Oosterhout, pink: LMU, orange: MMU and yellow: EMU. The interval between the MMU and LMU becomes really thin in this part. No biostratographic data is present along this line.

3.2 Interpretation with AI

In the northern Netherlands, six seismic surveys were interpreted using the AI interpretation tool available in Petrel. The seismic surveys that were interpreted in this study by using the Petrel AI tool are described in section 2.2 and shown on Figure 2.

As input, 2D interpretation data were provided with increments of 100 on both the inline and crossline directions, resulting in a defined grid structure (see input in Figure 9). Based on this grid, the AI tool generated a 3D interpretation, effectively extrapolating from the 2D data (see output in Figure 9). This approach enabled rapid processing of large volumes of seismic data. However, the tool’s performance varied across different surveys (Fig. 9). The AI algorithm performs best when tracing a single, continuous reflector with a strong acoustic impedance contrast. Since this study focused on broader seismic facies rather than individual reflectors (Fig. 6), the AI-assisted interpretations yielded mixed results. As discussed further in this report, the acoustic impedance contrasts associated with key stratigraphic horizons are not always sufficiently distinct, which poses challenges for reliable automated picking using AI.

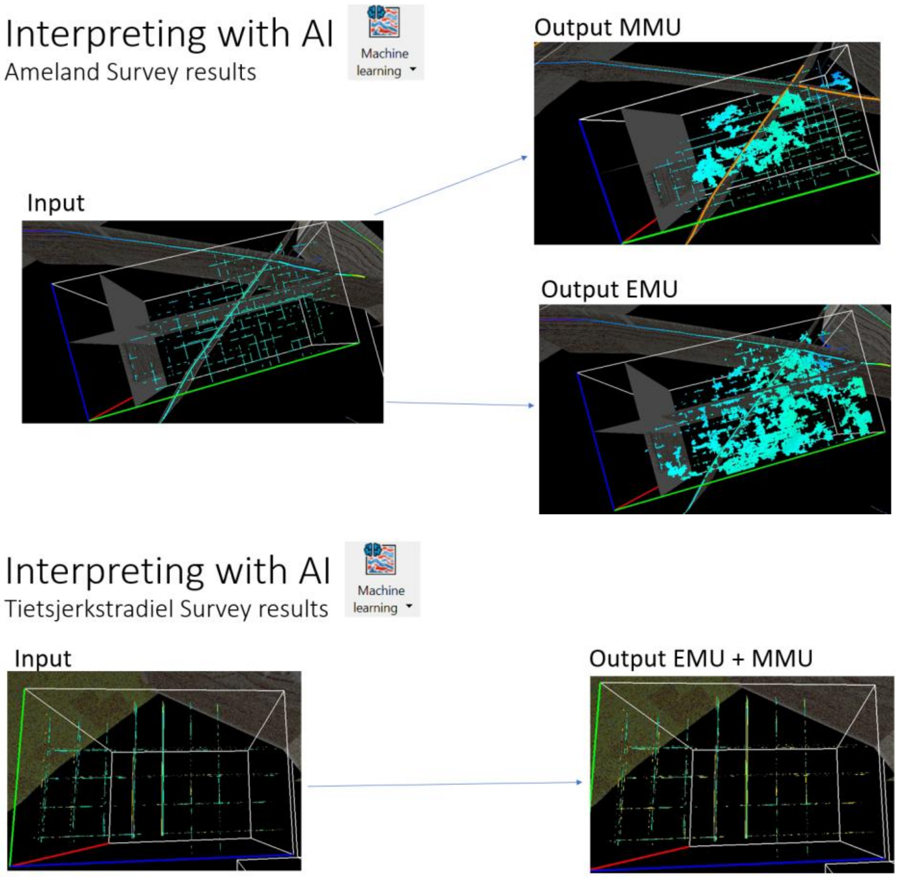

Figure 9 Results of the AI interpretation tool. The top panels show the input and output for the Ameland survey, for both the EMU and MMU. The input consists of a grid-based interpretation of 2D lines with an increment of 100, and the output demonstrates a denser set of interpreted features that is now 3D interpreted by the tool. In contrast, the results for the Tietjerksteradeel survey were less extensive, primarily because the tool was used to track seismic facies rather than a single, continuous reflector.

3.3 Seismic to well tie

Seismic-to-well tie (synthetics) for two wells that lay on seismic lines that are interpreted have been made for a quality check (Fig. 10).

In this study, two wells are considered; well Oost-Flevoland (OFL-01) located on the NAM deep composite line in the Zuiderzee Low area and well Epe (GLD) (EPE-01) located on SCAN line 14. Both wells contain a rather complete succession across the EMU, MMU, LMU and Oosterhout. In both wells the sonic velocity- and density logs were used to generate a synthetic seismogram using a 35 Hz zero phase negative polarity Ricker wavelet for EPE-01 and a 45 Hz zero phase negative polarity Ricker wavelet for OFL-01 to get the best fit.

The synthetic seismogram is compared to the seismic vintage used for interpretation to select the best fit base and top pick for the EMU, MMU, LMU and TopOO. The acoustic impedance (AI) in the synthetic is a result of a sum of the Sonic (DT) and the Density (RHOB). Something interesting occurs in both wells. Although the AI (Acoustic Impedance) calculated from the synthetic data does not show a strong signal, the seismic data reveals high-amplitude reflectors. This suggests that AI in seismic data is influenced by more than just sonic and density logs—it is a more subtle and complex phenomenon. In seismic interpretation, AI is derived from the product of density and P-wave velocity. However, this can be influenced by geological features such as clinoforms that we know are here (Fig. 8). Clinoforms can create acoustic interference, which may result in strong seismic reflections even when density and P-wave velocity are not particularly high. This phenomenon is known as positive interference (Brown, 2012). Another reason for the lack of a 100% match between the synthetic and seismic datasets lies in the effects of constructive acoustic interference, which can occur when stratigraphic units thin. This interference can amplify seismic amplitudes in the real data, a phenomenon that is not replicated in synthetic seismograms. Moreover, well log data are inherently point-based and do not capture lateral variations in thickness or lithology. These limitations contribute to discrepancies between synthetic and field seismic data, and explain why a perfect match is rarely achieved.

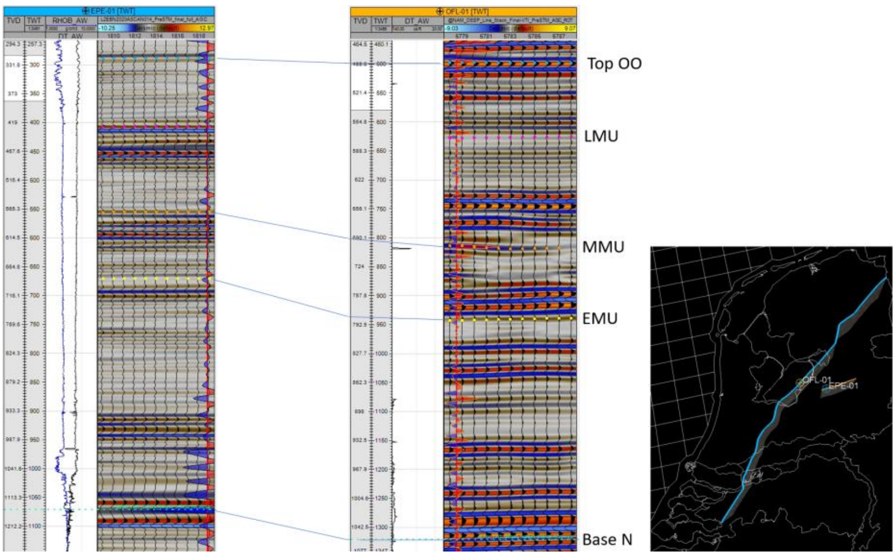

Figure 10. Seismic-to-well tie for wells EPE-01 and OFL-01. The synthetic trace is overlaid on the seismic section at the well location. The primary correlation marker for both wells is the Base North Sea horizon, which produces a strong seismic response. The leftmost track displays the sonic and, where available, the density log.

4. Depth and thickness maps

From the seismic interpretation depth and thickness maps for each horizon and their associated intervals have been made. The maps visualize the general trends. However, lower seismic quality in the shallower parts of a few seismic lines restricted us to trace the horizons for the entire Netherlands.

The depth maps indicate that the deepest parts of the EMU and MMU are situated in the Zuiderzee Low area (south of the TIJH) and RVG (Fig. 11). The thickness maps of the interval between the MMU and EMU demonstrates very low thicknesses (<45 m) in the northern and southwestern part of the Netherlands (Fig. 12). These low thicknesses could be due to erosion or even non-deposition in these areas. Highest thickness between the MMU and EMU is observed in the RVG and Zuiderzee Low with values of more than 400m.

The LMU displays a localized deepening restricted to a smaller part of the Zuiderzee Low (Fig. 11). The thickness between the LMU and MMU is largest in the RVG and Zuiderzee Low area, which is thicker and more extensive compared to the interval between the MMU and EMU (Fig. 12).

For the Top Oosterhout the deepest depth (> 700m deep) is reached in the west and northwestern part of the Netherlands (Fig.11). The thickness of the Oosterhout Formation is also largest in the NW of the Netherlands with values of more than 400m thick. The lowest thicknesses of the Oosterhout Formation are observed in the NE part of the Netherlands and the Peel Maasbommel High, with values <45m.

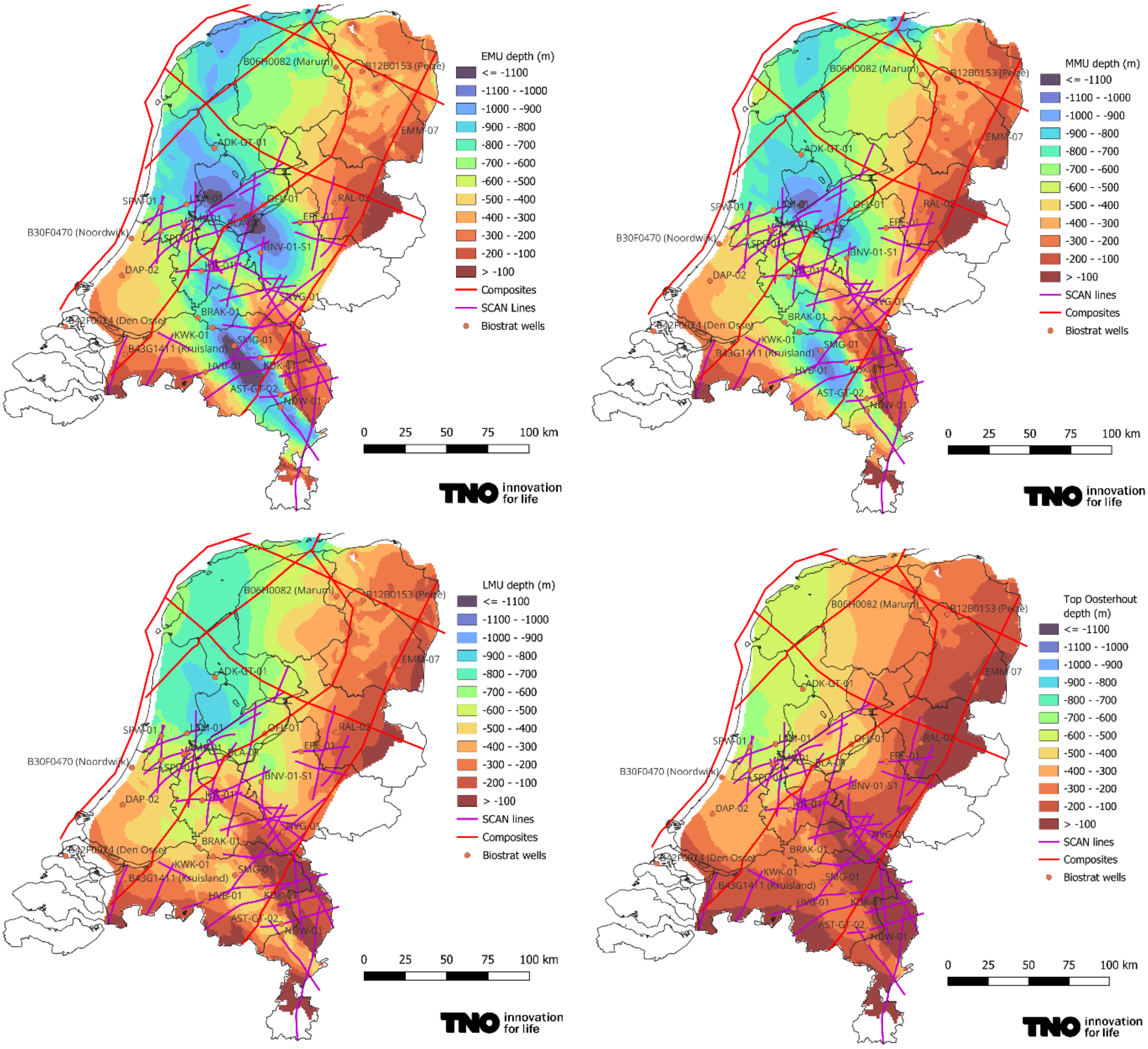

Figure 11. Depth maps of the EMU, MMU, LMU, and the top of the Oosterhout Formation. The maps illustrate regional structural trends across the Netherlands.

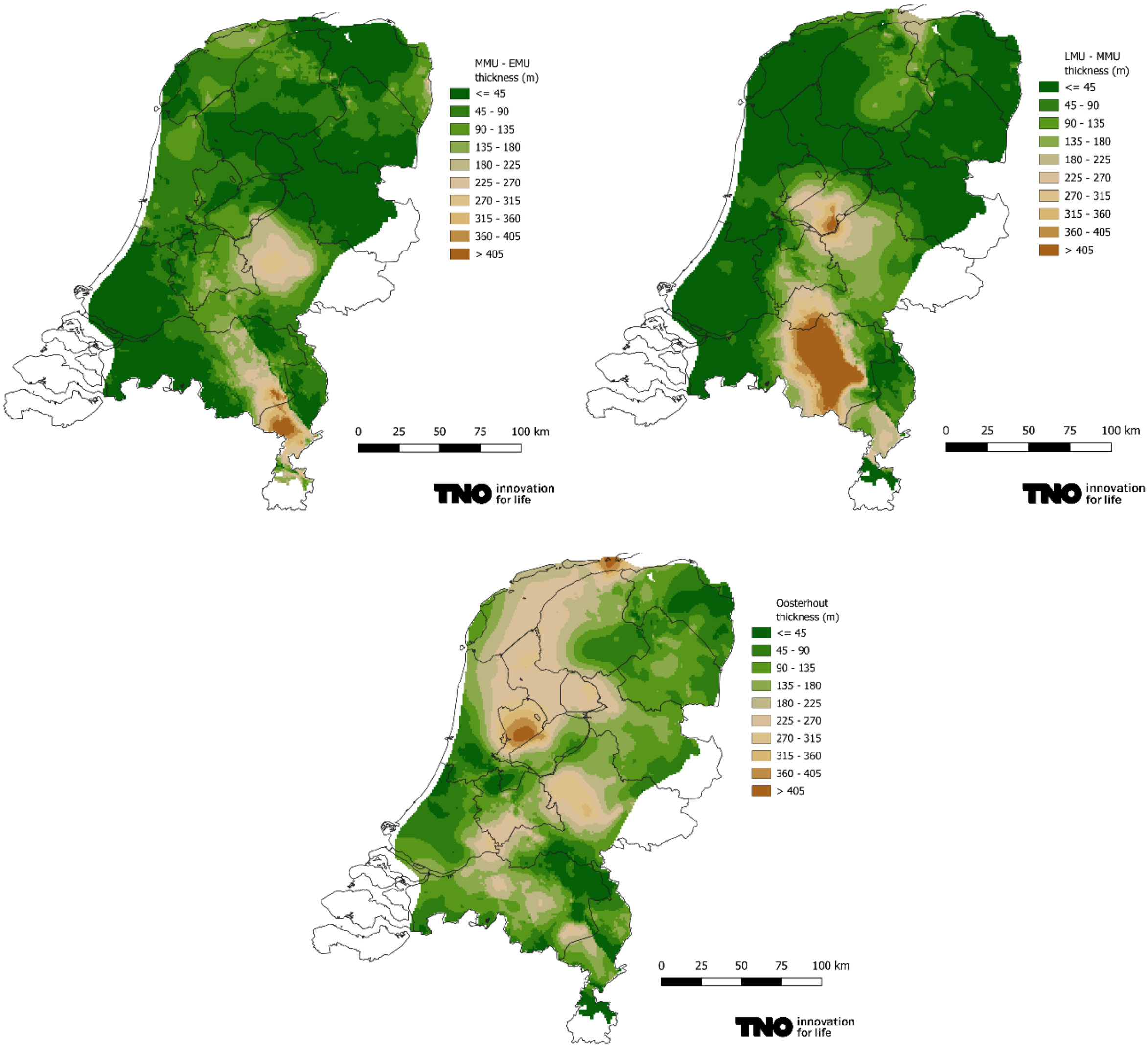

Figure 12 Thickness maps showing the intervals between the EMU and MMU, MMU and LMU, and the Oosterhout Formation.

5. Discussion

Stratigraphic issues

Munsterman et al. (2019) suggested redefining the lithostratigraphy of the Breda Formation, introducing a subdivision based on supposed regional unconformities. Specifically, the Early Miocene Unconformity (EMU) is considered to mark the base of the Groote Heide Formation, the Mid Miocene Unconformity (MMU) is considered to define the top of the Groote Heide Formation and the base of the Diessen Formation, and the Late Miocene Unconformity (LMU) is linked with the top of the Diessen Formation. They thus propose that the LMU also marks the base of the Oosterhout Formation. Although this stratigraphic concept has not yet been formally adopted in the Dutch stratigraphic nomenclature (https://www.dinoloket.nl/en/stratigraphic-nomenclature) — still pending approval from the Stratigraphic Commission — the use of the 'unconformities' has been implemented in this study. While these 'unconformities' have been extensively mapped within the RVG and its adjacent highs, their expression and/or existence is not in detail studied outside of this region. In this study, we attempted to map these regional unconformities across the entire Netherlands, at least where high-quality seismic data is available. The current work integrates seismic interpretation with biostratigraphic analyses (Houben, 2025) that allows for identification of the surfaces corresponding to these respective 'unconformities'.

In some cases, seismic reflections clearly align with biostratigraphically identified boundaries/'unconformities', such as at the JUT-01 well (Fig. 8a), where the EMU and MMU can clearly be recognized at the respective time/depth level. As also noted by Houben (2025) and evidenced in several seismic lines (Fig. 8c), complications arise when apparent chronostratigraphic boundaries do not align with clear seismostratigraphic reflectors/truncations. This is particularly the case for the LMU. Albeit this level is reported to be associated with the truncation of topsets of clinoform geometries in the RVG (Siebels et al., 2024). This is not a level that is associated with major truncation or a time-transgressive surface. In fact, the LMU is merely to be seen as a chronostratigraphic marker without an evident sequence stratigraphic significance. This means that the interpretation of the top of the Diessen Formation and/or the base of the Oosterhout Formation is problematic if one uses the LMU as a defining criterion. While EMU and MMU show a consistent gamma-ray signature and a clear seismic impedance contrast, they can thus be confidently mapped. In fact, substantially above the LMU, a clinoform-dominated sequence can be identified (e.g., the classic progradating cycle of the Oosterhout Fm., Fig. 8b).

In order to alleviate those issues, the study chose to prioritize priorly defined ‘unconformity’ surfaces (EMU, MMU, LMU) over – yet to be decided - formal lithostratigraphic unit names like Diessen, Groote Heide and the Oosterhout Formation. A systematic nation-wide seismic mapping of the Pliocene progradational sequences, the contact and their relation to the undelying Breda Subgroup, is essential to make sensible geometric models of the Oosterhout Formation and its internal reservoir units.

Different modelling methods: Comparing EMU-Based Surfaces Across Models

As a geological survey, we aim to maintain a high level of consistency across regional and local geological models. For instance, the base of the Breda Subgroup, or the EMU, as defined in one study should not differ substantially from that used in older models. As new data and interpretations become available, it is both necessary and scientifically appropriate to update existing models accordingly. Geological mapping and modelling is essentially a continuous process in which evolving insights are represented.

Under the new stratigraphic framework proposed by Munsterman et al. (2019), the Early Miocene Unconformity (EMU) marks the base of the Breda Subgroup and the base of the Upper North Sea Group**.** This enables a direct comparison between our model and earlier models developed by the Geological Survey of the Netherlands; the DGM-deep model and the REGIS II model (https://www.dinoloket.nl). Both models include a representation of the base of the Breda Subgroup. In REGIS this is referred to as NUBRz1in REGIS II and in DGM deep this can be compared to the Base Upper North Sea Group, the B_NU. Additionally, the base of the Oosterhout Formation has been mapped previously within REGIS referred to as NUOO.

While these models aim to represent the same geological boundary, differences in methodology, data sources, and resolution result in discrepancies. The REGIS II model, for example, is partially based on the DGM model—especially in the deeper subsurface—and thus shares a common foundation. However, our surface model of the EMU differs from REGIS II due to the use of integrated seismic and biostratigraphic data, whereas REGIS II relies primarily on lithological shallow borehole data supplemented by the seismic interpretations from DGM-deep.

Explaining Model Discrepancies: The Zuiderzee Low Case Study

One notable discrepancy is observed in the eastern lobe of the Zuiderzee Low, where differences of more than 200 meters occur between the base of the Breda Subgroup in REGIS II and DGM-Deep and the EMU surface mapped in this study (Fig. 13). This is visible along SCAN line 005-020, which crosses this area (Fig. 14). In REGIS II and in DGM-Deep, the mapped surface is significantly shallower, while our EMU surface correlates with biostratigraphic data from the Barneveld-1-S1 well. The recent biostratigraphic study by Houben (2025) confirms that the EMU lies between 1080 and 1040 meters depth at this location, which is not reflected in REGIS II due to its reliance on older, shallow borehole data and current lack of integration with seismic data. Current updates in the context of 'integrative mapping projects' are tackling this.

This significant variation highlights how the lack of updated seismics can affect model accuracy. Furthermore, thickness maps generated between the EMU–MMU and MMU–LMU surfaces reveal that the geological architecture of the Zuiderzee Low remains poorly understood (Fig. 12). These maps indicate substantial thickening in both intervals, suggesting that the area represents a paleogeographic low that extended eastward from the modern IJsselmeer region**.** Sediment accumulation in the Zuiderzee Low appears to have occurred in distinct phases: initially concentrated in the eastern lobe between the EMU and MMU, shifting to the northern part of the basin between the MMU and LMU, and later affecting both regions during the deposition of the Oosterhout Formation. This pattern could reflect changes in sediment transport direction, supported by observed facies variations in the Oosterhout Formation (e.g., Fig. 8a).

In this study the depth of the LMU was regionally mapped and subsequently modelled. A comparison with the depth of the base of the Oosterhout Fm. sensu REGIS/DGM reveals significant differences. For instance, in the Ijsselmeer area the LMU lies >200 m deeper than the base of the Oosterhout Formation (Fig. 13). This is, in a way, not surprising since the LMU is not the same level as the (lithostratigraphic) base of the Oosterhout Fm. as used in REGIS/DGM. It has been proposed by Munsterman et al. (2019) that the definition of the Oosterhout Fm. is to be emended in a way that the LMU becomes the main criterion for the top of Diessen/Base Oosterhout. While the LMU may have a lithostratigraphic significant signature in the RVG and notably on its adjacent platforms (where the Goirle mb. is a local sandy intercalation), the validity of this approach is challenged and not yet ratified by the stratigraphic commission. In areas where the Goirle fm. is absent, it is impossible to pick the top of the Diessen Fm., and therefore the base of the Oosterhout Fm. on lithological grounds. Hence, the base of the (classic/conventional) Oosterhout Fm. is consistently expected at a shallower level than the EMU. A second explanation for these discrepancies is the lack of (borehole) data on which DGM/REGIS (Houben et al., 2023) is based in areas where the Miocene and Pliocene occur at greater depth (>300 m). In essence, the base of the Oosterhout/Top Breda grid is constructed by taking the depth base of the Upper North Sea Group from DGM-Deep and to "fill in" stratigraphy from boreholes that penetrate shallower stratigraphies (e.g., Maassluis Fm. and shallower).

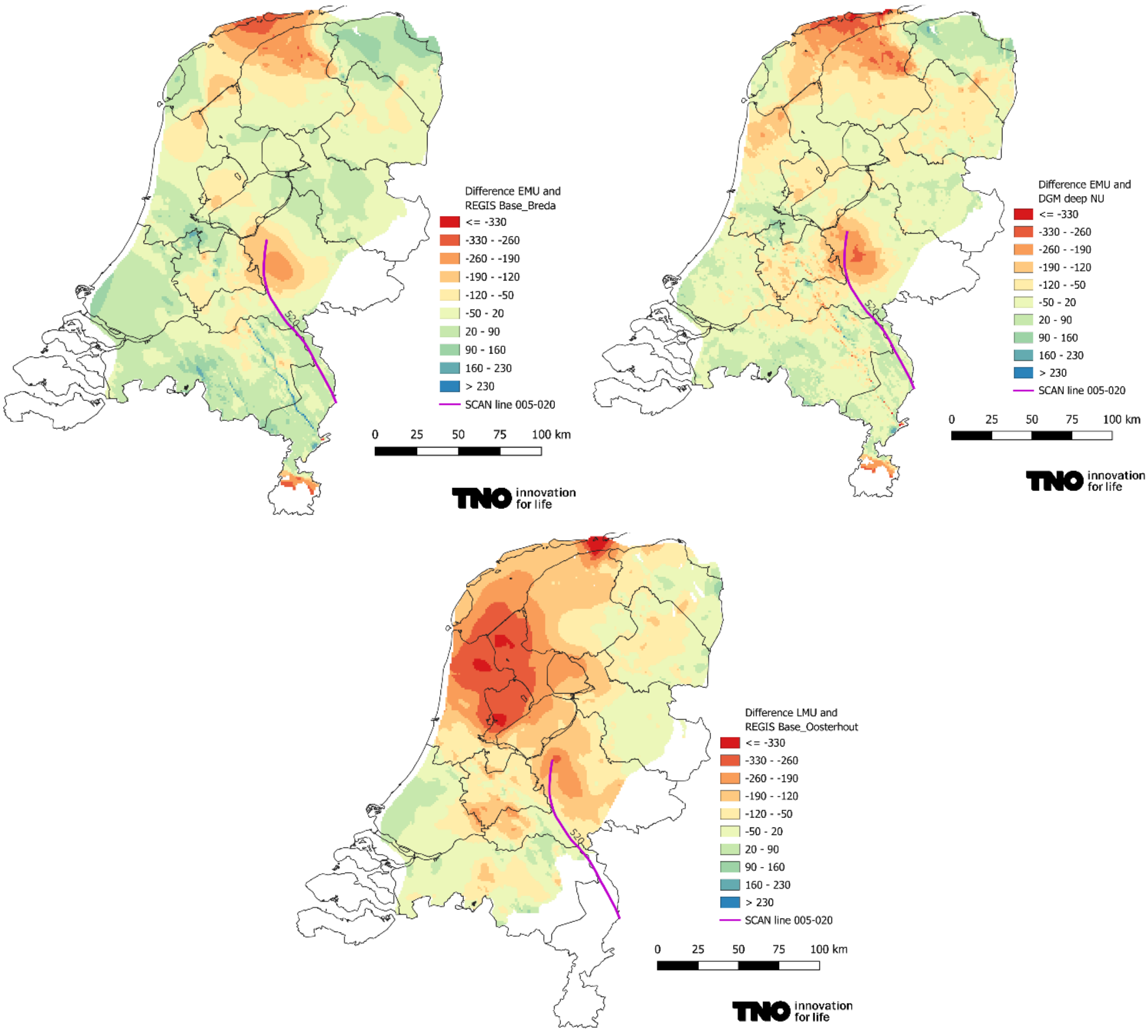

Figure 13. Difference maps between the EMU mapped in this study and REGIS (a), DGM-Deep (b) and the difference between the LMU mapped in this study and the Base of the Oosterhout from Regis.

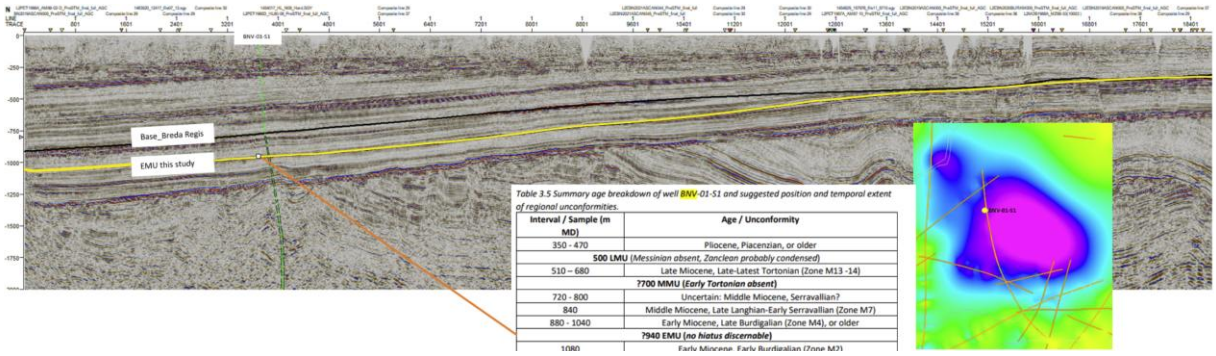

Figure 14. Seismic line SCAN 005-020 illustrating the difference in the Zuiderzee Low between the EMU as mapped in this study and the NUBRz1in the REGIS model (see figure 13). This discrepancy can be explained by the use of different input data and methodologies, making a direct 1:1 comparison between the two models not feasible.

Limitations, Data Constraints, and Future Directions

Several limitations and uncertainties influence the interpretations presented in this study and should be taken into account when applying the results in future research or geothermal exploration.

A key source of uncertainty arises from the velocity model (Velmod 3.1**)** used for time–depth conversion. This model applies a single V_0-k relationship across the entire North Sea Group, despite the known lithological variability within this unit. As a result, depth estimations derived from this model may deviate significantly—although the exact magnitude of the error (in meters) remains to be quantified and should be subject to further investigation.

Another important consideration concerns the biostratigraphic data, which are essential for correlating well data with seismic reflections. While the biostratigraphic interpretations from Houben (2025) provide depth ranges for the interpreted horizons, the uncertainty ranges should not be forgotten. Biostratigraphic uncertainty stems from several sources, including sampling interval resolution, potential reworking of sediments, stratigraphic fallback of fossils, and species diversity dependence. These factors can all influence the accuracy of horizon picks and therefore the reliability of the surfaces.

Data density is a key factor influencing interpretational uncertainty**,** which increases in areas with limited seismic and well control. While this study provides a regional framework for stratigraphic interpretation, it primarily captures broader trends, especially in shallower intervals where seismic resolution is often limited. Locally, detailed interpretations may be possibly different for this reason. Future work could focus on incorporating additional seismic data to refine the mapped surfaces and reduce the reliance on interpolation. It is also important to recognize that in local-scale studies, stratigraphic boundaries and geometries may differ from the regional trends presented here.

Furthermore, faults have not yet been incorporated into the current mapping framework**,** even though many are evident in the Breda Subgroup. In the Roer Valley Graben (RVG), fault juxtaposition suggests either thickening of the Groote Heide Formation due to syn-depositional fault activity or erosion at the footwall post-deposition. Similarly, in the northern Netherlands, faults appear to coincide with a thickening of the Diessen Formation, again implying tectonic activity during deposition or post-depositional erosion. Future efforts could benefit from incorporating faults into geological models and constructing Allan diagrams to better understand

Miocene tectonics—an area that remains largely understudied in the Netherlands. When incorporating faults, likely the difference between REGIS and EMU surface will be smaller in the Hantum fault area in the North of the Netherlands where we now see a difference of >300 m. Likely, incorporating faults will also reduce the differences between different models.

Looking ahead, forward stratigraphic modelling (FSM) offers a promising approach for interpreting lithological distributions and sediment provenance, especially considering the varying sediment transport directions inferred in this study. By integrating the stratigraphic surfaces mapped here, FSM could significantly improve our understanding of depositional environments and stratigraphic architecture, similar to the approach taken by Kleijbeuker (2025) in his recent modelling study.

Finally, once stratigraphic interpretations are validated, they could be used as a base for property maps and could become integrated into ThermoGIS to assess the geothermal energy and heat storage potential of these Neogene intervals.

6. Conclusions

This study provides a framework for mapping the key unconformities within the Breda Subgroup—namely the EMU, MMU, and LMU—as well as the top of the Oosterhout Formation. These interpretations are strongly supported by the biostratigraphic analyses of Houben (2025) and serve as the foundation for a nationwide stratigraphic model. While this framework offers a coherent basis for regional-scale mapping, it should be emphasized that local geological variations may lead to different interpretations at finer scales.

The results presented here mark an important step toward a better understanding of the sequence stratigraphy of the Paleogene in the Netherlands. Each unit in between the mapped horizons has its own seismic characteristics associated with their own lithostratigraphic characteristics. Biostratigraphic data have proven critical in validating the seismically characterized EMU, MMU, LMU and top Oosterhout boundaries. The stratigraphic framework proposed by Munsterman et al. (2019) is largely confirmed for the EMU and MMU, but revisions are recommended for the LMU, due to observed inconsistencies and its diachronous nature across the basin.

Several limitations and uncertainties influence the interpretations presented in this study and should be carefully considered when applying the results to future research or geothermal exploration. It should be taken into account that this study provides a regional framework for mapping the Breda Subgroup and Oosterhout Formation, primarily capturing broader stratigraphic trends. As a result, local and more detailed interpretations may differ. A systematic, nationwide seismic mapping effort is essential to develop geologically realistic geometric and reservoir models to support geothermal energy exploration. While this study provides a first step in identifying potential stratigraphic units and their distribution, further research is required to determine which intervals represent the most promising aquifers and where they are best developed. This work lays the foundation for future, more targeted studies aimed at optimizing subsurface utilization for geothermal and heat storage applications.

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