WarmingUPGOO

Geothermie & Opslag Opschaling

Data inventory for the improvement of Upper North Sea group geological models

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Contents

Samenvatting

De laatste jaren is de interesse in ondergrondtoepassingen zoals warmteopslag en ondiepe geothermie in het dieptebereik van ~300 m tot 1500 m sterk toegenomen. Door een gebrek aan historische interesse in dit dieptebereik zijn de ondergrondmodellen hier minder nauwkeurig. Minder inspanning in het verfijnen van de modellen in dit dieptebereik ligt hier aan de basis, maar ook een gebrek aan beschikbare gegevens. In dit rapport worden allereerst de relevante modellen beschreven en wordt getoond op welke gegevens en informatie deze zijn gebaseerd. In de tweede stap wordt een gegevensinventarisatie uitgevoerd van beschikbare gegevens die bijkomend gebruikt zouden kunnen worden om deze modellen te verbeteren.

De relevante nationale ondergrond modellen in dit dieptedomein zijn:

- Het Digitaal Geologisch Model - diep (DGM-diep): regionaal lithostratigrafisch model van de diepte van de belangrijkste geologische eenheden, gebaseerd op seismische gegevens en boringen geïdentificeerd in "diepe" putten.
- Het Digitaal geologisch model (DGM): regionaal lithostratigrafisch lagenmodel op formatieschaal, gebaseerd op boorgatgegevens (meestal < 100 m diep).
- REGIS II: hydrogeologisch model van de lagen van DGM, waarbij aquifers, aquitards en complexe eenheden in de DGM-lagen worden geïdentificeerd, gebaseerd op dezelfde boringen als DGM.

In deze inventarisatie wordt gefocust op drie stratigrafische eenheden die deel uitmaken van de Neogene Boven Noordzee Groep (van oud naar jong): de Breda, Oosterhout en Maassluis Formaties. Deze drie formaties zijn ongeconsolideerde, ondiepe mariene afzettingen die van bijzonder belang zijn voor de warmtetransitie: de Oosterhout en Maassluis Formaties komen vooral in beeld voor warmte-opslagtoepassingen en de Breda Formatie ook voor ondiepe geothermie.

De inventarisatie van de ondergrond modellen laat zien dat waar deze formaties zich dieper dan 150 m bevinden, het aantal boringen waarop DGM en REGIS II zijn gebaseerd erg klein wordt. Dit heeft tot gevolg dat de verbreiding van hydrogeologische eenheden hier slecht ondersteund wordt door gegevens.

De gegevens die beschikbaar zijn voor een verbetering van deze modellen kunnen ondergebracht worden in drie categorieën: 1) relatief nieuwe ondiepe boringen die nog niet zijn gebruikt; 2) diepe, of zogenaamde Nederlandse Mijnbouwwetboringen, en 3) seismische gegevens. De toegevoegde waarde van de verschillende categorieën kan uiteenlopen voor verschillende geografische gebieden en diepte-intervallen. Op basis van de data inventarisatie kunnen de volgende aanbevelingen gedaan worden om de ondergrond modellen van deze Formaties te verbeteren:

1. DGM en REGIS II kunnen worden verbeterd in Noord-Brabant, Zeeland en het noordelijke deel van Limburg, aangezien deze gebieden al systematisch in kaart werden gebracht met behulp van een combinatie van ondiepe en diepe boorputten en seismische gegevens als onderdeel van het H3O-projectpakket. Deze verbeterde interpretaties zullen worden geïntegreerd en toegevoegd aan de nationale modellen (2024-2025).
2. In vier specifieke gebieden waar de basis van de Breda Formatie zich op relatief grote diepte bevindt, kunnen modellen worden verbeterd door het opnemen van diepe putten en seismische gegevens.
3. De modellering van de Oosterhout Formatie kan over het algemeen worden verbeterd door gebruik te maken van seismische gegevens. De nieuw verworven SCAN-seismische

lijnen en *reprocessings* zijn hiervoor veelbelovend. De herkenning van de Maassluis Formatie is sterk afhankelijk van de specifieke kwaliteit van de seismiek. Het gebruik van petrofysische logs, ondersteund door biostratigrafische analyse van diepe putten, kan ook helpen bij de stratigrafische interpretatie van deze eenheden en een richtlijn bieden voor kartering op basis van seismiek.

4. Voor elke formatie worden 3 tot 4 gebieden aangewezen die baat kunnen hebben bij het opnemen van deze aanvullende gegevens.

Summary

In recent years, the interest in subsurface applications in the depth range of ~300 to 1500 m has increased considerably, such as heat storage and shallow geothermal energy. Because of a historical lack of interest in this depth range, subsurface models are less accurate than for the shallower and deeper depth domains. The reason for the lower quality of the models is mostly a lack of available data, but also less effort that has been invested in creating the models. In this report, first the relevant models are described and the data and information on which they are based is shown. In the second step, a data inventory is performed of available data that can be used to improve these models.

The relevant models in this depth domain are:

- Digital Geological Model - deep (DGM-deep): regional lithostratigraphic model of depth of the main geological units, based on seismic data and well tops identified in “deep” wells.
- Digital Geological Model (DGM): regional lithostratigraphic layer model on formation scale, based on borehole data (mostly < 100 m deep).
- REGIS II: hydrogeological model of the layers of DGM, identifying aquifers, aquitards and complex units in the DGM layers, based on the same boreholes as DGM.

The focus of this inventory are three units that are part of the Neogene Upper North Sea Group (from old to young): the Breda, Oosterhout and Maassluis Formations. These three formations are unconsolidated, shallow marine deposits which are of particular interest for the heat transition: the Oosterhout and Maassluis Formations especially for heat storage applications and the Breda Formation also for shallow geothermal production.

The results of the inventory of the models show that where these formations are positioned below a depth of 150 m, the number of boreholes on which DGM and REGIS II is based is very small. This also causes the lateral continuity of the hydrogeological units to be poorly supported by data.

The data available for improvement fall mainly in three categories: relatively new shallow boreholes that haven’t been used yet, deep, or so-called Dutch Mining Act wells and seismic data. In different areas and depth intervals, different data can be present and be most valuable. Based on the inventory, the following main recommendations were given:

1. DGM and REGIS II can be improved in Noord Brabant, Zeeland and the northern part of Limburg as these areas are already systematically mapped using a combination of shallow and deep boreholes and seismic data as part of the H3O-project suite and those results will be incorporated in the national models (2024-2025).
2. In four specific areas where the base of the Breda Formation is found at relatively deep depth, models can be improved by including deep wells and seismic data.
3. The modelling of the Oosterhout Formation can generally also be improved by using seismic data. The newly acquired SCAN-seismic lines and reprocessings are promising to this end. The recognition of the Maassluis Formation is very dependent on the specific quality of the seismic data. The use of petrophysical well logs aided by biostratigraphic analysis of deep wells can also aid the stratigraphic interpretation of these units, providing a guideline for seismic mapping.
4. For each formation, 3-4 regions are assigned that can benefit from the inclusion of additional data.

1 Introduction

1.1 Context

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[1]) 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[1]. The WarmingUP Geothermal and Storage Upscaling (WarmingUP-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 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 of 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. The middle-deep subsurface is for this purpose defined by the marine, aquifer-containing strata of the Miocene to Pleistocene Breda, Oosterhout and Maassluis Formations (chapter 2).

1.2 Objectives and report structure

This study addresses, as a first step of the Warming-UP-GOO program, the current knowledge base of the middle-deep Dutch subsurface. In particular, it investigates how the geology is represented in the three currently existing geo(hydrological) models (DGM, DGM-deep and REGIS II). This is achieved by outlining the used modelling methodologies (chapter 3) as well as exploring the data that *is*, and *is not yet* incorporated (chapter 4). A summary of those geological mapping activities within TNO-GDN that are not yet incorporated in the latest generation of models is also given. This is visualized in a series of thematic maps.

[1] MMIP 4: Duurzame warmte en koude in de gebouwde omgeving (inclusief glastuinbouw) Meerjarig Missiegedreven Innovatieprogramma Update mei 2021. MMIP4 Duurzame warmte en koude in de gebouwde omgeving (inclusief glastuinbouw) | Publicatie | Klimaatakkoord

By making an inventory of data that is currently not contained in the three geological models, several recommendations for the expansion and improvement of geological models in the middle-deep domain is given (chapter 5).

In this report, we will identify the parts of the three models which would benefit most from an additional characterization effort based on the combination of a high level of uncertainty because of the limited information/data included in the model and the availability of additional data. Based on the possibilities for future use, the order of addressing these parts of the models can be prioritized. Not included in the level of uncertainty in the models is the expected internal structure of the formations (lithological heterogeneity).

Albeit one of these models (REGIS II) is essentially a hydrogeologic model, including both geometry of aquifers and aquitards as well as their hydrological parameters, this study addresses chiefly data availability in terms of modelled geometries (depth and thickness). Nevertheless, the data density also is a strong indicator of the quality of the hydrogeological parametrization. General recommendations about the extent to which petrophysical well-log data are available to improve hydrological parameterization are therefore also provided. An evaluation of available chemical data and possible improvements when it comes to the set of parameters and parametrization aspects will be addressed in Warming-UP-GOO work-package 1.1 – Activity 1.1.4.

1.3 Overview of models and data types

The following models and data types are included in the inventory:

Geological Models:

- Digital Geological Model v2.2 (DGM)
- Digital Geological Model – Deep v5.0 (DGM-Deep)
- REGIS II

For a description, see chapter 3.

Boreholes and wells:

- A dataset of boreholes which was used for the construction of DGM v2.2
- A dataset of all boreholes in the DINO-database, including those not used in DGM v2.2
- A dataset of all (deep) wells. These are all wells to which the Dutch Mining Law applies

Borehole and well data:

- An extraction of petrophysical logs available for DINO-database “shallow” wells (d.d. 02-05-2023)
- An inventory of petrophysical logs and their respective depth-trajectories for “deep” wells, drilled under the Dutch Mining Law (d.d. 02-05-2023)

Seismic data:

- All publicly available 3D-seismic data
- All publicly available 2D-seismic data
- All Seismische Aardwarmte Campaign (SCAN) seismic 2D data and reprocessed data

(Ongoing) studies:

- Unpublished mapping results of the Neogene in the northeastern Netherlands (TNO-GDN)

- Mapping and modelling studies as part of the H3O-program (provinces of Noord-Brabant, Limburg and Zeeland)
- An overview of the search areas in which a number of 'scientific' exploration wells will be drilled in the framework of the SCAN program
- Integrated fault databases

2 Geological context

This inventory concerns data and models of geometries of Neogene (Miocene-Pliocene) and lower Quaternary (Lower Pleistocene) marine deposits in the Dutch subsurface. The following section is a brief summary of the geological context of this period, covering the tectonic history, paleogeographic evolution and stratigraphic nomenclature (Figure 2.1-1).

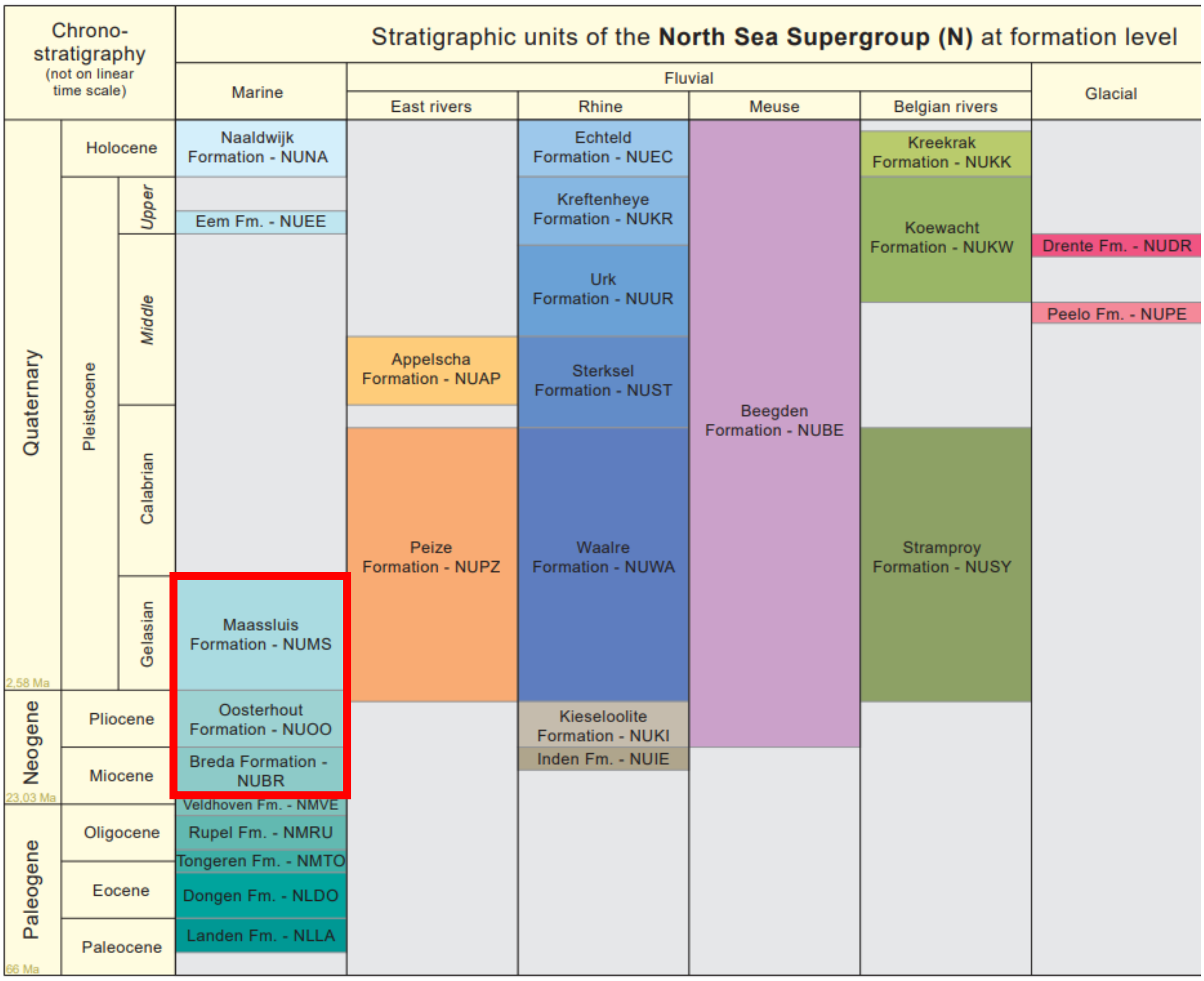

Figure 1.3-1 Overview of the ages and depositional environments of the lithostratigraphic units of the North Sea Group. The red box indicates the marine Neogene formations discussed in this report. Adapted from TNO-GDN 2022.

Over the course of the Cenozoic (the past 65 million years), the Netherlands were continuously located on the southern flank of the North Sea Basin, a large epicontinental basin bounded by Mesozoic NW-SE trending rift structures.

During the Paleocene (~ 60 million years ago), the area underwent thermal uplift and early Alpine compression, leading to erosion and the development of a clear unconformity, terminating the deposition of Upper Cretaceous and Lower Paleocene chalks. From this moment onwards, the North Sea Basin is progressively filled with the siliciclastic sediment of the Lower (Paleocene-Eocene), Middle (Oligocene) and Upper (Neogene, Miocene – present day) North Sea Groups. Over the course of the remainder of the Cenozoic, the combination of tectonism and eustatic sea-level variations led to a complex differentiation of sedimentation regimes (Figure 1.3-).

The Pyrenean phase and associated compression and erosion marks the boundary between the (Paleocene-Eocene) Lower North Sea Group and the (Oligocene-Lower Miocene) Middle North Sea Group. The Savian phase marks a renewed phase erosion in the Early Miocene. After the Savian unconformity the North Sea Basin is typically characterized by long-term gradual subsidence, leading to the blanketing of shallow marine clastic deposits (Figure 1.3-, fine sands, silt and clays) across much of onshore the Netherlands during the Miocene and Pliocene. These deposits are the Breda and Oosterhout Formation In the meantime, in the northern half of the Netherlands, and prominently including the northern Dutch offshore, a large northeasterly (Baltic) sourced delta system developed (Eridanos Delta, Figure 1.3-), whereas the southern part of the Netherlands became progressively influenced by the developing Rhine and Meuse rivers (Figure 1.3-). Near the base of the Pleistocene (2.6 million years ago), northern hemisphere glaciations started, leading to a regime shift in depositional environments, with cyclic variations in eustatic sea-level and weathering intensity. This level approximates the base of the Maassluis Formation, which is characterized as cyclic alternations of sand and more fine grained marine siliciclastic deposits.

In terms of lithostratigraphy the three formations that are discussed in this report are part of the Upper North Sea Group. The Breda Formation is of Miocene age, the Oosterhout Formation of Pliocene age and the Maassluis Formation of Early Pleistocene in age. The Breda Formation comprises glauconitic medium fine sand to silt. The Oosterhout Formation comprises glauconitic, very fine to coarse sands, but can locally be clayey in character. Characteristic is the presence of shell-material. Several specific facies types can be encountered, including extremely high concentrations of shells (so-called crags). The Maassluis Formation is more variable in nature, with intercalations of silt and clay in an overall sandy and upward coarsening sequence. The formation typically lacks abundant glauconite. Continental-fluvial influenced time equivalents of these units are the Ville & Inden Formation (Miocene), and the Kiezeloolite, Peize and Waalre Fm. (Pliocene - Pleistocene). The transition to these fluvial counterparts typically occurs in a denticulate character. The Kiezeloolite Formation is predominantly sandy in character, whereas the other formations are highly variable in terms of lithology.

Perhaps confusingly, it has recently been proposed to subdivide the Breda Formation into two separate formations, at least in the Roer Valley Graben (RVG) and its adjacent platforms. This subdivision erects the Groote Heide and Diessen formations (Munsterman et al., 2019). In essence, this subdivision is based on the (seismic and biostratigraphic) identification of major regional breaks in sedimentation (unconformities). Both because this stratigraphic subdivision cannot yet be unambiguously applied to other areas than the RVG and because these re-interpretations are not yet completed elsewhere in the Netherlands, these units are not yet discussed as potential separate model-units.

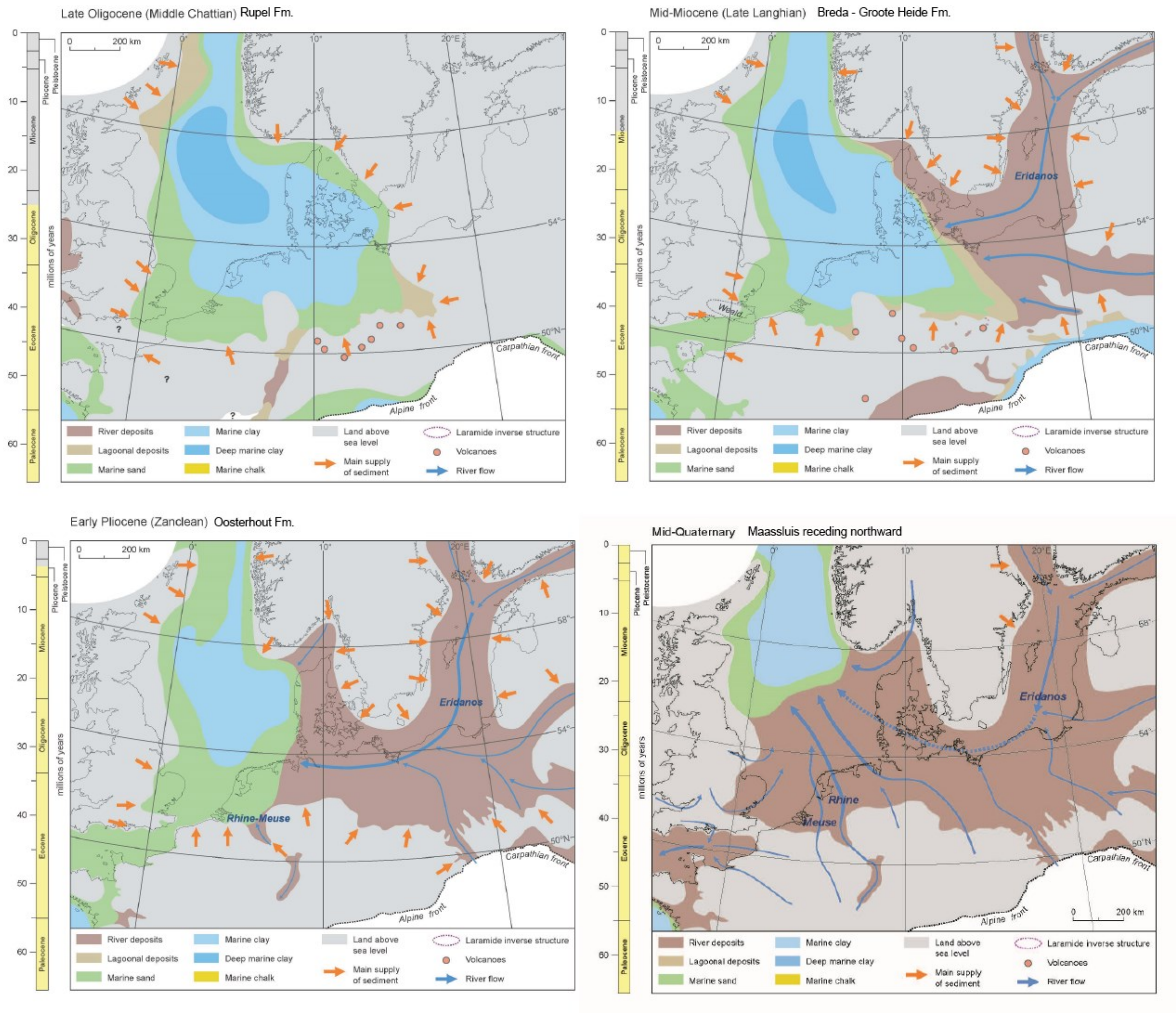

Figure 1.3-2 Paleogeographic maps of the environmental evolution of the Cenozoic (Middle Ypresian – Middle Miocene – Mid-Quartair). From: Munsterman et al. (in prep.)

3 Overview of geological models

This section describes the three subsurface models constructed and maintained by TNO-GDN that cover the Neogene – Quaternary strata in the Dutch subsurface. The order of description runs from deep and relatively low detail to shallow and more detailed. A fourth model, GeoTOP, is not discussed here because it only rarely reaches the respective formations due to the limited depth-coverage (up to ~ 50 m).

3.1 Digital geological model – deep (DGM-deep v5)

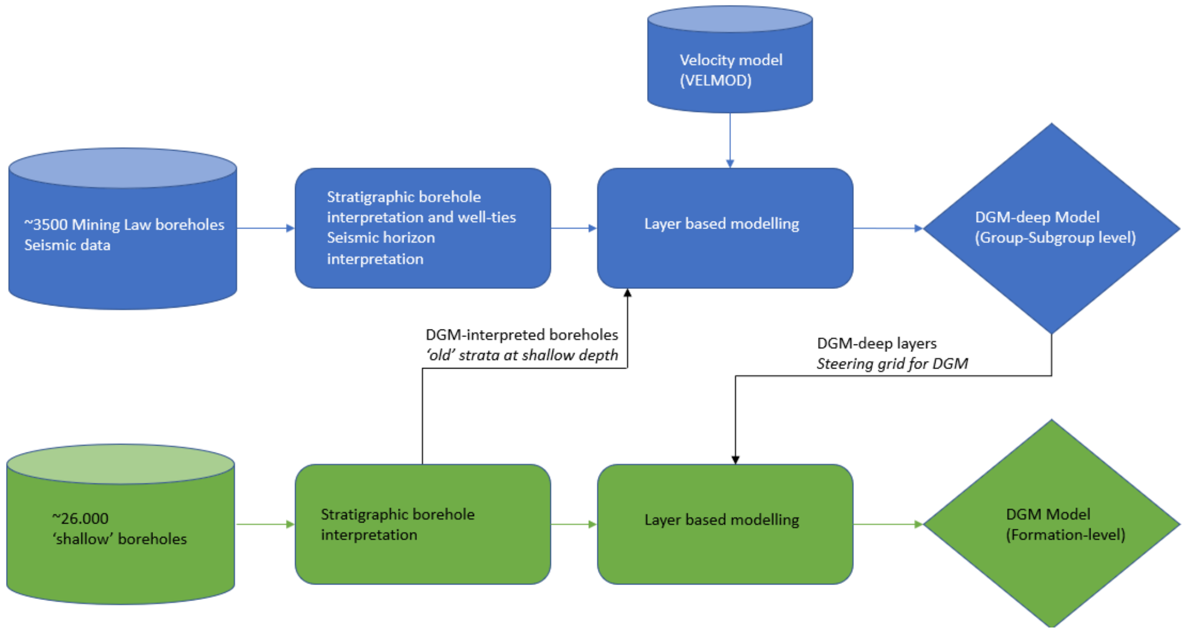

Figure 3.1-1 Modelling approach for the DGM-deep (blue) and DGM (green) subsurface models with the most important modelling steps involved as well as the interdependencies between the models. The cylinders refer to data-types, the rectangles to processes and the diamonds to the end-products.

The Digital Geological Model - deep is a regional lithostratigraphic layer model of the Dutch subsurface, on a group scale. The modelling of the deep subsurface relies on the combined interpretation of seismic data and 'deep' well data (Figure 3.1-1). The latter refers to hydrocarbon- and geothermal exploration and development wells that were drilled under the jurisdiction of the Dutch Mining Law[2]. During seismic acquisition, an acoustic signal (a sound wave) is generated at the surface. It penetrates downward into the earth and is reflected at the interfaces between different rock layers. After reflection, it travels back to the surface. The travel time between the offset of the wave (the source) and its return at the surface (the receiver) is measured in seconds. The real depth, in meters, can only be obtained when the seismic velocity of the wave in the different rock intervals is known. This velocity depends on many factors. Generally, it increases with depth due to compaction, but it can vary significantly per layer. As in situ velocity measurements are sparse, the conversion of time to depth is one of the biggest sources of uncertainty in deep geomodelling. Whereas the seismic data provides information on geometries, well data (especially interpreted well stratigraphy or well tops) help to ground-truth the seismic interpretation by providing stratigraphic information in the depth-domain. Approximately 3500 wells are available to constrain the seismic interpretation. A good seismic-to-well tie is essential for the seismic interpretation of seismic reflectors that represent sensible geological boundaries. Petrophysical well log data (sonic velocities

[2] Wells having an end depth exceeding 500 m below surface level must be drilled according to the Mining Law.

and densities) are used to generate synthetic seismograms, that can be compared with the real seismic data in order to establish an optimal seismic-to-well tie.

Seismic interpretation for DGM-deep focusses on 13 stratigraphic levels that represent the (near) bases of Paleozoic, Mesozoic, and Cenozoic lithostratigraphic Groups (Table 3.1.1) as defined in the Stratigraphic Nomenclature of the Netherlands (TNO-GDN, 2022).

Table 3.1-1 Listing of lithostratigraphic units (Group level) modelled in DGM-deep

stratigraphic code	lithostratigraphic unit	period
NU	Upper North Sea Group	Neogene
NL/NM	Lower and Middle North Sea Groups	Paleogene
CK	Chalk Group	Late Cretaceous - Early Paleogene
KN	Rijnland Group	Early Cretaceous
S	Schieland and Niedersachsen Groups	Late Jurassic - Early Cretaceous
AT	Altena Group	Early and Middle Jurassic
RN	Upper Germanic Trias Group	Middle and Late Triassic
RB	Lower Germanic Trias Group	Early Triassic
ZE	Permian Zechstein Supergroup	Late Permian
RO	Permian Rotliegend Supergroup	Permian
DC	Limburg Group	Late Carboniferous

Faults evident in seismic data are interpreted as well. Both the seismic interpretations and the well markers are used to produce the DGM-deep model, a stacked layer model of the deep subsurface of the Netherlands represented at 250x250m grid resolution. In every new update of DGM-deep, new available public data is incorporated. The latest 2019 version, DGM-deep v5, combines on- and offshore data into a single layer model (Figure 3.1-2).

The applied modelling workflow initially produces time grids that are generated by interpolating seismic horizon picks using a convergent gridding algorithm. Subsequently, a conversion from the time to the depth domain is made using VELMOD, a velocity model built from well log and check-shot data (Van Dalfsen et al., 2006). In the southeast, southwest and easternmost parts of the country, where Cretaceous and Paleogene units are close to the surface, interpreted boreholes from the DGM-model of the shallow subsurface are used to assist in the construction of the DGM-deep layer model. In these areas, the depth range of the Chalk and North Sea groups is too shallow to be detected by seismic data.

Note that the base of the Upper North Sea Group corresponds to the base of the Breda Formation.

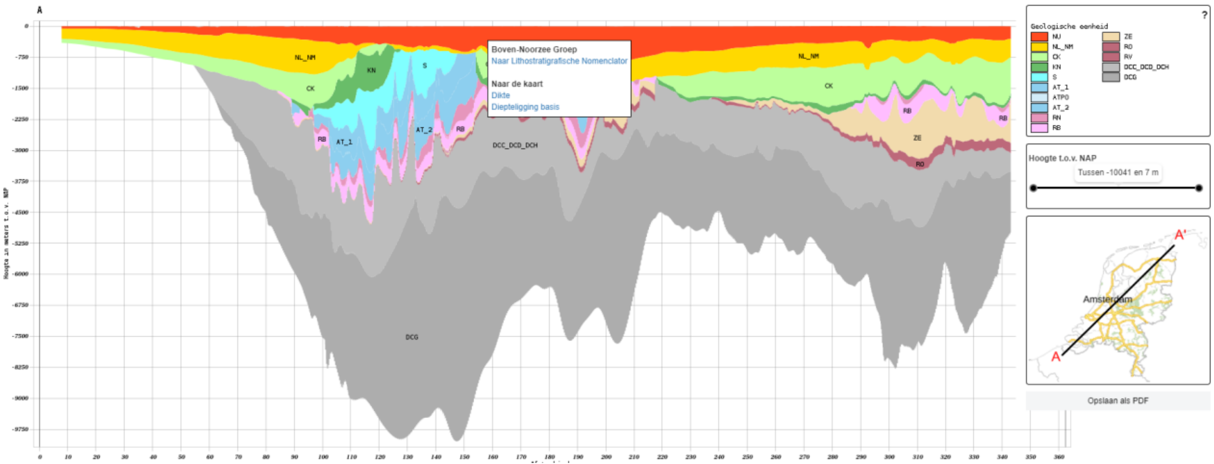

Figure 3.1-2 *Example cross section made with DGM-deep v5.0. The focus of the inventory is on the uppermost layer of this model, the upper North Sea Group (NU). The base of this unit is used as a steering grid in DGM (see Figure 3.2-1).*

3.2 Digital Geological Model (DGM)

The Digital Geological Model is a regional lithostratigraphic layer model of the Dutch subsurface, on a formation-scale. It is constructed using a set of about 26,000 consistently interpreted boreholes. These are predominantly so-called 'shallow' boreholes that were not drilled under the jurisdiction of the Dutch Mining Act. These are mostly drilled for ground-water exploration and production or mapping purposes. In contrast to the 'deep' wells used for DGM-deep, the shallow well data are mainly detailed lithological descriptions of the sedimentary layers, sometimes combined with log data (usually (spectral) gamma ray, spontaneous potential, resistivity and/or conductivity). The selection of the boreholes aims at an even lateral and vertical distribution of good quality data for the Quaternary and Neogene deposits the DGM covers. Seismic data have not (yet) been used for the construction of DGM. The interpreted boreholes constitute the basis for a 2.5D stacked layer lithostratigraphic model of the entire onshore part of the Netherlands, down to a depth of about 500 m (extending down to about 1200 m in Roer Valley Graben). It consists of a series of raster layers, where each formation is represented by rasters for top, base and thickness of the unit (cell size 100 x 100 m).

The oldest formation in DGM is the Eocene Dongen Formation (Figure 3.3-2), but only in those regions where it occurs at a depth below 200 m. Boreholes with an end depth less than 10 m below surface are not used in DGM, except in the northern Netherlands where mapping of the hydrologically important till deposits at the base of the Drente Formation required their use. The selected boreholes are interpreted stratigraphically by determining to which formation or member each layer belongs (TNO-GDN, 2022). The base of each of the lithostratigraphic units in the boreholes is subsequently used for interpolation and modelling. The basic strategy for the lithostratigraphic interpretation is to work from nation-wide cross-sections to regional-scale cross-sections that constitute the geological framework for the final interpretation of individual boreholes. These cross-sections are not explicitly used in the interpolation process. In addition to the boreholes, a map of known major faults in the Cenozoic deposits was constructed. For each lithostratigraphic unit, the faults that influenced the base of the unit are selected and used as 'barriers' in the interpolation process. The geometrically complex Holocene units at the top of the Neogene succession are considered as a single confining layer (see Figure 3.2-).

The DGM-deep model grid of the base of the Upper North Sea (by approximation the base of Breda Formation) was used as a steering grid for the base of the DGM-model.

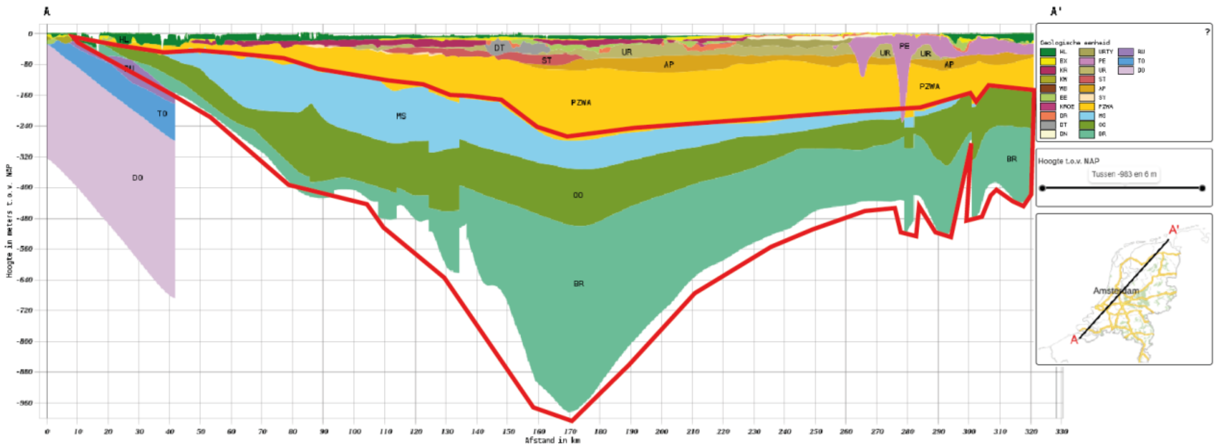

Figure 3.2-1 Example cross section made with DGM. The red outlined interval corresponds to the three units described in this report. The base of the Breda Fm. (BR) in this models is largely based on the base of the Upper North Sea Group in DGM-deep (see Figure 3.2-1, not different vertical scale). In the southwest of the Netherlands the oldest units of the DGM model are older than the Breda Fm. Here, Eocene-Oligocene units of the Lower and Middle North Sea Group occur at depths above 500 m.

Figure 3.2-1 displays maps of the base of the Upper North Sea Group according to DGM-deep and the base of the Breda Formation according to DGM. The former was used as a steering grid for the construction of the latter. The residuals between the depth of the base of the Upper North Sea Group grid and that of the Breda Formation in the wells was interpolated and added to the grid. Finally, the grid was cut according to the distribution of the Breda Formation It is also clear that details of the modeled level differ due to different interpolation techniques.

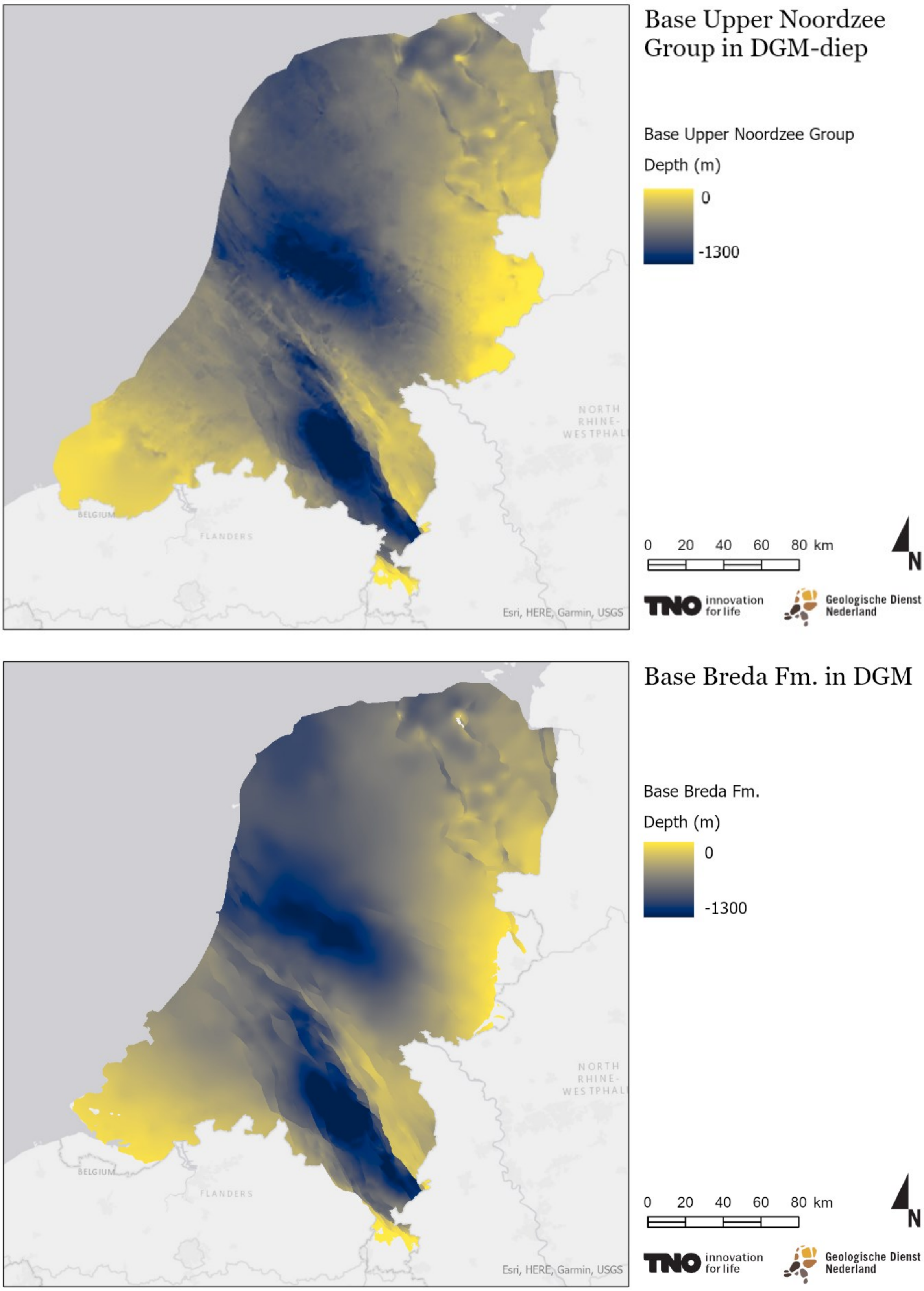

Figure 3.2-1 Comparison of the depth of the base of the base Upper North Sea Group (upper map) according to DGM-deep and the base of the Breda Formation (Fm.) according to DGM (lower map).

3.3 REGIS II

DGM constitutes the basis for the hydrogeological model REGIS II (**Re**gional **G**roundwater **I**nformation **S**ystem; Vernes et al., 2005; Vernes et al., 2021). Within REGIS II the lithostratigraphic units of DGM are subdivided into hydrogeological units (aquifers, aquitards and complex layers). The model uses the same dataset of boreholes as used in DGM. In addition, representative values of hydrological parameters (e.g. hydraulic conductivity) are calculated and assigned to the model, making it suitable for groundwater flow modelling on a regional scale. Like DGM, REGIS II models the complex Holocene deposits as a single confining layer.

During the hydrogeological interpretation of the borehole data, each formation in a borehole record is subdivided into one or more of 14 lithological classes (Vernes et al., 2021). Based on the hydraulic properties of the lithological layers in the boreholes, layers with similar properties are combined using an automated procedure. The results of the aggregation step are subsequently interpreted manually. Based on their main lithology, six types of hydrogeological units are defined: sand, clay, peat, lignite, chalk and 'complex'. The modelling procedure of the tops and bases of the hydrogeological units is similar to the procedure followed in DGM, with two exceptions. First, the modelling of units within a DGM unit (formation) require the interpolation of two surfaces rather than the base surface only. Second, in many cases it is difficult or even impossible to recognize consecutive sandy hydrogeological units within a single geological unit. This is especially the case if these sandy units are not separated by a clayey, peaty of complex unit. This problem is solved using a three-step approach where the clayey units, or any other unit that is recognizable by its lithological contrast, are modelled first. The second step is the construction of so-called hypothetical horizons. The percentage thickness distribution of the sandy units at the top of the clayey, peaty and complex units is used as data points in the interpolation procedure of these horizons. In the third step, the geometry of the sandy units is derived by combining the top or base of the clayey units with the hypothetical horizons.

The modelling workflow ultimately subdivides the 34 DGM lithostratigraphical units into 125 hydrogeological units. The next step in the modelling workflow is the parameterization of the hydrogeological units (Gunnink et al, 2013; Vernes et al., 2021). Hydraulic conductivity measurements in the horizontal (k_h) and vertical (k_v) directions are only sparsely available, and therefore hydraulic conductivity is correlated with the distribution of lithological classes in the boreholes. This leads to a weighed interpolation to populate the entire volume of each hydrogeological unit in a specific borehole. The uncertainty on the sets of data used for the assignment of lithoclasses and the rather sparse hydraulic conductivity measurements used for interpolation, hampers an evaluation of the reliability of the hydrogeological interpretations. A critical aspect in this regard is on what basis both the litho-classes and the eventual hydrogeological units are assigned to individual borehole sections. Unfortunately, there is no borehole catalogue associated with the release of the REGIS-model that elucidates what data types were used for the interpretation. This would require a rigorous review of the contents of the dataset of REGIS.

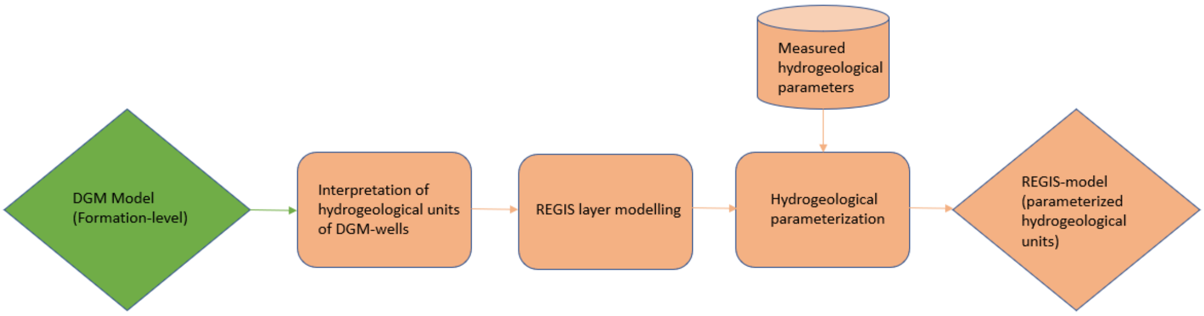

Figure 3.3-1 Schematic representation of the REGIS-modelling workflow. The DGM-model is populated with hydrogeological information, resulting in a model with parameterized hydrological units (Table 3.3.1).

The distribution of mapped hydrogeological units is influenced by their distribution boundaries. These are prescribed by distribution polygons made by regional experts, based on literature, maps, etc. Because hydrogeological units can easily interfinger and can be dissected by faults, the potential distribution is therefore continuously clipped with the geological unit it belongs to. This is process is carried out by hand.

For the interval covered in this inventory (the Breda., Oosterhout and Maassluis Formations), Table 3.3-1 depicts the respective hydrogeological units.

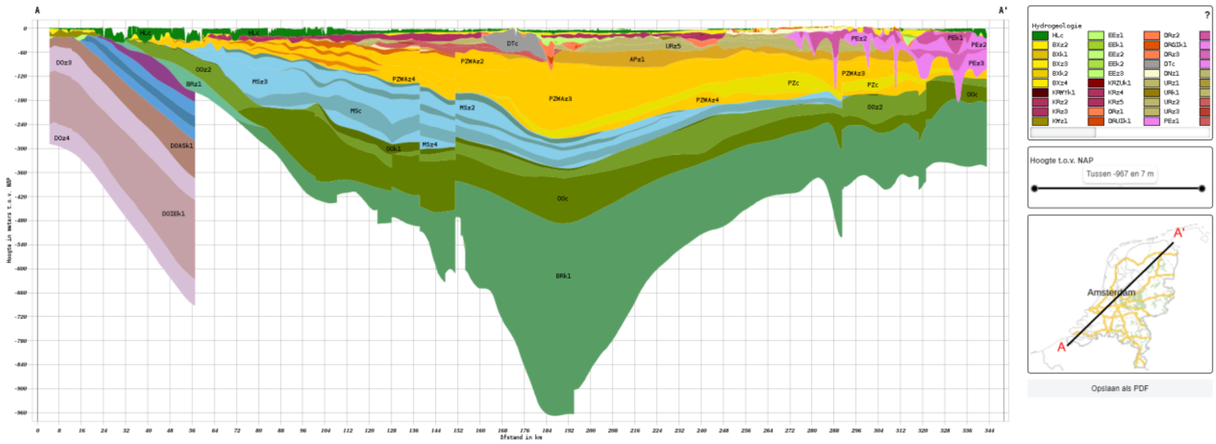

Figure 3.3-2 Cross section through the REGIS-II model in southwest to northeast direction through the Netherlands. Note the presence of older strata in Zeeland (Lower and Middle North Sea Groups). Hydreogeological units are contained within the formation framework following the DGM model.

Table 3.3-1 Overview of the hydrogeological units modeled in REGIS-II that are contained in the Breda, Oosterhout and Maassluis Formations (Fm.). In addition, the interfingering Inden and Kiezeloolite Formations are shown. The numbers and abbreviation relate to the REGIS hydrogeological units (e.g., MSz1 = Maassluis Fm. Zand/Sand – 1, MSk1 = Maassluis Klei/Clay-1).

MSz1	Fm. van Maassluis, 1e zandige eenheid			
MSk1	Fm. van Maassluis, 1e kleiige eenheid			
MSz2	Fm. van Maassluis, 2e zandige eenheid			
MSk2	Fm. van Maassluis, 2e kleiige eenheid			
MSz3	Fm. van Maassluis, 3e zandige eenheid			
MSc	Fm. van Maassluis, complexe eenheid			
MSz4	Fm. van Maassluis, 4e zandige eenheid			
Klz1	Kiezeloöliet Fm., 1e zandige eenheid			
Klk1	Kiezeloöliet Fm., 1e kleiige eenheid			
Klz2	Kiezeloöliet Fm., 2e zandige eenheid			
Klk2	Kiezeloöliet Fm., 2e kleiige eenheid			
Klz3	Kiezeloöliet Fm., 3e zandige eenheid			
Klk3	Kiezeloöliet Fm., 3e kleiige eenheid			
Klz4	Kiezeloöliet Fm., 4e zandige eenheid			
Klk4	Kiezeloöliet Fm., 4e kleiige eenheid			
Klz5	Kiezeloöliet Fm., 5e zandige eenheid			
OOz1	Fm. van Oosterhout, 1e zandige eenheid			
OOk1	Fm. van Oosterhout, 1e kleiige eenheid			
OOz2	Fm. van Oosterhout, 2e zandige eenheid			
OOc	Fm. van Oosterhout, complexe eenheid			
OOz3	Fm. van Oosterhout, 3e zandige eenheid		*A.*	*I.*
IEz1	Fm. van Inden, 1e zandige eenheid		*A.*	*I.*
IEk1	Fm. van Inden, 1e kleiige eenheid			
IEz2	Fm. van Inden, 2e zandige eenheid			
IEk2	Fm. van Inden, 2e kleiige eenheid			
IEz3	Fm. van Inden, 3e zandige eenheid			
BRz1	Fm. van Breda, 1e zandige eenheid	*5.*		
BRk1	Fm. van Breda, 1e kleiige eenheid	*5.*		*II.*
BRz2	Fm. van Breda, 2e zandige eenheid	*5.*	*B.*	
Vlb1	Fm. van Ville, 1e bruinkooleenheid	*5.*	*B.*	*II.*
BRz3	Fm. van Breda, 3e zandige eenheid	*5.*	*B.*	
Vlb2	Fm. van Ville, 2e bruinkooleenheid	*5.*	*B.*	*II.*
BRz4	Fm. van Breda, 4e zandige eenheid	*5.*	*B.*	

4 Data inventory

4.1 Data used in DGM and REGIS II

This data inventory aims to identify data that contribute to an improvement of the layer models of the subsurface. Furthermore, the DGM borehole set is used for hydrogeological interpretation. The quality of the hydrogeological interpretation is strongly dependent on the petrophysical log data that is available in a specific borehole. For this purpose boreholes that reach the studied Formations and that have e.g. gamma ray log data are also given.

In this section, an overview of the data that are currently incorporated in the DGM model is given. This eventually identifies areas and intervals in the model that are relatively poorly constrained by borehole data. In Section 4.2, additional data (and types) that can improve the model are discussed.

4.1.1 Breda Formation

The base of the DGM-model for the Breda Formation is predominantly defined by the DGM-deep steering grid of the base of the Upper North Sea Group (NU). This is because of an overall absence of wells reaching its base (Figure 3.2-1, Figure 4.1-1). The depth of the top of the Breda Formation is based on the DGM-borehole selection set (1665 boreholes reaching into the Breda Formation). In the southernmost Zeeland, South Limburg and easternmost Overijssel and Gelderland, the distribution limit of the Breda Formation is delineated by boreholes, in which the formation is proven absent (n=858, Figure 4.1-1). High densities of boreholes that extend vertically into but not fully penetrate the Breda Formation contribute to a reliable reconstruction of the top of the Breda Formation, especially on the flanks of the Roer Valley Graben (RVG, Figure 4.1.2). The same applies to the southern parts of Zeeland and the eastern part of Gelderland and Overijssel. In most of Drenthe and Groningen, the Breda Formation is relatively thin and well constrained by boreholes. Elsewhere, where the Breda Formation is either relatively deep and thick (RVG and Zuiderzee Low) and where it is relatively thin but deeply buried (i.e., in the western part of the Netherlands), borehole control on the DGM-model is minimal.). It goes without saying, that also in those areas the hydrogeological interpretation becomes far less reliable.

Recently, Munsterman et al. (2019) proposed to redefine the Breda Formation into two new units, the Groote Heide en Diessen Formations. The units can be seen on seismic data in the Roer Valley Graben as two distinct seismic sequences, separated by three recognizable unconformities: the Early Miocene Unconformity (EMU), the Mid-Miocene Unconformity (MMU) and the Late Miocene Unconformity (LMU). The MMU defines the boundary between the older Groote Heide and the younger Diessen formations. These formations will be incorporated in the stratigraphic nomenclature (TNO-GDN, 2022)of the Netherlands soon (2024), and will therefore turn out as separate model-units in future releases of DGM. Application of this new subdivision requires insights from seismic data and (biostratigraphic) age-control, because the pure lithostratigraphic definition is not unequivocal. Nevertheless, in stratigraphically complete sections of the Breda Formation, a characteristic petrophysical log response is seen for the MMU level. It is as yet uncertain how the two formations differ in hydrogeological character although first steps were already set[3]. A full hydrogeological characterization still requires substantial future effort.

[3] https://www.thermogis.nl/en/breda-formation

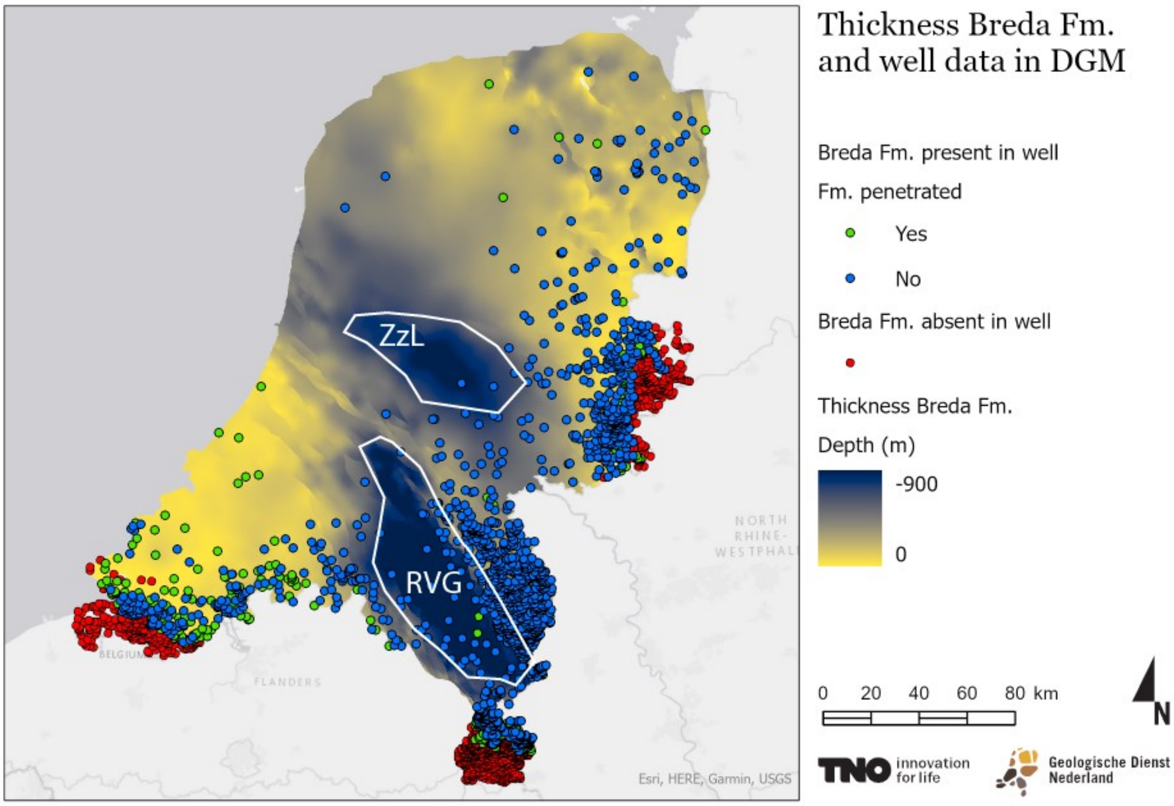

Figure 4.1-1 *Thickness map of the Breda Formation (Fm.) according to DGM and the associated DGM borehole data. Red dots indicate boreholes in which the Breda Formation is absent. Green dots indicate that the Breda Formation is completely penetrated and blue those with a vertical termination within the Breda Formation.*

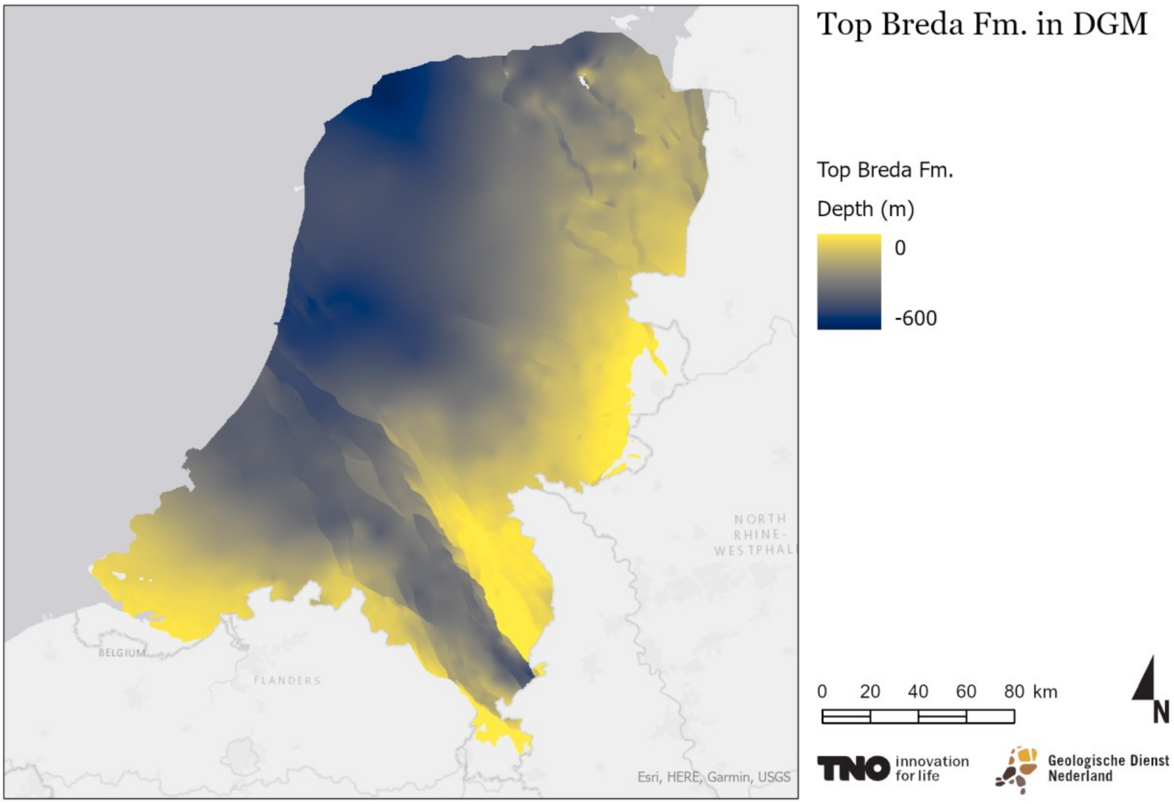

Figure 4.1-2 *Depth of the top of the Breda Formation (Fm.) according to the DGM model.*

4.1.2 Oosterhout Formation

A total of 1557 boreholes constrain the distribution of the Pliocene Oosterhout Formation In a total of 1923 wells the formation is stratigraphically absent (Figure 4.1-3). The absence of the Oosterhout Formation in southern Zeeland, eastern Overijssel and Gelderland, eastern Noord Brabant and Limburg is due to a facies transition to the fluvial sediments of the Kiezeloolite, Beegden and Stramproy Formations.

Although its lateral distribution is thus very well constrained, the thickness of the Oosterhout Formation is only well-constrained by boreholes close to its southern and eastern distribution limit. Elsewhere, the Oosterhout Formation appears at a depth too large to be penetrated by DGM-boreholes (Figure 4.1-3). In those areas the hydrogeological interpretation becomes far less reliable.

Particularly the RVG and the area covering the Provinces of Zuid Holland, Noord Holland, Flevoland and Friesland are characterized by limited borehole control. Nevertheless, the Oosterhout appears to reach substantial thickness in some of these area with extremely poor borehole-control (e.g., the Lauwerszee Trough and the Ijmuiden area). This large modeled thickness is a consequence of interpolation with the Breda Fm. geometry and a few boreholes that reach younger strata.

An additional problem is that the base of the Oosterhout Formation is difficult to identify accurately where it overlies the Breda Formation. This is due to the general transitional nature of the contact, resulting in lithostratigraphic criteria for the boundary between the units that are not unequivocal.

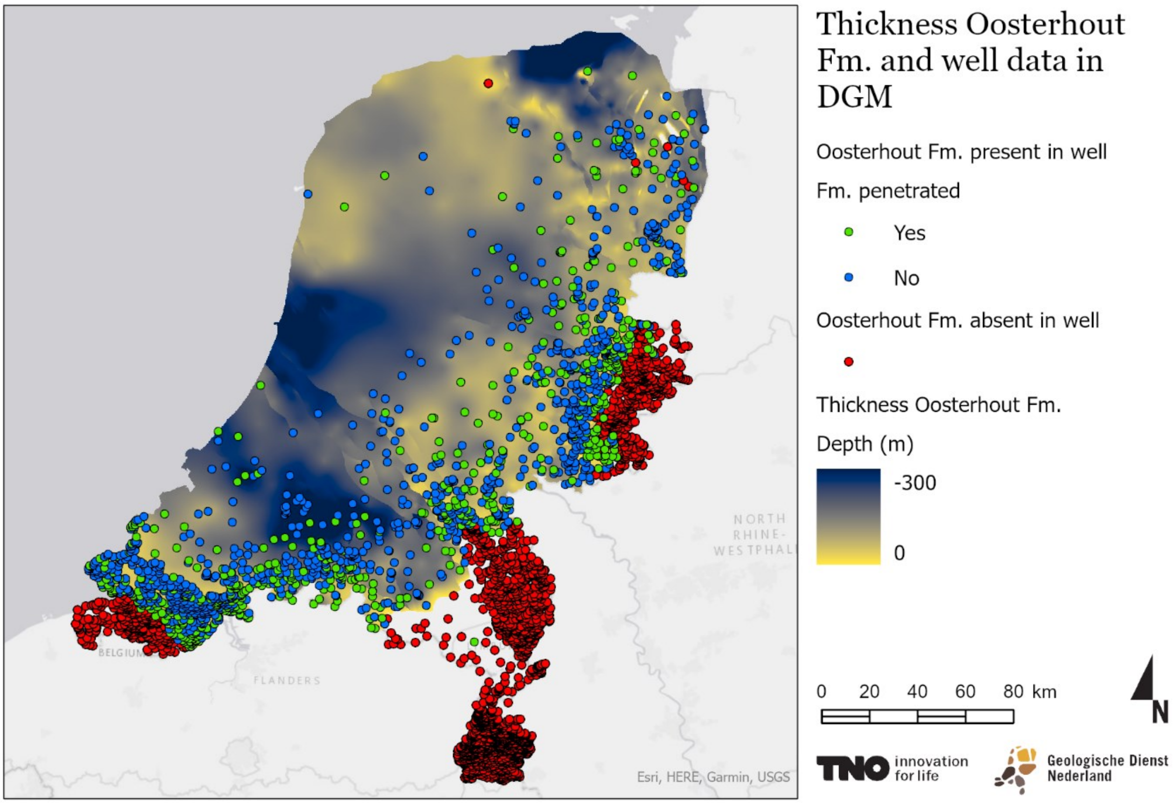

Figure 4.1-3 Thickness map of the Oosterhout Formation (Fm.) and the DGM 2.2 borehole data. Red dots indicate those in which the Oosterhout Formation is absent. Green dots those in which the Oosterhout Formation is completely penetrated and blue those that have a termination within the Oosterhout Formation

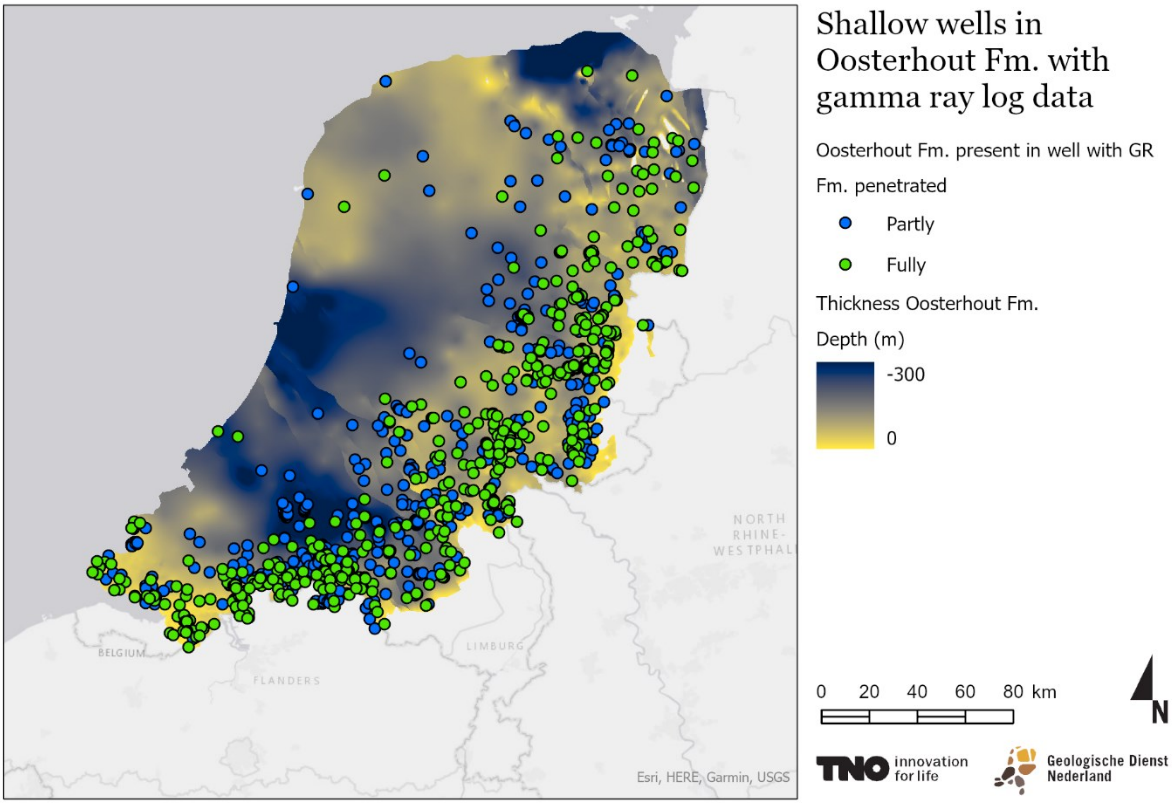

Figure 4.1-4 Boreholes reaching the Oosterhout Formation, included in DGM that have a GR-log available. Particularly for these boreholes, the lithofacies interpretation is reliable.

4.1.3 Maassluis Formation

Of the three marine formations discussed in this report, the Maassluis Formation is constrained by the largest number of boreholes (Figure 4.1-4). This is because this formation occurs at the most shallow depth. Its distribution is also the most confined, due to the overall west- and northwestward progradation of fluvial sediments of the Peize-Waalre and Beegden Formations by Early Pleistocene times. In 3478 boreholes, the Maassluis Formation is absent, whereas the formation is recorded in 1024 boreholes. Particularly poor borehole control, and, as a consequence, high uncertainty regarding thickness and distribution, pertains to most of Noord Holland, Flevoland and Friesland.

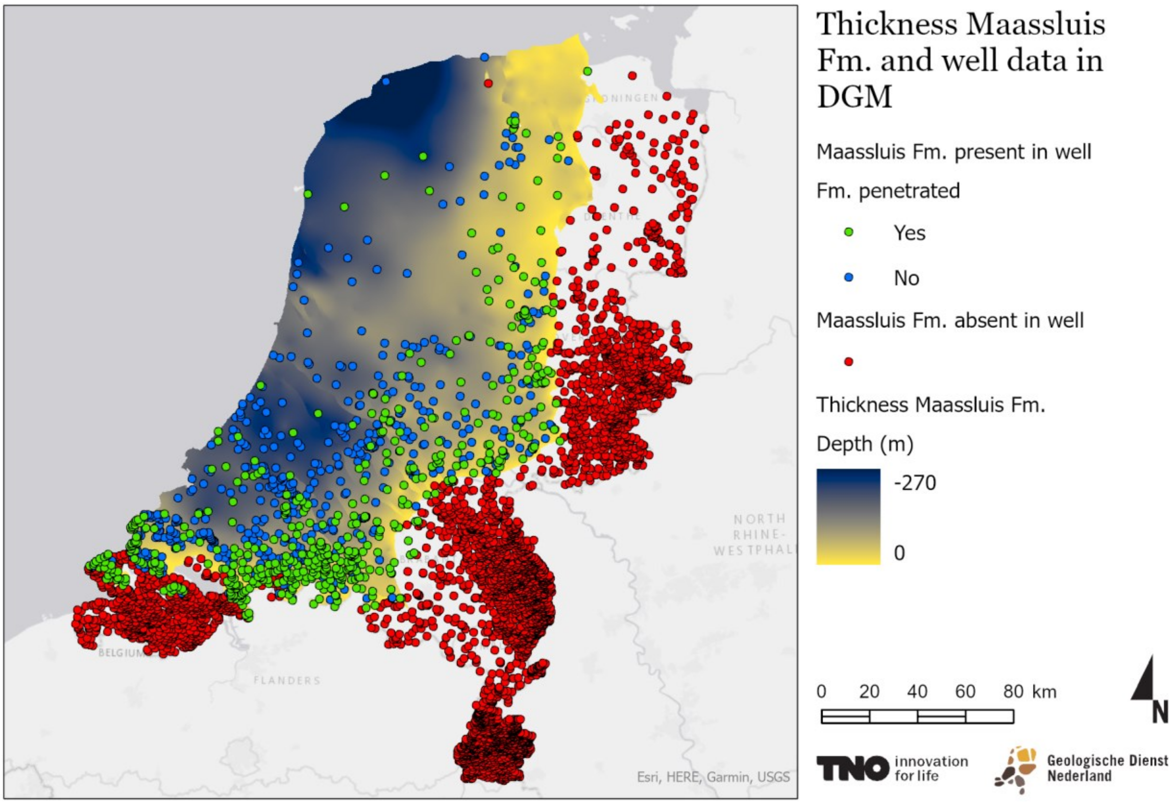

Figure 4.1-5 Thickness map of the Maassluis Formation (Fm.) and the DGM 2.2 borehole data. Red dots indicate those in which the Maassluis Formation is absent. Green dots those in which the Maassluis Formation is completely penetrated and blue those that have a termination within the Maassluis Formation.

4.1.4 Intersecting units

In the north of Netherlands, ice-marginal fluvial, lacustrine to glaciomarine deposits of the Peelo Formation appear at very shallow depth, near the top of the Upper North Sea Group (0-20 m depth). In a complete and continuous sequence, where the Peelo occurs on a valley shoulder, the Urk, Appelscha and Peize Formations are present below a thin Peelo Formation above Maassluis Formation and/or older strata. The Peelo Formation, however also occurs as erosive glacial valley and channel fills, which form deep incisions as deep as the Breda Formation. The mapping of the Peelo incisions is in progress but not yet included in the official models, leading to uncertainty in terms of their depth and location (Figure 4.1-5). When assessing the geothermal or heat storage potential in the area in these areas, one should consider this important aspect of the geology (Figure 4.1-5).

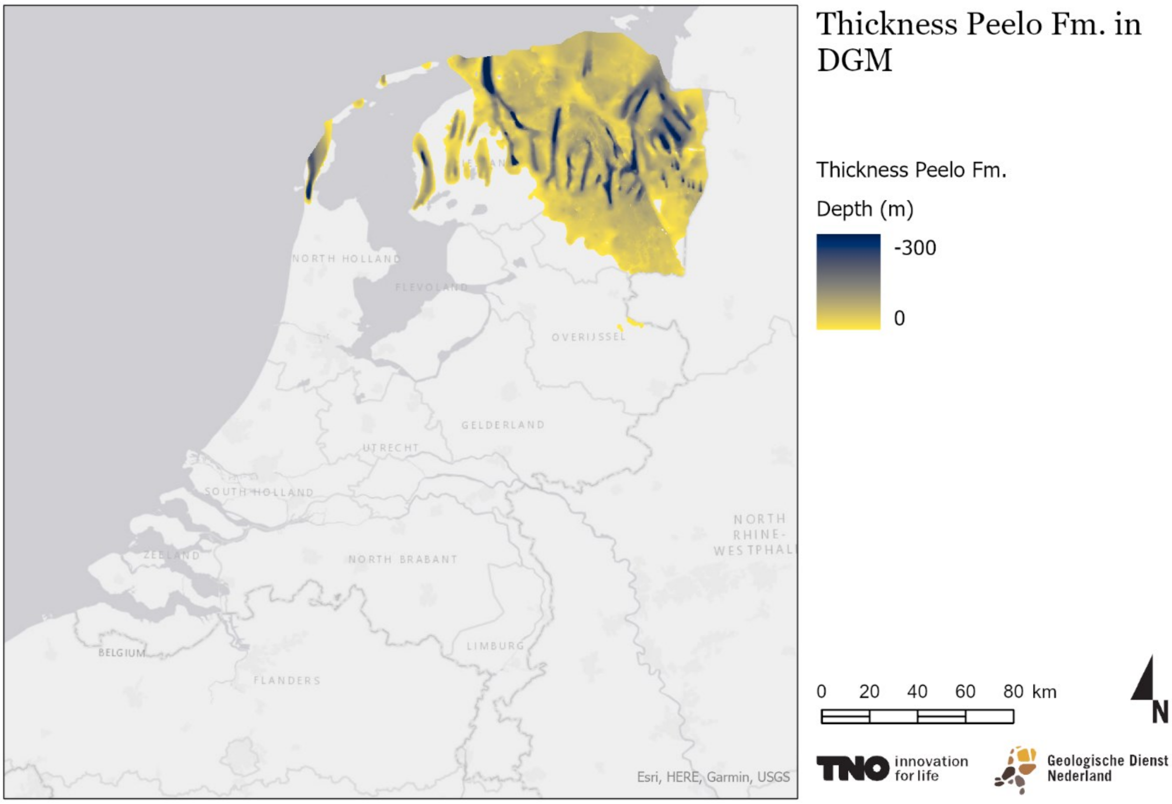

Figure 4.1-6 The Peelo Formation (Fm.) thickness modeled by DGM. The precise delineation and depth of the incised glacial valleys and channels is uncertain.

The transitions between the marine sedimentary formations discussed here and their continental stratigraphic equivalents, are interfingering in nature. For instance, the transition between the Oosterhout and the Kiezeloolite Formation is highly dentate in nature, with several pro- and retrogradation cycles along the paleo-coastline. The DGM and REGIS-model workflow are not suitable for dealing with this kind of transition (Figure 4.1-7). This leads to a simplification of the models and difficulty predicting the hydrogeological nature of these transitions.

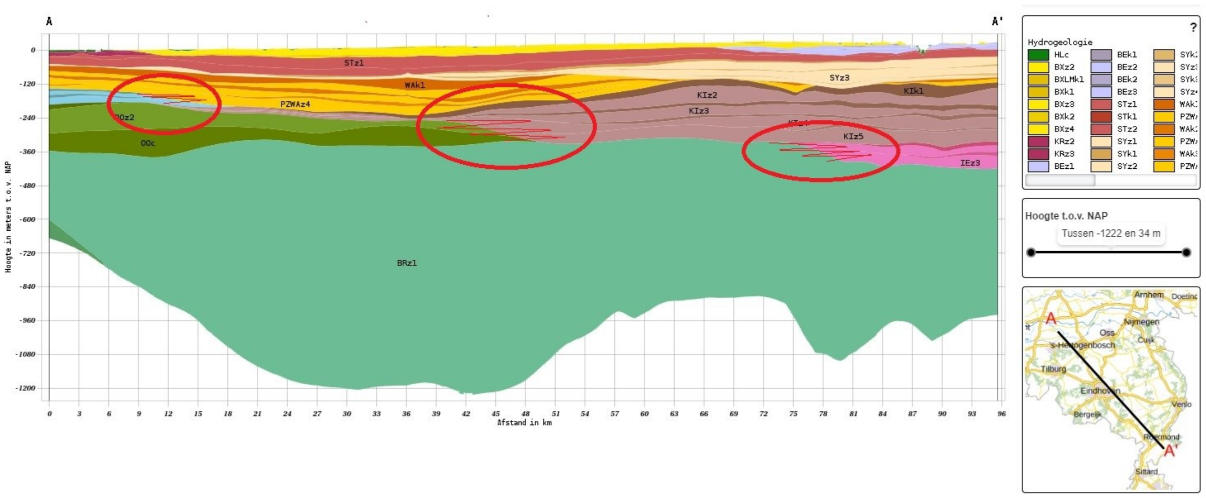

Figure 4.1-7 Example x-section through REGIS running SE-NW through the RVG, where the transition between a Breda Formation (Br) and Oosterhout and their fluvial counterparts is not realistically modeled.

4.2 Inventory of data currently not used in DGM

This section provides an inventory of data that is currently *not* included in the mapping and modelling of the DGM-model. This concerns seismic data, 'shallow' non-Mining Law boreholes and 'deep' Mining Law boreholes. The inventory includes a 20 km buffer zone into the offshore. The latter is relevant because offshore and seismic data can aid to improve geological understanding and mapping in the coastal areas.

4.2.1 'Shallow' wells – non-Mining Law, not included in DGM

The DGM-model is based on a selection of all available boreholes. For a description on the difference in data collection, techniques used and storage of so-called shallow and deep well information, the reader is referred to Veldkamp et al. (2022). This section simply gives an overview of the boreholes that are not included in DGM. To this end, an extraction from the Dinoloket database was made, which contains all public boreholes that extend into the respective formations. In some cases, these are more recent boreholes that were drilled after the latest release of DGM. In some other cases, these concern 'deep' Mining Law boreholes that are also included in the 'shallow' Dinoloket database (with a so-called NITG-code) and thirdly, some boreholes did not stand up to the quality control for inclusion in DGM. It is however beyond the scope of this study to re-assess whether boreholes are of sufficient quality to be included in future modelling efforts.

4.2.1.1 Breda Formation

For the Breda Formation it is particularly clear that additional boreholes are present in southern Noord Brabant, on the Campine Block near the southern edge of the Roer Valley Graben (Figure 4.2-1). This likely is the result of the recent drilling of hydrogeological exploration wells.

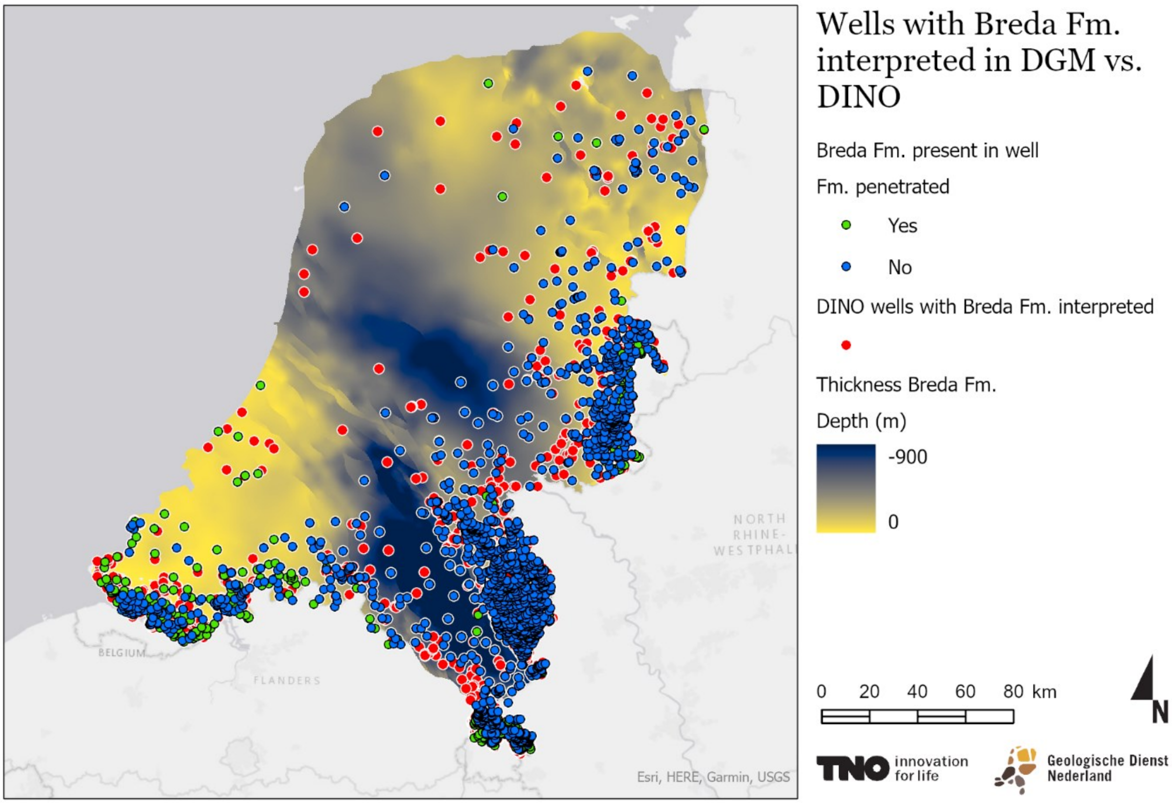

Figure 4.2-1 Comparison between DGM-borehole selection for the Breda Formation (Fm.) (n = 399 for penetrating wells, n = 1267 for non-penetrating wells) and boreholes in database that reach the Breda Formation but are not yet included in DGM and REGIS (n = 9846).

Also in Zuid Holland, Noord Holland, Groningen and Friesland potentially useful datapoints are not yet used in DGM.

4.2.1.2 Oosterhout Formation

For the Oosterhout Formation it seems that currently unused boreholes can aid future modelling activities in Zuid Holland, Noord Holland and Friesland particularly.

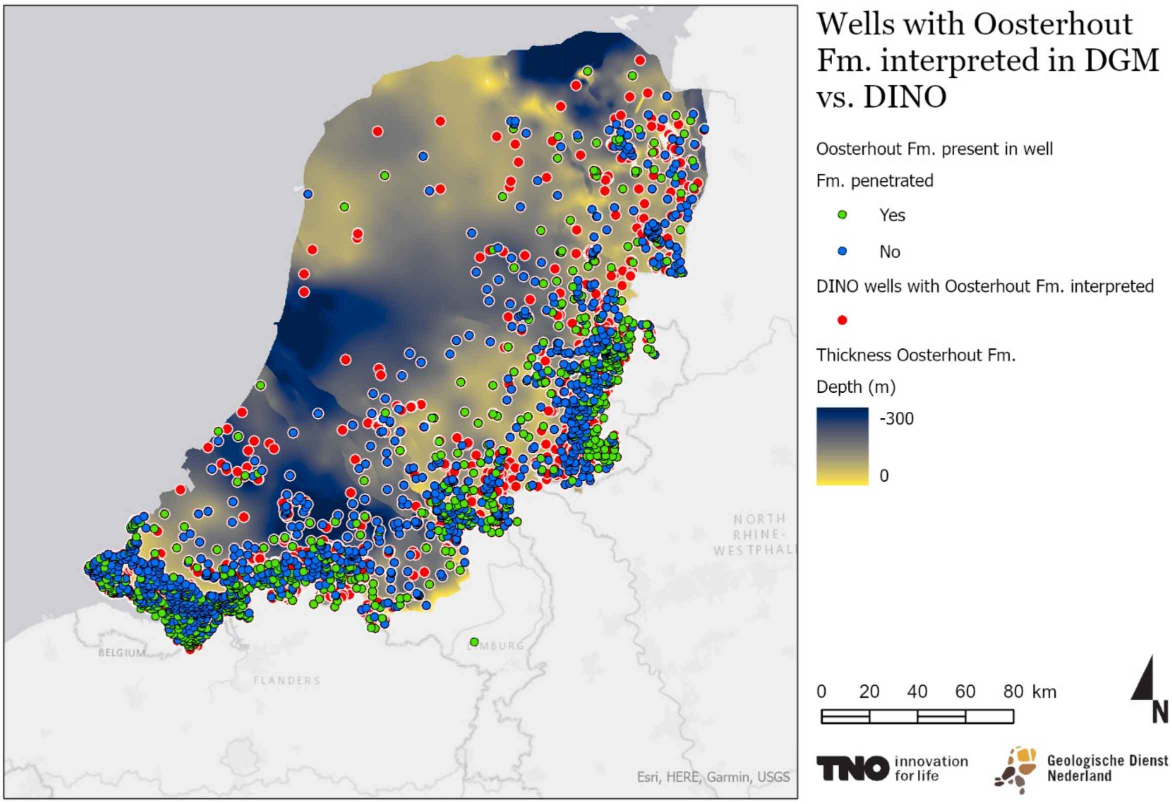

Figure 4.2-2 Comparison between DGM-borehole selection for the Oosterhout Formation (Fm.) (n = 575 for penetrating wells, n = 983 for non-penetrating wells) and boreholes in database that reach the Oosterhout Formation but are not yet included in DGM and REGIS (n = 5149).

4.2.1.3 Maassluis Formation

For the Maassluis Formation the inclusion of yet unused boreholes does not seem to immediately affect the reliability of DGM. Only in Noord Holland and the Wadden Sea area clusters of unused data are present.

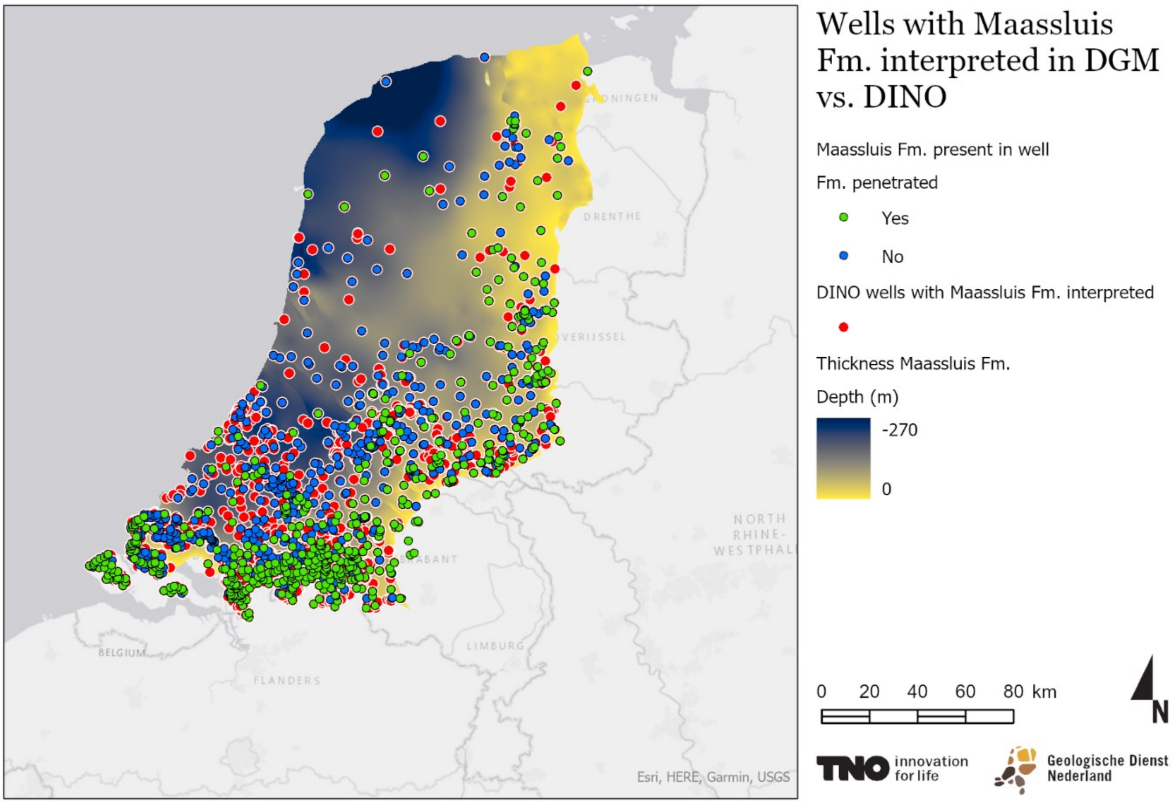

Figure 4.2-3 Comparison between DGM-borehole selection for the Maassluis Formation (Fm.) (n = 521 for penetrating wells, n = 504 for non-penetrating wells) And boreholes in database that reach the Maassluis Formation but are not yet included in DGM and REGIS (n = 3835).

4.2.2 'Deep' wells – Dutch Mining Law

In addition to the boreholes used for modelling DGM, there is also a large number of wells that were drilled for the exploration and production of oil and gas and geothermal energy (Figure 4.2-4). These wells are fundamentally different from the boreholes used for DGM. For the latter, lithological descriptions are typically available, not in the least part because ample material is recovered by coring or air-lifting sections. For the 'deep' wells, only rock material from ditch cuttings is available. For unconsolidated sediments like present in the Upper North Sea Group, these cuttings can not be used as a reliable indicator of lithology due to down-hole contamination and mixing with drilling mud. In addition, the collection of cuttings often starts at about 200 m depth, thereby hampering the collection of Upper North Sea Group sediment samples in 'deep' wells. Coring of the North Sea Group has been extremely rare in 'deep' wells as they are not hydrocarbon reservoir targets.

The most significant data source for the stratigraphic information of Cenozoic sections in 'deep' wells are petrophysical well logs, notably the gamma-ray (GR) and sonic velocity (DT), in combination with stratigraphic information that was collected during the drilling by the wellsite geologist. A total of 2430 'deep' wells have petrophysical log data available (Figure 4.2-4). However, these logs are typically acquired in the deeper sections of the wells. In addition casing shoes are typically placed in the upper ~300 m to stabilize the well's unconsolidated upper part. This affects the quality of petrophysical well log measurements. A thorough assessment of the quality of the petrophysical well-trajectories is extremely labour-intensive, and beyond the scope of this study. Here we therefore assume that if the respective formations are interpreted in the wells, there has been a reasonable ground for doing so. In other circumstances, one often notices that the well's lithostratigraphic interpretation does not exceed the level of "North Sea Supergroup" or "Upper North Sea Group".

In addition, an inventory of GR and DT-data in deep wells within the intervals assigned to the respective formations is made. Albeit no QC is made for casings and/or drilling mud disturbances. This should be envisaged to provide insight in the possible contribution of such 'deep' well data for improving DGM and associated hydrogeological models.

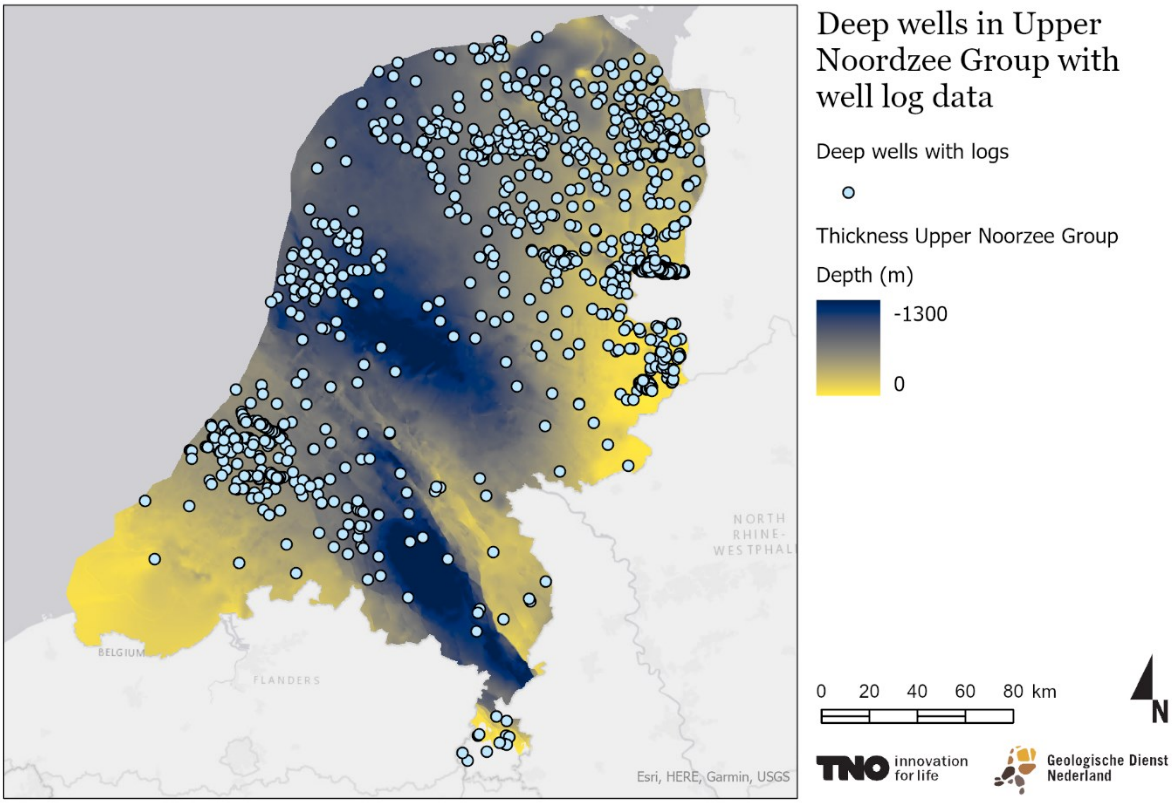

Figure 4.2-4 Map showing all onshore 'deep' Dutch Mining Law wells.

4.2.2.1 Breda Formation

Figure 4.2-5 shows that in many wells (n=653), the Breda Formation is interpreted as a recognizable lithostratigraphic unit. Many of these occur in areas where intensive hydrocarbon, salt and/or coal exploration was undertaken (viz. in Groningen, Friesland, Noord Holland, the Rotterdam area and the Meinweg area in Northern Limburg). Figure 4.2-6 and Figure 4.2-7 show wells that have the important petrophysical logs (GR and DT) within the well-trajectories overlapping with the grid of the respective Breda Formation These show that numerous wells have GR log (n=856) and fewer a DT-log (n=429) data available within the Breda interval. Note however, that no quality assessment of the respective logs was carried out for the purpose of this report. Despite substantial remaining uncertainty as to whether the quality of the 'deep' well data, this collectively shows that substantial improvements in the mapping of the top and thickness can be expected by including information from 'deep' wells. This is particularly the case for the Zuiderzee Low area (Flevoland and eastern Noord Holland, see Smit (2023)), where the formation reaches a large thickness. Elsewhere, despite being thin, the Breda Formation could be mapped more reliably. Of particular importance for an accurate distinction between the Breda (and its new subdivision) and the Oosterhout Formation in deep wells is to have biostratigraphic (age) control. Especially palynology has been very successful to this end (Munsterman and Brinkhuis, 2004). Such interpreted biostratigraphic data from 'deep' boreholes is typically scarce and confined to the major depocenters of the Breda Formation and Oosterhout Formation in the Roer Valley Graben and its adjacent blocks (Munsterman et al., 2019 and references therein) and the Zuiderzee Low (Houben, 2023).

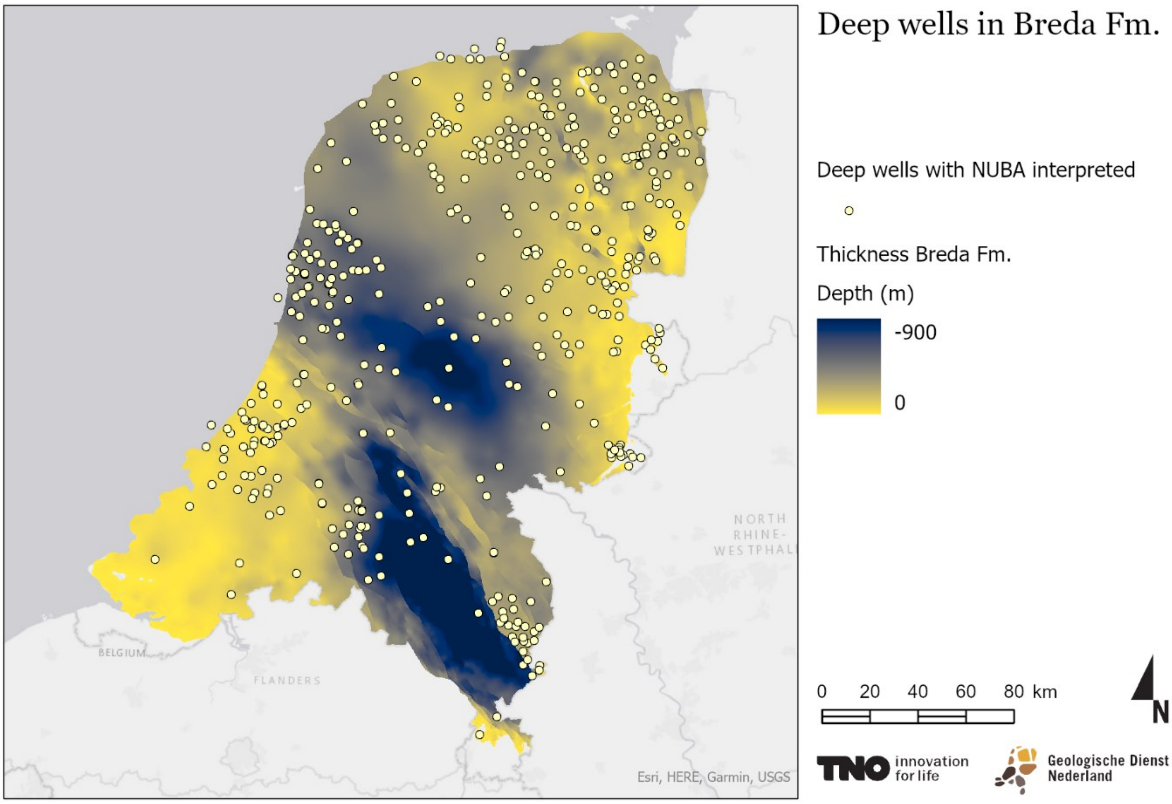

Figure 4.2-5 Deep wells in which the Breda Formation (Fm.) is recognized as a lithostratigraphic unit.

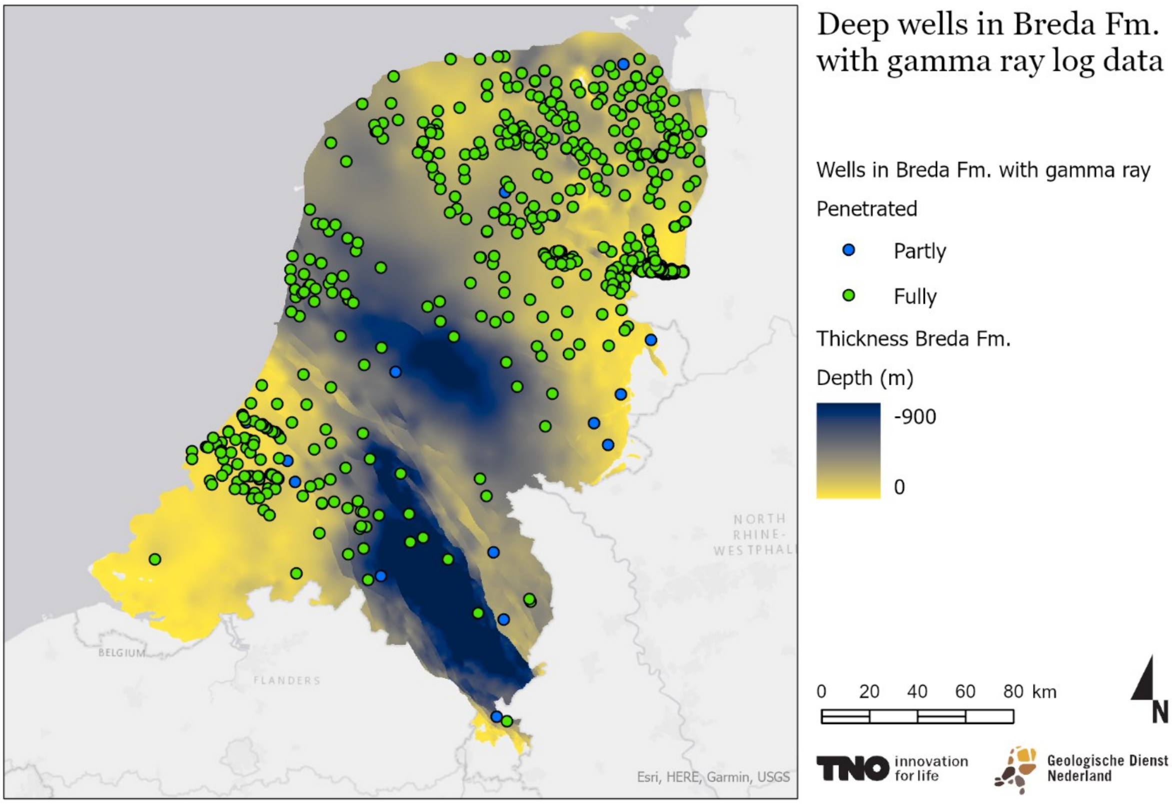

Figure 4.2-6 'Deep' wells intersecting the Breda Formation (Fm.) with a gamma-ray (GR) log available in that interval.

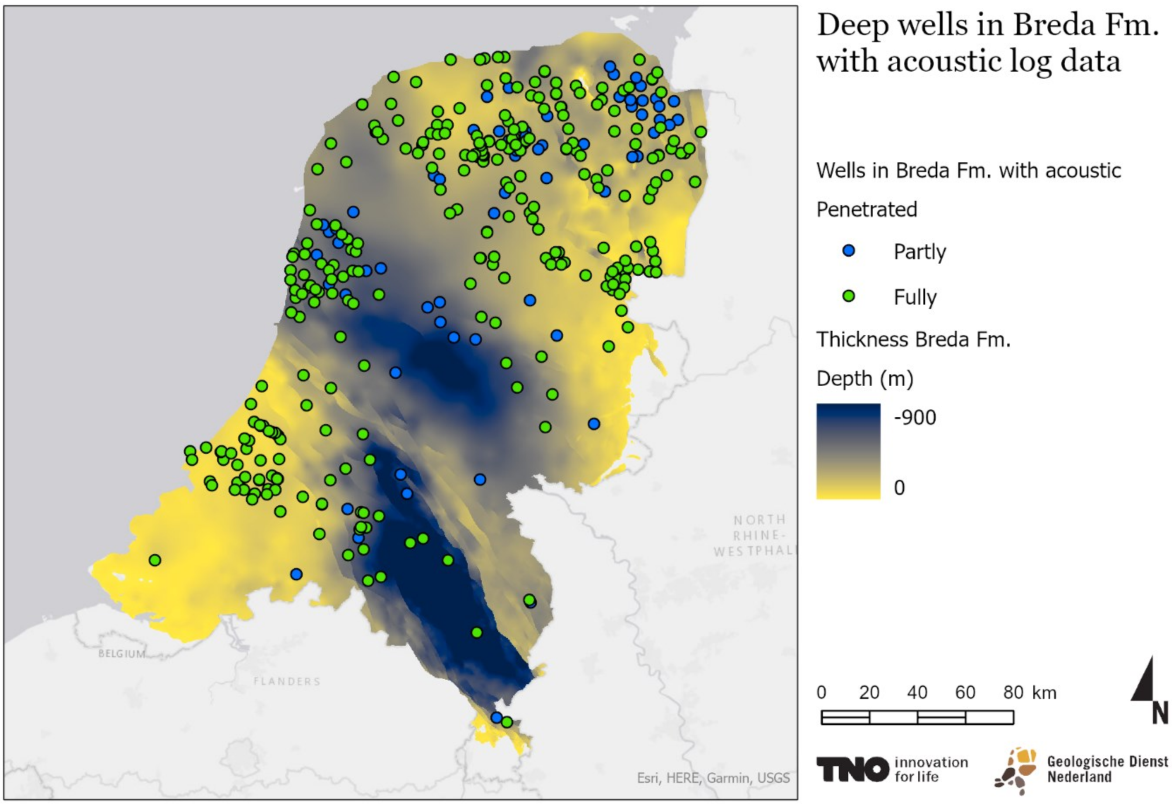

Figure 4.2-7 'Deep' wells intersecting the Breda Formation (Fm.) with an acoustic log available in that interval.

4.2.2.2 Oosterhout Formation

Figure 4.2-8 shows that there is a large number (n=439) of 'deep' wells in which the Oosterhout Formation is interpreted - similarly to the Breda Formation The Oosterhout Formation was not encountered in wells in the eastern and southernmost part of the Netherlands due to the beforementioned basinward progradation of fluvial deposits by Pliocene times.

The screening of the availability of petrophysical logs (Figure 4.2-9 and Figure 4.2-10) indicates a good coverage in Groningen, Friesland, Drenthe, Noord Holland and in Zuid Holland. Here, inclusion of 'deep' wells will likely support future mapping and modelling of this unit. If compared with the regions where the Oosterhout Formation is currently thought to reach substantial thickness, significant improvements by inclusion of 'deep' well data can be foreseen in the area around Haarlem, in northwestern Noord Brabant and the Rotterdam area.

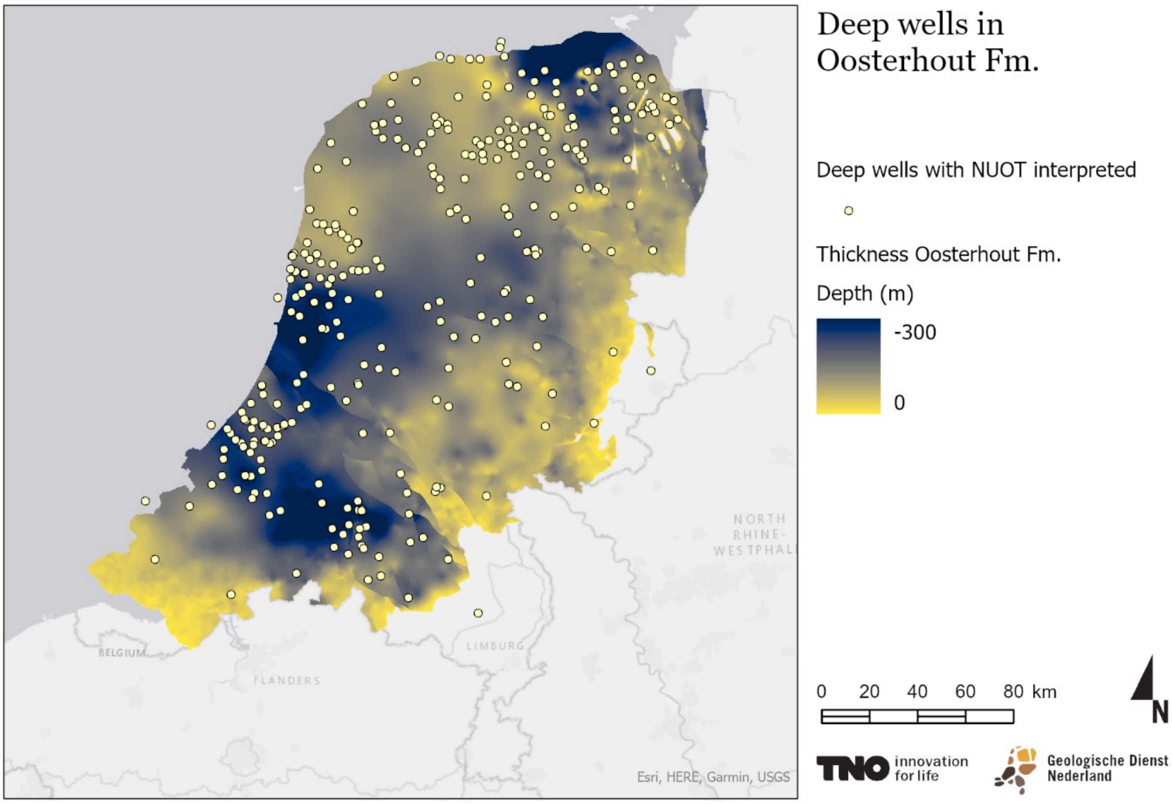

Figure 4.2-8 Deep wells in which the Oosterhout Formation (Fm.) is recognized as a lithostratigraphic unit.

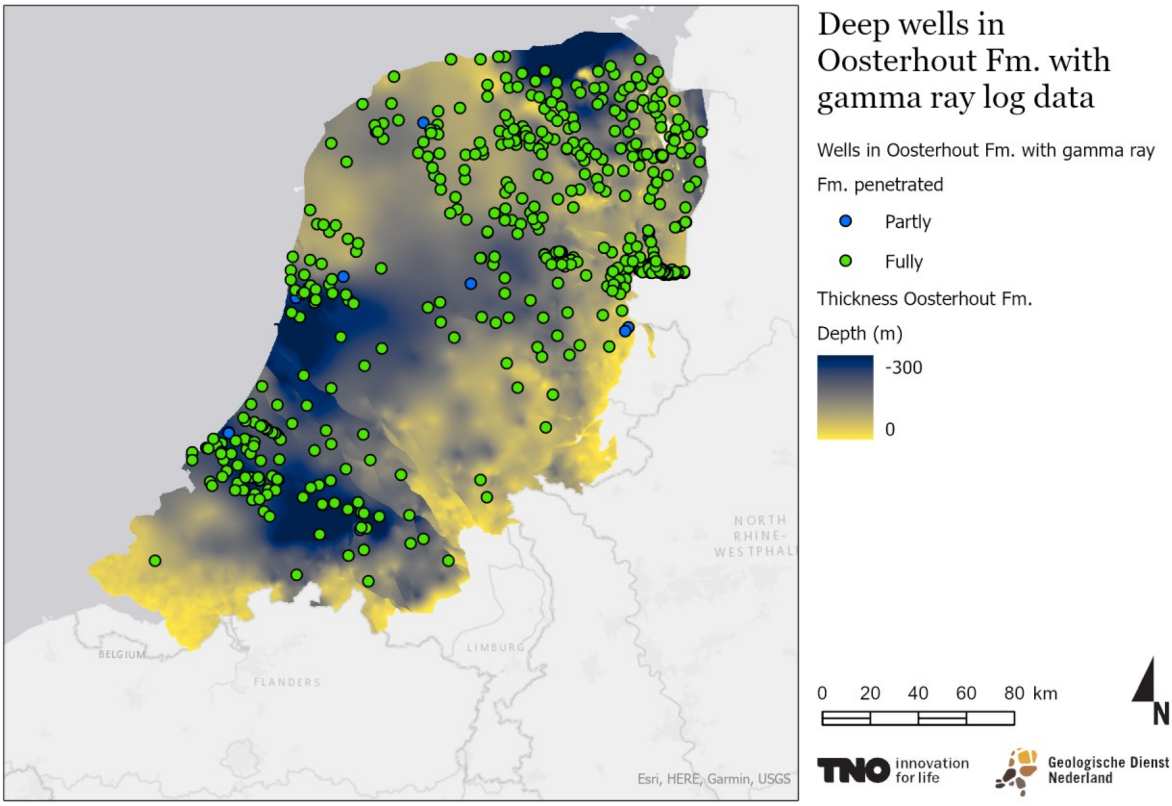

Figure 4.2-9 'Deep' wells intersecting the Oosterhout Formation (Fm.) with a GR-log available in that interval.

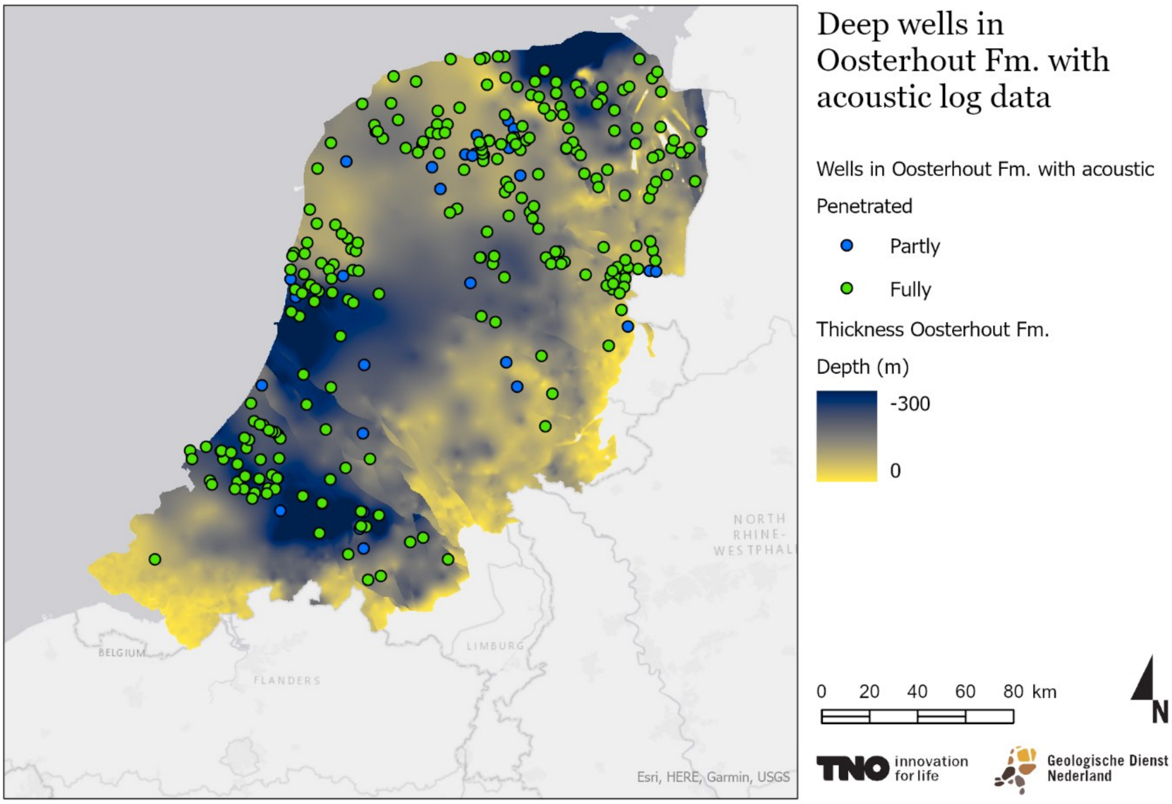

Figure 4.2-10 'Deep' wells intersecting the Oosterhout Formation with an acoustic -log available in that interval.

4.2.2.3 Maassluis Formation

Figure 4.2-11 shows that in numerous 'deep' wells in Friesland, Noord Holland and Zuid Holland, the Maassluis Formation (n =353) is lithostratigraphically interpreted. The distribution of the Maassluis is more confined, due to the basinward progradation of fluvial formations during the Pleistocene. Well-logs are still abundant in those areas too (Figure 4.2-12 and Figure 4.2-13). It can however be expected that the use of those logs is strongly compromised by the emplacement of casings, given the depth range at which the formation occurs.

Nevertheless, 'deep' wells have the potential to improve mapping and modelling of the Maassluis Formation most clearly in Noord Holland, Zuid Holland and in northern Zeeland.

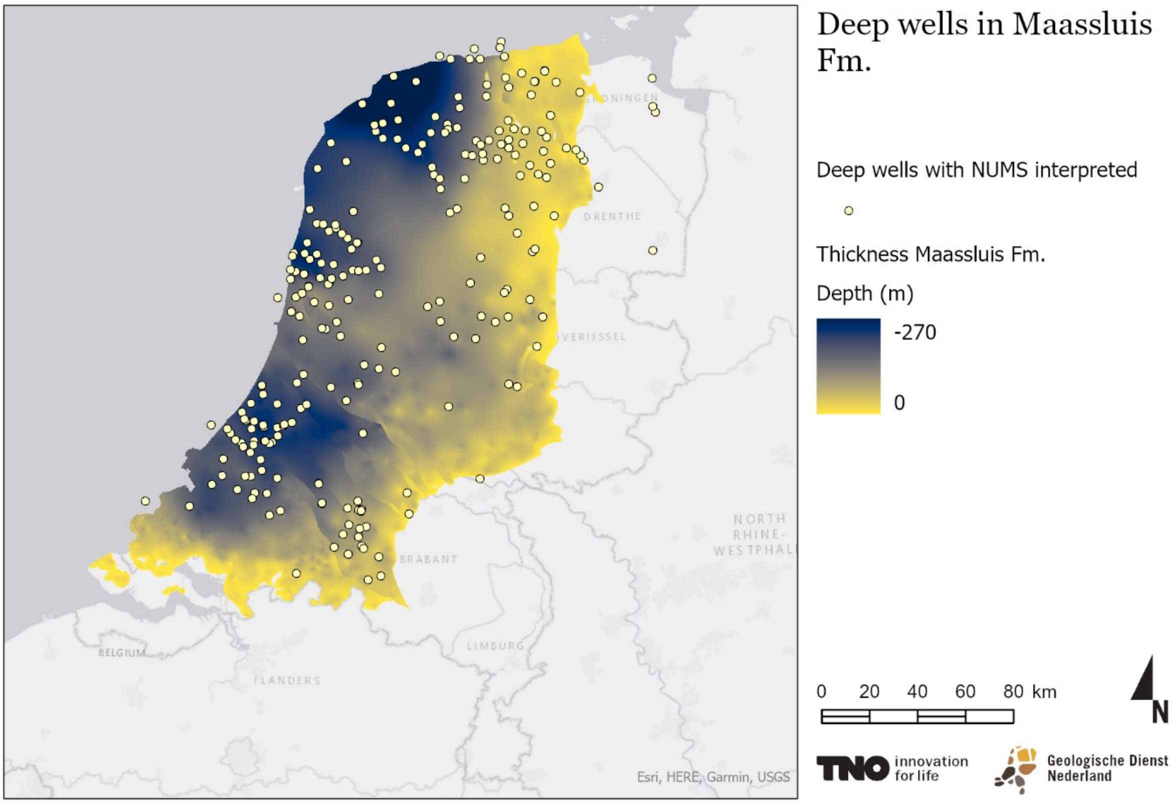

Figure 4.2-11 Deep wells in which the Maassluis Formation is recognized as a lithostratigraphic unit.

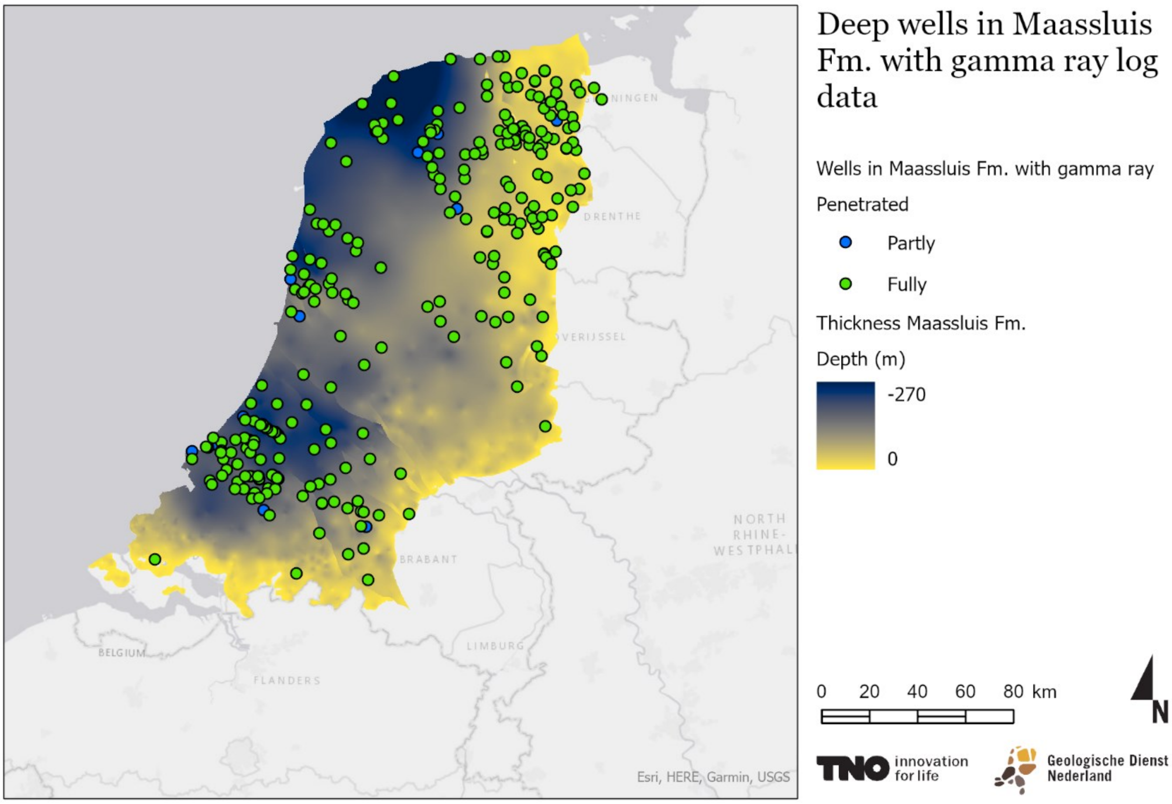

Figure 4.2-12 'Deep' wells intersecting the Maassluis Formation with a GR-log available in that interval.

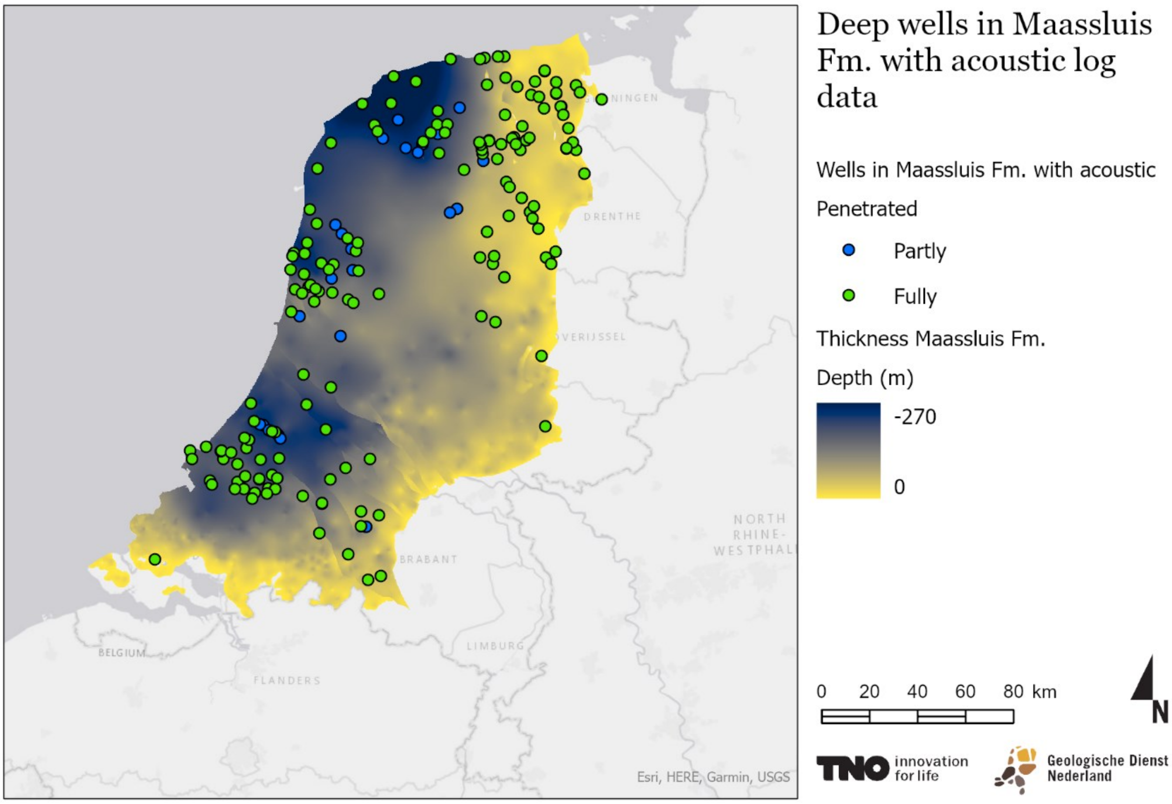

Figure 4.2-13 'Deep' wells intersecting the Maassluis Formation with a DT-log available in that interval.

4.2.3 Seismic data

This section presents an inventory of seismic data for the onshore Netherlands as well as a number of offshore seismic lines that contribute to constrain the geometries of the respective formations. Seismic data was currently only used for the construction of the DGM-deep model, of which the base of the Upper North Sea Group serves as a steering grid for the base of the Breda Formation It goes without saying that incorporation of seismic data can potentially improve the modelling of the Breda, Oosterhout and Maassluis Formation substantially. This is illustrated by the interpreted seismic composite line depicted in Figure 4.2-14. This is particularly the case in areas where the respective formations are thick and buried deeply (>~200 m depth). In addition, recently acquired and reprocessed vintage seismic lines of the SCAN-program have a particularly good resolution in the section down to 1500 m depth (Figure 4.2-15). Beyond the SCAN-seismic data, it is difficult to provide a quick quality assessment of seismic quality in the relatively shallow domain covered in this study (Figure 4.2-15 and Figure 4.2-16). A coastal seismic line however is of particularly good quality and may serve important for mapping in the coastal region (Figure 4.2-17).

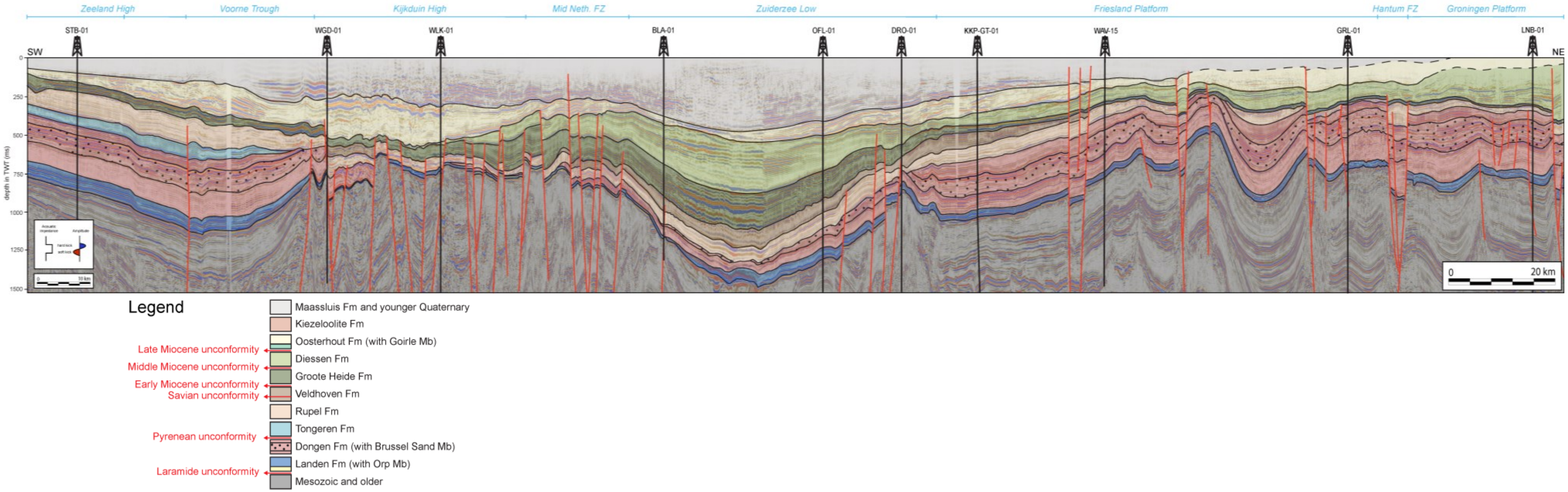

Figure 4.2-14 Cross-section illustrating the potential to map the intra-Breda, Oosterhout and Maassluis Formations. Adapted from Munsterman et al. (in prep). Courtesy of Johan ten Veen.

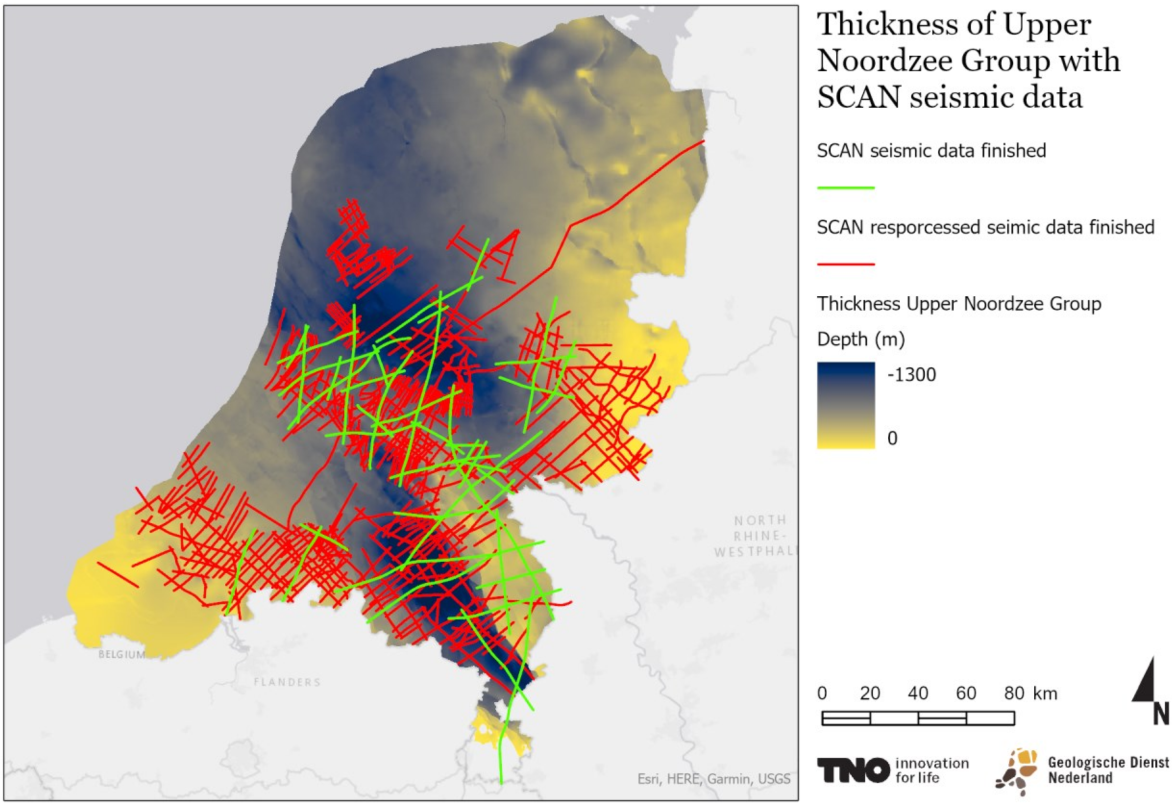

Figure 4.2-15 Location of newly acquired SCAN seismic 2D-lines (green) and reprocessed lines (red).

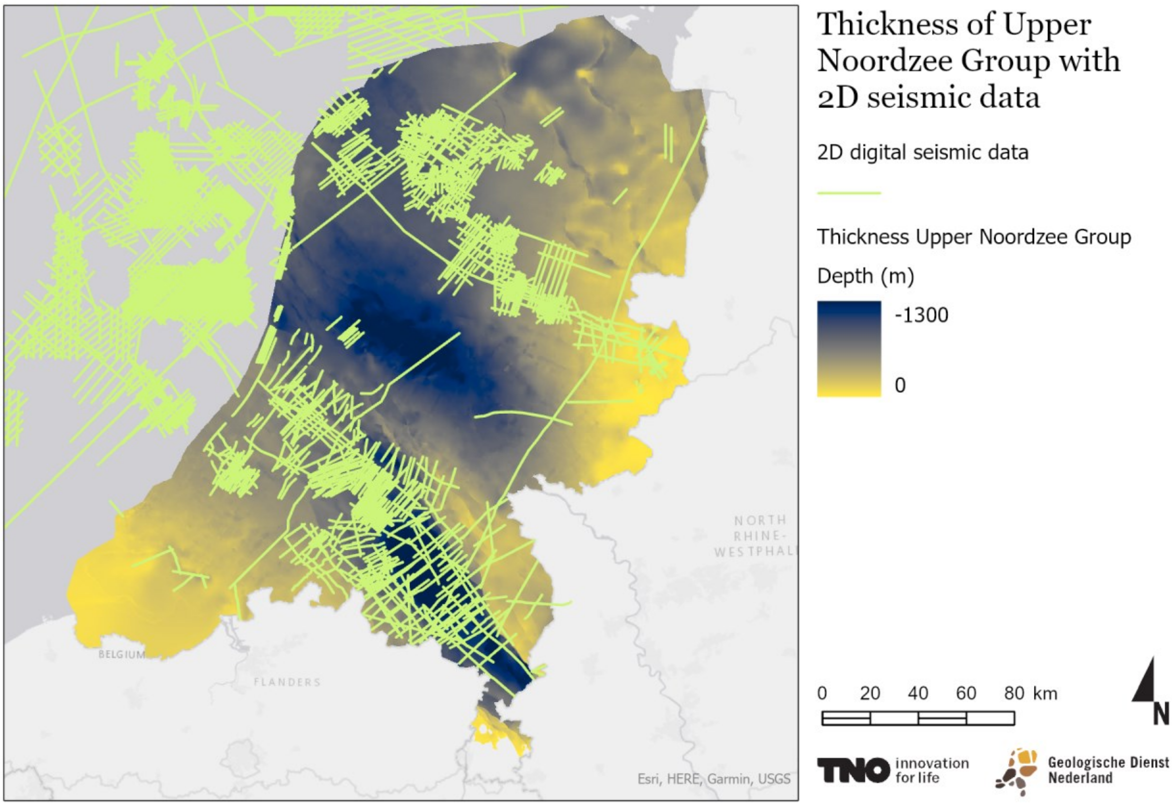

Figure 4.2-16 Location of 2D seismic data. These are confined to the offshore.

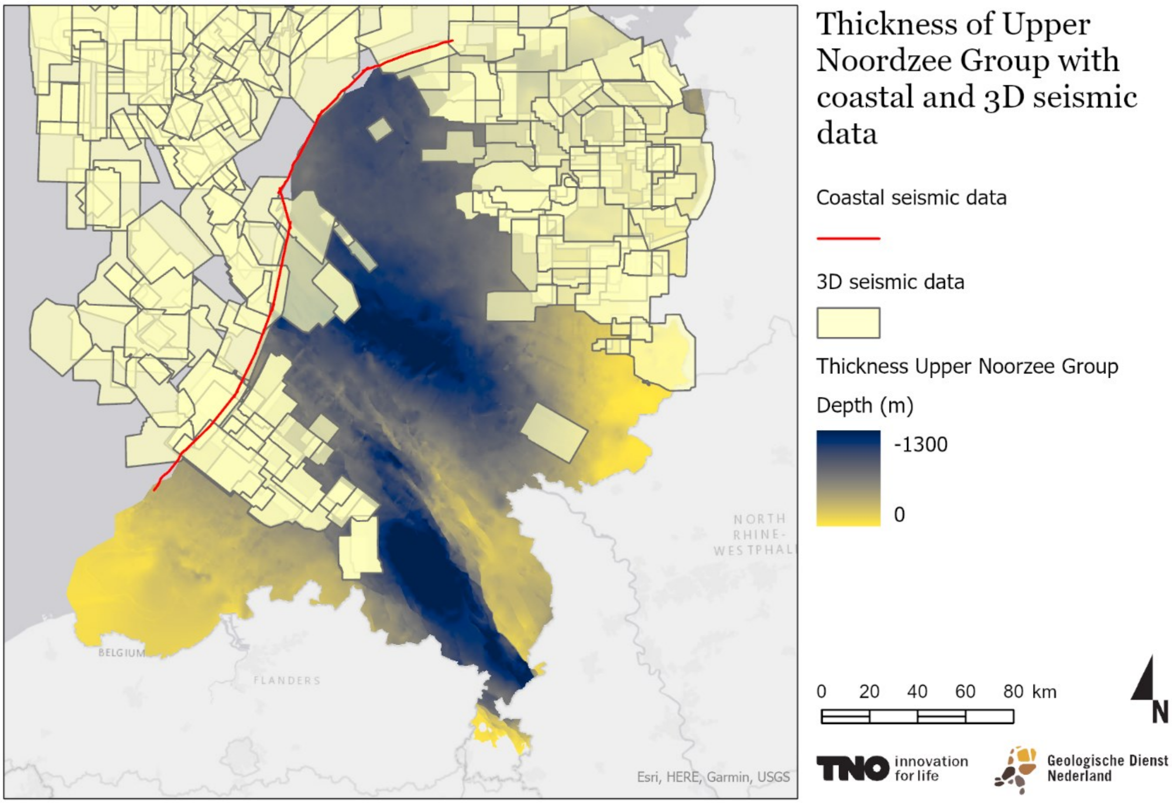

Figure 4.2-17 Map depicting the location of publicly available 3D-surveys and in red, a specific coastal seismic line that can prove valuable for future mapping of the North Sea Group.

4.2.4 Inventory of mapping/modelling studies

4.2.4.1 H3O-Projects

For several areas in Noord Brabant and Limburg (Figure 4.2-18), seismic and borehole data have been combined for the first time for the purpose of modeling all Cenozoic formations in the North Sea Supergroup. These projects were executed under the umbrella of the various H3O programs (*Hydrogeologische 3D-modelling van de Ondergrond*). A digital layer model at formation or higher level will be ready for all these areas in the foreseeable future. Most of the projects are cross-border and therefore model units (hybrid Belgian-Dutch lithostratigraphic units) that are applicable across borders, meaning that model units do 1:1 correspond to the respective Dutch formations. One can consider these geometric models of the Upper North Sea Group units to be as good as they can possibly become, based on the available data. The separate models are still to be combined into a single layer model and incorporated in to the national subsurface models.

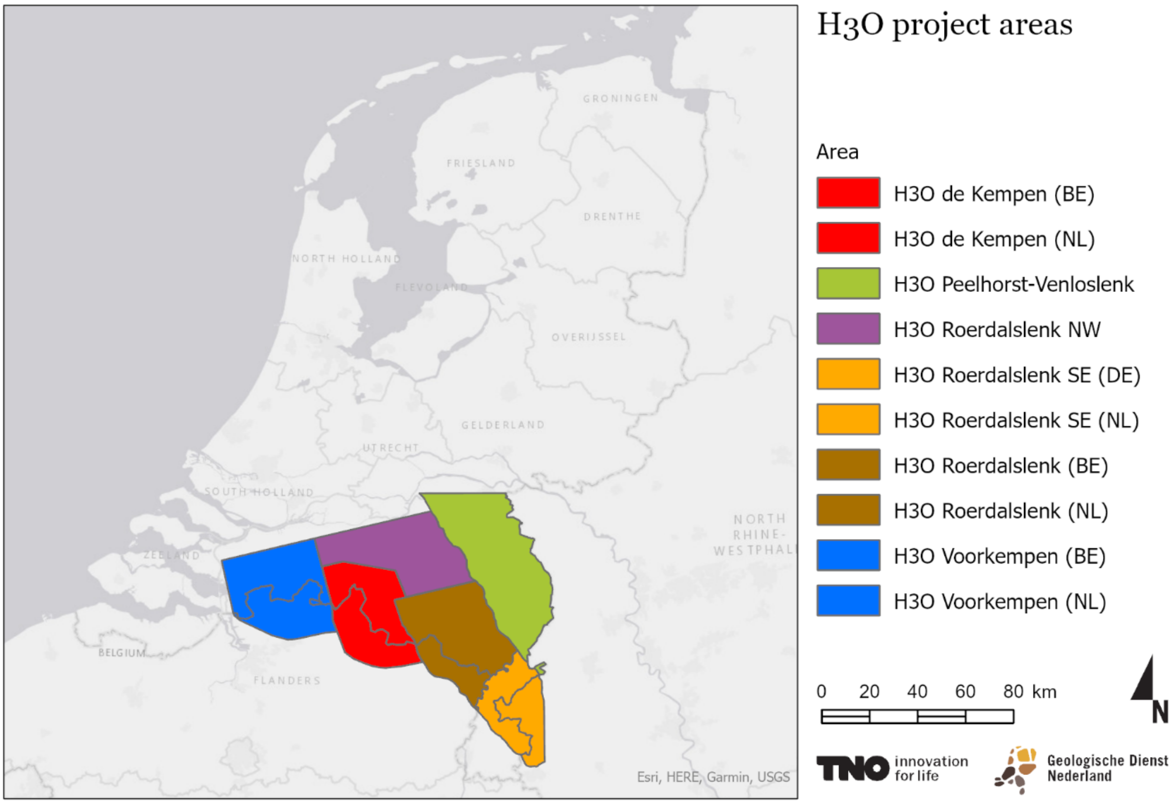

Figure 4.2-18 H3O-project areas

4.2.4.2 Mapping in northeastern Netherlands

In the northeast of the Netherlands, various projects, often commissioned by municipalities and regional water authorities (Table 4.2-1), have focused on the seismic interpretation of, among others, the Upper North Sea Group (Figure 4.2-19) at a level which is more detailed that contained in the current models of GDN. This is possible because of the extensive availability of 3D-seismic data (Figure 4.2-17). Various projects focused on mapping the lithostratigraphy around tunnel valleys of the Peelo Formation, which lies above the Maassluis Formation. For some of these projects, the raw data and project delineation remain confidential. On the other hand, the interpretations made based on the (public) data can be used in future work.

Table 4.2-1 Overview of mapping projects carried out by TNO-GDN that can serve as input to an updated model of the Neogene formations (Maassluis, MS; Oosterhout, OO; Breda, BR)

Project area	**Focus on Peelo**	**MS, OO, BR (base)**
Nij Beets	X	Only a couple of cross-lines
Burval		Few OO en BR horizons
Hoogeveen		Few lines met OO en BR
Hebrecht	X	OO fully mapped
Kastelenakkers		OO en BR within Kiel-Windeweer survey
Leeuwarden HTO		A few 2D-lines
Poelkampen		BR
Zwolle		
Groeve		

NO_NED tunneldalen kartering		
Assen west		
Overijssel		BR and older unites

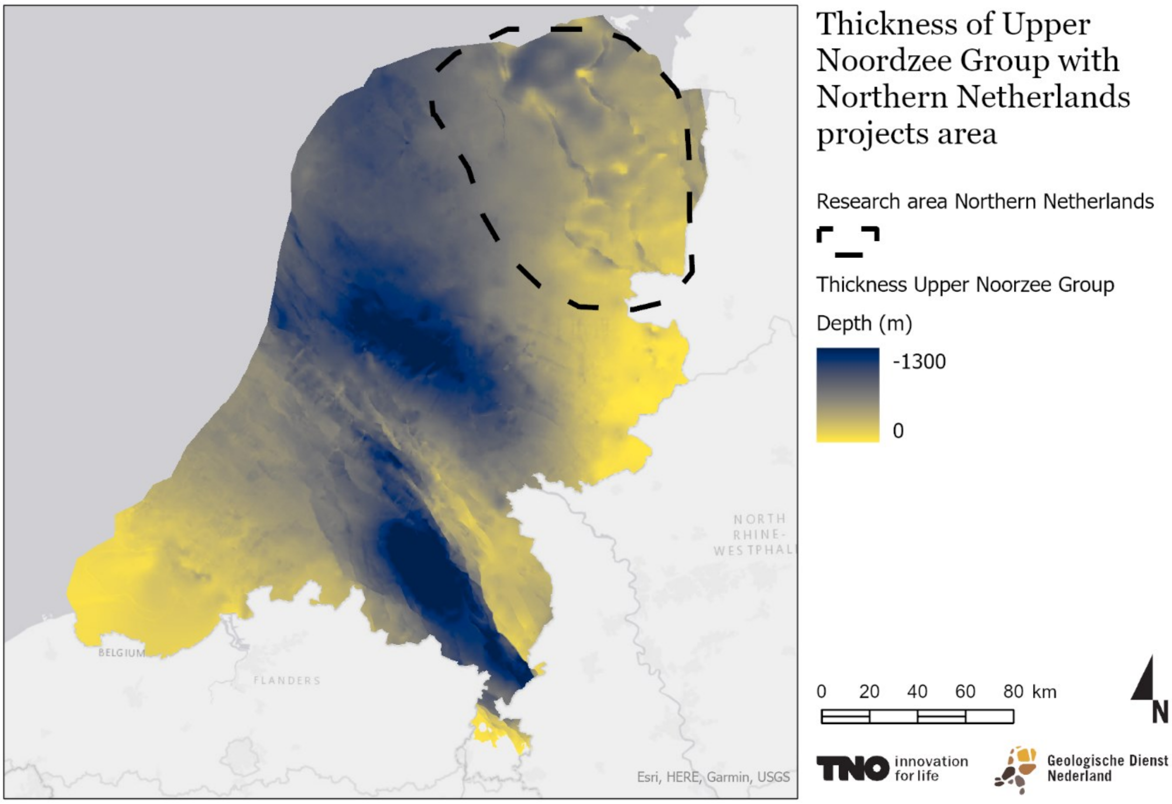

Figure 4.2-19 Outline of regional mapping campaigns in the northeastern Netherlands based on extensively available 3D-seismic data.

4.2.4.3 Mapping of the Breda Formation in WarmingUP (Roer Valley Graben and Zuiderzee Low)

In the framework of the WarmingUP project, the Breda Formation has been mapped in detail in two areas: the Zuiderzee Low (Smit, 2022) and the Roer Valley Graben (Peters et al., 2022). Figure 4.2-20 shows the main results. The top and bottom of the Breda Formation and the boundary between the still informal Groote Heide and Diessen Formation were identified on seismic data.

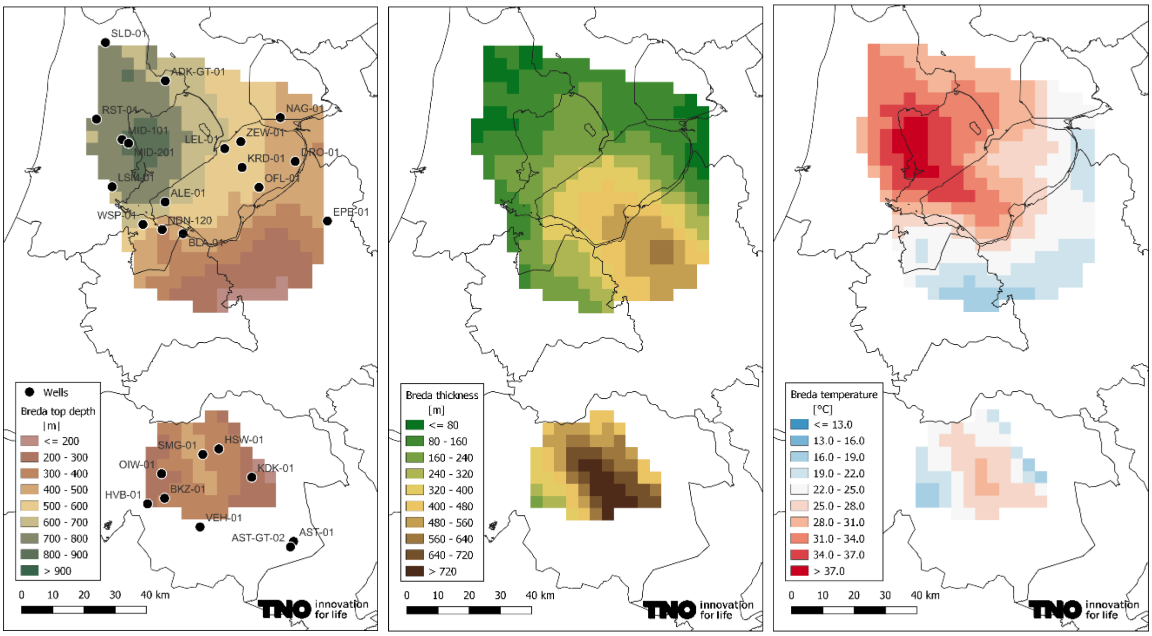

Figure 4.2-20 Top depth (left), thickness (middle) and temperature in the middle of the aquifer of the Breda Formation in the Roer Valley Graben and the Zuiderzee Low. Black dots indicate the wells used. Source: www.thermogis.nl/breda-formation

4.2.4.4 Faults

Figure 4.2-21 depicts the main faults identified intersecting the Upper North Sea Group. These are predominantly associated with Mesozoic and older structures. This means that faults may exist in younger strata that are yet overlooked in the current modeling.

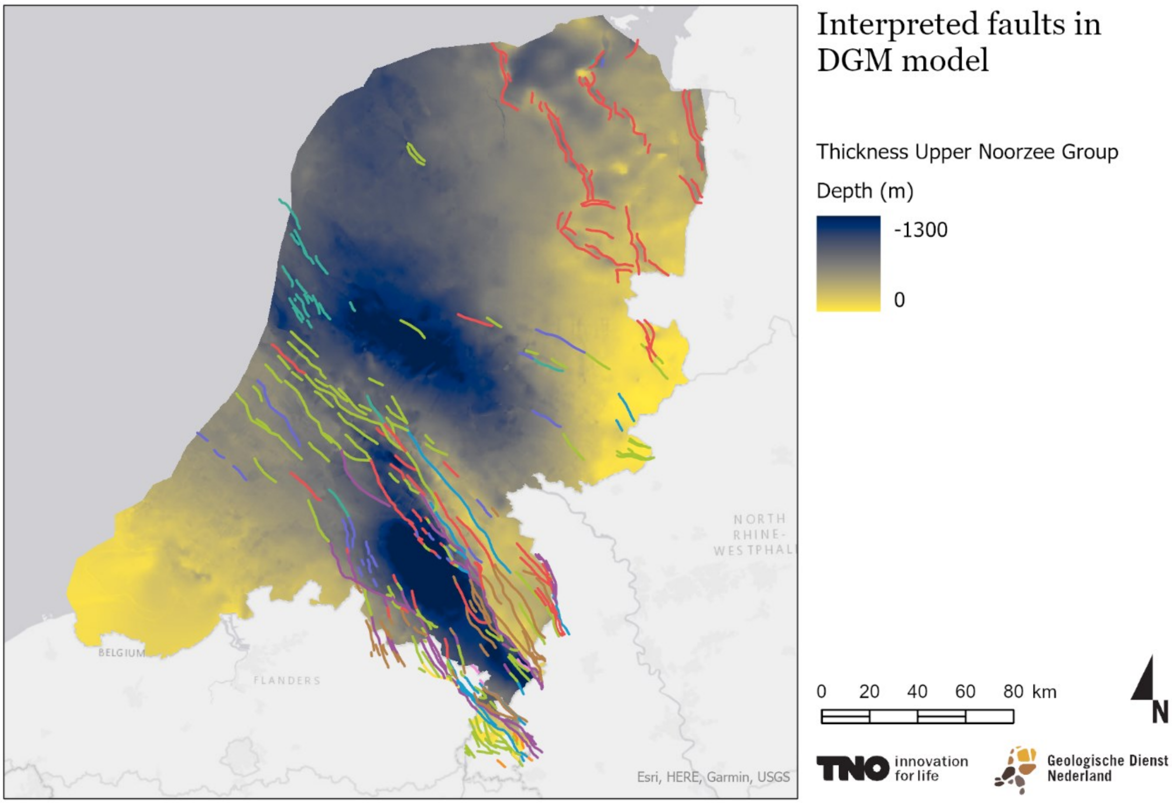

Figure 4.2-21 Overview of interpreted faults in the DGM model

4.2.4 Expected data

4.2.4.1 SCAN wells search area

The first phase of the SCAN program consisted of seismic acquisition and reprocessing. The next phase is the drilling of a number exploration wells. The actual drilling has just started in October 2023 with the Amstelland well. The primary purpose is to gather critical data in areas where well-coverage is insufficient (Figure 4.2-22). Important aspects are the collection of porosity and permeability data from cores and sidewall cores for key potential geothermal aquifers, as well as understanding the geological and stratigraphic architectures in those areas. In addition, a state-of-the-art petrophysical logging campaign will be carried out.

For these scientific boreholes, SCAN selected 10 so-called search areas, based on a combination of (lack of) subsurface knowledge and potential heat demand (Figure 4.2-21 and Table 4.2-2). It is currently unknown whether wells will be drilled in all of the search areas. Table 4.2-2 shows that most of the wells target deeper and therefore older aquifers than those of the Upper North Sea Group. An exception is the Eindhoven area, in the centre of the Roer Valley Graben (RVG), which will focus on the Paleogene-Neogene section. Nevertheless, all these boreholes will drill through the Neogene section and will acquire an optimized log-suite and an evenly sampled collection of cuttings.

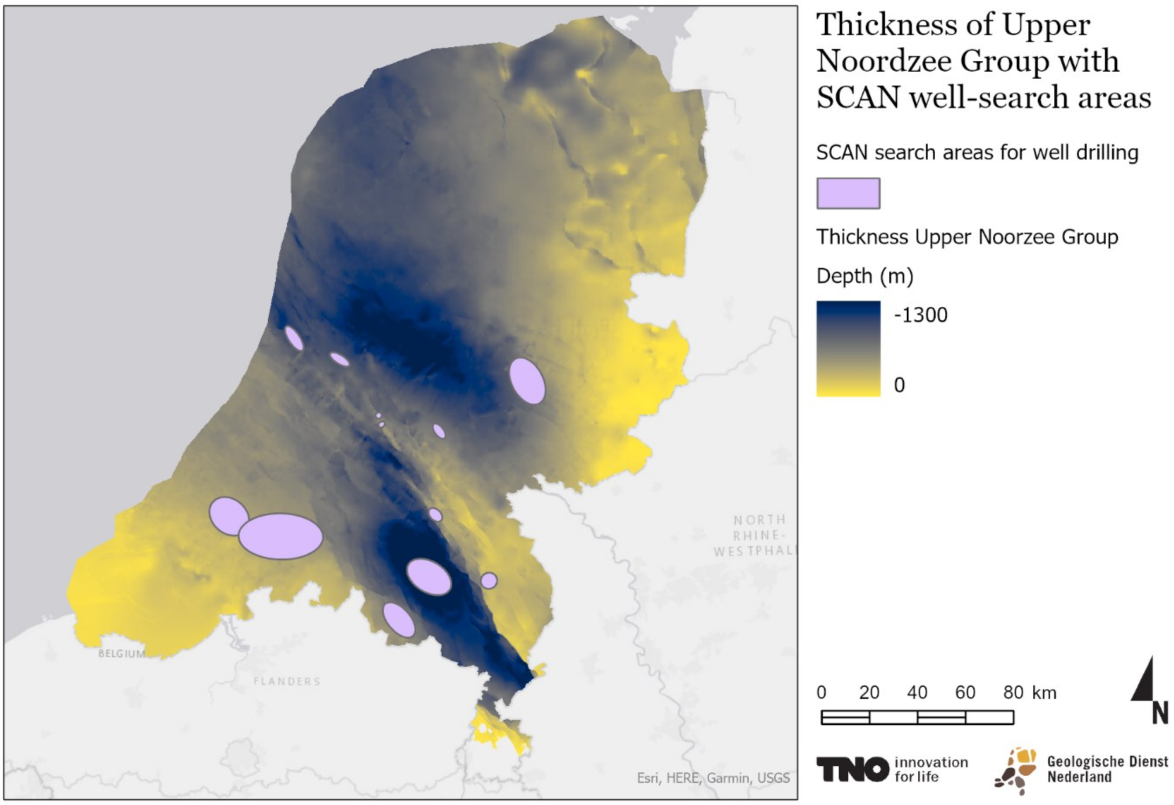

Figure 4.2-22 Map with overview of SCAN-borehole search areas

Table 4.2-2 SCAN-borehole search areas and primary and secondary study objectives Phase 4 is the most adult stage, phase 6 is the most embryonic stage.

Search area	Primary target	Secondary target	Planning phase
Amstelland	Rotliegend (Permian)	Rijnland & Chalk (Cretaceous)	46
Utrecht	Rotliegend (Permian)	Triassic, Rijnland & Chalk (Cretaceous)	2
West-Brabant Noord	Lower & Middle North Sea (Paleogene)	Upper Middle North Sea (NeogeneOligocene)	3
Oss	Triassic	Rijnland & Chalk (Cretaceous), Rotliegend (Permian)	3
Ede – Veenendaal	Rotliegend (Permian)	Rijnland (Cretaceous)	23
Haarlem – Amsterdam West	Rijnland (Cretaceous)	Schieland (Jurassic - Cretaceous)	32
Apeldoorn – Deventer	Rotliegend (Permian)	Lower North Sea (Paleogene), Limburg Gp. (Upper Carboniferous)	23
Kempen	Triassic	Limburg Gp. (Upper Carboniferous)	2
Eindhoven	North Sea (Paleogene – Neogene)		23
Deurne	Triassic	Chalk (Cretaceous)	12

5 Selection of regions for modelling improvements

Based on the model descriptions (chapter 3) and the inventory of available data for geometric and hydrogeological subsurface models in (chapter 4), this section aims to comprehensively describe regions where the modelling can be improved, by including new and previously unused data. These regions are not ‘white spots’ (i.e. low data density areas) in the strict sense as data is often available but has either not yet been incorporated in the current models (see chapter 4) or is potentially of inferior quality. To evaluate the latter, for a specific aquifer, a more in depth, regional data evaluation is often necessary. Instead of white spots we therefore prefer to refer to selected regions where additional effort could lead to improved subsurface models.

The following section is structured per Formation, addressing first the Breda, followed by Oosterhout and Maassluis formations. The information and selection of regions where models could be improved should be weighed against the regional heat demand to decide and prioritize where, in terms of area and depth interval, efforts for national and regional model updates should be made.

5.1 Breda Formation

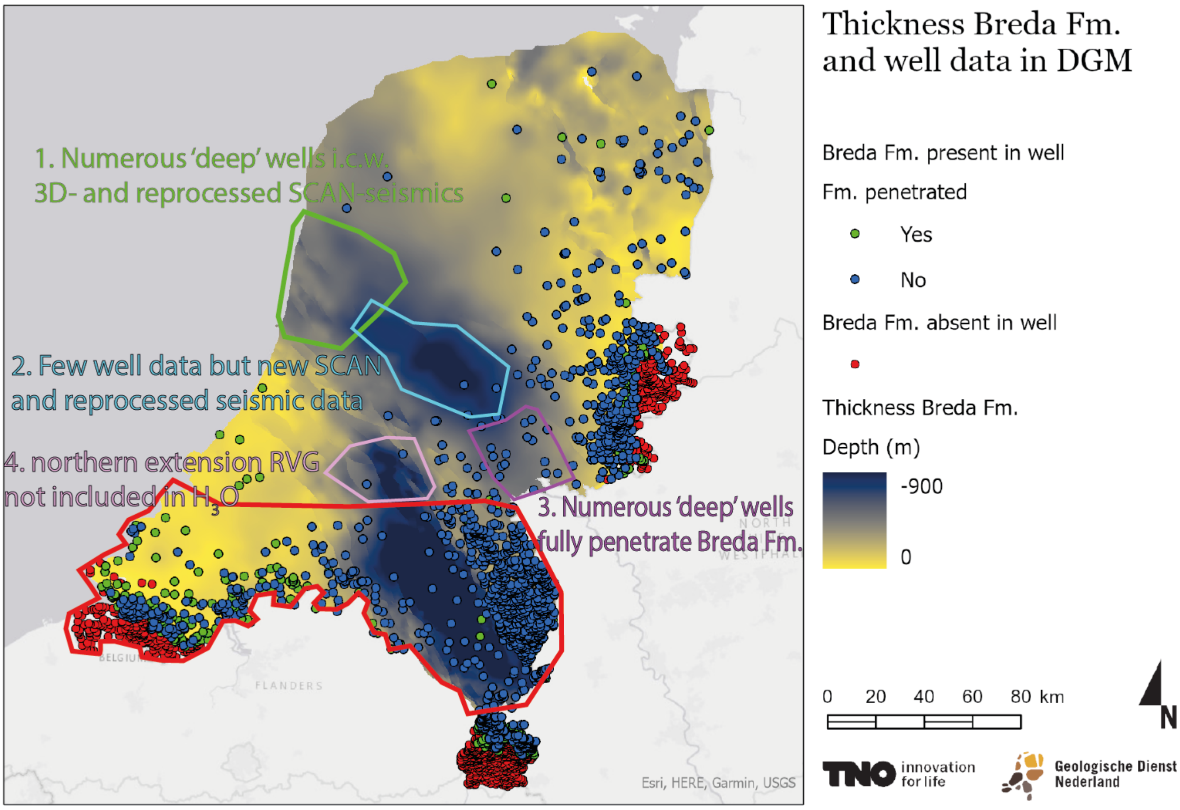

Figure 5.1-1 Regions where substantial improvement can be expected for modelling the Breda Formation by including new and omitted data.

Area 1: Abundant 3D and SCAN-reprocessed seismic data has become available in combination with a substantial inferred thickness for the Breda Formation

Area 2: Zuiderzee Low area, a major depocenter of the Breda Formation Although the number of available wells is limited, 2D seismic coverage (especially data acquired in the context of the SCAN program) is fair. In combination with an existing and/or expected increase in heat demand, this becomes a target area for regional mapping.

Area 3: In this area, inclusion of 'deep' wells and interpretation of numerous SCAN lines will improve mapping.

Area 4: Despite the presence of substantial heat demand, the continuation of the Roer Valley Graben (RVG) has not been included in the H3O projects.

A major complication for the development of hydrogeological modelling of the Breda Formation is the poor understanding of its lithofacies development, let alone its hydrological parameterization. This can be partly overcome by petrophysical interpretation of suitable 'deep' wells and obtaining dedicatedly cored and/or airlifted sedimentary records from the depocenters, either as part of SCAN or as part of geothermal projects. A second hurdle is the need to better understand the stratigraphy of the Breda Formation, in order to accurately constrain the boundary with the Oosterhout Formation, on seismic data. Biostratigraphic age-control is required for key regional sections/boreholes (cf. Houben, 2023).

5.2 Oosterhout Formation

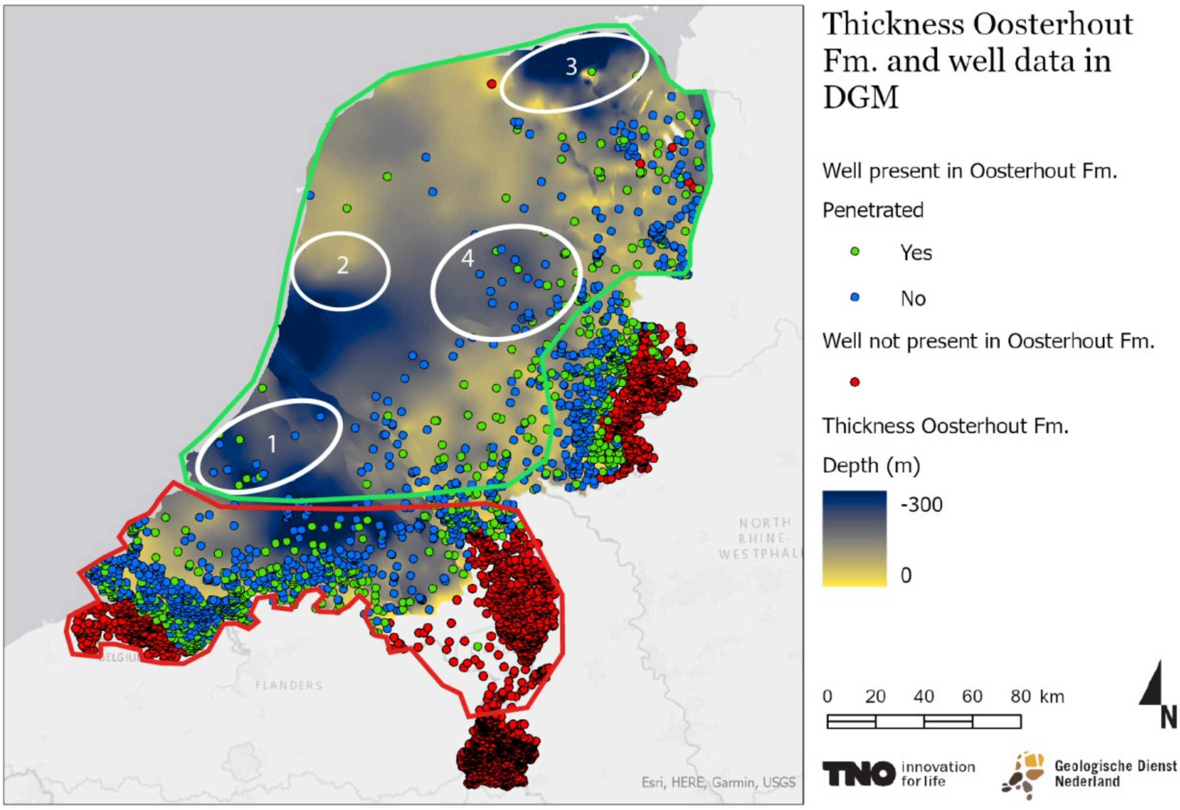

Figure 5.2-1 Delineates the regions where substantial improvement can be expected for modelling the Oosterhout Formation by including new and omitted data.

The green outline indicates the area that can strongly benefit from the use of seismic data for modelling the Oosterhout Formation Here, the depth of the unit is likely within the depth-range where it can be visualized on seismic. In addition, four specific sub-areas are indicated that can benefit from specific activities.

Area 1: has extensive 3D-seismic coverage in combination with a large number of 'deep' wells that can be used for calibration. The combination with a substantial heat demand, modelling of the Oosterhout Formation seems warranted in this region.

Area 2: has extensive 3D-seismic coverage and large number of 'deep' wells for calibration.

Area 3: the suggested large thickness of the Oosterhout is questionable and may arise from complexity associated with Peelo incisions. This seems to be an important issue to derisk for heat demand in the Groningen area.

Area 4: has good 2D-seismic coverage. In combination with both a large number of 'shallow' as well as 'deep wells' a promising hybrid borehole- and seismic based modelling can be achieved here.

A major issue with the modelling of the Oosterhout Formation is the interfingering nature of the transition to the fluvial counterparts. This plays a role in particular around the distribution limit of the formation. In addition, biostratigraphic validation is required when it comes to identifying the base and top of the formation.

5.3 Maassluis Formation

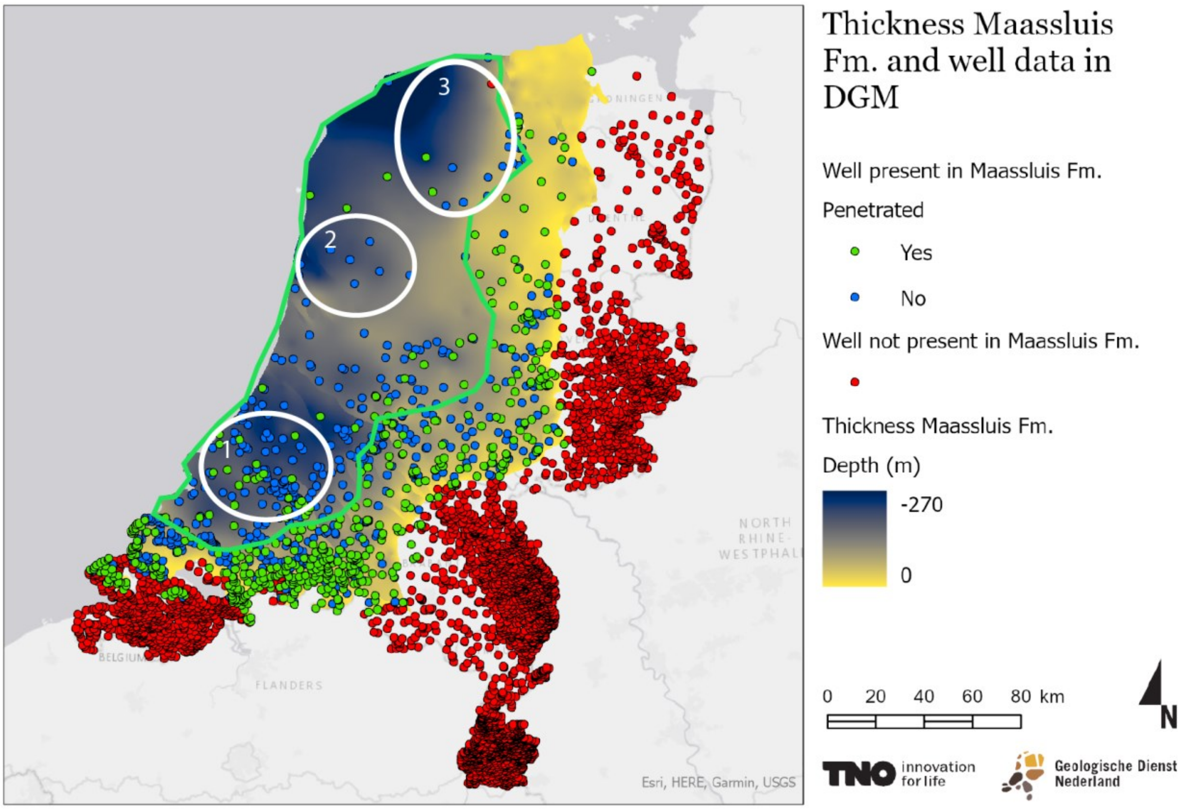

Figure 5.3-1 delineates the regions where substantial improvement can be expected for modelling the Maassluis Formation by including new and omitted data.

The green area will benefit from systematic seismic interpretation aimed at identifying approximate base of the Maassluis Formation Towards the coast this will be more feasible, away it will become problematic. Particularly the seismic interpretation of the top of the Maassluis Fm. is problematic because of its limited depth and surface disturbance.

Area 1: Numerous ‘deep’ wells in the West Netherlands Basin can aid to constrain Maassluis geometry. Hydrogeological parameterization can only be based on shallow boreholes as deep boreholes are typically cased in this depth-range.

Area 2: Numerous deep wells as well as 3D-seismic data is available here.

Area 3: The potentially large thickness needs to be validated using seismic data. Ample 3D-data and deep boreholes in this area will likely enable the validation.

In all areas it is recommended to carry out systematic biostratigraphic analysis based on both ‘deep’ and shallow borehole sections, to explore genuine thickness trends of the three formations. The lithostratigraphic concepts of the Maassluis and Oosterhout are expected to be difficult to apply to ‘deep’ wells using petrophysical data alone.

6 Conclusions and recommendations

This study has described the three geological models (DGM-Deep, DGM and REGIS II) covering the middle deep subsurface of the Netherlands. An inventory was carried out, of the data upon which the resultant models of the marine Breda, Oosterhout and Maassluis Formations are based. In general, where these formations are positioned below a depth of 150 m, the number of boreholes on which DGM and REGIS II is based is very small. This also causes the lateral continuity of the hydrogeological units to be poorly supported by data. The recognition of hydrogeological units is best for the more shallow units (Oosterhout and notably Maassluis), albeit the expected facies heterogeneity is expected to be greater for these. The Breda Formation will – even with inclusion of additional data – remain difficult to hydrogeologically map in detail. However, given its expected higher degree of lithological homogeneity, it may contain relatively continuous properties as a whole. This will have to be investigated using the data outlined below.

The currently omitted data that can enhance modelling fall in three categories:

1. Shallow boreholes that have not been used in DGM and REGIS II.

2. Deep, or so-called Dutch Mining Law wells and their petrophysical logs.

3. Seismic data.

In different areas and depth intervals, different data can be present and be most valuable. Based on the inventory, the following main recommendations were given:

1. DGM and REGIS II can be improved in Noord Brabant, Zeeland and the northern part of Limburg as these areas are already systematically mapped using a combination of shallow and deep boreholes and seismic data as part of the H_3O-project suite.
2. In four specific areas where the base of the Breda Formation is found at relatively deep depth, models can be improved by including deep wells and seismic data.
   The modelling of the Oosterhout Formation can generally also be improved by using seismic data. The newly acquired SCAN-seismic lines and reprocessings are promising to this end. The recognition of the Maassluis Formation is very dependent on the specific quality of the seismic data. The use of petrophysical well logs aided by biostratigraphic analysis of deep wells can also aid the stratigraphic interpretation of these units, providing a guideline for seismic mapping.

More general recommendations are:

1. Include seismic data and data from ‘deep’ boreholes in the geometrical modelling of the Neogene strata.
2. A regional understanding of the chronostratigraphic relations is required. This can be achieved by biostratigraphic analysis of regional reference sections.
3. The hydrogeological parameterization of the REGIS II-model remains difficult to assess based on the current data inventory. As a rule of thumb, the lack of ‘shallow’ boreholes in large parts of the model area gives indications where an alternative approach might be valuable. This approach should be based on paleogeographic insights and a thoroughly QC’ed petrophysical dataset from deep boreholes. The use of 'forward stratigraphic modelling' tools can be considered to this end.
4. There are numerous boreholes not yet included in the current database of the geological survey. This for instance concerns WKO-boreholes. Albeit the associated data are often

not very detailed, insights from these boreholes that are delivered through the BRO could in the future be incorporated.

5. We recommend to quickly incorporate critical new insights from developing geothermal and/or storage projects and other research activities, such as SCAN, in future model releases.

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