Summary of main characteristics of the depleted gas fields in the Netherlands that could be candidates for UHS

Authors

Germonda Reijnen-Mooij[1], Silke van Klaveren[1], Bastiaan Jaarsma[1], Ryan Haagenson[2], Deyan Draganov[2], Hadi Hajibeygi[2]
1: Energie Beheer Nederland B.V.
2: Technische Universiteit Delft

Involved partners:

Energie Beheer Nederland B.V., Technische Universiteit Delft

Date of achievement of result:

October 20, 2025

Task / subtask

This report was written by the partners involved in subtask 5.4 of Task 5 of HyTROS. It represents HyTROS project deliverable number D5.4.1.

Disclaimer

The HyTROS project concerns a collaborative R&D effort out of a consortium of 33 participants and which concern: The Netherlands Organization for Applied Scientific Research (TNO), Eindhoven University of Technology, University of Groningen, Wageningen University, Erasmus University Rotterdam, Leiden University, University of Twente, Radboud University, Delft University of Technology, Deltares, HAN University of Applied Sciences, Hanze University of Applied Sciences, Utrecht University, University of Amsterdam, CWI (Dutch National Research Institute for Mathematics and Computer Science), HyET Electrolysis B.V., VSL B.V., EBN B.V., Nobian Industrial Chemicals B.V., Shell Global Solutions International B.V., Allseas Engineering B.V., Worley Nederland B.V., N.V. Nederlandse Gasunie, Voyex B.V., SKF B.V., ENI Energy Netherlands B.V., Netbeheer Nederland, DNV Netherlands B.V., Fluidwell B.V., TAQA Energy B.V., ONE-Dyas B.V., Bureau Veritas, Equinor.

The HyTROS project is funded out of the Dutch Growth Fund Program GroenvermogenNL (Green capacity for the Dutch economy and society) via the NWO call “NGF: Transport en opslag van waterstof Groenvermogen NL - Werkpakket 2”. This funding is further complemented with in-kind and cash funding from several of the HyTROS participants.

Executive summary

This report, produced as part of the GroenvermogenNL WP2 R&D Project HyTROS, focuses on the potential for Underground Hydrogen Storage (UHS) in depleted gas fields in the Netherlands, with a particular emphasis on Noord- and Zuid-Holland. The aim is to characterise the fields in terms of reservoir parameters that are relevant for UHS.

Context and motivation

As the Netherlands aims for net-zero emissions by 2050, large-scale energy storage is crucial for balancing the growing share of renewable energy sources. Hydrogen is identified as a key energy carrier for this transition, and after salt caverns depleted gas fields are considered the largest and promising storage option. Recent studies estimate the required storage volume, converted to required energy, for hydrogen to be between 7–20 TWh by 2050.

Scope, approach and data

The Netherlands has about 580 depleted gas fields; a previous screening study (van Klaveren, 2025) has shown that about 140 are potentially suitable for UHS, with another 280 having some risks or unknowns. The demand for UHS is expected to arise early in industrial areas, in particular around the Port of Rotterdam and the province of Noord-Holland, since in these regions no salt is present in the deep subsurface. This report therefore focusses on Noord- and Zuid-Holland, characterising 27 onshore and near-shore gas fields in these provinces, selected after screening for geological suitability and risk factors. The analysis uses datasets and operator reports that are publicly available (NLOG).

Apart from reservoir characteristics, which are the topic of this report, other aspects like well integrity, proximity to supply and demand, and societal embedding will drive future selection of gas fields for UHS.

Key findings

Reservoir Parameters: the study collects and analyses key parameters such as porosity, permeability, depth, temperature, reservoir size, thickness, heterogeneity, transmissivity, well productivity, pressure depletion, recovery factor, gas composition, and salinity.

Geological Context: Rotliegend and Bunter sandstones comprise the most suitable reservoirs; Zechstein carbonates are considered higher risk due to potential chemical reactions with hydrogen.

Field Selection: fields were excluded because of lithology, low temperature, thick oil rims with small gas caps, low productivity, or an elevated risk of chemical/microbial reactions. The final selection includes 9 fields in Noord-Holland and 18 in Zuid-Holland, operated by NAM, TAQA, Vermilion, and ONE-Dyas.

Reservoir Quality: Noord-Holland's Rotliegend fields are sizeable, homogeneous, and have good permeability. Zuid-Holland's Upper Bunter fields are smaller but have excellent permeability, though with more shale barriers. Middle Bunter fields are deeper, with lower porosity but generally good permeability.

Implications and recommendations

The field characterisation supports the site selection for UHS (demonstration) project(s) and informs the transferability of international UHS experience to Dutch reservoir conditions. It also provides a strong basis for constructing models to predict UHS reservoir behaviour and suitability. To accurately

predict reservoir behaviour and assess the suitability of individual fields for hydrogen storage, a more detailed analysis of the spatial variability of properties within reservoirs is required. Further fundamental research is needed to address uncertainties regarding caprock integrity, microbial risks, and heterogeneity.

Conclusion

The Netherlands possesses a substantial portfolio of depleted gas fields that are geologically potentially suitable for UHS, particularly in Noord- and Zuid-Holland. The report's detailed geological characterisation of these fields lays the groundwork for future hydrogen storage projects, supporting the country's energy transition goals.

Contents

List of Figures

List of tables

List of abbreviations

CGR	Condensate Gas Ratio
GIIP	Gas Initially In Place
NLOG	Nederlands Olie- en Gasportaal
N/G	Net-over-Gross
RF	Recovery Factor
UGS	Underground Gas Storage
UHS	Underground Hydrogen Storage
WGR	Water Gas Ratio

1 Introduction

Since the Netherlands aims to achieve net-zero emissions by 2050, the increasing share of renewables in the energy mix necessitates substantial energy storage to balance supply and demand. Hydrogen is expected to play a crucial role in this process, serving as an energy carrier that can be stored and transported in large quantities. Additionally, hydrogen will aid in the de-carbonization of the industry.

Depleted gas fields present the largest-scale storage option for gaseous hydrogen. Several studies estimate the required storage volume in 2050 to be in the range of tens of TWh, with the most recent study (Netbeheer Nederland, 2025) estimating it to be between 7-20 TWh.

The Netherlands has around 580 depleted gas fields, both onshore and offshore. A screening study (van Klaveren et al., 2025) indicates that approximately 140 fields are potentially suitable for Underground Hydrogen Storage (UHS), with no showstoppers identified. Furthermore, for around 280 fields risks and unknowns have been identified; nevertheless, these fields could still be considered. The demand for UHS is likely to materialize first in the industry-rich western part of the Netherlands, where a hydrogen system is already developing around the Port of Rotterdam (Port of Rotterdam, 2025) and in the Province of Noord-Holland (Provincie Noord-Holland, 2025). Therefore, this study mainly focuses on characterising the screened fields in Noord- and Zuid-Holland that are located onshore or near shore[1] in this area and in which provinces no geological salt is present.

Reservoir parameters that are relevant for UHS are briefly reviewed in Section 2. Section 3 describes a comprehensive analysis into the characteristics of the reservoir parameters (porosity, permeability, and depth) of all fields in the Netherlands, as was carried out by TU Delft (Ossetchkina et al., 2025). This has been achieved by developing a computer code script to screen all national databases available to the public. Section 3 highlights the importance of seismic and microseismic data acquisitions, which are crucial for uncertainty reduction and societal acceptance, and are provided by TU Delft. Sections 4-6 describe the selection and characterisation of the gas fields in Noord- and Zuid-Holland, as carried out by EBN. First, Section 4 shows the 27 gas fields in Noord- and Zuid-Holland selected for this study, excluding fields considered unsuitable for UHS upon manual inspection of the reservoir properties as explained in section 4. Next, the geological setting of these fields is described in Section 5, and three groups are defined by their main stratigraphic group. Finally, Section 6 shows the distributions of the field averages of the reservoir parameters listed in Section 2, based on estimates that were collected manually per field from reports published by the field operators on NLOG. A characterisation of the three groups of fields is derived from analysing these distributions for each group.

2 Reservoir parameters relevant for UHS – *TU Delft and EBN*

Many reservoir parameters are relevant when considering the conversion of a gas field to UHS. Here, it is chosen to collect parameters that are important for UHS reservoir performance (from the comprehensive review and outlook published by van Rooijen and Hajibeygi (2025), which includes also the study of Okoroafor et al. (2022) among many other studies), provided that they are available in public resources. The reservoir parameters for which data were collected for the 27 fields under study are as follows.

Stratigraphy

Rotliegend and Bunter reservoirs are sandstones which are suitable for UHS, while Zechstein carbonate reservoirs are considered higher risk due to potential chemical reaction with hydrogen.

Reservoir size

The Gas Initially In Place (GIIP) of a field determines the maximum UHS storage capacity.

Proven gas trap

---

[1] Near shore means that the field is offshore but the well head(s) and production facilities are onshore

In a producing gas field, both top seal and boundary faults have been proven sealing for reservoir gas. For evaporite cap rocks, the confidence that a seal for methane is also a seal for hydrogen is rather high for sandstone rocks (Hashemi et al., AWR 2022). For clay cap rocks, such confidence is built based on research into capillary entry pressures (IEA Technology Monitoring Report, 2023). Indeed, evaporite top seal is the most reliable for UHS, while clay top seals are also suitable, especially if they are thick (van Rooijen and Hajibeygi, 2025). Bounding faults can pose a risk of hydrogen leakage, depending on the juxtaposition across the faults and their behaviour under cyclic pressure.

Reservoir thickness

Sufficient reservoir thickness supports increased hydrogen withdrawal rates, which, combined with the right attic and dipping geometry, increase the presence of the light hydrogen near crestal producers. On the other hand, flat reservoirs, with small dipping angles and extended thin layers, can prevent migration of hydrogen to the crest, which results in spreading away from the well and the potential for increased hydrogen loss.

Heterogeneity

Presence of shales and low Net-over-Gross (N/G) ratios may indicate barriers to vertical flow, especially if shales are correlated between wells. Some sand layers have lower permeability than others, especially the so-called waste zones (Weissliegend, Röt) at the top of some reservoirs, which impacts the amount of effective utilizable reservoir space available for hydrogen storage and potentially loss of trapped hydrogen.

Permeability and transmissivity

An obvious reservoir parameter that impacts the suitability of a gas field for UHS is permeability. Fluid flow in the reservoir is convenient when the permeability is high. When combined with net gas column or sand (and perforation) height into transmissivity, permeability determines well productivity and injectivity. Higher permeability allows for lower injection pressures as well as higher production rates with less drawdown for the same flow rates, which positively impacts the economics of the surface facilities.

Well productivity

A consistent way to quantify well productivity is based on the well test results. However, final results from well test analyses are often not publicly available. Additionally, operators use different definitions: kh in mDm, PI in MMm^3/bar, or Q50 in MMm^3/d (defined as the well flow rate potential for 50 bar drawdown). The closest dataset that is publicly available is the monthly averaged highest rate a single well has ever been flown in a field. Although a well may not be operated at its full capacity, this rate can still be used as a confirmation of the reservoir flow quality. Especially where it is very low (<0.4 MMm^3/d), it indicates unsuitability of a field for UHS, if combined with other indicators (low RF, fracking practices).

Pressure depletion

UGS sites in the Netherlands are realized in depleted gas fields that have weak aquifer support and, in the case of Bergermeer, low abandonment pressure. In Australia (SEAL Energy, 2020), fields with high abandonment pressures (>80% of initial pressure) have successfully been converted to UGS, and in Denmark (Laier, 2009), a UGS site is established in a prolific aquifer layer. All these examples are reservoirs with excellent reservoir quality. Therefore, the full range of abandonment pressures is considered suitable for UHS, at least for fields with excellent reservoir quality.

Recovery factor

Higher natural-gas recovery factors lower the risk of producing remaining reservoir gas with the hydrogen, assuming hydrogen itself is used as the cushion gas. Very low recovery factors (<40%) indicate a risk of unsuitability for a field to be used for UHS. It is shown for a real-field case in Australia that recoverability factor estimation is indeed sensitive to the right choice of the hydrogen transport functions, and that proper calibration of the petrophysical parameters with lab data is essential (Bo et al., 2023).

Gas composition

Fields in the West Netherlands basin (see Section 5) produce condensates with the gas, which may increase separation requirements in the early years. Therefore, fields with a lean gas composition mostly consisting of methane are less complicated for UHS. Higher CO_2 concentrations in the reservoir gas elevate the risk of microbial reactions as methanogens and acetogens can use CO_2 with H_2 to create methane or acetate (Dopffel, 2025).

Salinity

Publicly available data on salinity in Dutch reservoir formation waters is limited. Salinity is, however, a critical environmental parameter influencing microbial reactions. High salinity levels, particularly in combination with high temperatures, create conditions that are less favourable for the activity of micro-organisms that convert hydrogen into contaminants or contribute to hydrogen loss.

3 National perspective – *TU Delft*

To evaluate the potential of depleted gas fields in the Netherlands for UHS (and provide a perspective on the choice for Noord- and Zuid-Holland), we compiled a suite of publicly available geological datasets into one single integrated dataset and developed a Python code to allow for a framework for data analyses and processing (Ossetchkina et al., TU Delft Repository, 2025). The primary data source was the Netherlands Oil and Gas Portal (NLOG, 2025), which provides borehole records, field and license boundaries, and associated reservoir property data. Additional data sources included GEODE (GEODE, 2023), the atlas of deep subsurface resources in the Netherlands, ThermoGIS (ThermoGIS, 2025), which focuses on geothermal energy resources, but provides general reservoir data as well, and DINOloket (DINOloket, 2025), related to geotechnical and geological research topics. Based on the data available from these sources, we concentrate on only a few of the parameters listed in Section 2. Reservoir attributes considered in this study were porosity, permeability, and depth, which collectively influence pore-volume capacity, injectivity, and storage performance of a given reservoir. These three properties are critical to consider when selecting sites for potential UHS, in addition to the other parameters listed in Section 2. From a performance perspective for UHS, higher porosity and permeability are advantageous because they correspond to larger effective pore volumes and improved injectivity and productivity during storage cycles (Bo et al., 2023; Tarkowski, 2019; Heinemann et al., 2021; Camargo et al., 2023). While greater depth allows for slightly more energy storage and fewer gravity overrides (Buscheck et al., 2024), this slightly higher performance may not offset the additional technical and economic challenges that arise with deeper reservoirs, such as drilling costs or the potential geomechanical issues due to higher operational pressures (van Rooijen and Hajibeygi, 2025).

All spatial datasets were standardized to WGS84 datum to ensure compatibility across various sources. A progressive borehole-to-field and borehole-to-license matching algorithm was implemented (e.g., if borehole data was collected but not tagged with a field, the nearest field was assigned to that borehole data, except in cases where the distance was relatively far). Such a strategy was used to assign the borehole data to fields for better characterisation on the field scale. This procedure combined keyword-based field name matching with spatial queries of borehole locations within field shapefiles, supplemented by a nearest-field search for boreholes located outside of field shapefiles. This approach produced a national dataset encompassing both on- and offshore fields, which can be queried by field name, field type, and region.

This integrated national-scale dataset facilitated a comparative assessment for onshore versus offshore fields, as well as a regional evaluation at the province level. We specially highlight offshore vs onshore as they are quite different regarding surface facilities and social-economic perspectives. Generally, results show that offshore fields are characterised by lower porosity and permeability values and occur at greater depths, while onshore reservoirs tend to be shallower and exhibit higher-quality reservoir properties for storage operations. Note that the depth reported in Section 3 is Total Vertical Depth (TVD), which includes the sea depth for offshore boreholes. Hence, it is fully expected that reported depths for offshore boreholes exceed depths for onshore boreholes. Moreover, this preliminary comparison is not between on- and offshore within a given stratigraphic unit but simply based on the data provided in each well, regardless of the stratigraphic units involved. Therefore, we are not suggesting that offshore reservoirs tend to be lower porosity and permeability than onshore reservoirs within a given stratigraphic unit, but simply that the reservoirs already developed offshore tend to have lower porosity and permeability. Future analysis will account for stratigraphy to provide an improved comparison.

The distribution of porosity and permeability for each region in the Netherlands is shown in Figure *1* and Figure *2*, which exhibit significant variation both between regions and within each region. Drenthe, Groningen, Noord-Holland, and parts of Zuid-Holland provide the most porous and permeable reservoirs on average, whereas Gelderland, Noord-Brabant, and Overijssel exhibit the least favourable permeability and porosity values.

The depth distributions shown in Figure *3* indicate that Groningen, Friesland, and Noord-Brabant contain the deepest reservoirs, while Limburg, Overijssel, and Gelderland have generally shallower reservoirs. These regional contrasts in reservoir properties are critical for evaluating technical suitability, as they directly influence decisions regarding where to place UHS sites.

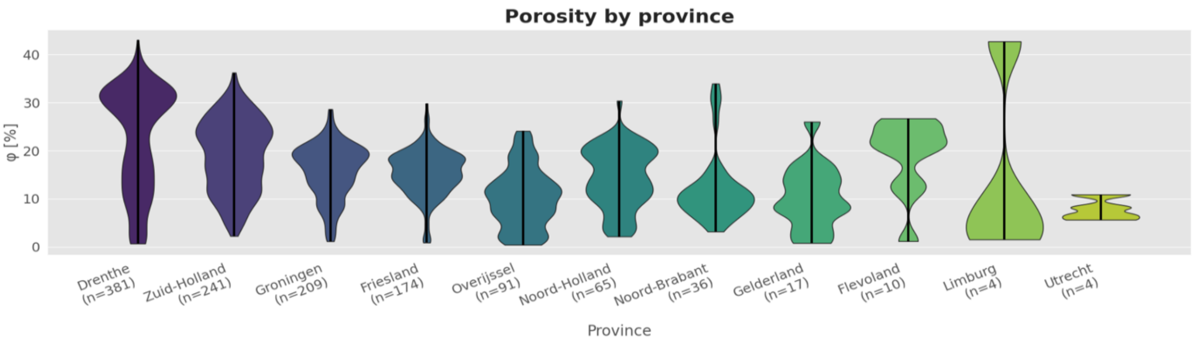

Figure 1 Violin plots of porosity of fields located in various provinces in the Netherlands.

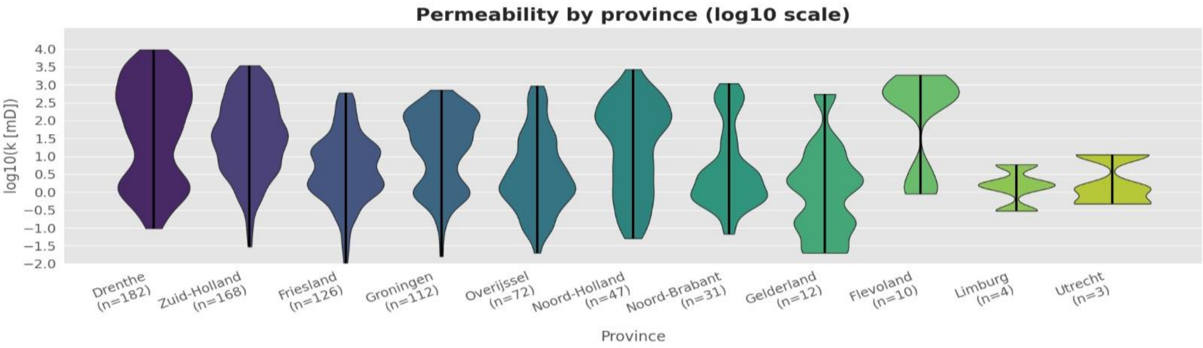

Figure 2 Violin plots of $\log_{10}(k)$ (i.e. permeability) of fields located in various provinces in the Netherlands.

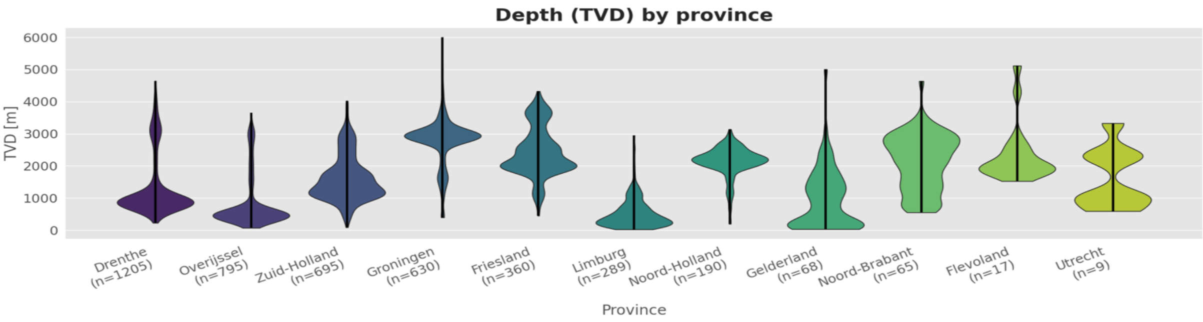

Figure 3 Violin plots of depth of fields located in various provinces in the Netherlands.

Overall, this preliminary analysis suggests that Drenthe, Groningen, Noord-Holland, and parts of Zuid-Holland may be among the most promising regions for UHS, at least regarding favourable porosity and permeability. Friesland, Noord-Brabant, and offshore reservoirs may also provide opportunities for UHS, particularly for deeper reservoirs where higher storage density can be achieved. Note that this analysis is still preliminary. Further research is required to evaluate the other critical reservoir properties (see Section 2) on a more granular level (i.e., field scale) to further assist in the site selection process for UHS in the Netherlands.

In addition to reservoir properties, locating candidate sites near hydrogen-demand centres and infrastructure should be strongly considered. Early deployment of UHS is expected to focus on proximity to industrial clusters and gas-distribution networks (for the Netherlands, gas-distribution networks are already present). In this respect, Noord- and Zuid-Holland (i.e., Noord-Holland and Zuid-Holland) represent attractive locations. Parts of Zuid-Holland, in particular, combine suitable onshore reservoir properties with immediate adjacency to the port of Rotterdam, while Noord-Holland offers strong reservoir quality and suitable geographic proximity to infrastructure. More insights into the characterisation of specific fields in the provinces of Noord- and Zuid-Holland are provided in the following sections.

The available nation-wide data sets, although important to allow quantifying the main characteristics of the Dutch subsurface properties, are certainly not perfect nor without uncertainties. Having a critical assessment of the reliability of the data sets, their accuracy, and time of collection, is essential to build confidence in the presented survey and study. The uncertainty of some of the reservoir parameters, e.g., spatial variability of the thickness and heterogeneity, could be constrained using active-source seismic reflection data. Such data is available for the fields from their exploration and possibly production phase. The data, though, is legacy, meaning that it was recorded, processed, and interpreted years ago. Reprocessing of the legacy data with the newest seismic imaging and characterisation algorithms would help constrain uncertainties. If required, even new seismic data could be acquired, making use of the newest acquisition techniques (e.g., recording both P- as well as S-wave data), which would provide additional data.

Another non-reservoir factor that must be considered is societal acceptance related to the natural (i.e., tectonic) microseismicity. Having data about the natural seismicity near and within a given field before storage operations commence is very important for informing the public of what could be expected during operations. Such data would be used as a baseline for microseismic monitoring during the exploitation of a field for UHS. Seismicity information is not available for the fields in Noord- and Zuid-Holland. As learned from geothermal projects in these provinces, though, they do experience microseismicity (Muntendam-Bos et al., 2022; Naranjo et al., 2025). Recording a baseline survey with an adequate seismic-monitoring network should thus be performed for fields chosen for UHS. Preferably, such a network should be installed permanently for continuous monitoring of microseismicity (natural and possibly induced) during the cyclic operation of UHS, which will allow monitoring of the activity of local faults.

4 Fields in the Western Netherlands – *EBN*

This Section 4, together with Sections 5 and 6, describe the analysis of the fields in Noord- and Zuid-Holland as carried out by EBN and explained in the last paragraph of the introduction (Section 1). Upon manual inspection of field data in public reports, several fields were considered not suitable or found to carry significant risk, as explained below. These fields were excluded from further analysis, leaving 27 fields to be characterised in the following sections. This step is described in this section.

For this reservoir characterisation study, only fields that have a history of gas production are considered, thereby excluding twelve undeveloped accumulations. The existing Bergermeer UGS is included because of its storage history, even though it is too large for UHS.

Low temperatures (<70 °C) seen in shallow formations could be conductive to microbial reactions with hydrogen, and therefore, two reservoirs in shallow formations with low temperatures are dropped.

Microbial reactions can occur in deeper/warmer formations as well, but this risk is very low (Hystories D3.4, 2023) and (Doppfel, 2025). Similarly, more uncertainties exist regarding the chemical reactions of hydrogen with carbonates compared to sandstones. Several gas fields in Noord-Holland have carbonate reservoirs: the peak gas storage Alkmaar and seven other reservoirs. These Zechstein carbonate reservoirs have held natural gas for long periods of time. However, due to the uncertainties these were excluded in this study. We will focus on sandstone reservoirs, of which enough are available. In a later stage this may be reconsidered.

Two fields that only have a small gas cap above a thick oil rim are not considered for UHS, because it is not proven that the top seal can hold a significant gas column.

Finally, while collecting the reservoir properties described in Section 2, six fields were found to have low productivity, evidenced in very low permeability (<10 mD), well stimulation by hydraulic-fracturing, and/or very low maximum well rates (< 0.3 m^3/MMm^3) and sometimes recovery factors (<40%). These fields were dropped as well.

That leaves 27 fields in this study: 9 in Noord-Holland and 18 in Zuid-Holland , having four operators (NAM, TAQA, Vermilion, and ONE-Dyas) as shown in Figure 4.

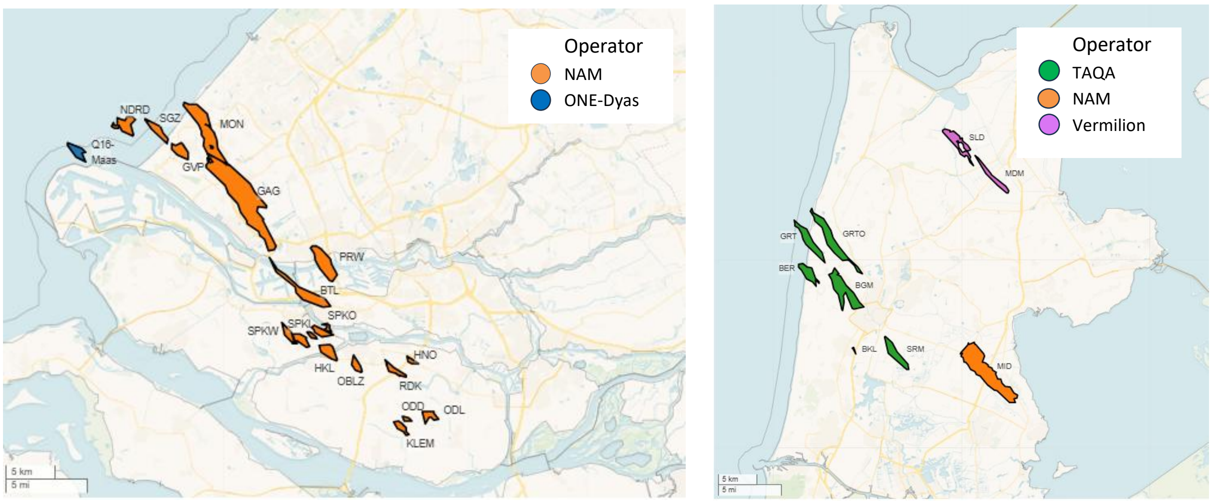

Figure 4 The 27 gas fields considered in this study, coloured by current field operator.

When considering depleted gas fields for conversion to a UHS, many reservoir parameters are crucial based on research and pilot studies (Okoroafor et al., 2022). Reservoir geometry (thickness, attic volume above the well), quality (permeability, heterogeneity), pressures (initial and abandonment pressure), and reactivity with hydrogen (temperature, rock chemical composition) all impact the suitability of fields for UHS. Integrity of especially legacy wells is also an important condition for suitability for UHS but is not publicly available and, therefore, not taken into account here.

Describing the 27 fields in these terms allows for them to be evaluated for suitability for UHS. This reservoir characterisation will be input to reservoir simulation studies and compared to analogue fields. It also forms input for modelling of future UHS (pilot) projects to predict the type of UHS behaviour they will exhibit and how they will need to be managed and optimize their design.

5 Geological context of the screened fields in the Western Netherlands

- EBN

In the Netherlands, hydrocarbons are found in different stratigraphic plays. Most Dutch reservoirs are found in the Rotliegend, as shown in the pie chart below. The second biggest hydrocarbon play is the Triassic. As described in the introduction, we focus on the two provinces of Noord-Holland and Zuid-Holland in this study. Therefore, it is relevant to see which plays are present in these regions.

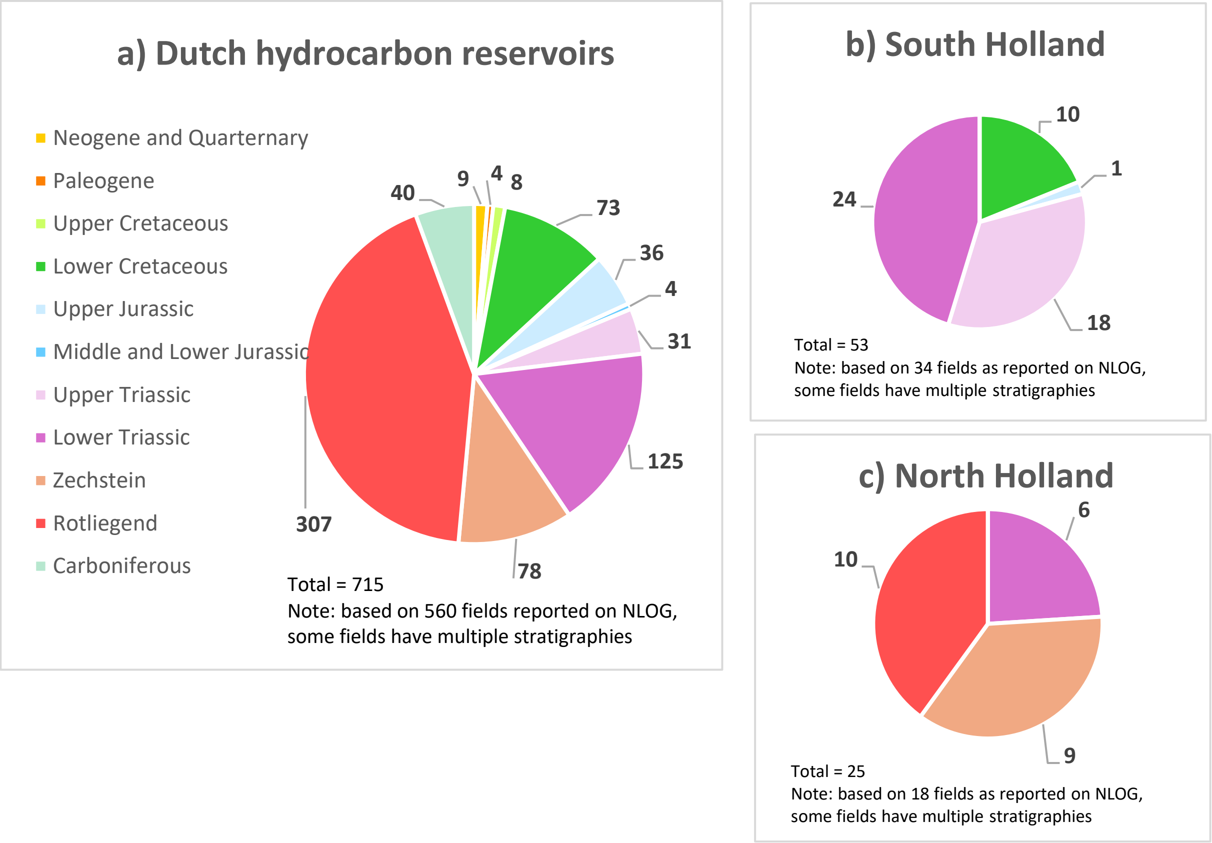

Figure 5 – Play count of hydrocarbon fields a) in the Netherlands, b) in Zuid-Holland and c) in Noord-Holland. Data from NLOG.nl.

The pie charts in Figure 5 show the stratigraphy of all fields present in Noord-Holland and Zuid-Holland. This includes fields that have not produced, e.g., stranded or reserve assets. As described in the introduction, not all the fields are suitable for UHS and were dropped before the evaluation was done in this study. This pre-filtering resulted in 27 fields. It is even more relevant to see what stratigraphies are present in the set of fields evaluated in this study. The distribution of those 27 fields over the various plays is shown in Figure 6.

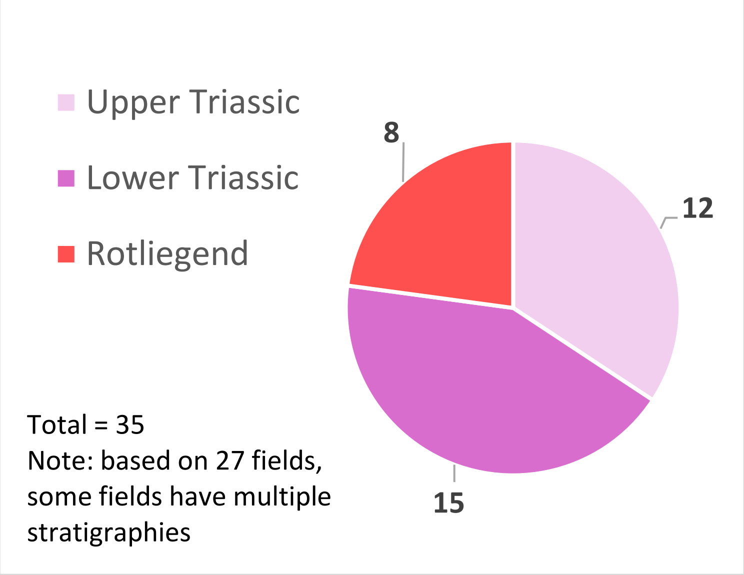

Figure 6 - Stratigraphic play count of 27 fields evaluated in this study. Data from NLOG.nl.

The producing reservoirs in Noord-Holland are found in the Rotliegend. The producing reservoirs in Zuid-Holland are found in the Upper and Lower Triassic. Groups, units, and members of the reservoirs considered in this study are specified in Table 1.

	Zuid-Holland	Noord-Holland
Stratigraphy (group/unit/member)	#	#
Röt Formation	2	
Upper Bunter unit	10	
Main Buntsandstein Subgroup	5	1
Middle Bunter sandstone	9	
Upper Rotliegend Group		3
Slochteren Formation		5

Table 1 - Producing stratigraphies of gas fields in Noord-Holland and Zuid-Holland selected in this study.

5.1 Depositional history Permian and Triassic

5.1.1 Structural elements during deposition

Structural elements refer to the major tectonic features that define the architecture of a sedimentary basin. Particularly during the Permian (Rotliegend and Zechstein) and Triassic periods, structural elements played a crucial role in shaping the depositional environments and the distribution of sediments across the West Netherlands Basin (WNB) and the Central Netherlands Basin (CNB). These two basins cover most of the provinces of Noord- and Zuid-Holland, and 25 fields lie within. The North Holland Platform (NHP) was not buried as deeply as the CNB and WNB, as elaborated on in the next paragraph, and holds two fields (Figure 7).

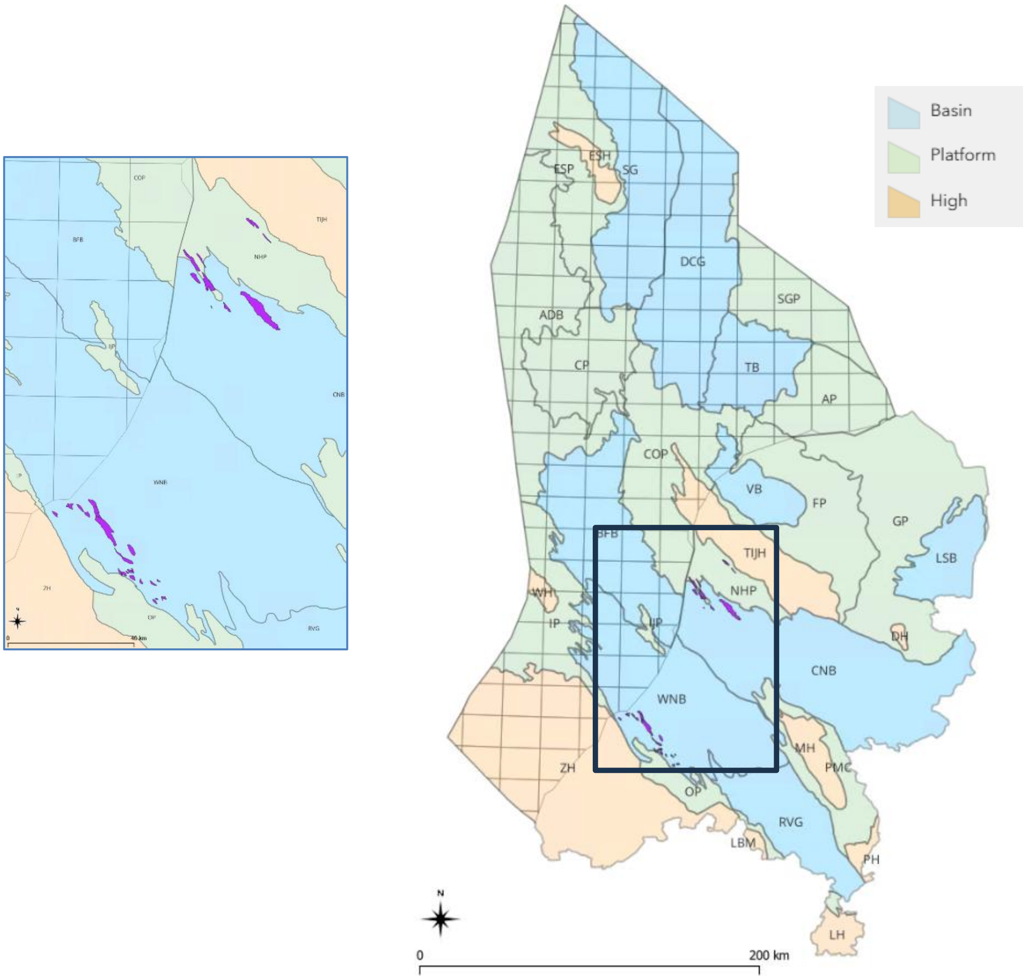

Figure 7 - Structural elements of the Netherlands and gas fields selected in this study in purple. Selected abbreviations of elements shown in figure: WNB = West Netherlands Basin, RVG = Roer Valley Graben, CNB = Central Netherlands Basin, LSB = Lower Saxony Basin, BFB = Broad Fourteen Basin, NHP = North Holland Platform. Adapted from Kombrink et al. (2012).

Structural elements are often inherited from particular tectonic events (e.g., Variscan or Caledonian orogenies) and may be reactivated during later phases (e.g., Permian rifting, Triassic extension). During the Permian and Triassic, the West Netherlands Basin (WNB) and Central Netherlands Basin (CNB) developed as structurally distinct yet tectonically linked depocenters within the Southern Permian Basin (ten Veen et al., 2025; Kombrink et al., 2012).

The central parts of CNB and WNB were buried deeply during a Late Jurassic-Early Cretaceous rifting phase, leading to a reduction in porosity and especially permeability of Rotliegend (and Triassic) reservoir sandstones due to compaction and cementation. During subsequent structural inversion, the rift-bounding faults were often reactivated, resulting in reverse movement and uplift. Therefore, these central parts may show anomalously poor reservoir quality.

During the Permian period (299-252 million years ago) and during the Triassic period (252-201 million years ago), the Netherlands was part of the Southern Permian Basin (SPB). Sediments were deposited in a large continental basin extending west-east from the UK to Poland. Sedimentation started with the Rotliegend Group, with volcanic and volcaniclastic deposits of the Lower Rotliegend, of which only a little is preserved. This was followed by widespread fluvial, aeolian, and playa-lake sandstones and evaporites of the Upper Rotliegend under arid conditions. The Rotliegend Group was succeeded by the Zechstein Group, a series of marine transgressions that deposited several cycles of carbonates and evaporites, including salt now often deformed into pillows or diapirs. During the Triassic, continental conditions persisted with alternating fluvial, aeolian, and playa environments. Meanwhile, episodes of marine flooding and evaporite deposition, reflected tectonic reconfigurations and climatic shifts during the fragmentation of Pangea (ten Veen et al., 2025).

5.1.2 Rotliegend with focus on Noord- and Zuid-Holland

During the Rotliegend, aeolian sediments were deposited whilst fluvial sands were mainly sourced from the southeast (Variscan Mountains and London Brabant Massif) and transported northward by fluvial systems, as shown in the depositional model in Figure 8 (Gast et al., 2010). As can be seen on the Rotliegend thickness map from the GEODE website (Kortekaas et al., 2025), thick accumulations of Slochteren Sandstone were preserved in the Noord-Holland province and further offshore.

As shown in the depositional model in Figure 8, the best Rotliegend reservoirs are expected in Noord-Holland, where thick sections of aeolian sands were deposited. Closer to the source, in Zuid-Holland, Rotliegend is thinner and less well-sorted. More distal, in the offshore K&L blocks, the quality of Rotliegend reservoirs is expected to be lower due to moving from a sand-rich facies to a more clay-rich facies in the wet sandflats.

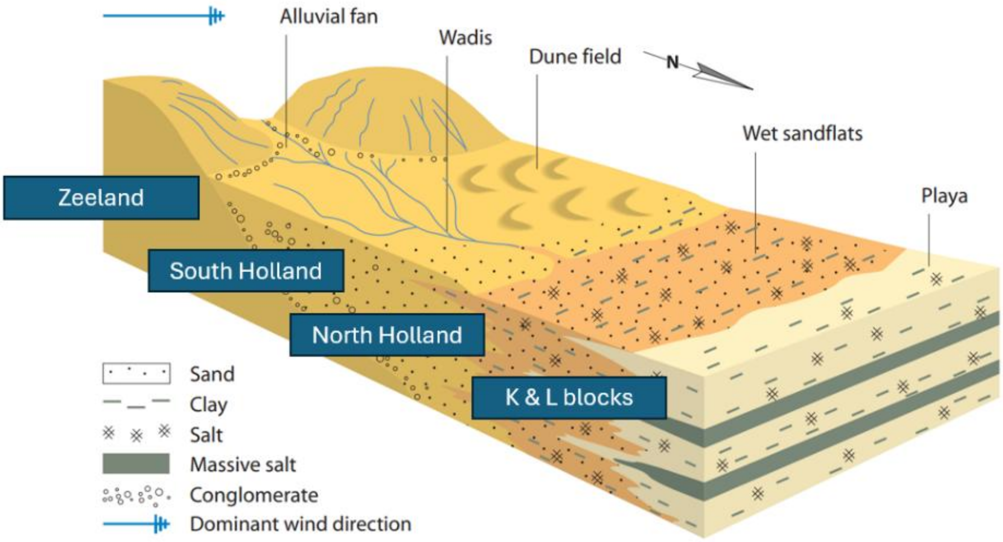

Figure 8 - Lithological cross-section through the Rotliegend succession of the Netherlands, adapted from Gast et. al 2010.

The CNB experienced pronounced differential subsidence, resulting in thick accumulations of Rotliegend sandstones, including both fluvial and aeolian facies. While both CNB and WNB were part of the broader SPB system, the CNB generally preserved a more continuous and thicker Rotliegend succession than the West Netherlands Basin. This is because of onlap of the sediments closer to the source as well as erosion during the Cimmerian tectonic event, leading to truncation of the Rotliegend successions along the southern flank of the WNB. Moreover, the Rotliegend in the WNB has been buried deeper, reaching 4-5 km depth, resulting in low-quality sands which later have been uplifted to the current 2-3 km depth.

Most Rotliegend gas fields in Noord-Holland have a low reservoir quality top layer of 20-50m thick. Informally, this layer is named *Weissliegend*. This top part was reworked during the Zechstein transgression, resulting in low permeabilities. Moreover, carbonate and anhydrite cementation, which have given the Weissliegend its name, could have reduced the porosity and permeability. Note that the Weissliegend may be a non-producing waste-rock; however, in, e.g., the Bergen concession, Weissliegend reservoirs have been produced, probably with modest Recovery Factors.

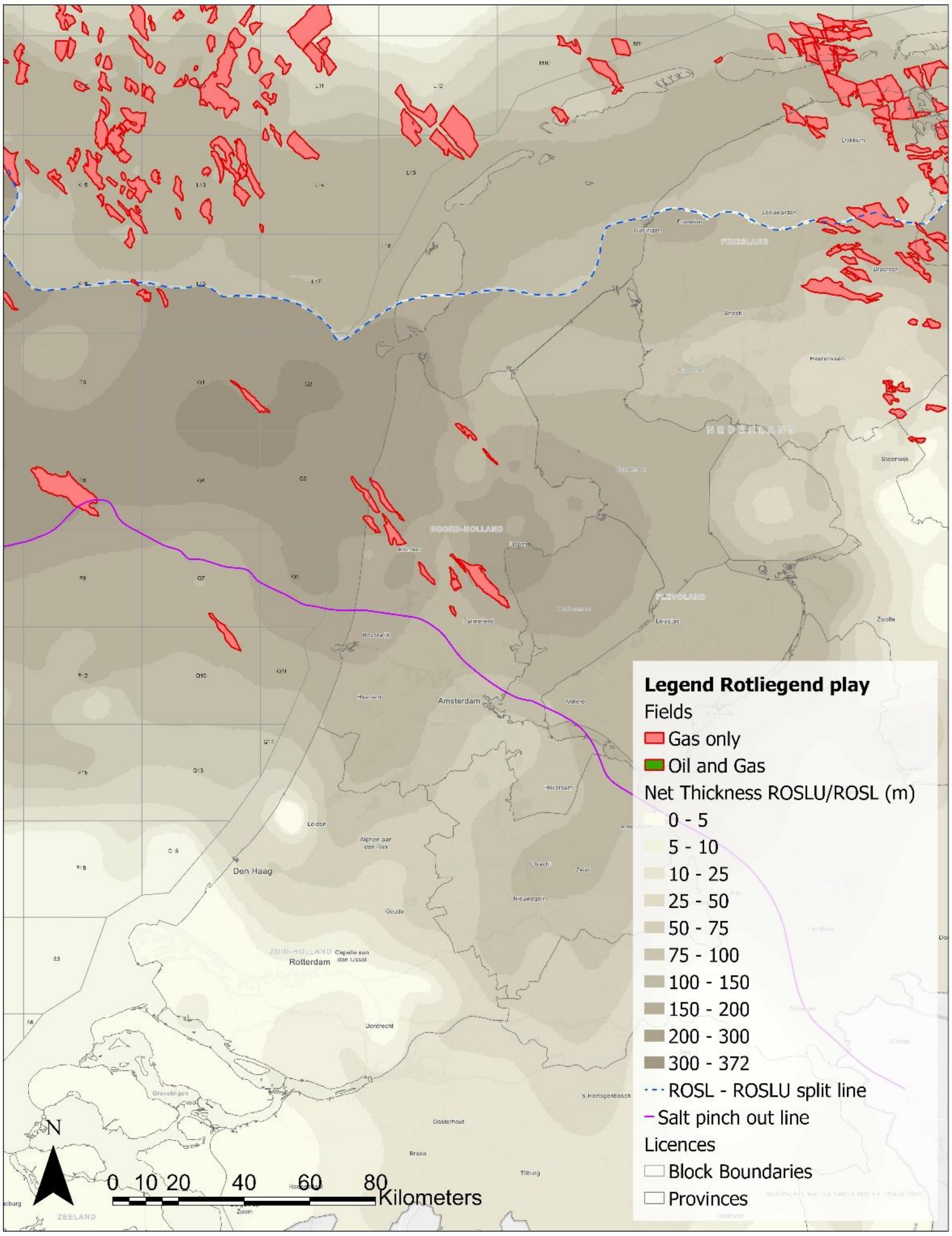

Figure 9 - Thickness map Rotliegend Slochteren and Upper Slochteren (resp. south and north of the pinch-out line of the Ameland Claystone, indicated in dashed blue). The purple line indicates the southern limit of Zechstein salt deposition. Adapted from GEODE, 2023.

As shown in Figure 9, no Rotliegend gas fields have been found in Zuid-Holland, due to a combination of a proximal depositional environment and deep burial of the WNB. Good quality reservoirs are found in Noord-Holland.

In Noord-Holland and Zuid-Holland, only the ROSL (Slochteren formation) exists. In this area, the Slochteren Formation has not been subdivided into Lower and Upper Slochteren Members; these have only been defined where the Ameland Claystone Member is present, i.e., north of the Ameland Claystone pinch out line (blue dashed line in Figure 9).

5.1.3 Triassic with focus on Noord- and Zuid-Holland

The most relevant stratigraphy within Zuid-Holland is the Triassic, since most fields in Zuid-Holland are found in this play (Figure 10). During the Triassic, sediments were transported from the London-Brabant Massif and Variscan mountains in the southwest into the SPB in the Noord-east, similar to Rotliegend times.

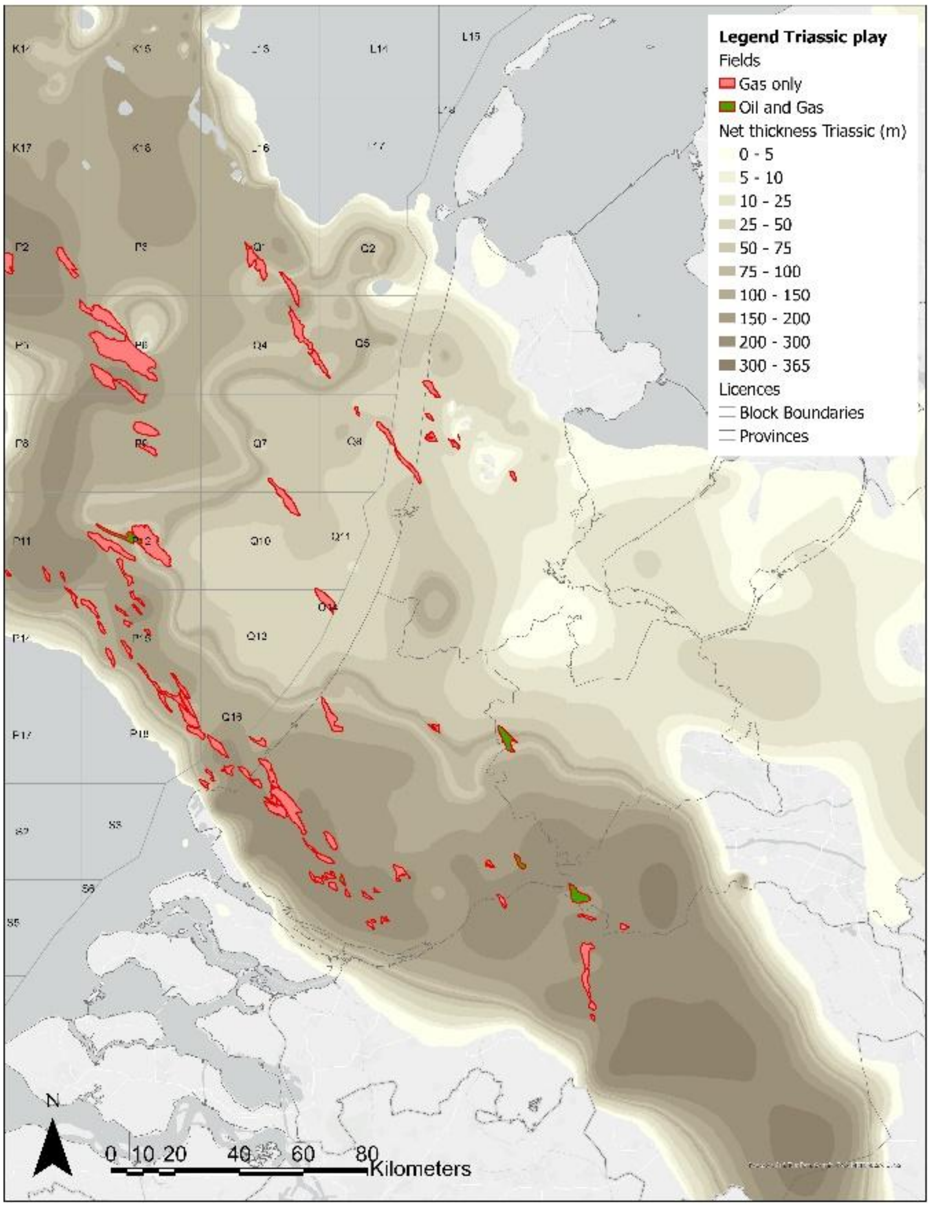

Figure 10 Thickness map Triassic play. Adapted from GEODE, Korevaar et al. (2023).

A depositional model is shown in Figure 11 and the corresponding stratigraphy and dominant facies are shown in Figure 12. The sediments forming Triassic reservoirs are likely similarly sourced and possibly even consist mostly of reworked Rotliegend sediment. Reworking by wind resulted in well-sorted sandstone reservoirs. Therefore, Rotliegend and Triassic reservoirs don't have very distinct differences in sand quality distribution.

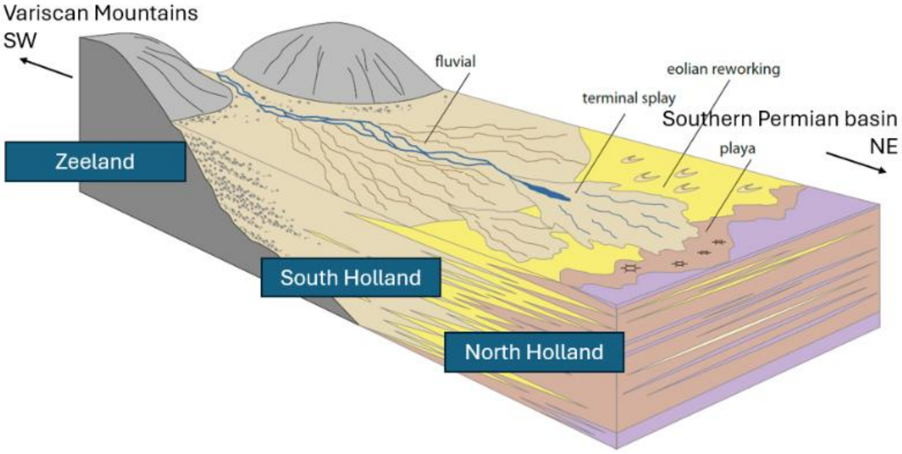

Figure 11 Depositional model for the fluvial-aeolian-playa systems of the Lower Germanic Trias Group and Upper Germanic Trias Group clastic fringe facies. Adapted from Geology of the Netherlands chapter 5, ten Veen et al, 2025.

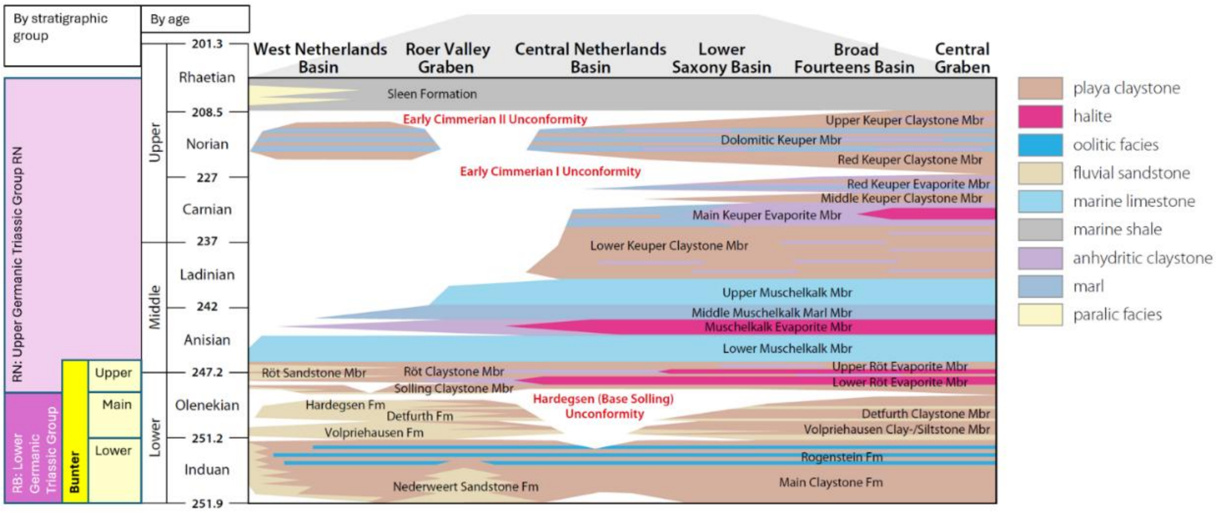

Figure 12 Stratigraphic sections illustrating the vertical and lateral distribution of Triassic reservoirs. Adapted from GEODE, 2023.

Figure 12 shows the stratigraphic sections found in the Triassic play. The gas fields in Noord- and Zuid-Holland are found in the Main and Upper Bunter Groups, shown in yellow. The relevant formations are the Volpriehausen Formation, Detfurth Formation, Hardegsen Formation, and Röt Sandstone Member. The combined stacked sandstones of the Volpriehausen, Detfurth, and Hardegsen Formations are in this area often referred to as the Middle Bunter Sandstone (NLOG, 2025), a name we will also use in this report.

In the West Netherlands Basin, sands from the Main Bunter are stacked directly on top of each other, whereas in the north, they are split by clays. This is shown in the schematic overview in Figure 13 and example wells log in

Figure 14. The Hardegsen unconformity marks the boundary between the Middle and Upper Bunter. Whereas the Base Cretaceous Unconformity marks the upper boundary of the Triassic sequence in this area, where Jurassic formations have been truncated. As shown in Figure 14, a thicker sequence of Muschelkalk and Röt is preserved in Noord-Holland compared to Zuid-Holland. The Early Cimmerian I and II erosion events removed most of the Keuper and Muschelkalk in the WNB, and partly in the CNB.

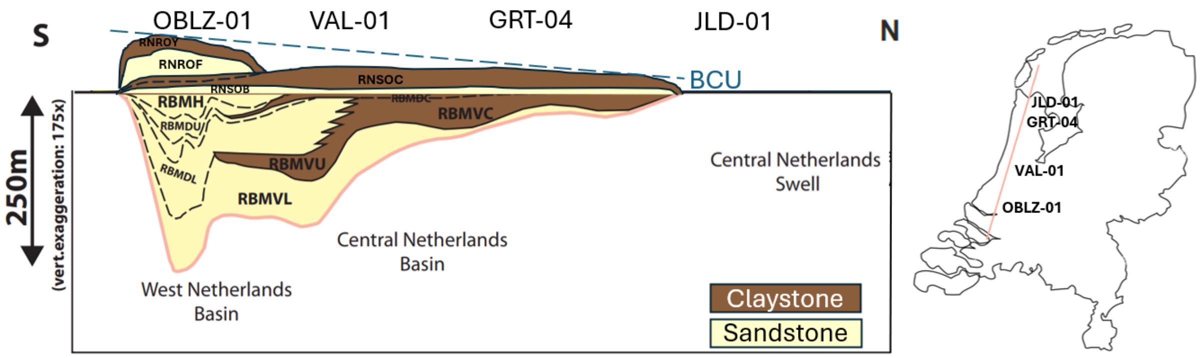

Figure 13 Stratigraphic section illustrating the vertical and lateral distribution of Triassic reservoirs. Ref. level: Top Middle Bunter (Hardegsen Unconformity). BCU = Base Cretaceous Unconformity. RNROY=Upper Röt Fringe Claystone Member, RNROF=Röt Fringe Sandstone Member, RNSOC=Solling Claystone Member, RNSOB=Basal Solling Sandstone Member, RBMH=Hardegsen Formation, RBMDU=Upper Detfurth Sandstone Member, RBMDC=Detfurth Claystone Member, RBMDL=Lower Detfurth Sandstone Member, RBMVU=Upper Volpriehausen Sandstone Member, RBMVC=Volpriehausen Clay-Siltstone Member, RBMVL=Lower Volpriehausen Sandstone Member. Adapted from Triassic annotated play map GEODE, 2023 and NLOG.

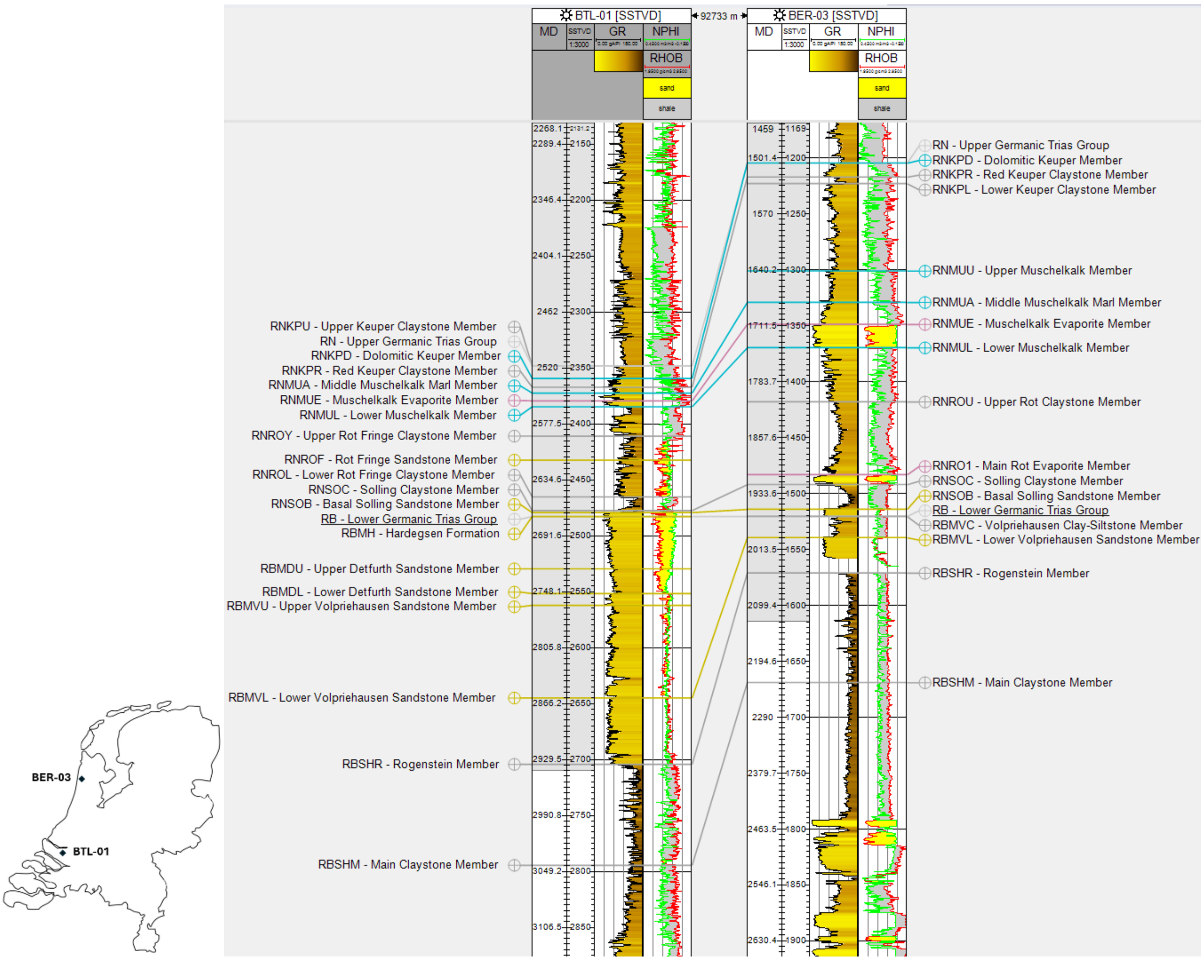

Figure 14 Two correlated well panels from BTL-01 and BER-03, flattened on Top Middle Bunter, showing the stratigraphy of stacked Middle Bunter sands in Zuid-Holland in relation to the Volpriehausen Sandstone in Noord-Holland.

Bunter reservoirs in Zuid-Holland generally increase in quality southwards, because inversion of the basin happened to a greater extent to the north, towards the basin, e.g., Noord- in Zuid-Holland or in Q13. This inversion both impacted Triassic and Rotliegend reservoirs in the WNB, resulting in less porous reservoirs in the centre of the WNB and higher porous reservoirs more on the edges of the basin.

In general, the Triassic is preserved in Zuid-Holland and to a lesser extent in Noord-Holland, shown on the map in Figure 10. This is due to the Middle Bunter sands being truncated by the Hardegsen Unconformity. When zooming in on the Upper Bunter formations, more specifically the Röt fringe sandstone, we see that thick accumulations of sand are preserved, but only in Zuid-Holland. In Figure 15 we see the gross thickness of the Röt fringe sandstone. These sands are in some places of high quality, which is indicated by the Net-over-Gross (N/G) in Figure 16. This is in the south-east of the Zuid-Holland province, indicated in red.

]

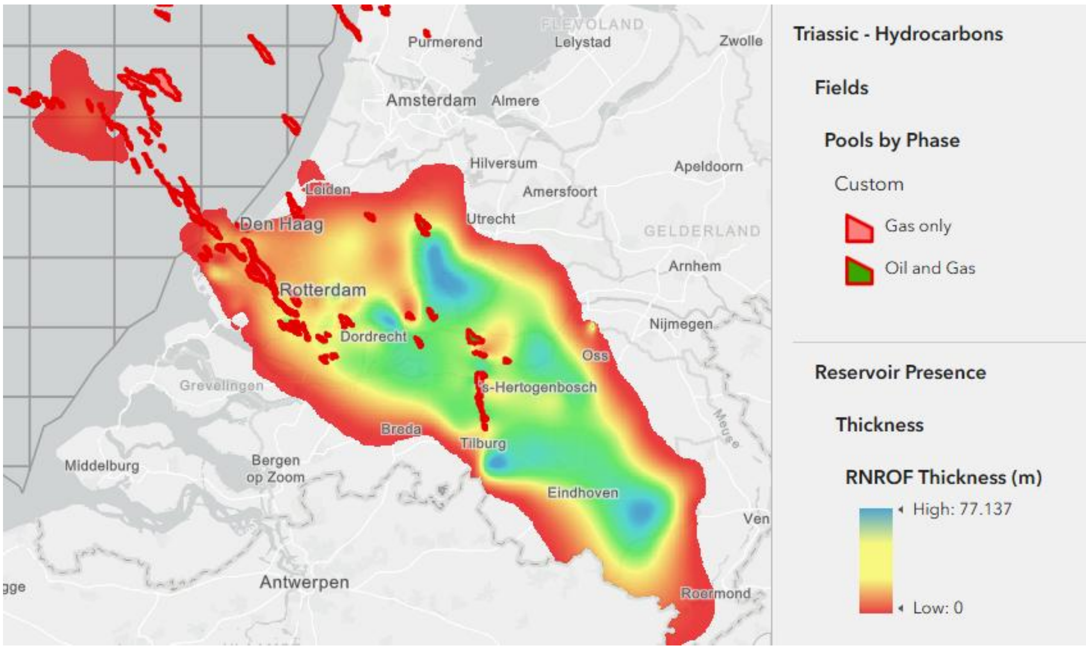

Figure 15 Triassic Thickness Röt fringe sandstone (RNROF), from GEODE.nl.

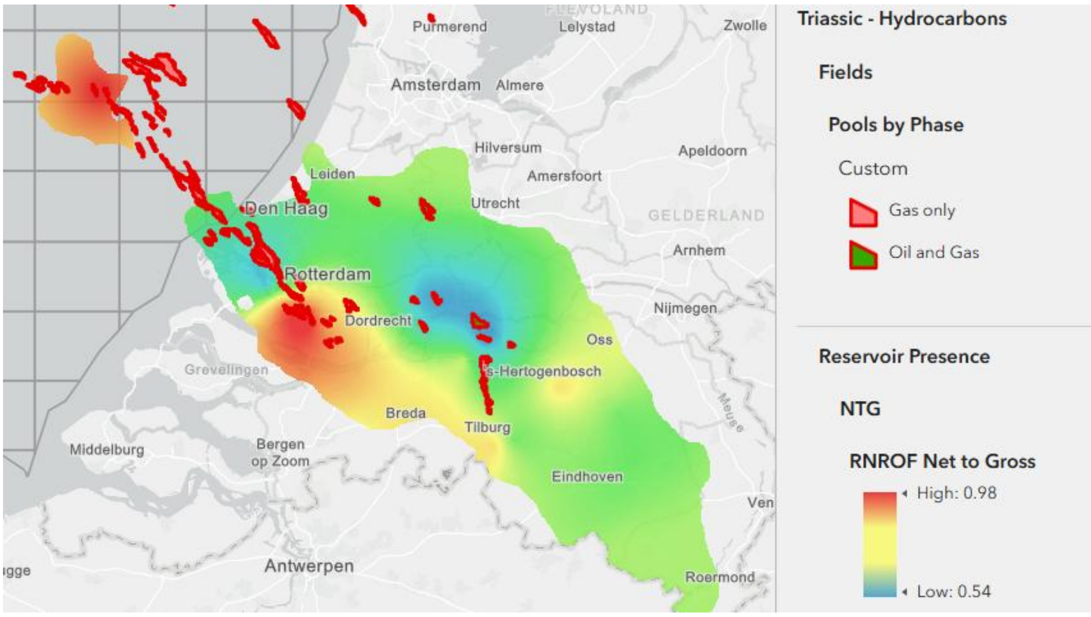

Figure 16 Triassic Net-over-Gross (N/G) Röt fringe sandstone (RNROF), from GEODE.nl.

5.2 Characteristics fields in Noord-Holland and Zuid-Holland

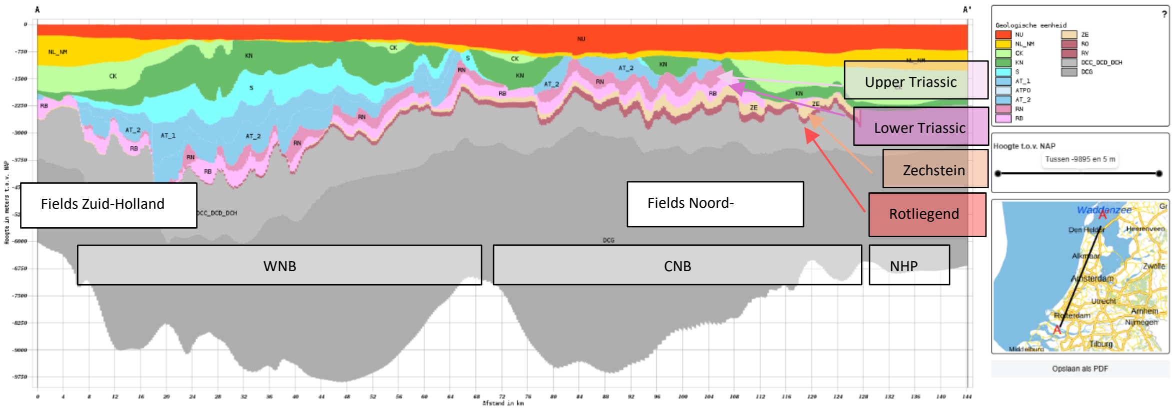

Figure *17* S-N cross section through Noord- and Zuid-Holland, based on DGMv5 from Dinoloket. Grey labels indicate the structural elements shown in *Figure 7*: WNB = West-Netherlands Basin, CNB = Central Netherlands Basin, NHP = North Holland Platform. RN = Upper Triassic, RB = Lower Triassic, ZE = Zechstein and RO = Rotliegend.

Figure 17 and concluding the subchapters above, we slightly converge to a grouping of the different fields in Noord-Holland and Zuid-Holland regarding characteristics.

5.2.1 Stratigraphy summary

Summarising and elaborating on Section 5.1, we see that only a thin Rotliegend is preserved in Zuid-Holland (0-10m), and much thicker sections are preserved in Noord-Holland (200-300m), see both Figure 17 and Figure 9. Triassic reservoirs are generally deeper in Zuid-Holland compared to Noord-Holland.

In the north of Noord-Holland, Jurassic erosion created an unconformity in such a way that Cretaceous (KN, dark green in Figure 17) is found on top of the truncated Zechstein, indicated in dark green on top of beige colour in Figure 17, or on top of truncated Rotliegend, indicated in dark green on top of red colour in Figure 18.

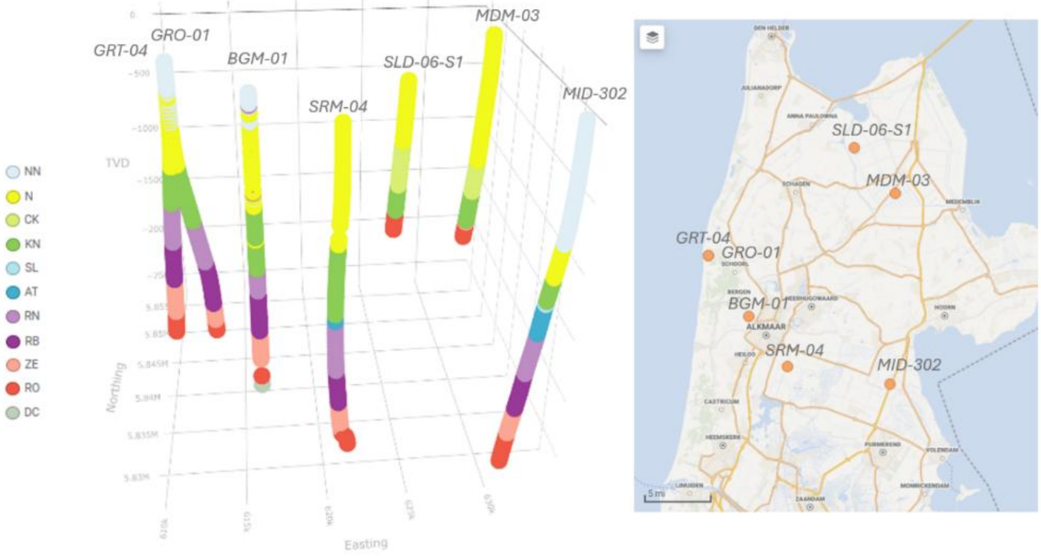

Figure 18 3D lithology plot from representative wells in Noord-Holland. Structural geology is not shown in this 3D plot. SLD-06-S1 and MDM-03 are crestal wells on horst blocks, since we know Zechstein is present around those wells.

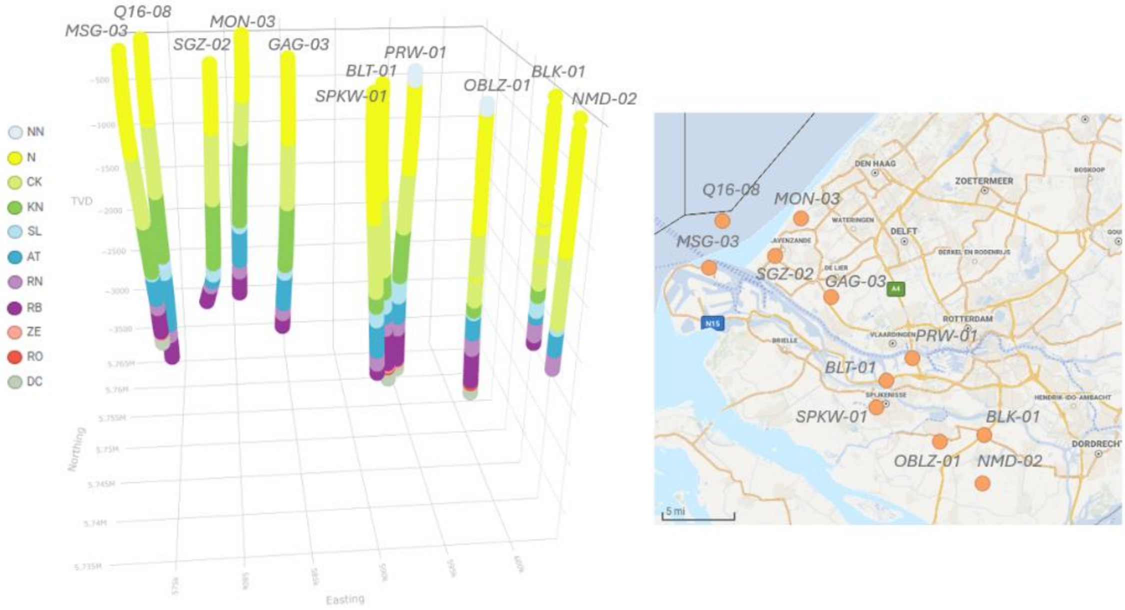

Figure 19 3D lithology plot from representative wells in Zuid-Holland.

To summarize the key findings presented in this section, interesting fields for UHS in Zuid-Holland are found in the Triassic play, none in the Rotliegend. In Noord-Holland, we find mainly interesting Rotliegend fields.

5.2.2 Hydrocarbon types

In Noord-Holland, both Rotliegend and Triassic gas fields are found. Sometimes gas is found in both formations, e.g., in Bergen and the offshore Q10-A field. In Zuid-Holland, Triassic gas and oil and gas fields are found, the fields with an oil rim were already filtered out. Oil was mostly generated from the Posidonia shale, a shale that was deposited later in time (Jurassic), releasing both oil and gas. Due to faulting, this oil and gas could migrate to the traps formed by horst structures. The Posidonia shale is a marine source rock, leading to wetter gas and liquids releases compared to dry gas from coal from ancient vegetation on land. That is also the reason why a high condensate gas ratio (> 40 Mmm3/m3) is often found in gas fields from Zuid-Holland. The gas in the dry-gas fields is purely sourced from deeper Carboniferous source rocks.

To summarize the key findings presented in this section, in Zuid-Holland, some fields could have a high condensate-gas-ratio.

5.2.3 Seal

In Noord-Holland, the Rotliegend reservoirs are sealed by 200-300 meters of significantly evaporitic Zechstein layers, providing an effective caprock. Gas fields in the north-east of Noord-Holland, Slootdorp and Middenmeer, are sealed by the Zechstein and the Cretaceous Vlieland Claystone. In Zuid-Holland, the situation is more complex. There appear to be two distinct groups of fields:

- In the western region, fields predominantly occur in the Middle Bunter and Solling sandstones.
- In the eastern region, fields predominantly occur in the Upper Bunter Röt sandstone.

The Middle Bunter (Volpriehausen, Detfurth, Hardegsen, and Solling) sandstones re often stacked. In locations where structural traps exist, the Solling claystone may act as a seal of this stacked sequence. In other areas, where there is no sealing Solling claystone, gas may have migrated into the Röt fringe sandstone (part of the Upper Bunter), which lies on top of this stacked sequence.

The presence of gas in the Röt fringe sandstone (Upper Bunter) is often uncertain. This uncertainty might be resolved when looking at the perforations. In some wells, the Röt fringe sandstone layer is perforated, as well as the Middle Bunter sections, allowing it to act as a producing zone. However, it may be difficult to determine whether the gas originates from the Upper or Middle Bunter once producing. If the Röt fringe sandstone does not contribute to production, it may be classified as a "waste zone". This is a layer where gas is trapped but remains unproducible due to poor reservoir quality. Above the Röt fringe sandstone, the Röt claystone can act as a seal. The ultimate sealing layers are the Altena shales, on top of the Upper Bunter, creating several hundred meters of seal.

In fields located further south-east in Zuid-Holland, most of the gas is found in the Röt fringe sandstone, which exhibits exceptionally good reservoir quality in that region. As shown in the well-correlation panel in Zuid-Holland below, the Röt fringe sandstone thickens towards the east, which was also already indicated in Figure 15. In the well-correlation panel below, it is shown that the Röt fringe sandstones shale out to the north-west, creating a "waste zone" more to the north-west.

The Upper Bunter reservoirs in the south-east are much more heterogeneous, as can be seen on the Gamma Ray logs, than the Middle Bunter reservoirs. In regional terms, the shales seem to be correlatable. When zooming in to the reservoir scale, they are probably continuous, but due to small faults, all sand layers within the Röt Fringe sandstone member can still be connected.

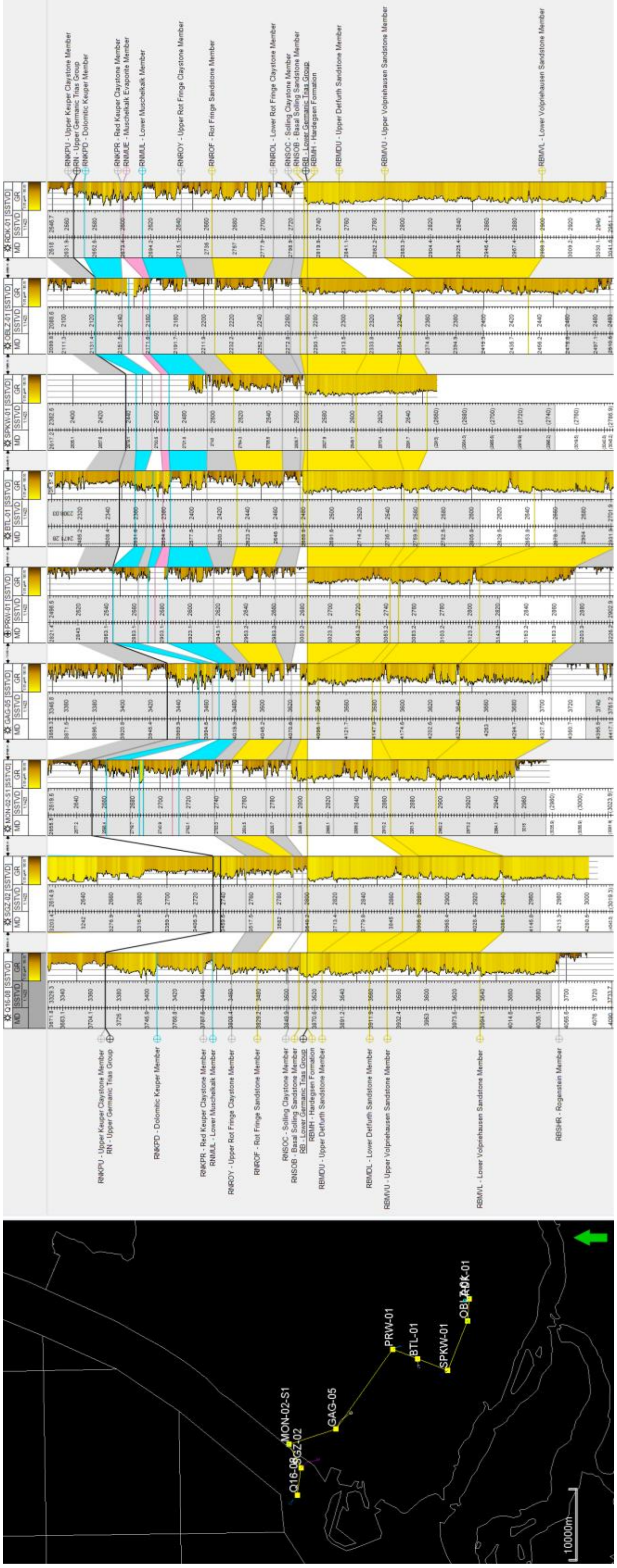

Figure 20 Well-correlation panel in Zuid-Holland. When a sand (yellow), shale (grey), limestone (blue) or evaporite (pink) could be correlated between wells, the space between two well logs is colour filled. It is white when no direct correlation could be made on member level.

To summarize the key findings presented in this section, in Noord-Holland, the Rotliegend fields have a Zechstein salt seal. In Zuid-Holland, there are two distinct groups: 1) thick clean Middle Bunter sandstone fields, which might have a Röt waste-zone on top, located more to the west of Zuid-Holland. And 2) the more heterogeneous Röt fringe sandstone fields are more to the south-east of Zuid-Holland. Both have thick sealing Jurassic Altena shales on top.

6 Characterisation of depleted fields in the Western Netherlands - *EBN*

For the analysis of the 27 fields in Noord- and Zuid-Holland , the reservoir parameters listed in Section 2 have been collected manually as reservoir averages per field from publicly available reports by operators on NLOG (Winningsplannen, well reports). A few data points were provided directly by the operators with permission to use in this analysis. Operator estimates are based on comprehensive analyses integrating all static and dynamic data, which have an advantage over using the data directly, but are not available publicly for all fields in the Netherlands. A limitation of using field averages is that within a field, properties may vary considerably, especially between layers, which should be captured when progressing to field-specific analyses.

6.1 Fields grouped by main stratigraphic group

Distributions of the reservoir parameters were analysed for fields grouped by the main stratigraphy group in each field:

1. Rotliegend fields in Noord-Holland;
2. Upper Bunter fields, mainly, to the South and South-East of Rotterdam;
3. Middle Bunter fields, mainly, in Zuid-Holland close to and to the West of Rotterdam.

In two fields where both Upper and Middle Bunter gas columns are equally present, the Middle Bunter is chosen as the main stratigraphy group as it dominates the production due to higher vertical homogeneity and sometimes higher pressure support. At this point, Zechstein carbonate reservoirs are not yet considered for UHS as more research is needed on the risk of geochemical and microbiological reactions, and sufficient sandstone reservoirs are available as UHS candidates to characterise in this study.

Figure 21 shows the 27 fields in this study and their main stratigraphy, which are derived from the selection explained in section 4. There are 8 Rotliegend (RO), 11 Middle Bunter (RB), and 8 Upper Bunter (RN) fields.

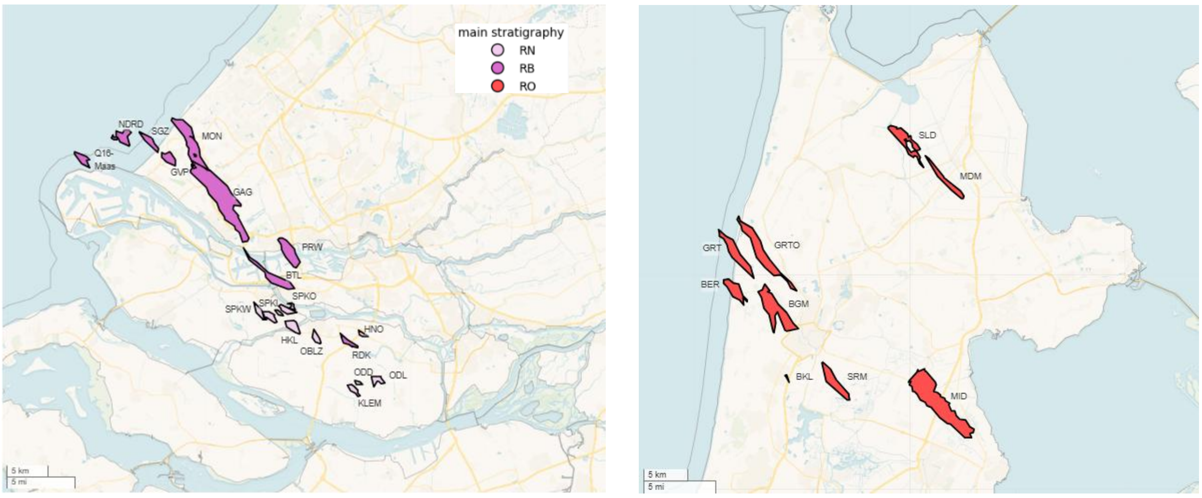

Figure 21 The 27 fields in this study coloured by main stratigraphy group (RN = Upper Bunter, RB = Middle Bunter, RO = Rotliegend). The Bunter fields are almost always a combination of Upper and Middle Bunter. In this case fields are labelled by the stratigraphy that contributes most to the gas volume.

6.2 Distributions of reservoir parameters

The field data that were collected and the related reservoir parameters from Section 2, are given in Table 2 together with the data coverage in % of fields. Figure 22-Figure 29 show distributions of these measures per stratigraphic group. Observations are made for each parameter.

Field Data	Coverage	Parameter in Section 2
GIIP	100%	Reservoir size
RF	100%	Recovery Factor
N/G	100%	Well productivity
Porosity	81%	Relation to permeability
Top reservoir	100%	Relation to porosity and initial pressure
Column height	100%	Transmissivity
Sand thickness	100%	Transmissivity
Permeability	85%	Permeability
Transmissivity	85%	Transmissivity
Qmax	100%	Well productivity
Initial pressure	100%	Pressure depletion
Final pressure	100%	Pressure depletion
WGR cumulative	96%	Relation to well productivity
CGR	96%	Gas composition

Table 2 Data coverage of collected reservoir averages across the fields in this study, linked to parameters relevant for UHS.

From the field GIIPs in Figure 22, it is clear that the Upper Bunter fields are small (< 0.5 bcm) to medium-sized (1-2 bcm). The smallest fields may not be of interest for a commercial UHS but may be suitable for a UHS demonstration project. In addition to these small Upper Bunter fields in Zuid-Holland, there is one small Middle Bunter field in Noord-Holland, Boekel, which could also be a candidate for such a demonstration project. The Middle Bunter and Rotliegend fields are split evenly between medium size (1-3 bcm) and large size (> 3 bcm).

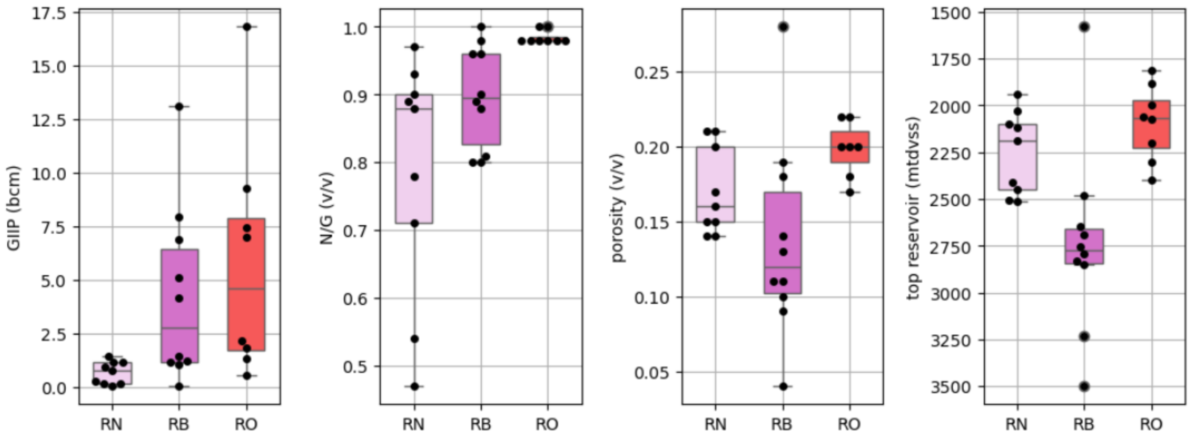

Figure 22 Distributions per stratigraphy group of field GIIP, average N/G, average porosity and top reservoir depth, for the fields shown on the maps in Figure 21.

The average N/G in Figure 22 shows a higher shale content in the Upper Bunter. Some of these shales are correlated between fields (see previous section), which means that they are potential continuous barriers to vertical flow. The Rotliegend shows a very high N/G, as can be seen in logs on NLOG (e.g., in TAQA, 2012), while the Middle Bunter sand is slightly less clean.

Middle Bunter fields in Figure 22 tend to have a lower porosity than the Upper Bunter and Rotliegend fields. This is explained by the deeper location of the Middle Bunter fields and a known downward trend in porosity with depth (see also Figure 23).

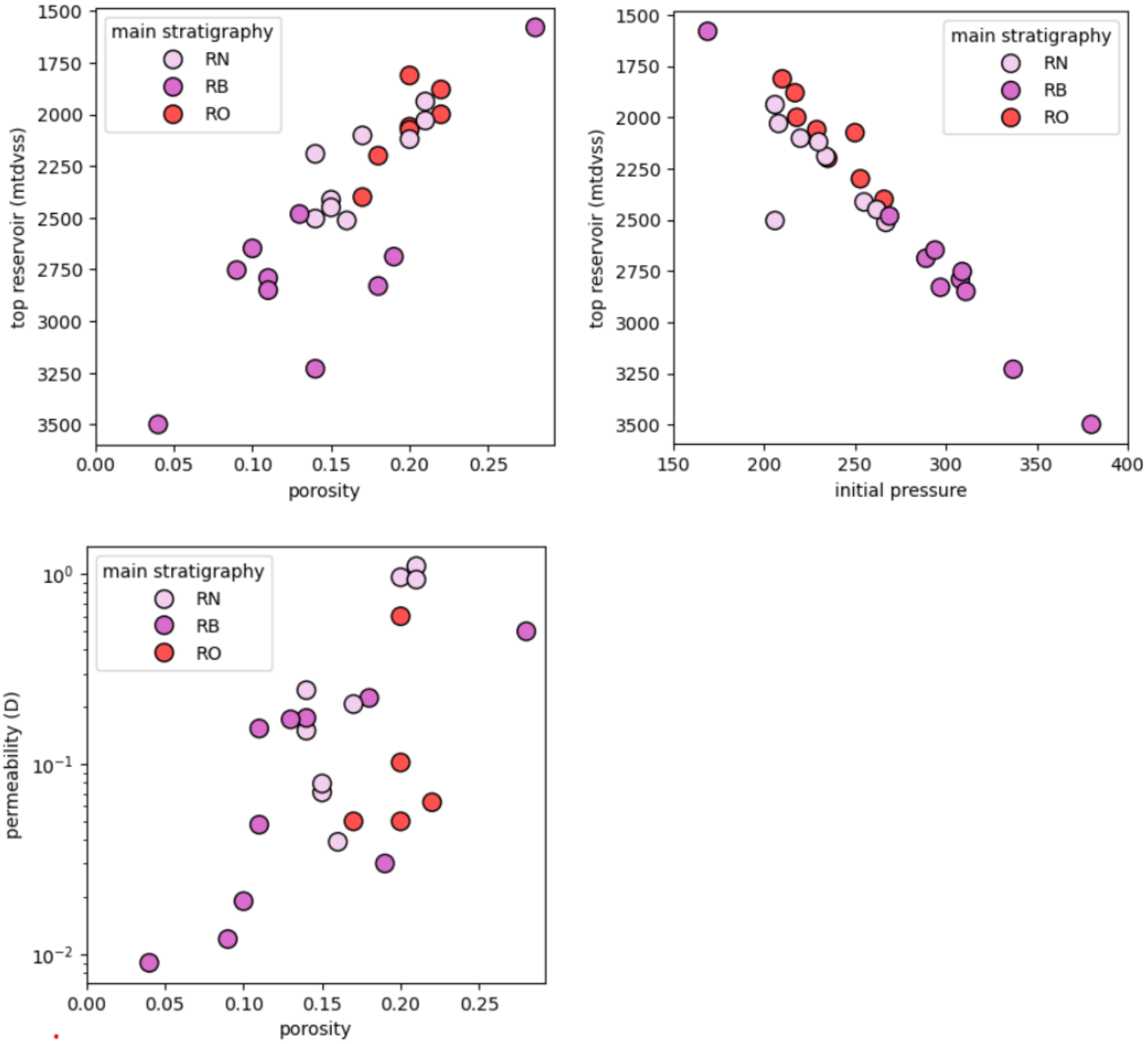

Figure 23 Correlations of average porosity and initial pressure with depth, and permeability with porosity.

In Figure 24 distributions of permeability are generally good (10-100 mD) to excellent (100-1000 mD) in all but a couple of Middle Bunter fields. Upper Bunter fields have the highest average permeability, but because of the lower sand thickness, the transmissivities are more equally distributed for all stratigraphies. The transmissivities are calculated with the full gas column net-height or net-sand thickness (whichever of the two is lowest) and are an upper estimate assuming the full height is available for inflow. The existing wells have not been perforated over the full height to keep a distance to any free reservoir water, and the partial perforations act as a ski, lowering well productivity. Well modelling can estimate the effect of this and also of tubing size limitations, as well as investigate new well designs that may increase productivity (e.g., horizontal). Such studies will then show whether a reservoir can provide the productivity required for UHS use cases and at what well cost.

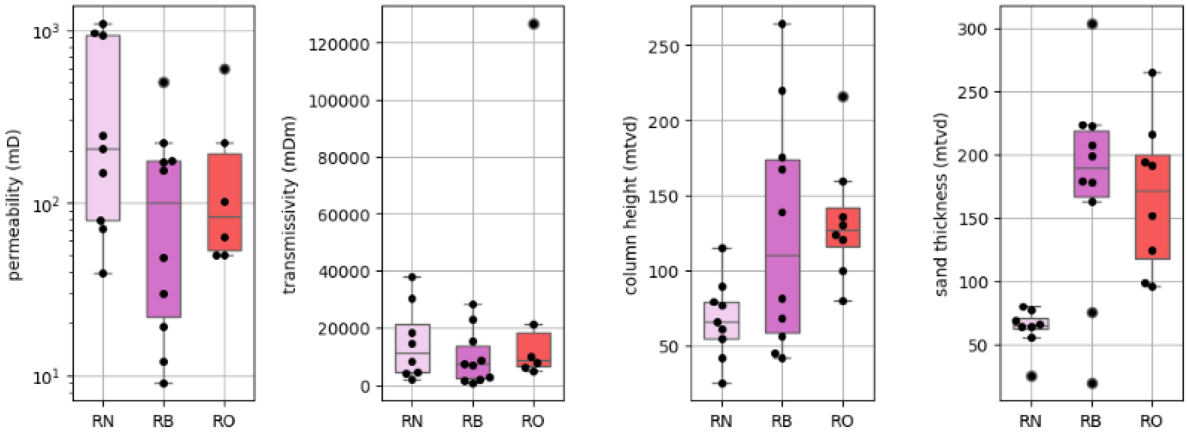

Figure 24 Distributions of field average permeability and transmissivity. Transmissivity is calculated as permeability times height, where height is taken as the minimum of gas column height and vertical sand thickness both also shown as distributions.

Another, more direct measure of well productivity is well tests, from which transmissivity can be derived. However, this data is often not publicly available. Monthly average production rates per well are publicly available, and although wells may not be produced at full rate, they do provide a minimum productivity and also a strong indication of low productivity if the rate is very low (< 0.4 MMm^3/d). Figure 25 shows that all fields have produced at rates > 0.5 MMm^3/d from a single well. And that half of the fields, all in the Middle Bunter and Rotliegend, have produced at rates of 1 MMm^3/d or more from a single well, which can be considered good productivity. The fact that wells in the Upper Bunter fields were not flowing at such high rates is more a reflection of the smaller size of these fields than their productivity.

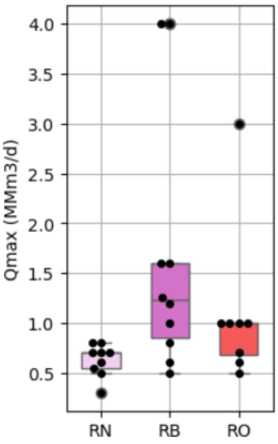

Figure 25 Distributions of the highest monthly production rate for individual wells in a field.

An interesting parameter to look at is the pressure depletion of the fields over their lifetime. The initial field pressures follow a well-known correlation with depth and are therefore higher in the Middle

Bunter fields. The distributions in Figure 26 and the map in Figure 28 show that the final pressures vary from close to the initial pressure down to as low as around 10 bar, and that there is no clear pattern. This variation is caused by differences in connectivity to an aquifer that can be limited by local features like faults and shale barriers.

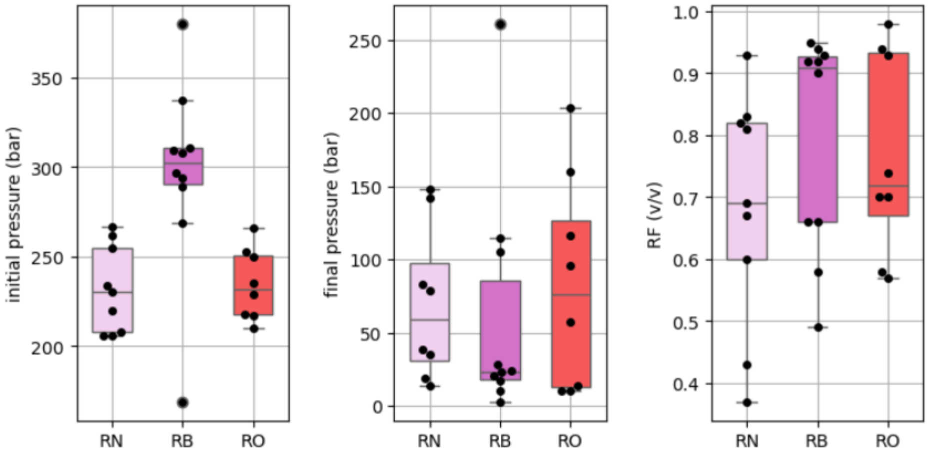

Figure 26 Distributions of initial and final reservoir pressures, and the recovery factor (RF) per field.

Field recovery factors are lower for higher final reservoir pressures (Figure 27), which is due to a combination of trapping of reservoir gas by water flood (~20%) and attic gas remaining in the reservoir after water reaches producers.

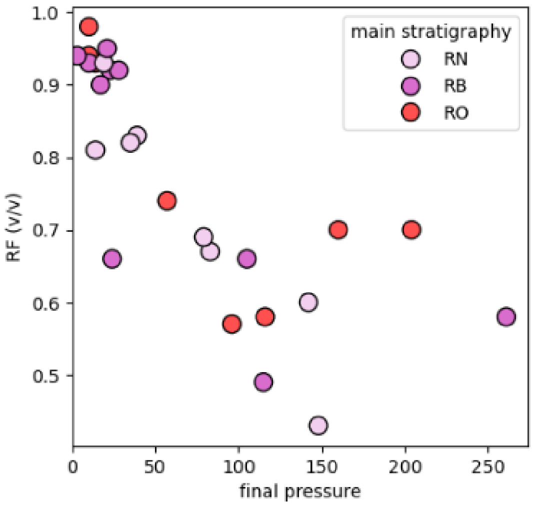

Figure 27 Correlation between field recovery factors and final reservoir pressures.

Behaviour of a UHS is expected to differ significantly between fields with and without aquifer support, and this has been studied by conceptual reservoir modelling in (Reijnen-Mooij et al., 2025).

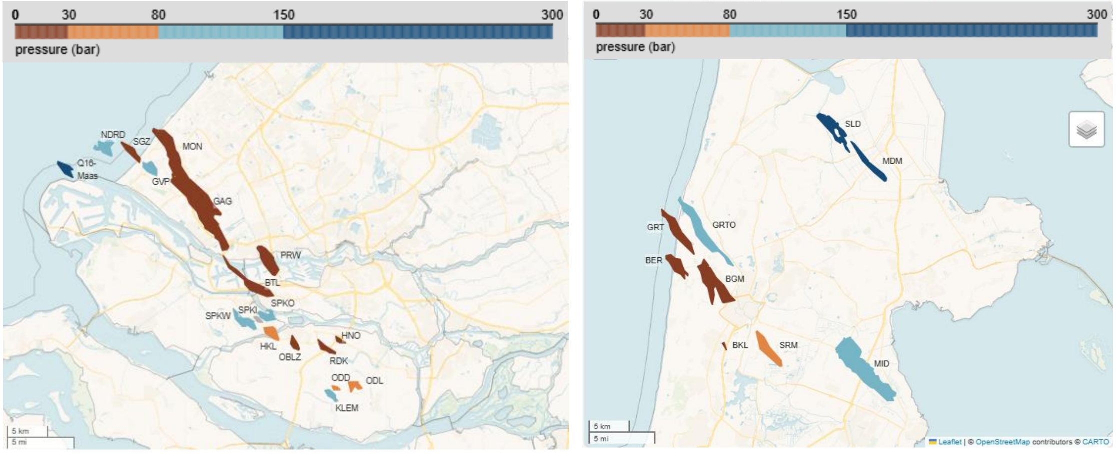

Figure 28 Map of the final pressures of the fields in Noord- and Zuid-Holland in this study.

Moreover, the production of fluids with the gas differs between fields, as shown in Figure 29, where the production of condensate is low in Rotliegend reservoirs in Noord-Holland and high in the Bunter reservoirs in Zuid-Holland (explained in the previous section by the source of charge). Water production is lowest in the Upper Bunter reservoirs.

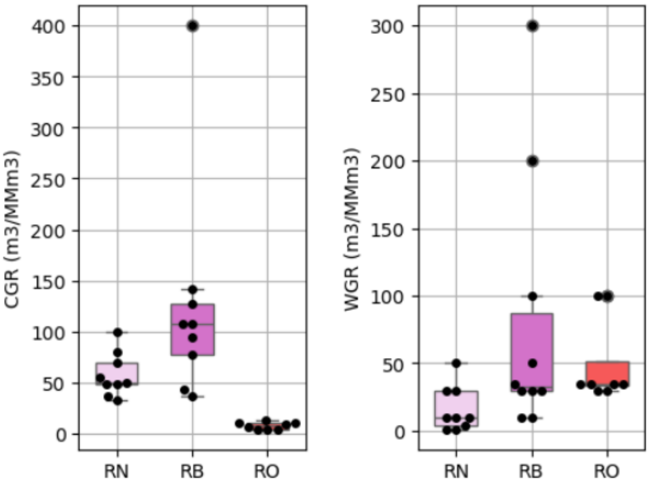

Figure 29 Distributions of producing Condensate Gas Ratios (CGR) and Water Gas Ratios (WGR).

The final parameter that is of interest is salinity, combined with temperature. The salinity and temperature of relevant formation waters of Triassic, Zechstein, or Rotliegend stratigraphy of approximate sampling data points are shown in the map below. Those measurements are plotted in a graph that compares critical temperature versus critical salinity for various cultivated strains of hydrogen-consuming microorganisms. A threshold has been identified above 1.7M NaCL and 55 °C, where microbial activity is anticipated to be minimal (Thaysen et al., 2021). Most data points from relevant reservoirs fall within this low-viability range. Although microbial activity under such extreme conditions, in the context of UHS, has been reported in salt cavern brine incubations, it was very limited (Dopffel et al., 2025). Microbial risks are therefore expected to be relatively low.

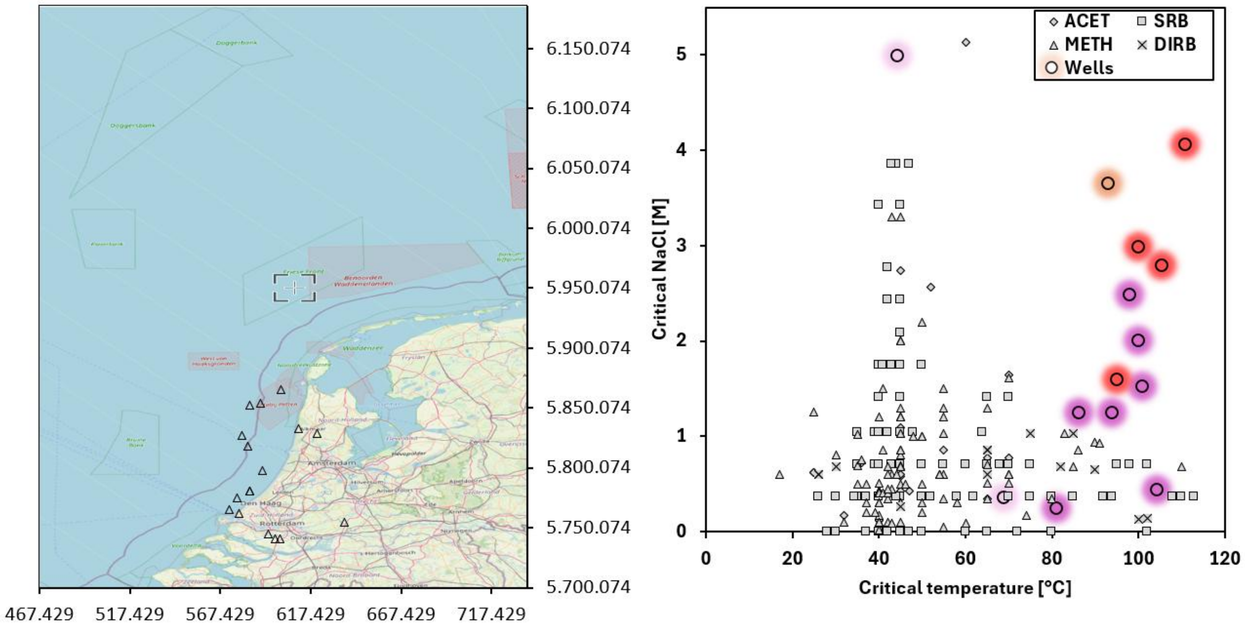

Figure 30 Available salinity data points (left) and how they plot in the critical temperature versus critical salinity for major hydrogenotrophic microorganisms (right). ACET: homoacetogens, METH: methanogens, SRB: sulphur species reducing microorganisms and DIRB: direct iron reducing bacteria, colours indicate the different stratigraphies. Created by Jari van Willigen (WUR) related to HyTROS ST5.1.

7 Conclusions

The Netherlands has a large number of depleted gas fields providing a substantial opportunity for UHS. The demand for UHS is expected to materialize first in the industry-rich western part of the Netherlands, in the provinces of Noord- and Zuid-Holland. This report compiles characteristics of the depleted gas fields in these provinces that are relevant for UHS. Ranges are determined for key average reservoir parameters such as depth, thickness, permeability, pressure depletion, and producing fluid properties, as well as geological characteristics like top seal, waste zones, and shale barriers.

Based on the parameter ranges in Figure 22-Figure 29, the three groups of fields can be characterised as follows:

1. Rotliegend fields, all located in Noord-Holland, are sizable GIIP (1-10+ bcm) with good permeability (50-500 mD) and low CGR (< 40 m3/MMm3). They are homogeneous without continuous shale barriers to vertical flow, and some fields have a 20-50 m low-permeability waste zone (Weissliegend) at the top.

2. Upper Bunter fields, which are located to the South and South-East of Rotterdam, are smaller GIIP (three fields < 0.3 bcm) and four fields ~ 1 bcm with excellent permeability (50-1000 mD) and higher CGR (~50 m3/MMm^3). They do have continuous shale barriers that split the reservoir into several layers and lower the N/G.

3. The remaining fields where Middle Bunter is the dominant stratigraphy, close to and to the West of Rotterdam, are mostly also sizeable GIIP (0.5-10+ bcm) with good permeability (10-500 mD) and high CGR (40-150 m^3/MMm^3). The fields are located deeper and therefore have

lower porosity, with a few exceptions. No continuous shale barriers are present in the Middle Bunter, but they are present in the overlying Upper Bunter sands. As these sands are getting thinner and of lower quality to the West, they act more as a waste zone than a reservoir (see Figure 27).

A large range of abandonment pressures (10-200 bar) is present in all groups, without a clear pattern (see Figure 28). This is probably dependent on local features like faulting and flow barriers that impact the connectivity of the reservoir to the aquifer.

These ranges support the transfer of insights from UHS projects in depleted reservoirs abroad or analogue fields to Dutch gas fields that may be considered for UHS (demonstration) projects. Additionally, these parameter ranges provide a foundation for constructing reservoir models. However, to accurately predict UHS behaviour and assess the suitability of individual fields for hydrogen storage, a more detailed analysis of the spatial variability of properties within reservoirs is required.

With this report we characterized depleted gas fields that can be candidates for UHS in Noord-Holland and Zuid-Holland. This works forms input to demonstrator selection and further field specific analysis needed for UHS developments in the Netherlands.

Acknowledgements

The data collection in bulk and the analyses in section 3 were made with Python code developed at TU Delft within the HyTROS project. The public data collected manually by EBN for section 6 in this study was reviewed and, in a few cases, supplemented by the 4 operator companies of the fields: TAQA, NAM, ONE-Dyas, and Vermilion.

References

Bo, Z., Boon, M., Hajibeygi, H., Hurter, S. Impact of experimentally measured relative permeability hysteresis on reservoir-scale performance of underground hydrogen storage (UHS). international journal of hydrogen energy 48 (36), 13527-13542. https://doi.org/10.1016/j.ijhydene.2022.12.270

DINOloket v2.5, TNO – GDN, 2025, *TNO – Data and Information on the Dutch Subsurface,* https://www.dinoloket.nl/webservices

Dopffel, N., Mayers, K., Kedir, A., An-Stepec, B.A., Beeder, J., & Hoth, S., 2025, Exploring Microbiological Dynamics in a Salt Cavern for Potential Hydrogen Storage Use. Environmental Microbiology Reports, 17(2), e70064. https://doi.org/https://doi.org/10.1111/1758-2229.70064

GEODE, EBN-TNO, 2023, *GEODE Atlas of deep subsurface resources in the Netherlands.* Accessed JAN 2025, https://geodeatlas.nl

Gast, R., Breitkreuz, C., Gaupp, R., Geluk, M. C., Glennie, K., Jones, N., Kabel, S., Kiersnowski, H., Schneider, J., Steenbrink, J., & Stemmerik, L., 2010, *Chapter 7: Rotliegend*. In K. Glennie (Ed.), *Petroleum Geological Atlas of the Southern Permian Basin Area* (pp. 100–121). European Geological Surveys. Retrieved from https://www.nlog.nl/sites/default/files/2018-12/spba-chapter7.pdf

Hashemi, L., Boon, M., Glerum, W., Farajzadeh, R., Hajibeygi, H., A comparative study for H2–CH4 mixture wettability in sandstone porous rocks relevant to underground hydrogen storage. Advances in Water Resources 163 (2025) 104165 https://doi.org/10.1016/j.advwatres.2022.104165

Huynh, N. D., Wagner, M. Hystories *Synthesis of the risks and actions to correct these risks depending on the environment* Hystories D3.4 https://hystories.eu/wp-content/uploads/2023/12/Hystories_D3.4-0-Microbial-risks-and-mitigation-measures.pdf

van Klaveren, S.D., Reijnen-Mooij, G.C.A.M., and Jaarsma, B., 2025, Portfolio-analyse geschiktheid Nederlandse gasvelden voor ondergrondse waterstofopslag https://www.ebn.nl/feiten-en-cijfers/kennisbank/portfolio-analyse-geschiktheid-nederlandse-gasvelden-voor-ondergrondse-waterstofoplag/

van Rooijen, W.A., Hajibeygi, H., Site Selection for Underground Hydrogen Storage in Porous Media: Critical Review and Outlook, Energy & Fuels (2025) https://doi.org/10.1021/acs.energyfuels.5c03665

Korevaar, S., R. Dalman, S. Nelskamp, S. Atkins, E. Boter, E. Wiarda, M. Nolten, and K. Beintema, 2023, GEODE Triassic play 5

Kombrink et al, 2012, New insights into the geological structure of the Netherlands; results of a detailed mapping project

Kortekaas, M., Bouroullec, R., Peeters, S., van Unen, M., Swart, M., den Hartog Jager, D., E. Wiarda, Nolten, M., and Beintema, K., 2023, GEODE Rotliegend play 7

Laier, T., and Øbro, H., Environmental and safety monitoring of the natural gas underground storage at Stenlille, Denmark, 2009, Geological Society, London, Special Publications 2009; v. 313; p. 81-92, doi:10.1144/SP313.6

Muntendam-Bos, A., Hoedeman, G., Polychronopoulou, K., Draganov, D., Weemstra, C., van der Zee, W., Bakker, R.R., Roest, H., 2022, An overview of Induced Seismicity in the Netherlands: Netherlands Journal of Geosciences, 101, https://doi: 10.1017/njg.2021.14

Naranjo, D., Isken, M., Boullenger, B., Toledo, T., Weemstra, C., and Draganov, D., 2025, Urban challenges in seismology: Seismic monitoring of Kwintsheul's geothermal operation (The Netherlands): Netherlands Journal of Geosciences, accepted.

Nederlands Olie- en Gasportaal (NLOG), TNO - Geologische Dienst Nederland namens Ministerie van Economische Zaken, 2025, https://nlog.nl

Netbeheer Nederland Scenario's Editie, 2025, https://www.netbeheernederland.nl/publicatie/netbeheer-nederland-scenarios-editie-2025

Okoroafor, E.R., Saltzer, S.D., Kovscek, A.R., Toward underground hydrogen storage in porous media: Reservoir engineering insights, International Journal of Hydrogen Energy, 2022, https://doi.org/10.1016/j.ijhydene.2022.07.239

Ossetchkina, K., Riahi, R.S., Haagenson, R., Almahmoudi, Draganov, D., Geiger, S., Hajibeygi, H., 2025, A Digital Portal for Integrated Analyses of Dutch Subsurface Data Sets, Python Code, TU Delft Repository

Port of Rotterdam, Hydrogen in Rotterdam, 2025, https://www.portofrotterdam.com/en/port-future/energy-transition/ongoing-projects/hydrogen-rotterdam

Provincie Noord-Holland, 2025, Waterstofprogramma 2025-2027, https://www.noord-holland.nl/Onderwerpen/Klimaat_Energie/Duurzame_energie/Waterstof

Reijnen-Mooij, G.C.A.M., van Klaveren, S.D., Jaarsma, B., and Godderij, R., Impact of abandonment pressure on hydrogen storage in onshore gas fields in the West Netherlands, 2025, 6th EAGE Conference and Exhibition on Global Energy Transition – GET 2025, EAGE Hydrogen and Energy Storage Conference

SEAL ENERGY, Dynamic modelling of the Fenton Creek gas field, Onshore Otway Basin, Victoria, Victorian Gas Program Technical Report 43, 2020, Geological Survey of Victoria. Department of Jobs, Precincts and Regions. Melbourne, Victoria. 55p. url: https://resources.vic.gov.au/projects/past-projects/victorian-gas-program/gas-storage

TAQA Energy B.V., Final Wellsite Geological Report Production Well GRöt-Oost-1 ST1 (GRO-01S1), 2012, https://www.nlog.nl/brh-web/rest/brh/document/1091161823

Technology Monitoring Report, 2023, p. 34, hydrogen TCP Task 42 Underground Hydrogen Storage

Thaysen, E.M., McMahon, S., Strobel, G., Butler, I., Ngwenya, B., Heinemann, N., Wilkinson, M., Hassanpouryouband, A., McDermott, C.I. and Edlmann, K., Estimating Microbial Hydrogen Consumption in Hydrogen Storage in Porous Media, 2021, Renewable and Sustainable Energy Reviews, vol. 151, p. 111481

Thaysen, E.M., Armitage, T., Slabon, L., Hassanpouryouzband, A., Edlmann, K., Microbial risk assessment for underground hydrogen storage in porous rocks, 2023, Fuel, vol. 352, p. 128852

ThermoGIS v2.5, TNO – GDN, 2025, TNO - Geological Survey of the Netherlands (Ed.), https://www.thermogis.nl/en

ten Veen, J.H., Vis, G.-J., De Jager, J., & Wong, T.E., 2025, Geology of the Netherlands, Chapter 1, 4 and 5, Amsterdam University Press