Overview of geological characteristics and expertise relevant to assess the geological safety case for deep borehole disposal in the Netherlands

A report by the Geological Survey of the Netherlands

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Introduction

1 Summary (ENG)

Long term containment is the main requirement for a geological radioactive waste disposal facility. Deep borehole technology can provide a natural barrier for containment of kilometers in thickness offers a robust natural containment solution and is feasible using deep borehole technology. Stagnant hydraulic conditions in ultra-deep sedimentary formations, along with the ultra-thick barrier between the canisters and the surface or biosphere, can significantly enhance long-term containment robustness compared to mined repositories in for example clay or salt in the shallow subsurface. To explore the possibilities of radioactive waste disposal in the ultra-deep subsurface of the Netherlands, the first step is to characterize the geology from surface down to around 5 kilometers.

An overview of the typical characteristics of the geological safety case for disposal in deep boreholes includes data on formation composition, temperature, pressure, mechanics, structure, fluids, and thermodynamic parameters for modelling reactive fluid transport for the systems safety assessment. Acquiring detailed data at such depths is often costly and complex. The Netherlands has sufficient data, models, and expertise to initiate an exploratory study to develop a framework for assessing the geology for ultra-deep disposal of waste in the deep borehole concept.

These endeavors will require strong collaboration between GDN-TNO, industry, universities, and government entities to bring the best data, models, knowledge, and innovative minds and provide the required conditions to make the case for safe and sustainable future deep borehole disposal in the Netherlands

2 Samenvatting (NL)

Veilige en langdurige isolatie is de belangrijkste eis voor een geologische eindbergingsfaciliteit voor radioactief afval. Diepe boorgattechnologie biedt een natuurlijke barrière van enkele kilometers dik en vormt zo een robuuste natuurlijke oplossing voor isolatie. De stilstaande hydraulische condities in diepe sedimentaire formaties en de extreem dikke barrière tussen de het radioactieve afval en de biosfeer, verbeteren de robuustheid van langdurige isolatie aanzienlijk in vergelijking met mijnbouwopslag in bijvoorbeeld klei of zoutlagen in de ondiepe ondergrond. De eerste stap om de mogelijkheden van eindberging in de ultradiepe ondergrond van Nederland te onderzoeken is het karakteriseren van de geologie vanaf het oppervlak tot ongeveer 5 kilometer diepte.

Een overzicht van de typische kenmerken van het geologische veiligheidsdossier voor eindberging in diepe boorgaten omvat gegevens over de eigenschappen van de formaties: temperatuur, druk, mechanische eigenschappen, structuur, vloeistof- en thermodynamische parameters voor modellering van vloeistofmigratie. Het verzamelen van gedetailleerde gegevens op dergelijke dieptes is vaak kostbaar en complex. Nederland beschikt echter over voldoende gegevens, modellen en expertise om een verkennend onderzoek te starten en een kader te ontwikkelen voor de beoordeling van de geschiktheid van de geologie voor ultradiepe opslag volgens het concept van diepe boorgaten.

Deze inspanningen vereisen een sterke samenwerking tussen GDN-TNO, industrie, universiteiten en overheidsinstanties om de beste gegevens, modellen, kennis en innovatieve ideeën optimaal te benutten en de noodzakelijke voorwaarden te scheppen om een veilige en duurzame toekomst voor diepe boorgatopslag in Nederland mogelijk te maken.

3 Introduction

The Dutch government announced that the preparations will now start for the decision-making process on the final disposal of radioactive waste. One of the steps to be looked into is the development of a disposal program investigating the various types of a final disposal. COVRA has explored options for subsurface disposal of radioactive waste, focusing on the current baseline strategy of constructing repositories within salt formations homogeneous clay layers [www.covra.nl]. Proposed disposal depths range between 300 and 800 meters, depending on local geological conditions. Currently, TNO is investigating advanced drilling technologies for creating large-diameter (1.5 meters), ultra-deep (up to 5 kilometers) boreholes (Figure 1).

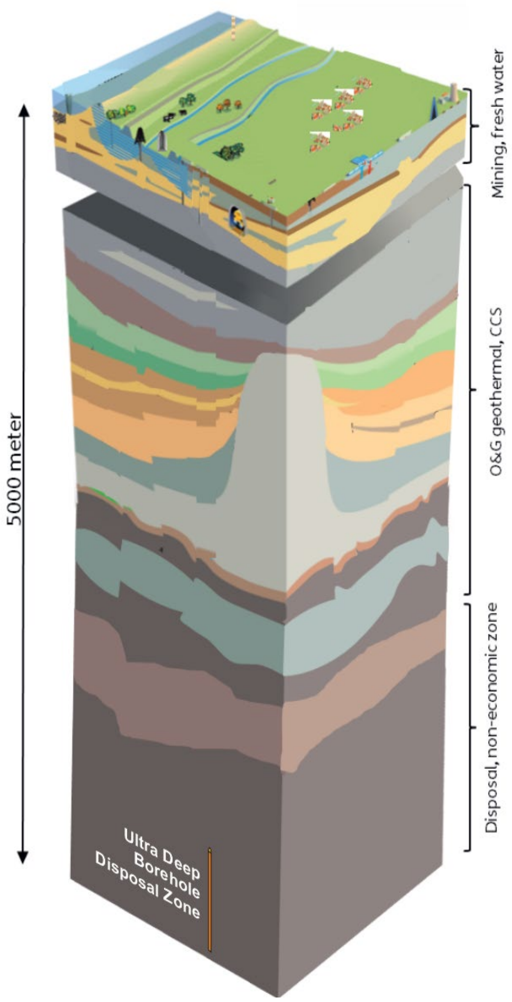


Figure 1. shows a conceptual model of subsurface and how the disposal, non-economic zone has no interaction with other subsurface activities (e.g., geothermal, energy storage, CCS, mining or oil and gas activities) and offers a solution for potential storage of waste at these depths.

This innovative concept offers significant advantages for the disposal of radioactive waste in ultra-deep geological formations. A mined repository is excavated at depth in hydrologically active formations close to the biosphere. Water transport can occur at rates of up to meters per day, involving either fresh water or brackish formation water. Engineered canisters containing radioactive waste must be shielded from corrosion-inducing water to maintain the long-term integrity of the canister and the engineered barrier. This necessitates a non-permeable shielding host formation in which the radioactive waste disposal mine is constructed. Clay and salt are proven non-permeable formations and are considered suitable. However, locations where these formations are present close to the surface with sufficient homogeneity and thickness are not widespread and only available in specific parts of the Netherlands.

While the non-permeable properties of the host formation close to the surface are of high importance, the host formation at ultra-deep depths is less critical. As the kilometers-thick formation between the canisters and the surface acts as a substantial robust barrier, which provides natural, impermeable containment, isolating waste from the biosphere. Unlike near-surface formation hydrology, physical fluid transport at great depths is known to be stagnant, and physical fluid transport-induced corrosion is expected to be absent. Although diffusion-induced migration of molecules will occur, the mass transport is extremely low, requiring timescales of millions of years before centimeters of metal can be compromised, which is much longer than required. Both the kilometers-thick sedimentary barrier and the absence of physical fluid transport will contribute to strengthening the post-closure safety case, which is the essential function of a geological disposal infrastructure to secure long-term containment for post-closure safety. The robustness of long-term containment in the subsurface is enhanced with increasing depth of disposal.

3.1 Geology relevant for Deep Borehole Disposal

While the shallow subsurface is accessible for the construction of mined-based repositories, characterizing the deep subsurface poses new challenges including obtaining detailed knowledge of the considered geological formations, their history, and properties. These factors are essential for conducting post-closure safety assessments of any geological disposal facility. Access to substantial and high-quality geological data is therefore crucial for initial assessments, as it supports the evaluation of the host formation's barrier function and overall suitability of the considered potential site. However, acquiring this data, along with the expertise and models required for such evaluations, involves substantial effort.
The Netherlands has a unique advantage in this regard, having developed one of the world's most detailed national subsurface set of databases. This achievement is due to the extensive amount of data acquired by the oil and gas industry, coupled with national policies mandating the collection and storage of geological data by the Geological Survey of the Netherlands, part of TNO. Currently, there is growing interest in cataloging and categorizing the available geological data, expertise, and models related to the deep subsurface. This effort aims to establish a foundational national assessment framework for evaluating the feasibility of ultra-deep geological waste disposal in large-diameter boreholes.
This report provides an introductory overview of the geological properties, data, expertise, and models readily available for assessing the deep subsurface of the Netherlands. Emphasis here is placed on their applicability for long-term geological containment, ideally exceeding a time scale of one million years. The report discusses established and emerging technologies that can advance the study of deep borehole disposal and what data, information, facilities, and expertise does the Netherlands possess to tackle this disposal question.

Disclaimer: This report provides an extensive but non-exhaustive list of Dutch dataset, research, and laboratories relevant to the topic of Deep Disposal, with a special focus on the capabilities of the Geological Survey of the Netherlands (GDN-TNO).

3.2 Emerging technology and drilling deep borehole

Drilling of deep boreholes (>3 kilometers) is a well-established industry in the Netherlands. In comparison, deep borehole disposal offers a substantial thick geological barrier between radioactive waste and the biosphere at depths of approximately 5 kilometers. This enhanced barrier is regarded as a significant improvement in post-closure safety over geological timescales (millions of years). The subsurface of the Netherlands has been very stable in the last 20 million years with the most recent period of substantial geological deformation occurring during the Early Oligocene (Knox et al., 2010). The safety margin is further strengthened by the stagnant or absent fluid transport typically observed at such depths. Although deep borehole drilling is routine current diameters drilled at depth are small typically ranging from 4 to 7 inches (10.1-17.8 cm) and rarely drill beyond 3-4 km. By contrast, the canisters used to encapsulate radioactive waste have much larger diameters, for example in the range of 40 inches (100 cm). One potential approach to utilize existing borehole drilling technology involves designing smaller-diameter canisters. However, this solution presents specific challenges, including the need to repackage radioactive material from large-diameter canisters into smaller ones. Additionally, oil and gas wells are not designed for the emplacement and retrieval of canisters but for fluid extraction, requiring specifications fundamentally different from those of disposal wells.

Emerging drilling technologies capable of creating large-diameter boreholes may offer a transformative solution. TNO, in collaboration with a consortium of Dutch companies, is currently investigating technologies to drill vertical boreholes with diameters of 1.5 meters to depths of up to 5 kilometers. This capability would enable the direct disposal of current large-diameter canisters, eliminating the need for overpacking. Furthermore, the large diameter would provide sufficient space to incorporate emplacement constructions with redundant safety mechanisms, ensuring higher operational safety. The increased diameter also significantly expands the available volume for canister emplacement. For example, a single borehole drilled to 5 kilometers depth with a 4-kilometer containment barrier would provide approximately 1,000 cubic meters of usable volume. At present the Netherlands has approximately 110 cubic meters of high-level, long-lived radioactive waste needed for disposal. Therefore even with the new ambitions for low-carbon electricity production through nuclear power, a single large-diameter ultra-deep borehole provides sufficient disposal volume for future generations.

4 Barrier Concept

4.1 Overview of the subsurface and barrier in the context of sedimentary basins

The geology of the Netherlands is defined by its sedimentary basins, large zones in the Earth's crust where sediments such as sand, clay, salt, and carbonates have accumulated over hundreds of millions of years due to gradual sinking (subsidence) of the Earth's crust. These sediments, transported primarily by water and wind, compact and lithify over time, forming a thick and diverse sequence of sedimentary rocks in the subsurface of the Netherlands. Unlike regions such as Scandinavia, which are dominated by uniform crystalline rocks like igneous and metamorphic formations, sedimentary basins are highly heterogeneous, with complex layering that extends to depths of more than 9 kilometers (See Figure 2).

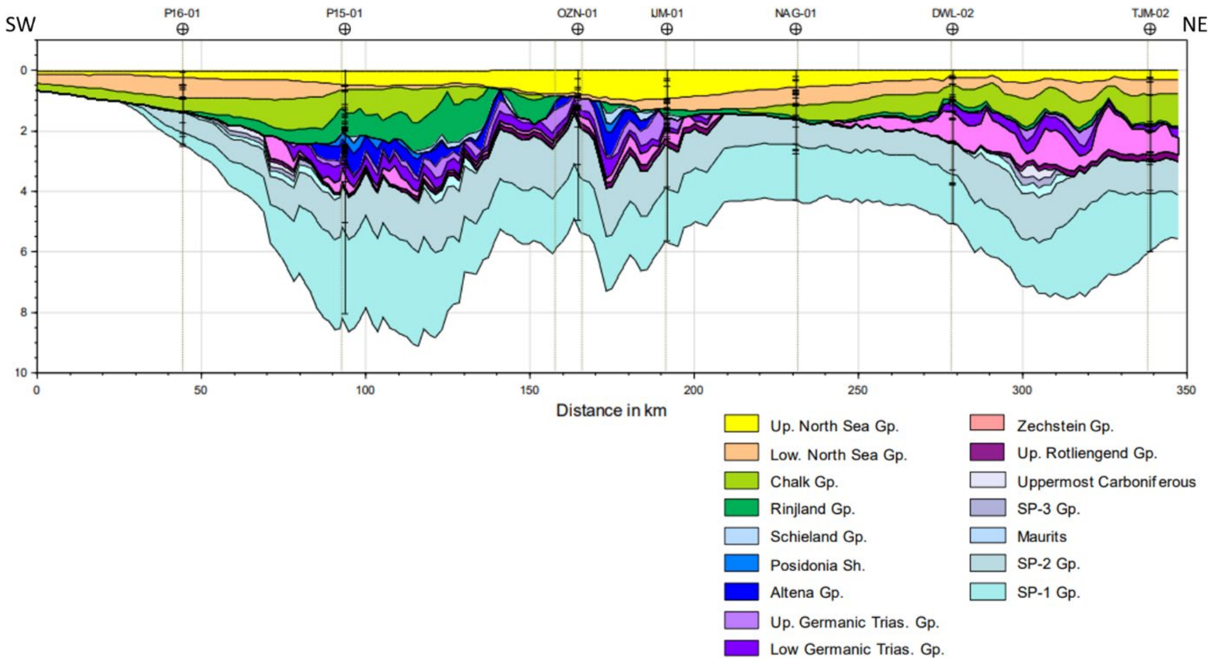


Figure 2: Cross-section of the onshore subsurface of the Netherlands from southwest to northeast. Note that every group that is described in this cross section itself consist of different formations down to the Namurian (SP-1) which rocks were deposited as sediments more than 320 million years ago and since buried down to 9 km locally. Modified from Bouroullec et al., 2019.

One of the key features of sedimentary basins is their natural heterogeneity, with layers varying in composition, permeability, and thickness. In the Netherlands, this includes sequences of sandstone, carbonate rocks, and impermeable layers such as evaporites and clay. Several of these layers are naturally occurring seals and are effective geological barriers.

In engineered repositories, salt and clay are often considered for disposal because they are naturally impermeable and have the ability to flow slowly, sealing any fractures. In the Dutch subsurface, multiple layers of these impermeable materials are stacked on top of each other, providing an even more robust system of seals. These thick, impermeable formations—combined with the multilayered structure—offer an additional natural containment advantage and is proven to be the ideal environment for trapping fluids such as hydrocarbons or hydrogen over tens to hundreds of millions of years.

The heterogeneous nature of the sedimentary basins enhances their ability to act as a long-term containment system. Faults and salt bodies within the basins provide additional structural complexity, potentially contributing to the safety and stability of the geological seals. The presence of multiple impermeable layers ensures that even if one layer were to be compromised, others would continue to provide a barrier, reducing the risk of leakage. These characteristics make sedimentary basins have significant natural safety features, providing containment.

The geological safety case is defined here as the containment function of the formation to ensure long term separation of radioactive waste from the biosphere. To evaluate the deep subsurface containment characteristics, a geological assessment must be done. This requires an overview of the relevant data, models, and expertise. The relevant subsurface characteristics that should be included in the geological safety case for deep borehole disposal are listed below in 4 distinct categories. Geological stability, natural barrier function, thermal and mechanical behaviour, and geochemical conditions (Table 1). While these characteristics can also be relevant for assessing a mining repository, a deep borehole disposal involves a kilometre thick, robust formation barrier. Therefore, a more extensive assessment of these criteria is required.

Table 1: Key subsurface characteristics relevant to Deep Disposal in sedimentary basins

Geological stability	**Natural barrier function**	**Thermal and mechanical behaviour**	**Geochemical conditions**
Plate tectonics	Permeability	Temperature	Hydrogeology
Seismicity	Heterogeneity	Pressure	Hydraulic flow
Volcanism	Lithostratigraphy	Stress regime	Mineralogy
Faulting	Porosity		Diagenesis
Salt tectonics			Isotopes
Glaciation			

Geological stability

Ensuring geological stability is crucial for the safe disposal of radioactive waste over the long time required for radioactive decay, typically 1 million years. This involves understanding key geological factors such as **plate tectonic processes**, **seismic activity**, **faulting**, salt tectonics **volcanism**, and potential future **glaciations**. On a geological timescale, 1 million years is brief compared to the slower, large-scale processes such tectonic movements or volcanism. For context, the last volcanic activity in the Netherlands occurred during the **Cretaceous period**, roughly 70 million years ago, when North America separated from Europe and the Atlantic Ocean began to form. Salt tectonics may play a role in the stability of the subsurface due to the ductile behavior of salt at depth, but most salt diapirs present in the Netherlands are located in the northern part of the Dutch offshore and the northern part of the onshore. A large part of the Dutch onshore is devoid of salt diapirs (Bouroullec and ten Veen, 2025).

Glaciations, by contrast, occur on much shorter timescales, potentially within the 1-million-year period relevant to waste disposal. While glaciations can drastically alter surface landscapes through local erosion, they have no significant impact at the depths relevant for **deep borehole disposal**. Glacially induced subsidence due to loading of the crust by thick glaciers can affect the sedimentary basins underneath but would only increase the burial depth of potential disposal sites by a few hundred meters. In a similar fashion, glacial retreat would allow for the Earth's crust to move back up (isostatic rebound) and bring the disposal site back, potentially to its original burial depth. Processes such as **sea-level changes** and glaciations typically affect only the uppermost layers of the Earth's crust, to depths of around 1000 meters or less (Ten Veen, 2015). At depths in the range of 4 to 5 kilometers **such** surface processes are irrelevant.

Natural Barrier Function

For the disposal of radioactive waste, the safety remains upon the barrier which is with Ultra-Deep Disposal that relies on the thickness of the overlying rocks as a safety barrier rather than on the isolating properties of the rock surrounding the waste (which is the case for mined solutions). The potential benefit of Ultra-Deep Disposal is the considerable level of isolation from the biosphere, with effective containment primarily dependent on natural barriers, that are all the different rock types that are present in the subsurface in the Netherlands. Unlike crystalline rock formations the subsurface of the Netherlands is highly heterogeneous, which forms the natural barrier of the Ultra-Deep Disposal concept. This heterogeneity of the subsurface forms one of the most important aspects for the vast robustness and redundancy of the barrier function and consists of different lithologies, including natural impermeable layers (e.g., salt and clay). The different geological layers and their lithologies are well known in the Dutch subsurface. These different lithologies have different porosity and permeability which are important parameters for accessing hydraulic flow and therefore potential migration of nuclides. Impermeable layers are important to prevent fluid movement. In a sedimentary basin setting, porosity decreases with depth due to the increasing pressure which is a result of the compaction and cementation of the overlying sediments, creating a natural seal (Scott, 2015). Permeability at a certain depth is dependent on porosity and pressure. Data for permeability, porosity and pressure can be derived from well data. In the case of the barrier function, the capacity of multiple stacked layers to properly seal the disposal site should be analysed with a focus on pressure, permeability and porosity which can determined based on lithology.

Thermal and Mechanical Behaviour

At depth, temperature and pressure rises. Pressure estimation is important for drilling parameters design and borehole mechanical stability; temperature has a catalyst effect on chemical reactions and impacts the mechanical behavior of minerals and rocks. While pressure depends on depth, lithology density, and compaction processes; the temperature is determined by the geothermal gradient, that in sedimentary basins typically varies from 15 to 35°C per kilometer. For the Netherlands, the average temperature at 4 and 5 km depths is between 120 and 175 °C, respectively. Pressure and temperature are stable parameters at ultra-depth conditions, particularly under static scenario of radioactive waste disposal in a borehole. Its characterization is key for the system design and the modelling of processes involved in the containment of radionuclides in the long term.

Geochemical Conditions

Understanding the geochemistry of the subsurface, including mineralogy, pH, redox potential, and the presence of corrosive elements in the formation water and thereby assessing the potential for chemical reactions between waste, engineered materials, and host rock is essential for disposal. With mined repositories one of the biggest concerns is the influence of groundwater. At depths of 4 to 5 km, investigations into flow within sedimentary sediments, have revealed no propensity for flow systems to develop, even in thin formations (tens of meters), within the timescales for disposal safety (Chapman and Gibb, 2003). Under negligible fluid flow conditions (the design aims for geological intervals with extremely low porosity and permeability due to compaction and mineral composition), the chemical gradient at the host rock is the main driver for radionuclide movement due to diffusion which is the dominant transport process. An accurate characterization of the initial geochemical conditions and its evolution will enable the representative modelling of the complex reactions involved in the retention process (sorption, ion exchange, precipitation/dissolution, complexation, etc.).

5 Geological data and relevant knowledge from the Geological Survey of the Netherlands

5.1 The Geological Survey of The Netherlands GDN-TNO

TNO, or the Netherlands Organisation for Applied Scientific Research, is an independent research organization in the Netherlands. Established in 1932, TNO focuses on applied scientific research to create practical solutions for societal challenges. The Geological Survey of the Netherlands , https://www.geologischedienst.nl/en/) is part of TNO (GDN-TNO), as the principal centre of expertise for geo-information and geoscientific expertise of the Dutch subsurface with approximately 300 scientists . The GDN is located across 3 sites in the Netherlands, primarily in Utrecht, with facilities in Zeist and Rijswijk, and is the knowledge and data centre for the Dutch subsurface and subsurface research. GDN-TNO helps businesses and governments make well-informed, sustainable decisions about the energy transition in the subsurface, groundwater stewardship, and land utilization. The GDN-TNO works with a variety of stakeholder ranging from governments (National and EU), industry partners and academic institutions.

GDN is responsible for the statutory tasks defined by the government stakeholders as well as R&D with and for national and international organizations in the fields of subsurface use for energy extraction and storage, ground subsidence, groundwater, and critical raw materials (Figure 3).

The GDN has a wide spectrum of research disciplines which can help in assessing the geological safety case for radioactive waste. The GDN subsurface research and modelling teams focuses on interpreting and analyzing the Dutch subsurface by compiling relevant datasets, creating state-of-the art workflows, and establishing detailed geological models at various scales of investigations and depths. These approaches promote sustainable subsurface uses and reduce exploration and storage risks for subsurface activities. The research spans various disciplines including geology, geochemistry, geophysics, reservoir modelling/ optimization and geomechanics.

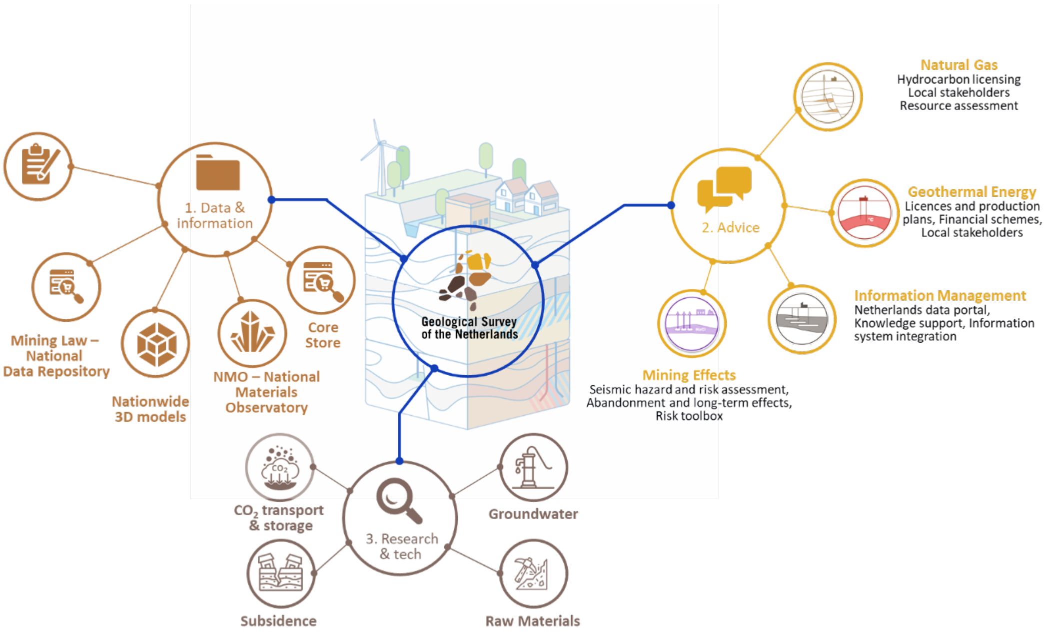


Figure 3. Overview of the distinct role and responsibilities of the GDN

Geology

The GDN geological expertise is broad with geologists active in multiple teams, from reservoir geology, exploration geology, shallow subsurface modelling and deep subsurface modelling as well as working on various subsurface applications such as groundwater, energy storage (CCS and hydrogen), geothermal, critical raw materials, windfarms, and subsidence risks. The GDN-TNO geological research and modelling teams have a strong focus toward building knowledge and concepts that allow a sustainable use of the subsurface and exploration risk mitigation. The research disciplines include sedimentology, stratigraphy, structural geology, biostratigraphy, and basin modelling (Figure 4). The research is routinely conducted in a multi-disciplinary manner using established and innovative techniques. GDN geoscientists are involved in subsurface research in the Netherlands and abroad, with projects and collaborations covering the British, Norwegian, Danish, German, Belgium subsurface as well as projects in the Middle East, Asia and Africa, in collaboration with international and local industries and government organizations. The main techniques (and associated dataset) deployed by the geologists are:

- sedimentological analysis (cores and outcrops),
- petrographic analysis
- petrophysical and electro-facies analysis (wireline logs),
- palynological analysis (core and cuttings),
- stratigraphic analysis (core, wireline logs, outcrop and seismic),
- 2D/3D seismic interpretation, including regional to local-scale mapping, seismic stratal slicing, seismic amplitude mapping,
- geological modelling (from reservoir- to basin-scale)
- mineralogical and provenance analysis (core, shallow borehole, and outcrop),
- structural geology (core, wireline logs, seismic, outcrop), including salt tectonics, fault kinematic analysis, damage zone parameterization, palinspastic restoration, AI-driven fault interpretation and photogrammetric outcrop analysis characterization of outcrop analogue
- numerical simulations: coding/programming, developing applications
- conventional and digital (Gamma Ray, XRF, photogrammetry) outcrop characterization

- basin modeling and petroleum systems analysis, including burial/uplift modeling, compaction evaluation, subsurface fluid flow analysis, geochemistry, source rock maturity/expulsion modelling, and heat flow parameterization.

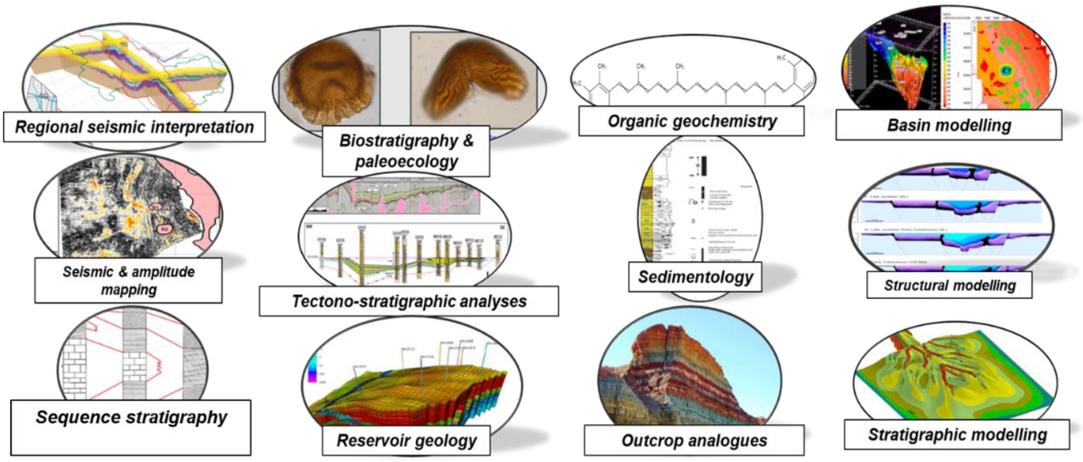


Figure 4: GDN-TNO subsurface research. Some of the key techniques used to investigate the deep subsurface.

Geochemistry

At GDN, geochemical research of the deep subsurface focuses on characterizing sediments and pore/groundwater and modelling their geochemical reactions. This work includes data acquisition by laboratory analyses of cores, data processing, modelling with geochemical software to understand the geochemical processes occurring or to predict future processes. Examples of expertise areas are the geochemical modelling of geothermal systems, underground thermal energy storage systems and subsurface CO_2 storage. The effects of long-term storage of heat or gases on reservoir rock and caprock, such as mineral precipitation, cement alteration and well integrity are also analyzed. Additionally, the effects on groundwater quality and the shallower environment are investigated by both groundwater sampling and geochemical modelling. In addition, geochemical characterization of sediments is routinely done for our core drilling program TOPINTEGRAAL, but also for specific research on potential host rocks for radioactive waste storage. Our laboratory facility at Rijswijk facilitates (more details, see section 3) upscaling of smaller laboratory experiments e.g. leaching of heavy metals from grouts and the testing of the effectiveness of ‘green’ filters for geothermal usage. Some geochemical analysis is done to target the deep subsurface such as stable-, sulphur- and clumped isotope analysis, XRD/XRF minerology and fluid composition analysis, providing valuable information to understand the geology and the evolution of the geological systems through time.

Geophysics

The geophysical research at GDN focuses on novel techniques and methods to characterize the subsurface and monitor activities by data acquisition, processing, interpretation, modelling, and inversion utilizing Machine Learning (ML) and Quantum Computing where applicable (examples shown in Figure 5). These methods are used to explore and characterize the subsurface without direct access. This is achieved by measuring and interpreting geophysical properties, such as seismic vibrations and the electromagnetic field. The measurements often involve active sources (such as a seismic vibrator, or explosives), but the research is also especially proficient in dealing with passive sources, such as (induced) earthquakes and (ambient) seismic noise. The expertise ranges from data acquisition, through data processing, modelling, and inversion, with special attention to raising the technology readiness level for new developments in the field, such as seismic interferometry, Distributed Acoustic Sensing (DAS) using optical fibers, induced seismicity monitoring and network design.

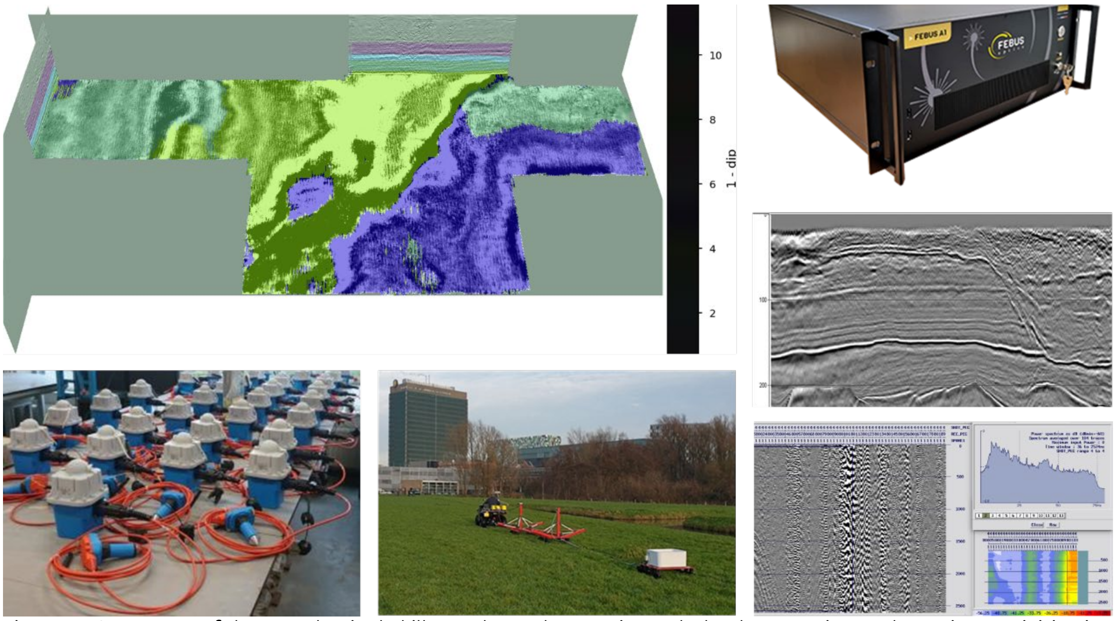


Figure 5. Summary of the geophysical skills, tools, and expertise to help characterize and monitor activities in the subsurface.

Reservoir Modelling & Optimization

This research focuses on the construction of data driven workflows for optimal design, management, and monitoring of the deep formations in the subsurface (including gas disposal / storage sites). The group has developed robust, uncertainty-handling workflows and software tools based on optimization and history matching. The research also extends to developing new management workflows based on Value of Information concepts and on machine learning techniques applied to flow modeling and reservoir/seal studies. Example of detailed geological and reservoir models which can be simulated by this research expertise is shown in Figure 6.

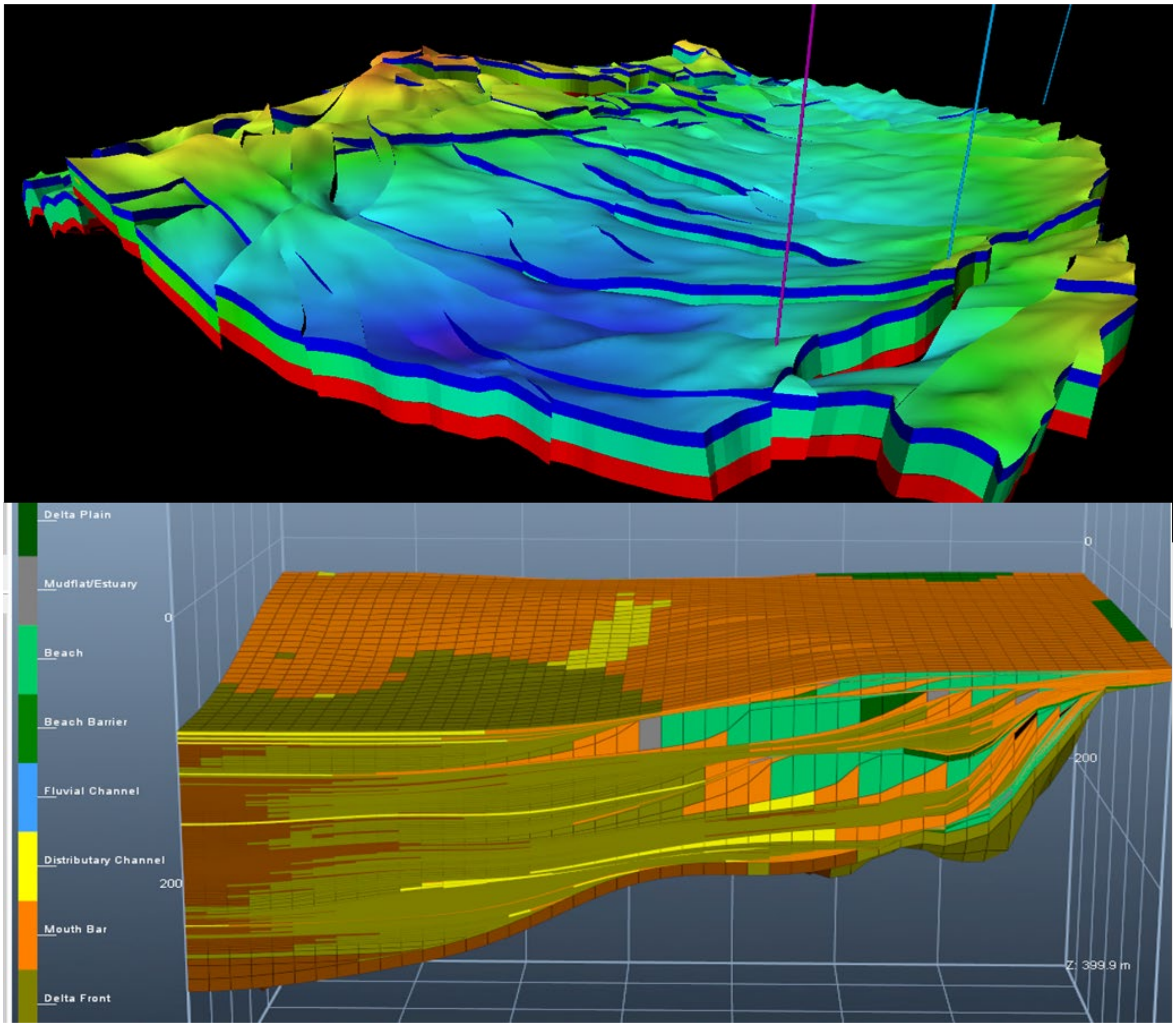


Figure 6. Image above: a typical example of a reservoir scale geological model. Image below: Detailed depositional environment model.

Geomechanics

The GDN geomechanics research focuses on the understanding and modelling of the mechanical behavior of the earth in relationship with anthropogenic activities in the subsurface (Figure 7). Models are applied to HSE risks associated with human activities, but also to economic optimization of subsurface operations. GDN own numerical and experimental facilities (Im4RockLab at TNO Utrecht and the HPT Laboratory at Utrecht University) allow for various mechanical testing to investigate mechanical and flow properties for various subsurface conditions. The integration of experimentally derived material models with geo-mechanical models was enabled through a strong connection with the Utrecht University. The main techniques deployed are (1) seismic and hazard risk analysis, (2) numerical and experimental geomechanical modelling, (3) data assimilation and inversion for subsidence (including multitemporal InSAR and radar remote sensing), (4) hydraulic, thermal and fracture analysis, and (5) damage zone structure and property numerical modelling. TNO geomechanics is currently instrumenting several field observatories near geothermal projects in the Netherlands to monitor microseismicity and deformation (TKI DHARA, TKI Geo4All).

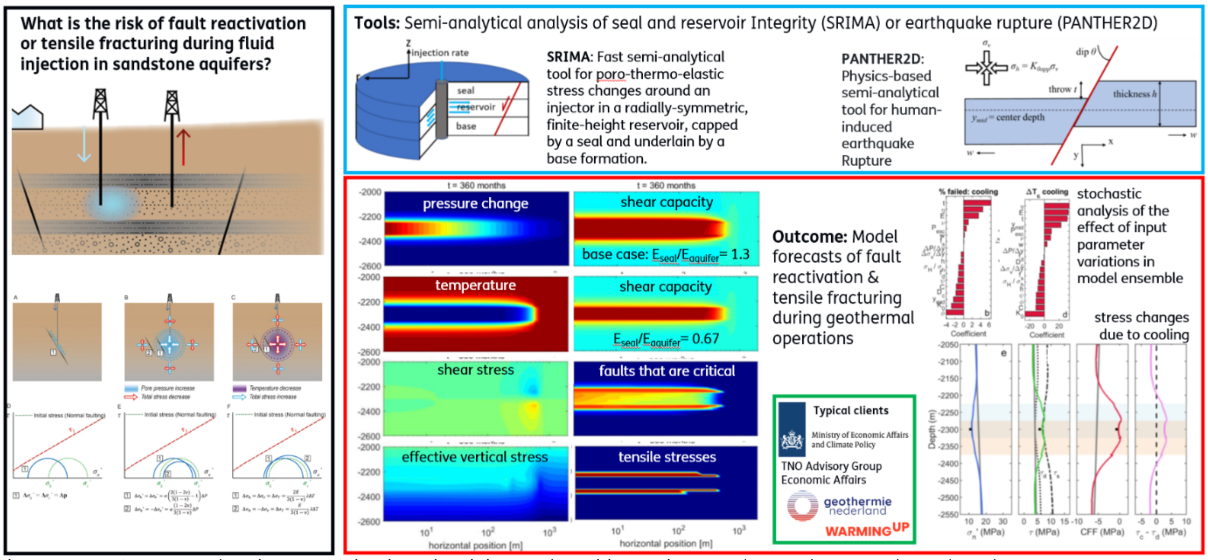


Figure 7: TNO geomechanics expertise in seismicity and seal integrity geothermal research and tool development.

Data/Information/Models

Data and information are key products of the GDN (Figure 8) to allow stakeholders to understand and access the subsurface parameters:

- Geological processes that shape the subsurface,
- Conceptualize processes into identifiable and modelled geological units to guide data interpretation and modelling.
- Use geostatistical tools and expertise to create models from interpreted data.
- Systemizing and automating workflows to reproduce work done on national scale, handling large datasets
- Performing quality assessment.

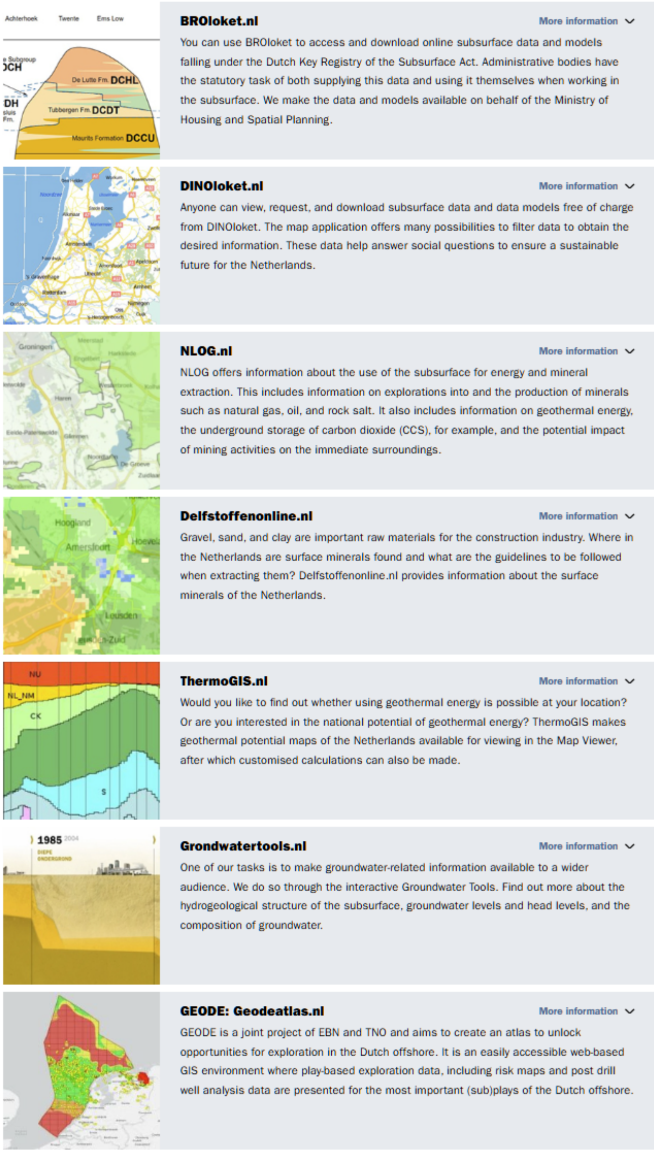


Figure 8: GDN-TNO products (https://www.geologischedienst.nl/en/products/)

At TNO-GDN the focus is on the sustainable use and management of the subsurface in the Dutch on- and offshore regions. For this purpose, is the development and maintenance of a suite of national subsurface models and databases (DGM, DGM-Deep, GEODE, ThermoGIS, VelMod, GeoTOP and REGIS II) which serve the interest of the built environment, groundwater stewardship and geo-energy domains. All these models and databases are freely available online and are commonly used by academic, industry and government entities involved in research, exploitation, management and derisking of the Dutch subsurface.
For the deeper subsurface the management and utilization of information is governed by the Mining Act (Rijksoverheid, 2002), while for the shallow subsurface a new key registry was implemented in 2015 (Van der Meulen et al., 2013; Rijksoverheid, 2015). This key registry is a national database for subsurface data and information, which the Dutch government bodies are obliged to use when making policies or decisions related to the subsurface. GDN has constructed and maintains four national models (DGM-Deep, DGM, GeoTOP and REGIS II – Figure 9), which are all data-driven and stochastic in nature (Stafleu et al., 2019).

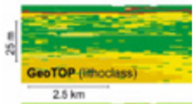
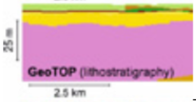
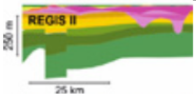
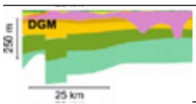
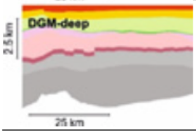
Model	Type, resolution, units	Area, range (depth, strat.)	Attributes	Applications
 	• voxel • 100 x 100 x 0.5 m • 93 geologic units (to date) • 9 lithologic classes	• onshore (current coverage ~75%) • extends to 50 m below Dutch ordnance datum (NAP) • mostly upper Pleistocene - Holocene	Standard: • geological unit probability • lithologic class probability • information entropy Experimental: • seismic velocity • hydraulic properties • geochemical parameters • geotechnical parameters	built environment, hydraulic engineering, geotechnical studies, aggregates potential, subsidence susceptibility (desk) studies
	• stacked layer, parameterized • 100 x 100 m • 131 hydrostratigraphic units (to date)	• onshore • approx. 500 m (max 1200 m) • mostly Neogene and Quaternary	• depth of unit base and top, thickness • aquifers: hor. conductivity and transmissivity • aquitards: vert. conductivity and hydraulic resistance	groundwater management
	• stacked layer • 100 x 100 m • 32 lithostratigraphic units (to date)	• onshore • approx. 500 m (max 1200 m) • mostly Neogene and Quaternary	• depth of unit base & top, thickness	general purpose, base model for REGIS II and GeoTOP
	• stacked layer • 250 x 250 m • 13 seismostratigraphic horizons (to date)	• onshore and offshore • 3-5 km (max ~7 km) • Silesian - Miocene	• depth of horizon, thickness	assessments of geothermal, subsurface storage and hydrocarbon potential

Figure 9: Models created within the GDN. All can be found at dinoloket.nl/modellen; DGM-deep is published on NLOG.nl

DGM-Deep (www.dinoloket.nl/en/subsurface-models/map)

The Digital Geological Model for the deep subsurface (DGM-deep) characterises down to a depth of ca. 10km. The model maps Carboniferous to Neogene seismostratigraphic horizons, using exploration data that energy and mining companies must submit to GDN under the Mining Act. Over several decades, GDN has executed such well-constrained seismic interpretations for both nationwide and regional studies, in the on- and offshore regions. Over 95% of the publicly available 3D-surveys were used in the interpretation (Figures 10 and 11) and all non-confidential wells were consulted.

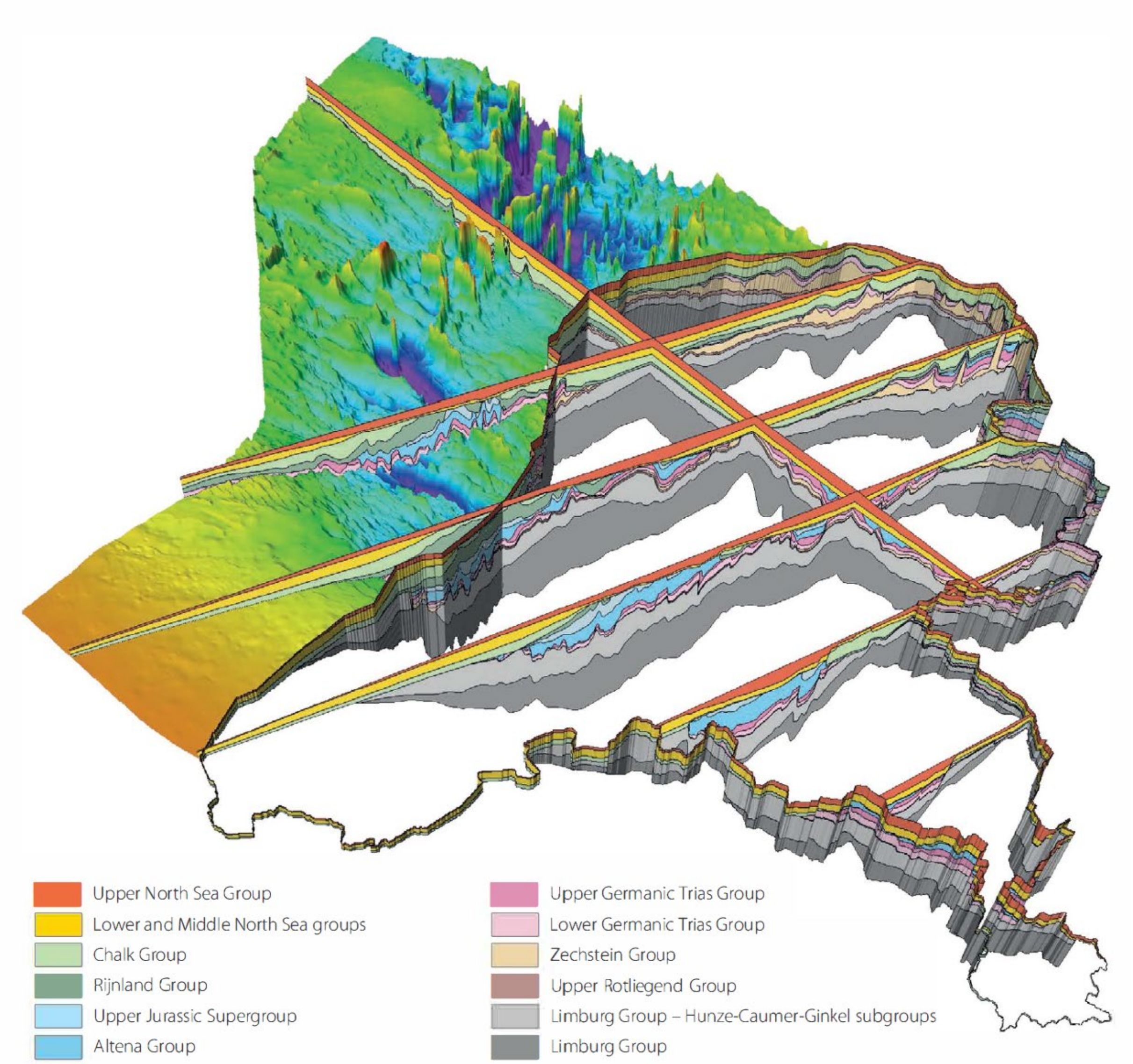


Figure 10: Oblique view on the 3D layer model DCM-deep v5, covering both the on- and offshore domains of the Netherlands. The visualized surface represents the top of the Zechstein Group in the offshore domain. Colour ranges in the offshore indicates depth from shallow (red) to deep (purple). From Stafleu et al., in press)

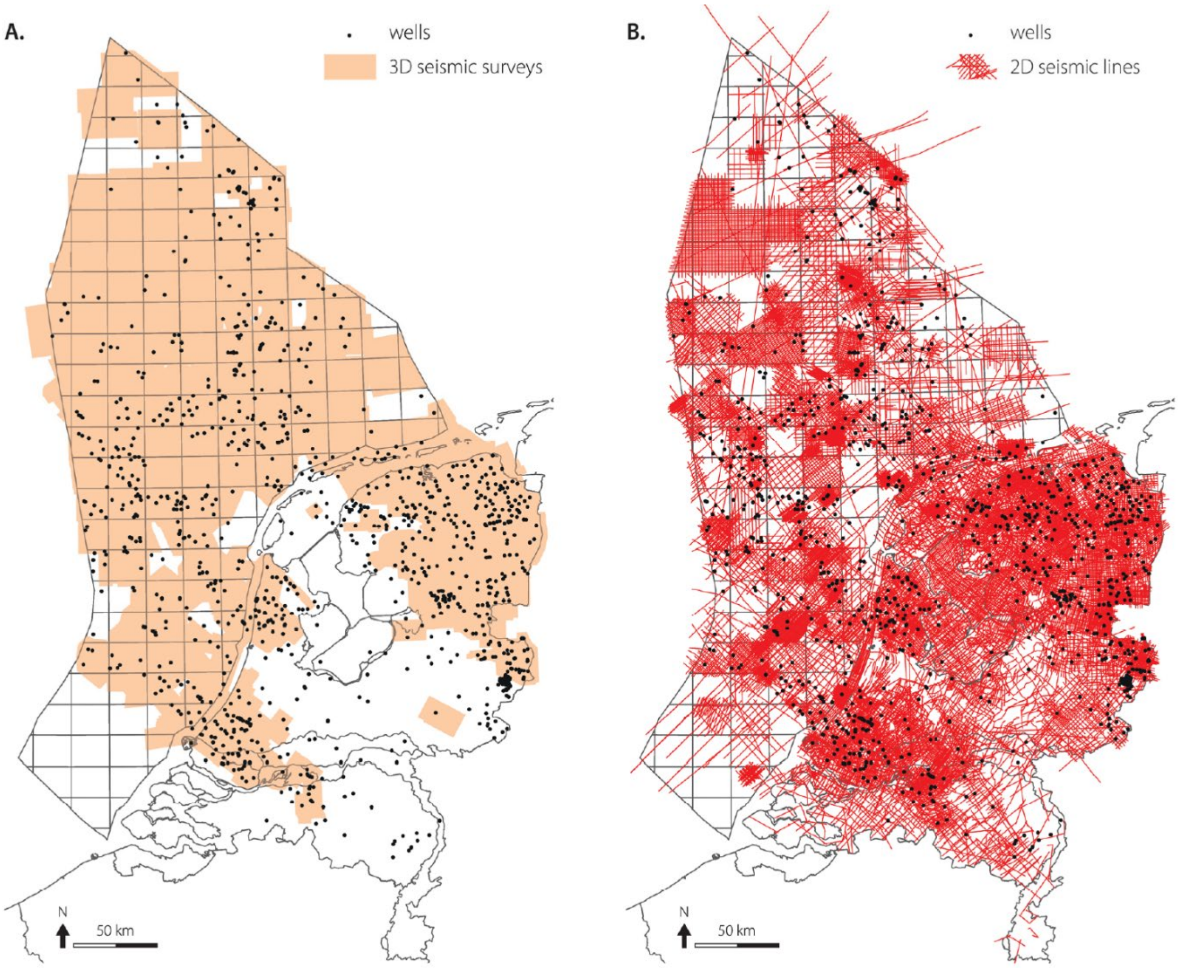


Figure 11: Seismic and well coverage for the DCM-deep model (from Stafleu et al., in press)

DGM and REGIS II (www.dinoloket.nl/en/subsurface-models/map)

The Digital Geological Model for the shallow subsurface (DGM) and the Regional Groundwater Information System II (REGIS II) reach down to a depth of 500m in the Dutch subsurface, these models map the geometries and hydrological characteristics of the shallow subsurface. The DGM model is constructed using a set of 26,500 boreholes and serves as the framework for the REGIS II model, which subdivides lithostratigraphic units into hydraulically parameterized hydrogeological units. REGIS II is the de facto hydrogeological standard used in groundwater flow models and other assessments for Dutch water and environmental authorities (Figure 12).

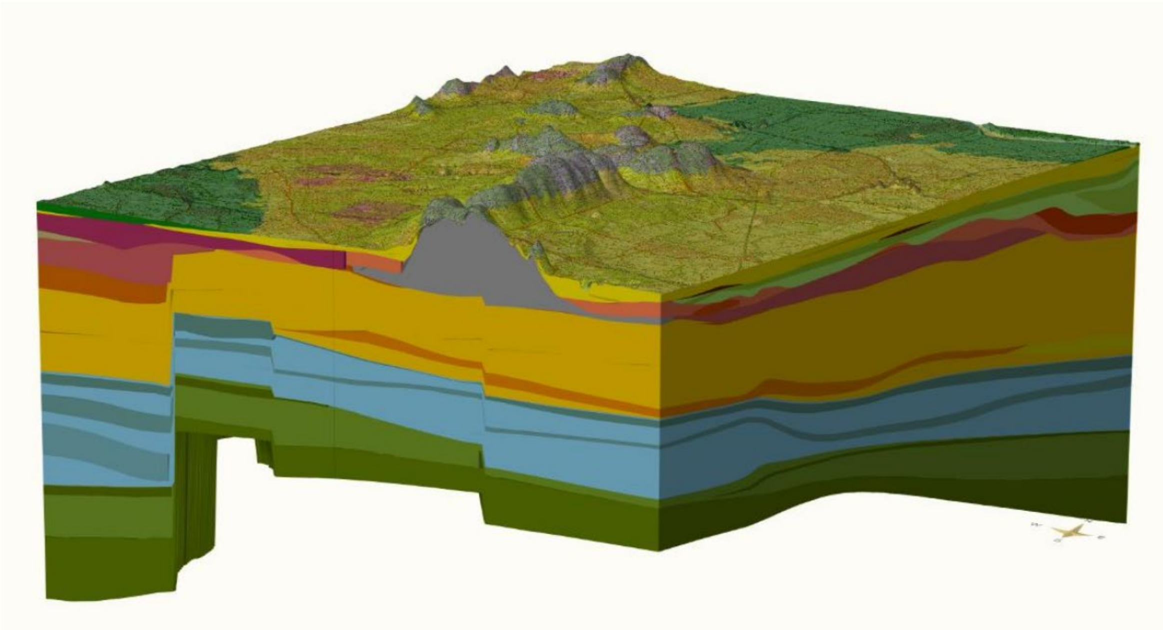


Figure 12: Example of a 3D visualization in REGIS II

GeoTOP (www.dinoloket.nl/en/subsurface-models/map)

GeoTOP maps the subsurface down to 50 m the lithostratigraphy and lithology of the Neogene, Pleistocene, and Holocene stratigraphic record in a 3D voxel model. GeoTOP is a multi-purpose model supporting several applications involving the shallow subsurface, for example the planning of large infrastructural works, land subsidence predictions, groundwater flow studies and site-response assessments of induced earthquakes (Figure 13).

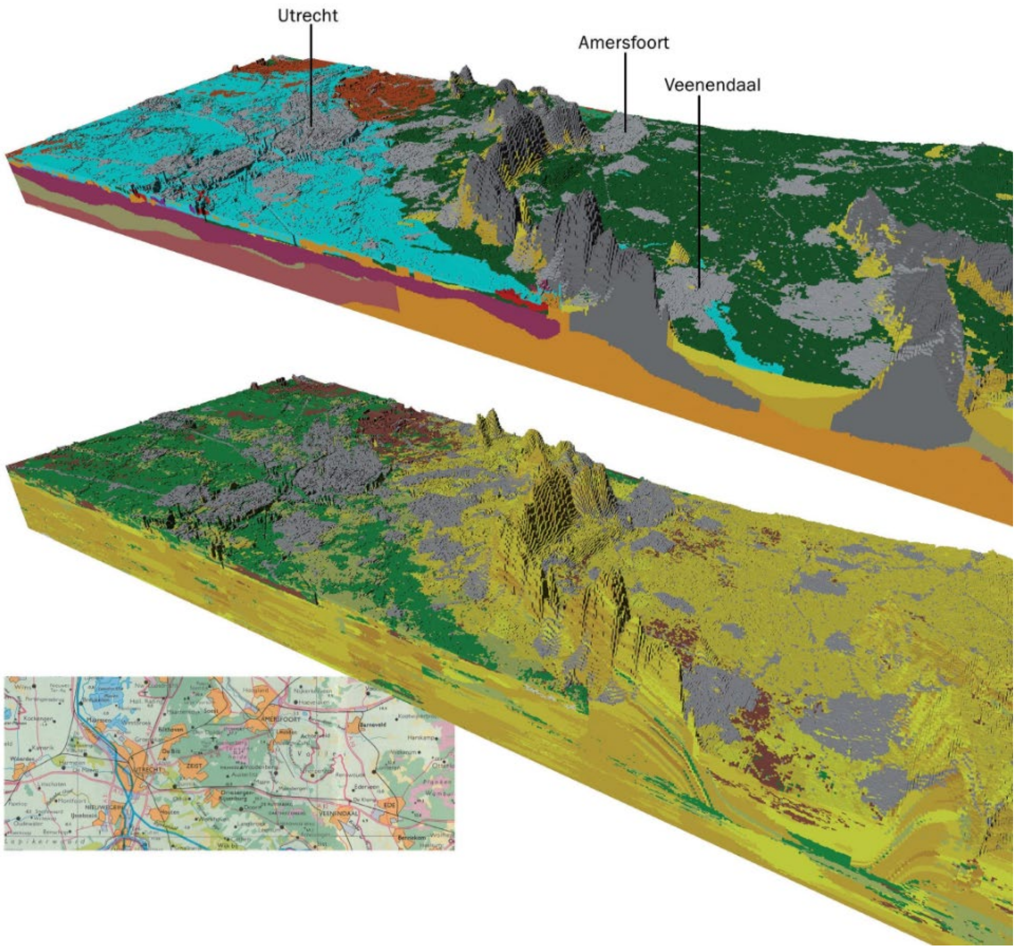


Figure 13: 3D representation of the GeoTOP model

GEODE (https://www.geodeatlas.nl/)

The GEODE atlas is a joint initiative of EBN B.V. and TNO. Its main goal is to provide an easily accessible, web-based GIS environment where play-based exploration data and specialist knowledge are consolidated, such as net-to-gross, porosity, paleogeographic or fault maps (Figure 14). The online platform provides a support of the future economic exploitation and energy storage needs of the Netherlands in formats that can be easily accessed and transfer (ArcGIS, Annotated play maps, web-based viewer).

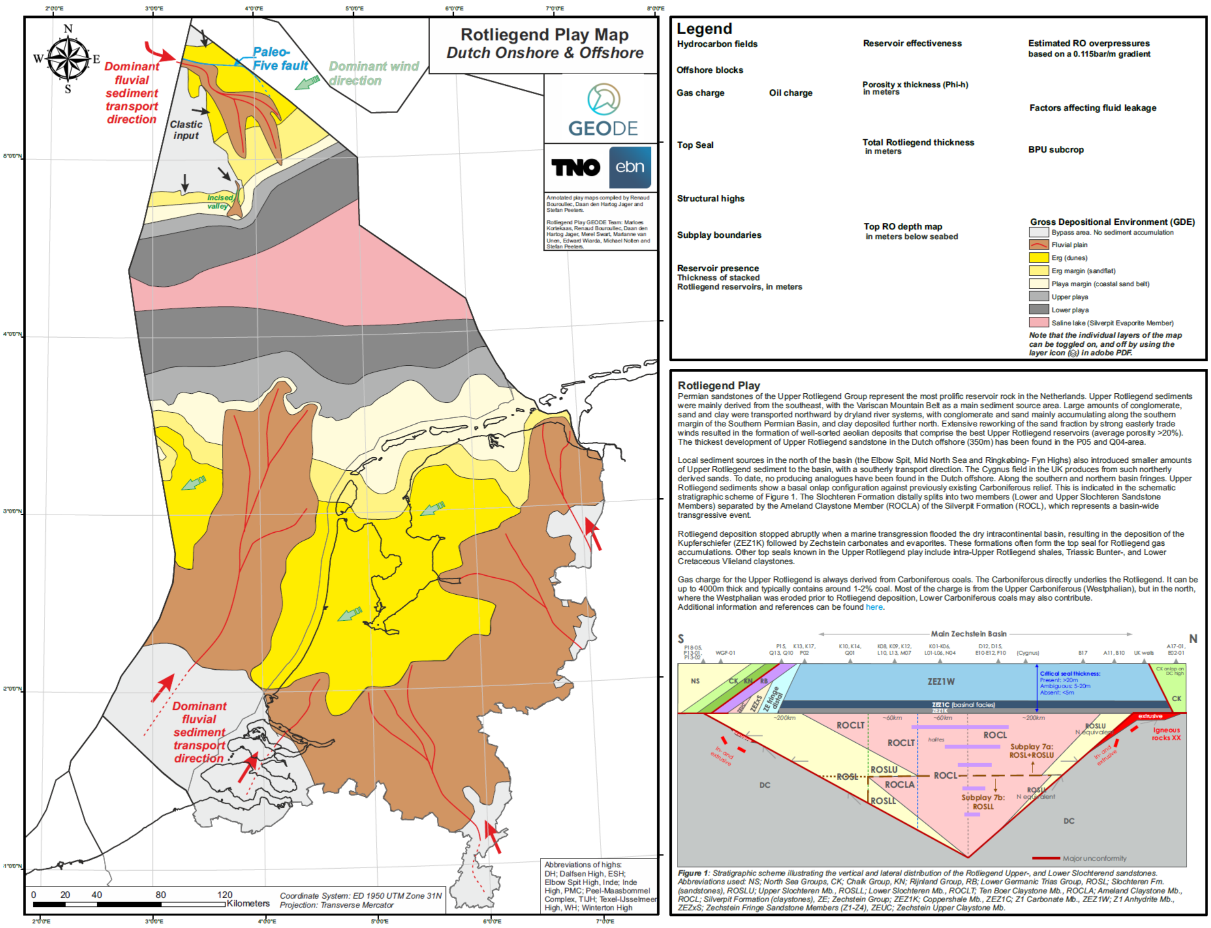


Figure 14: Paleogeographic map of the Upper Slochteren (Rotliegend Group, Permian) from the GEODE atlas

ThermoGIS (https://www.thermogis.nl/)

ThermoGIS ,which is unique in the Netherlands and abroad, is a platform composed of modules for temperature modelling of sedimentary basins, high resolution thermal property representation, tectonic heat flow, reservoir property mapping and techno-economic models (Figure 15). This platform is a public, web-based geographic information system that displays the regional potential of geothermal energy in the Netherlands using several subsurface maps. The main goal of ThermoGIS is to support industry and governments in developing geothermal heat extraction from the Dutch underground.

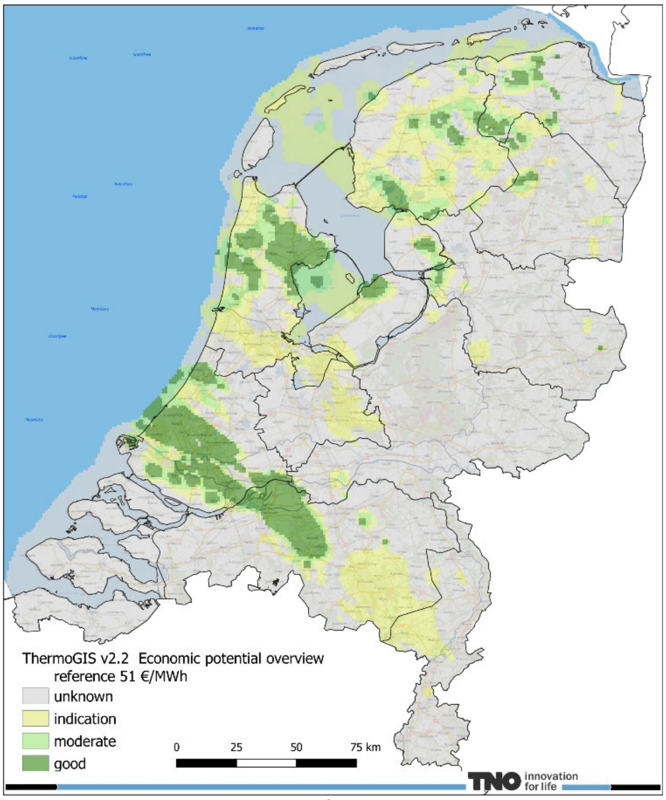


Figure 15. Economic potential of the Netherlands (www.thermoGIS.nl)

VelMod (https://www.nlog.nl/en/seismic-velocities)

The VELMOD regional velocity models has been developed for supporting the DGM model, using velocity data recorded in wells (sonic logs and time-depth relationships). The ‘layer cake’ approach has been applied for all lithostratigraphic units Mesozoic and Cenozoic units. Each latest version of VELMOD includes various changes, such as a switch from analogue to digital, increased data density and more detail in the lithostratigraphic units (Figure 16).

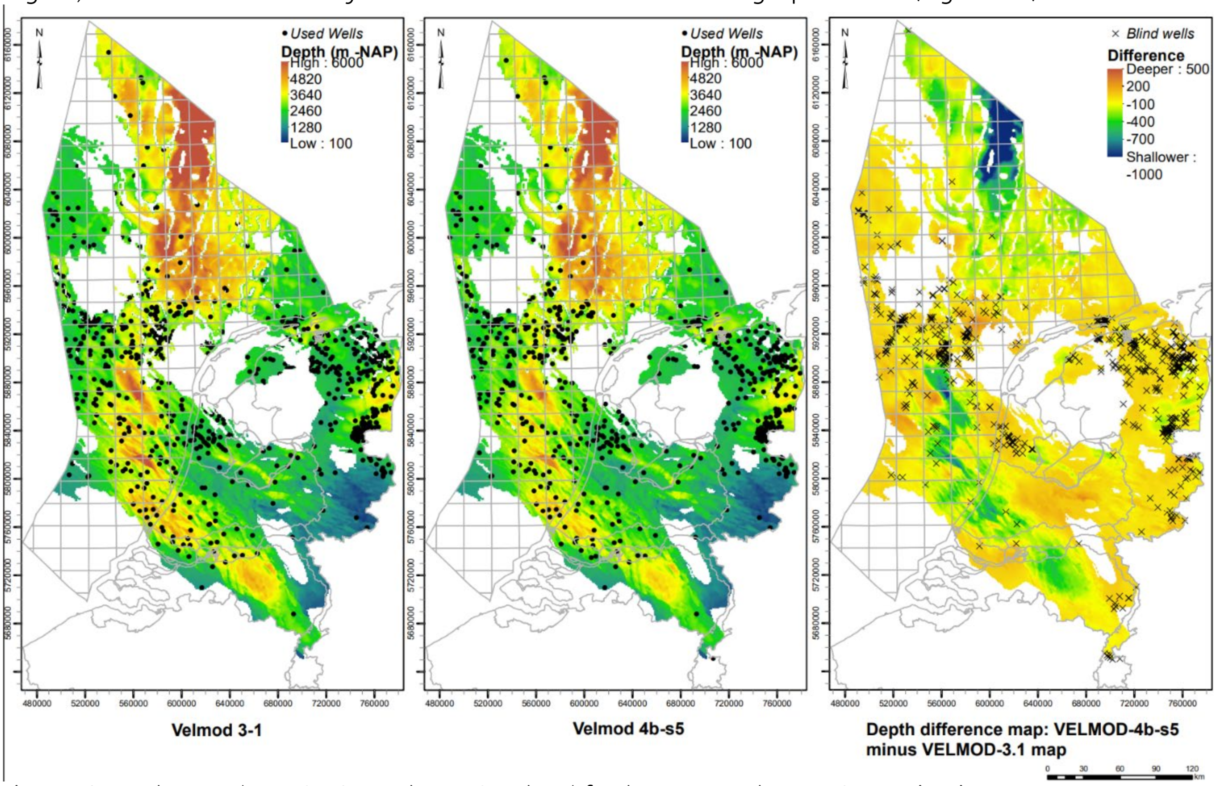


Figure 16: Depth maps (VELMOD-3.1 and VELMOD-4b-s5) for the Upper and Lower Germanic Trias groups

Datasets

Beside the models and map products accessible via the GDN-TNO models, a diverse collection of datasets, maps and reports are also available for download from NLOG (https://www.nlog.nl/), including:

- Boreholes (including cores) data (https://www.nlog.nl/datacenter/brh-overview)
- Seismic data (https://www.nlog.nl/datacenter/smc-lines)
- Fields (https://www.nlog.nl/datacenter/field-overview)
- Licences (https://www.nlog.nl/datacenter/lic-overview)
- Reservoir characteristics (maps and properties) - https://www.nlog.nl/en/reservoir-characteristics
- Pressure data (https://www.nlog.nl/en/pressure-data) (https://www.nlog.nl/en/pressure-data) (https://www.nlog.nl/en/pressure-southern-north-sea-psns-database)
- Maturity (https://www.nlog.nl/en/maturity)
- Gas properties (https://www.nlog.nl/en/gas-properties)
- Gravity and magnetic field (https://www.nlog.nl/en/gravity-and-magnetic-field)
- Geomechanical data (https://www.nlog.nl/en/geomechanical-data)
- Temperature data (https://www.nlog.nl/en/temperature-data)
- Reports (https://www.nlog.nl/kennisbank)

Software capabilities

GDN-TNO routinely uses various commercial software suites. The main software used in the characterization of the deep subsurface are Petrel (Schlumberger), PaleoScan (Eliis), OpenDtec (dGB), PetroMod (Schlumberger), Eclipse (Schlumberger), Diana FEA (Geomechanics) and 2DMove (Midland valley). GDN-TNO has also developed several specialized software codes for different applications, such as EVEREST, Basin3D, DoubletCalc, ThermoGIS, PetroProb and OPM.

6 Technologies, Facilities and Labs

6.1 TNO-GDN Central Core Storage (Zeist) https://www.nlog.nl/en/core-collection-geological-survey

For over a century, the central core storage of the Geological Survey of the Netherlands collects drill cores, cuttings, slabs, lacquer profiles and other materials from the Dutch subsurface. The collection contains material from both the shallow and deep (subject to the Mining Law) subsurface (Figure 17). This is the largest, physical inventory and long-lasting record of the shallow to deep subsurface of the Netherlands and its offshore territories. The amount of available subsurface material is ever growing and is invaluable for research and in projects that make use of the Dutch subsurface. Typical visitors are geoscientists from TNO, from universities (including students and researchers, for training and research), reservoir engineers from energy companies and mining companies.

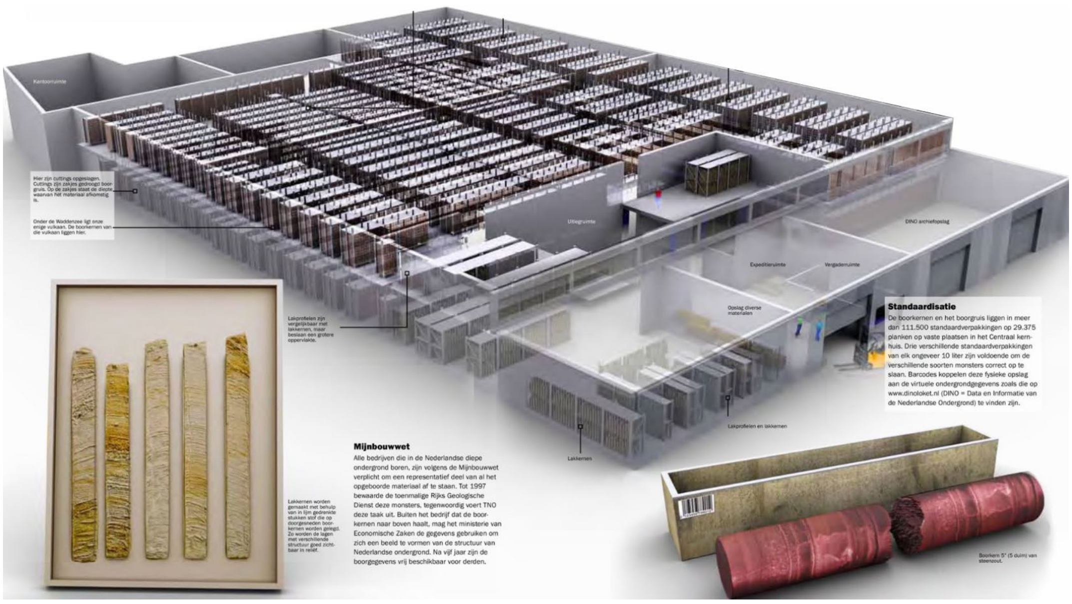


Figure 17: Rendered 3D view of the GDN-TNO Central Core Storage in Zeist

6.2 TNO-GDN Borehole Sample Laboratory (Utrecht)

The GDN has a borehole sample laboratory where rock core samples taken from the subsurface can be analyzed and quantitative information collected (including sample images captured in the in-house photographic laboratory (Figure 18). The sample descriptions are also stored in the DINO database (https://www.dinoloket.nl/en).

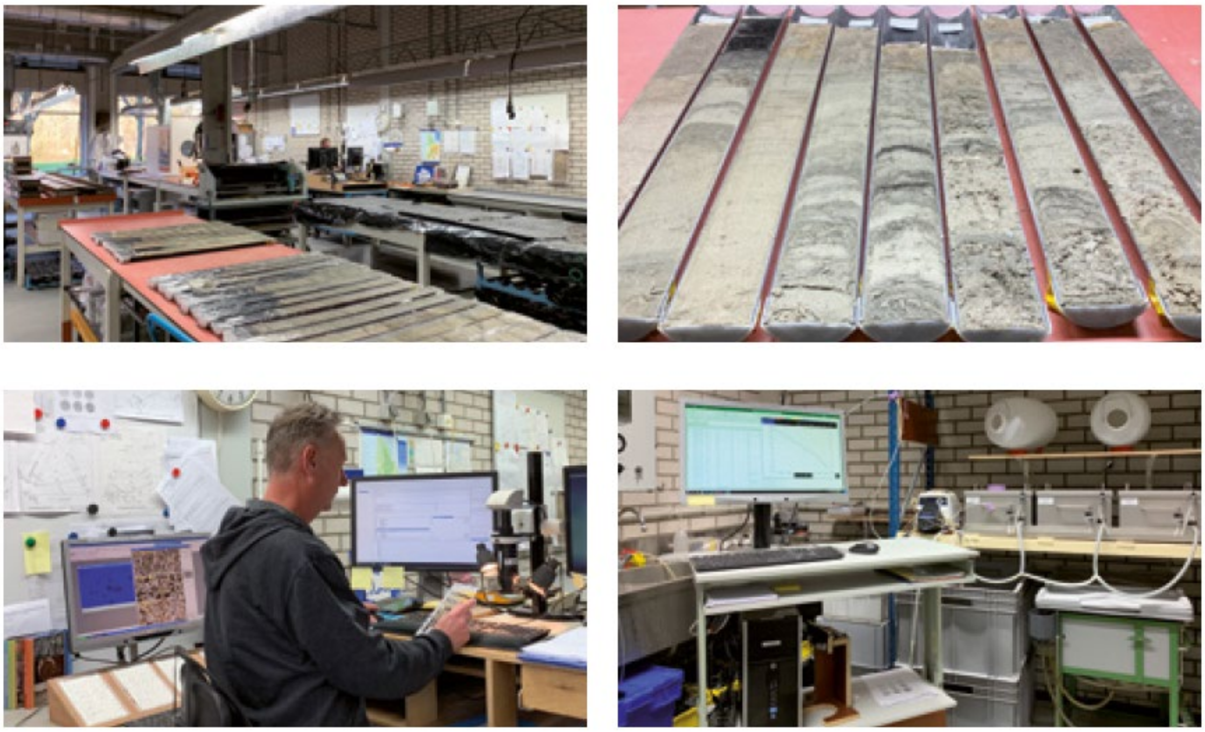


Figure 18: Top left: Images of GDN core description laboratory. Top right: Cut core samples in a PVC liner. C) A lab technician doing grain-size and petrographic analysis. Bottom right: Detail of our hydrolab.

6.3 TNO-GDN – Im4RockLab (Utrecht)

https://www.geologischedienst.nl/en/facilities/geomechanics-laboratory-im4rocklab/
This geomechanics laboratory is equipped with two triaxal apparatus with associated flow pressure pumps for investigation of geological and geomechanical parameters and processes. This laboratory allows for better validation and calibration of numerical geomechanical and reservoir model forecasts by using real rock samples in analogous subsurface conditions (Figure 19). The facility also closely collaborates with the HPT Laboratory at Utrecht University.

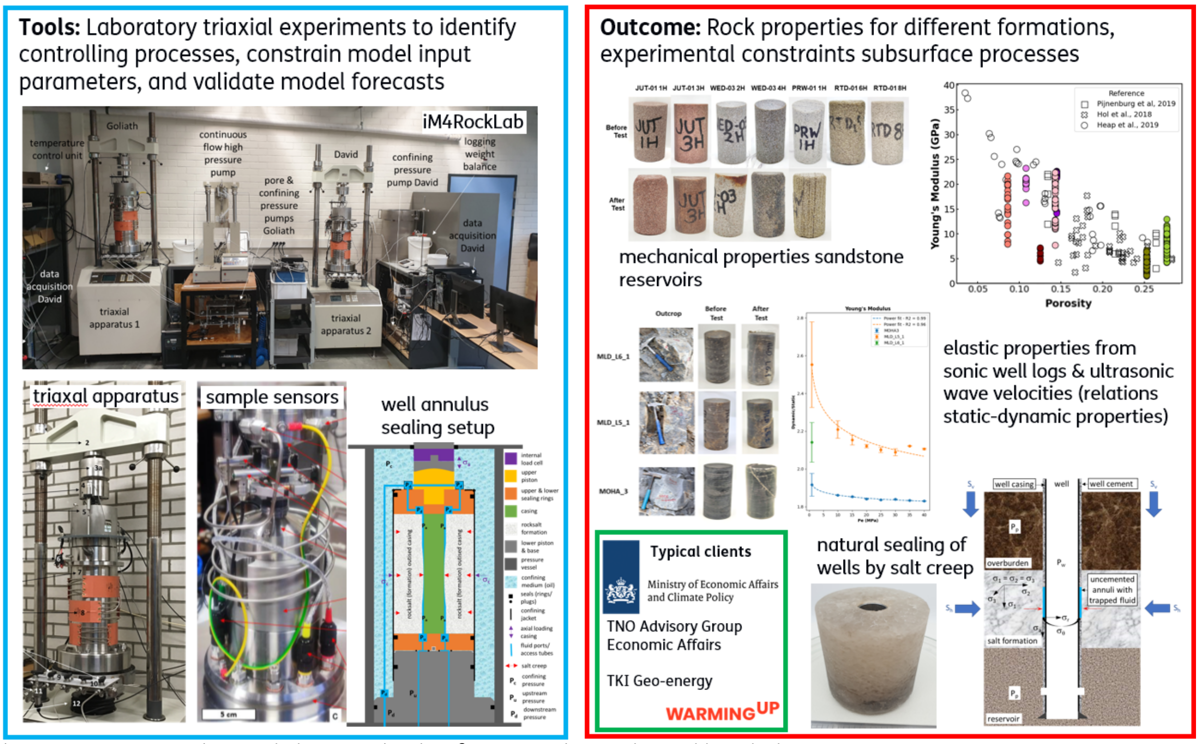


Figure 19: TNO experimental characterization for reservoirs, seals, and boreholes.

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6.4 Rijswijk Centre for Sustainable Geo-energy (RCSG) www.rcsg.nl

Developing technology for the ultra-deep subsurface involves a significant challenge that requires conducting experiments and tests under conditions representative of the expected subsurface conditions at these depths. This is similar to the need for de-risking technology in mining and well construction, where testing ideally requires access to a mine or a borehole that mirrors the intended operational setting. However, test sites for such applications require substantial investments and are technically challenging to operate. Currently, there is no single facility that enables comprehensive testing for all aspects of ultra-deep borehole technology.

For well technology, the TNO has a research facility in Rijswijk known as the Rijswijk Centre for Sustainable Geo-energy (RCSG), an open innovation center for geo-energy that offers unique and world-class research opportunities to support research on geothermal energy and other subsurface technologies. The facility allows full-scale testing and demonstrating new drilling techniques which includes specialized equipment such as a drilling rig (Figure 20), high-pressure drilling units, large-scale pressure vessels, and systems for studying fluid flow and material behavior under high pressure and temperatures.

The RCSG is used for developing and testing various borehole technologies, including innovations in drilling, well construction, borehole monitoring, and borehole sealing using materials such as bentonite. Current research projects focus primarily on geothermal energy but also extend to other areas, such as carbon capture and storage (CCS), hydrogen storage, and borehole abandonment. The center's infrastructure is designed to enable experiments that replicate real-world subsurface conditions, such as high pressure and temperature, allowing researchers to observe and evaluate the performance of new technologies.

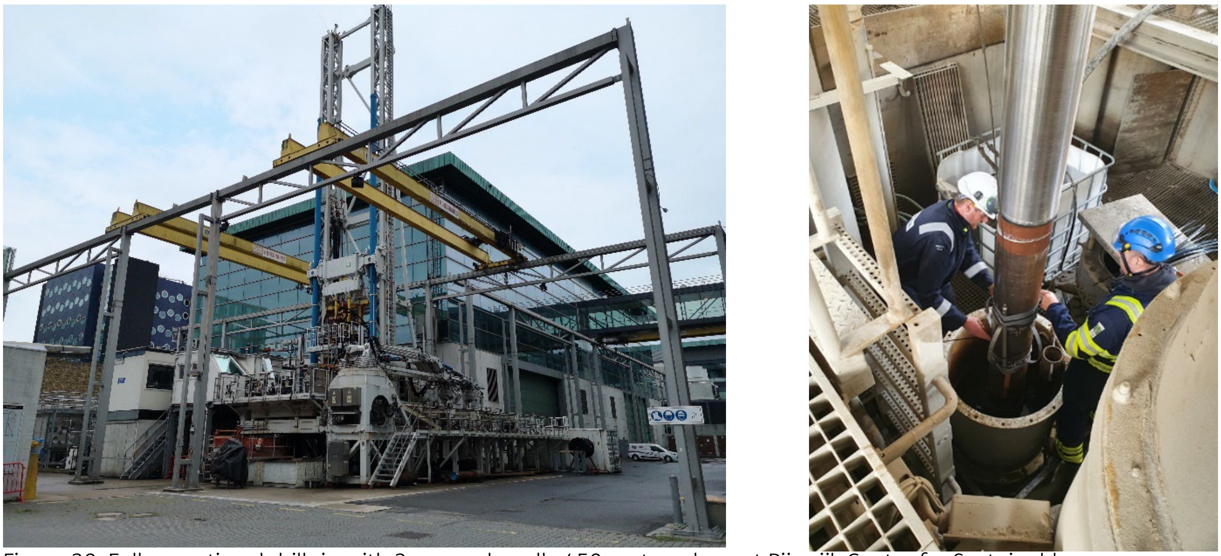

Figure 20: Full operational drill rig with 2 research wells 450 meters deep at Rijswijk Centre for Sustainable Geo-energy

The RCSG is particularly suited for large-scale experiments that require representative subsurface conditions (Figure 21). The ability to control key parameters, such as pressure, temperature, and flow dynamics, allows for precise testing and qualification of technologies. Testing in this controlled environment enables systematic evaluation of the operational limits of a system or technology, which is essential before moving to a pilot test site which can be inherently expensive. By providing a controlled intermediate step, the RCSG helps reduce the risks associated with full-scale field implementation.
TNO experts and external researchers use the facility to conduct experiments and demonstrations. The center is designed to accommodate a stepwise testing approach, beginning with controlled laboratory experiments and progressing to large-scale, realistic simulations. This structured approach ensures that technologies can be systematically tested and improved before deployment in the field.

Figure 21: Research equipment at Rijswijk Centre for Sustainable Geo-energy. Lower left: building research well; lower right: high pressure drill bit test; upper left: cutting removal flow tests; upper right: rock strength test.

In addition to supporting research for geothermal energy and other subsurface applications, the RCSG is well-positioned to contribute to studies on radioactive waste disposal in ultra-deep boreholes. Geological disposal of radioactive waste requires an integrated understanding of both geological conditions and well technology. These aspects are closely interrelated: geological data are essential to assess the containment properties of deep

formations, while well technology ensures safe drilling, waste emplacement, and final borehole closure.
The RCSG provides the infrastructure to investigate several key topics relevant to radioactive waste disposal in deep boreholes. Potential areas of research include:

- **Formation Properties:** Assessing permeability, mechanical strength, and other properties of geological formations under representative conditions.
- **Drilling Technology:** Testing and optimizing methods for drilling ultra-deep boreholes.
- **Liner and Casing Placement:** Evaluating placement techniques to ensure borehole stability during construction and operation.
- **Canister Placement:** Developing and testing procedures for safely lowering radioactive waste canisters into boreholes.
- **Liner and Casing Removal:** Investigating techniques for removing casings and liners to prepare for borehole closure.

- **Borehole Backfilling and Sealing:** Testing engineered barriers such as bentonite and methods for restoring the formation during borehole closure.
- **Monitoring Systems:** Developing and testing systems for monitoring the integrity and performance of boreholes during and after operations.

6.5 Test Facility at Huisman Equipment BV

In addition to the facilities at TNO, Huisman Equipment BV in Schiedam houses a large-scale drilling rig that offers complementary capabilities. This rig is approximately three times the height of a single drill rig, such as the one in Rijswijk, and is particularly well-suited for testing and demonstrating technologies for ultra-deep canister placement and retrieval (Figure 22).
The Huisman installation features a 400-meter-deep test well with a diameter of 0.5 meters. The upper section of the test well has an expanded diameter of 3 meters and extends to a depth of 50 meters. While a detailed analysis of this facility is beyond the scope of this report, it represents a valuable resource for advancing drilling technologies and validating operational procedures under highly specific conditions relevant to ultra-deep borehole disposal.
Both facilities, with their distinct capabilities, contribute to the development and de-risking of ultra-deep borehole technology for radioactive waste disposal.

Figure 22: Huisman test facility in Schiedam

6.6 Other relevant academic departments and collaborations

Several Dutch universities have specific and often complementary research, technologies, and laboratory than TNO-GDN and collaborations occur on regular basis in many domains. As an example, the TNO-GDN geomechanics team are actively involved in multiple DeepNL projects on induced seismicity, co-supervising PhD students from the department of Earth Science Utrecht University (Department of Earth Sciences - Utrecht University) and the department of geoscience & engineering TU Delft (Geoscience & Engineering) to improve understanding of Dutch subsurface (https://www.nwo.nl/en/researchprogrammes/deepnl)

GDN-TNO is part of the EPOS-eNLarge Roadmap for Large-Scale Research Infrastructure project (https://epos-nl.nl/enlarge/) a Dutch contribution of national research infrastructures to provide services for scientists in the Netherlands and Europe to undertake research for understanding subsurface processes. TNO-GDN facilities such as Rijswijk Center for Sustainable Geo-energy (RCSG) and the TNO-GDN geomechanical Im4RockLab in Utrecht are part of the multi-scale research infrastructure in this nation-wide project, together with laboratory and field observations at Utrecht University, TU Delft and KNMI (https://www.knmi.nl/home)

Below is a non-exhaustive list of academic institutions and groups that are of importance in the topics surrounding ultra deep disposal. This list below does not cover the breadth of the applicable Dutch academic research topics yet clearly show the complementarity of disciplines, technology, laboratories,and knowledge with those of TNO-GDN.

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